Overhead Line Electrification for Railways

Garry Keenor CEng FPWI MIET
Version Details

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<th>Edition</th>
<th>Date</th>
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<td>6th</td>
<td>October 2021</td>
<td>Additional and expanded sections</td>
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<tr>
<td>5th</td>
<td>December 2018</td>
<td>Additional sections and diagrams, photo refresh</td>
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<tr>
<td>4th</td>
<td>November 2016</td>
<td>General update and refresh, GW and Series 1 practice included, general legislation and best practice update, focus on GLRT1210.</td>
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<tr>
<td>3rd</td>
<td>February 2012</td>
<td>General update, trolley bus section added</td>
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<tr>
<td>2nd</td>
<td>August 2008</td>
<td>AC &amp; DC supply principles sections expanded, protection section expanded, materials section added, turnout wiring section added, spanwire portal added.</td>
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<tr>
<td>1st</td>
<td>October 2004</td>
<td>First issue</td>
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1. Foreword

Since the earliest days of railways it has been obvious that it is senseless to haul the power plant around with the train. Isambard Kingdom Brunel clearly understood this. He realised that not carrying the weight of the steam engine gave significant advantage. Never one to pass by the opportunity to be in the vanguard of technical novelty, in 1840 he took on the building of the South Devon Railway over the Devon Banks. Seduced by the possibilities that technology used by the London and Croydon Railway offered, he advised the use of the "Atmospheric System". This used fixed steam engines to create a vacuum, and a 15 inch diameter pipe between the rails. A slot with a seal in the top of the pipe allowed a piston attached to a tow truck to be pushed along by atmospheric pressure.

Ignoring the reservations of his great locomotive Engineer, Daniel Gooch, the obvious railway operation limitation of a system only operable as a single line, and the folly of relying on greased leather as the only available way to seal the top of the tube around the mechanical connection between piston and truck, Brunel gambled the South Devon shareholders’ capital. The decision drove that company to near bankruptcy, presented Gooch with the problem of building powerful enough locomotives to haul the trains and left us to this day with a line so aggressively graded and curved that train speeds remain severely restricted.

It is easy to dismiss the attempt to build a railway needing no self-powered locomotives as an act of hubris, but Brunel was in fact right; hauling the source of motive power is restrictive of train speed, causes more rapid degradation of the rails and track supports and is energy-inefficient. Mid-19th century technology was unable to realise Brunel’s ambition, and it was not till 20 years after his death that the eventual solution began to emerge.

In 1879 Siemens and Halske demonstrated a technology destined to mature into electric traction. Siemens had produced an electric locomotive picking up electrical supply from fixed conductors at the side of the track.

Various systems for electric traction emerged; conductor rails on the ground and overhead lines were developed in various forms, some more successful than others. Whenever analysis has been undertaken through the last century, electric traction has always been found superior. But there is another theme which runs constantly through that history. Whilst the benefits of electrification of a railway are beyond debate, the capital cost of the fixed equipment and the service disruption involved in building the system leave no margin or fat in the cost benefit case. For that reason, in the UK electrification of the main line railways, which started in the late 19th Century, is still not complete.

The fifth edition of this book has been widely praised, accepted as required reading by practitioners in the UK (and across many other countries) and is an established reference guide for designers and engineers. This revised edition updates and adds to the wealth of detail. Practical examples are presented in such a clear and practical way that the book will be indispensable for beginners new to the discipline through to those with much longer experience.

Garry Keenor writes about and presents the complex and deeply technical aspects of OLE in a way which is engaging, and shares his widespread and deep knowledge making a great contribution to equipping future generations of Engineers and Designers to understand the intricacies of electric traction overhead line.

Since the first edition was published much has changed - changes to which the railway and indeed wider society must respond. Climate change due to human activity is no longer credibly questioned by anyone. The UK government has committed to a legally binding aim to bring our whole economy to net zero carbon by 2050. Transport is a significant contributor of atmospheric carbon and the only sector which is not reducing its burden; and so the railway has developed plans for traction decarbonisation. Battery and hydrogen powered trains will be part of that response, but neither technology can support high speed or heavy loads. The plan
is therefore to roll out overhead electrification across an additional 15,000 single track kilometres by 2050. All this must be done within the available resources of the UK economy and with competition for those resources from other sectors. It will be engineers who will lead the definition of economically affordable and practical answers to the many challenges that will bring.

With better background knowledge Engineers and Designers can produce better results. The challenge that all of us who dedicate our working lives to the traction electrification discipline is to keep the cost of electrification at a point where the economics work. The climate emergency means the case for finally providing a practical solution over the Devon Banks remains valid, and is in the traction decarbonisation plan. The continued relevance of railways in a post-carbon emissions world demands affordable solutions. For the specialist electrification Engineers and Designers who must rise to meet that challenge, this book will assist them along their path.

Peter Dearman
July 2021
2. Preface to the 4th Edition

The genesis of this book lies in a presentation I gave in 2003. A client on a major resignalling scheme asked for a lunchtime session on overhead line electrification, since most of their staff were unfamiliar with the system; and for the first time in my life my ego won out over my fear of public speaking and I accepted. The request for 30 minutes of material was soon forgotten in my new-found enthusiasm for powerpoint, as I proceeded to cram all my knowledge at that point into a file which grew to more than 70 slides.

The final product came in at over two hours, and I knew I was in trouble. Luckily my client was understanding and arranged to extend the session. I’m glad to say that my audience were also in forgiving mood, and most of them were still awake at the end. However, I had learned an important lesson: don’t overstay your welcome on the stage.

So, having stripped back the talk for future sessions, I needed somewhere to put the more comprehensive material. I had always been struck by the paucity of accessible literature around the subject; when I was entering the industry at the tender age of 19, I was handed a slim booklet titled "Railway Electrification: 25kV a.c. Design on B.R."\(^1\), and that was it. At the other end of the scale there is of course the standard text on the subject, "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance"\(^2\); but although fearsomely comprehensive (and expensive), even the most able engineer would not describe it as an easy read.

I therefore resolved to write something which would provide an approachable and reasonably comprehensive study of overhead contact systems, which would explain the *why* as well as the *what*, aimed at people with a basic mechanical and electrical knowledge who are new to the topic. In essence this is the book I would like to have been given when I joined British Rail as a graduate trainee. At the end of the book you will not be able to undertake all the tasks involved in OLE design, but I hope you will understand what needs to be done and why.

I am always nervous when an experienced colleague asks for a copy of the book, perhaps for one of their trainees. I do not pretend that everything is covered, and the book is inevitably biased towards my experience, which is predominantly 25kV AC systems in the UK. It is also exhibits a bias towards the mechanical side, with the electrical sections being less comprehensive. Additionally, this year’s best practice can quickly become last year’s unwise experiment, and so it is necessary to refresh the book from time to time.

3. Preface to the 5th Edition

The 4th edition was the first to be placed in the public domain, and I was naturally keen to get it published after months of preparation. A number of additional topics warranted inclusion, but some items weren’t ready in time for publication - like so many engineers I have a troubled relationship with deadlines. The 5th edition includes these new sections and is (I think) the first complete version - in terms of topics at least.


When I wrote the words above for the 5th edition, I genuinely believed them. Alas, it is now clear they were pure hubris; in a system as complex as a railway there is always more that can be written, and further topics to

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cover. Never again will make the mistake of claiming that the book is complete!

This edition contains several new sections that are beyond my own competence, and so I have leaned very heavily on both the written work of experts in their fields, and the kind assistance of several of those experts in checking my drafts.

New sections are as follows:

- Section 7.6 - alternative traction options;
- Section 10.2.2 - supply transformers;
- Section 10.2.4 - isolating transformers;
- Section 10.7.5 - rationalised auto transformer system protection;
- Section 10.2.8 - LV DC supply equipment in substations;
- Section 10.7.6 - power interlocking;
- Section 10.8.1 - voltage controlled clearances;
- Section 11 - electric traction;
- Section 12.19 - vehicle incursion, wildlife, vandalism and icing mitigations;
- Section 15 - trolley systems;
- Section 16.1 - 50kV OLE;
- Section 16.4 - inclined OLE;
- Section 16.7 - offset OLE;
- Section 16.6 - roundhouse OLE;
- Section 16.8 - electric-steam traction;
- Section 17.3.1 - bridge fixings;
- Sections 17.4 and 17.5 - OLE in modern and historic tunnels;
- Section 17.9.1 - signal supply points;
- Section 17.12 - overhead power lines;
- Section 18 - the planning phase;
- Section 19.1 - surveying;
- Section 20 - the construction phase;
- Section 20.2.2 - training spans;
- Section 21.5.1 - tether testing;
- Section 21.8 - entry into service;
- Section 21.9 - As Built drawings.

Updated sections are as follows:

- Section 7.3 - advantages of OLE;
- Section 10.1.3 - AC supply principles;
- Section 10.7 - protection, monitoring and control;
- Section 12.5 - turnouts;
- Section 17.8 - telecoms interfaces;
- Section 19 - the design phase.

New or amended sections are shown with a change bar (as right).

This edition also included a large number of new and improved images and diagrams. It also affords
the opportunity to correct several errors pointed out by readers of the 5th edition\(^3\). However new material means new potential for errors, so as always, corrections or clarifications are gratefully received at garry.keenor@gmail.com, or via twitter where I am @25kV.

The positive reception to the 4th and 5th editions has been overwhelming, and it is always nice to see a copy on someone’s desk in an office, or in the background on a video call. I hope you will find this edition just as useful.

5. Acknowledgements

The production of this book is far from a solo effort, and for the 6th edition I relied even more on experts in fields adjacent to mine than for previous ones. I am incredibly grateful to all the individuals who have been so generous with their valuable time, expertise and encouragement.

The following people have provided specific input:

Zoe Armitage helped me understand geotechnical survey practice; Brian Armstrong helped with earthing and bonding; Graeme Beale provided help with side wear; Louise Benwell provided programme management expertise; Matt Bowey provided numerous corrections and clarifications; Ron Broomfield kindly donated his copy of Dover to me and opened a window into past design practice; Tom Camps helped me to understand how electric traction works; Michael Y K Chung provided input on power modelling; Constantin Ciobanu helped with UK turnout geometry; Rob Dafern and Ankur Saxena assisted with OLE in tunnels; Bryce Denboer provided useful corrections on aspects of electrical equipment; Gareth Dennis helped with survey accuracies; David England helped with OLE materials; John Ewing provided photos of inclined OLE; Andy Gardner assisted with various sections; Peter Harris provided his invaluable expertise for the tunnel section; Paul Hooper helped with the electrical and planning sections; Ashley Jordan helped with protection systems; Stephen Lock helped with power & distribution advice and drawings; Adam McCreadie pointed me towards the current rules on mast rake; Allen McDonald helped with feeding and protection diagrams; Ed Mellor helped with structure loadings and foundation design; Robin Morel gave me guidance on current coasting practice; Laura Reardon provided hazard management expertise; David Shirres updated the picture on the tricky moving feast that is carbon emissions; Sanchay Singhal helped with ancillary conductors and isolators; Simon Skinner, Tim Young, Greg Salisbury, Tom Walker, Sam Hinks, Tim Ellis and Kenny Reith helped me to understand current construction practices; Bradley Wannell, Kara Jin, and Jamie Barratt kindly allowed the use of my survey photo; Anne Waters helped with the planning, design and construction sections; Dr Roger White helped with the dual voltage section, and along with Allen McDonald rescued my incorrect AT feeding description and diagram; Chris Wilson helped with traction power and P&D planning, design and construction, and made sense of my hopelessly confused transformer ratings numbers; and Martin Wright and Bernie Geiger offered good advice and guidance on trolley systems. David Fenner let me know about a number of typos in the initial version in good time to correct them for the print edition.

I’ve tried to keep good records as I’ve gone along, but if you helped and I missed you out, please accept my apologies and thank you!

Various colleagues and online friends have kindly given permission to use their images - a full list of credits is contained in the Table of Figures. Particular thanks are due to Morris Line Engineering for permission to use their isolator images, Pace International and Rebosio for permission to use their tunnel arm render, Barrow

\(^3\) The complete errata list for the current version as well as all previous versions is available online at www.ocs4rail.com/errors.
Hill Roundhouse Museum for providing access to their cross-arm pantograph, and SPL Powerlines UK for assistance with the construction section and use of their images.

Peter Dearman did me the huge honour of writing an excellent foreword - without doubt the only time that my name will appear on the same page as Brunel’s; and for that I am very flattered and grateful.

Arturs Dobrecovs did a fantastic job on the cover artwork - it’s not often I get to be the client, and they were a joy to work with. If you need rail-related graphic design, look them up.

The responsibility for any errors remains (as always) with me and me alone, but there would be far more of them without the generosity of colleagues in agreeing to check the new material. In addition to all the people mentioned above who checked various sections, Simon Warren kindly repeated his role as overall proof-reader for this edition, and as always was remarkable unflustered when the 350 page draft landed on his (home) desk.

A number of people deserve special thanks for their patience and good career advice - without them I would not be in a position to write the book in the first place. They are: Erik Bates, Graeme Brindle, Alan Clegg, Peter Dearman, Paul Hooper, David Humphrey, Russell Jackson, Shaun Leatherbarrow, Allen McDonald, Ian Moore, Rob Tidbury, Andy Ward, Anne Watters, Mick Whelan, Dr Roger White, the late Adrian White and the late David Ingram.

Finally I must thank the people in my life who put up with my nonsense, keep me sane during times when I was tempted to give up, helped me make the book more than just a download, and aren’t afraid to tell me when I’m being a jerk. Thank you to my ever-supportive wife Claire, and my beautiful and talented daughter Chloe.

Garry Keenor
Wiltshire
2021
6. How to Use This Book

This book gives an introduction to overhead line electrification systems for railways, and covers all types of railway and Overhead Line Equipment; all developments are covered, together with examples of UK systems. It applies to all overhead power supply systems for tram systems, light and heavy rail, low speed and high speed.

The book assumes a basic knowledge of maths and mechanical and electrical engineering concepts. All new terms are explained as the book goes along, and the explanation of a term is indicated by italicised text. Occasionally a term is unavoidably used earlier in the book, without explanation, in which case a cross-reference is provided, like this: (section 4). For those reading the document on-screen, these are clickable hyperlinks. Most images are high resolution and will benefit from zooming into the PDF.

Most PDF software has a search function triggered by typing [ctrl]+f – this is an easy way to find a reference from anywhere in the book.

Within the book the following terms are used:

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beyond</td>
<td>Object A is beyond Object B when a train passes Object B before Object A</td>
</tr>
<tr>
<td>DMU</td>
<td>Diesel Multiple Unit</td>
</tr>
<tr>
<td>Distribution Network Operator</td>
<td>An operator of an electricity network whose voltage is no higher than 132kV</td>
</tr>
<tr>
<td>EMU</td>
<td>Electric Multiple Unit</td>
</tr>
<tr>
<td>Electricity Supply Industry</td>
<td>The whole of a supply industry, including Distribution Network Operators and National Grid Companies</td>
</tr>
<tr>
<td>High speed</td>
<td>Speeds above 200km/h</td>
</tr>
<tr>
<td>High Voltage (HV)</td>
<td>Voltages above 1000V</td>
</tr>
<tr>
<td>Heavy rail</td>
<td>Traditional railway systems; as opposed to light rail and tram systems</td>
</tr>
<tr>
<td>Low Voltage (LV)</td>
<td>Voltages up to 1000V</td>
</tr>
<tr>
<td>National Grid Company</td>
<td>An operator of an electricity network whose voltage is above 132kV</td>
</tr>
<tr>
<td>On approach to</td>
<td>Object A is on approach to Object B when a train passes Object A before Object B</td>
</tr>
<tr>
<td>Overbridge</td>
<td>A bridge over the railway</td>
</tr>
<tr>
<td>Road-Rail Vehicle</td>
<td>Any vehicle capable of being driven on a road and also driven along a railway</td>
</tr>
<tr>
<td>STK</td>
<td>Single Track Kilometre. One STK is equal to a kilometre of single track.</td>
</tr>
<tr>
<td>Substation</td>
<td>Generic term covering feeder stations, TSCs, TSLs, and AT sites, whether sectioning or intermediate</td>
</tr>
<tr>
<td>Underbridge</td>
<td>A bridge under the railway</td>
</tr>
</tbody>
</table>
Within the book the following symbols are used in circuit and mechanical diagrams:

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Supply</td>
<td>![AC Supply Symbol]</td>
</tr>
<tr>
<td>Auto Transformer</td>
<td>![Auto Transformer Symbol]</td>
</tr>
<tr>
<td>Bonds (red, yellow)</td>
<td>![Bonds Symbol]</td>
</tr>
<tr>
<td>Capacitor</td>
<td>![Capacitor Symbol]</td>
</tr>
<tr>
<td>Circuit Breaker (open, closed)</td>
<td>![Circuit Breaker Symbol]</td>
</tr>
<tr>
<td>Contactor</td>
<td>![Contactor Symbol]</td>
</tr>
<tr>
<td>Damper</td>
<td>![Damper Symbol]</td>
</tr>
<tr>
<td>Earth</td>
<td>![Earth Symbol]</td>
</tr>
<tr>
<td>Fault</td>
<td>![Fault Symbol]</td>
</tr>
<tr>
<td>Thyristor</td>
<td>![Thyristor Symbol]</td>
</tr>
<tr>
<td>Insulator</td>
<td>![Insulator Symbol]</td>
</tr>
<tr>
<td>Inverter</td>
<td>![Inverter Symbol]</td>
</tr>
<tr>
<td>Isolator</td>
<td>![Isolator Symbol]</td>
</tr>
<tr>
<td>Load Break Switch (open, closed)</td>
<td>![Load Break Switch Symbol]</td>
</tr>
<tr>
<td>Motor</td>
<td>![Motor Symbol]</td>
</tr>
<tr>
<td>Neutral section</td>
<td>![Neutral Section Symbol]</td>
</tr>
<tr>
<td>Overlap</td>
<td>![Overlap Symbol]</td>
</tr>
<tr>
<td>Rectifier or DC substation</td>
<td>![Rectifier Symbol]</td>
</tr>
<tr>
<td>Resistor</td>
<td>![Resistor Symbol]</td>
</tr>
<tr>
<td>Section Insulator</td>
<td>![Section Insulator Symbol]</td>
</tr>
<tr>
<td>Spring</td>
<td>![Spring Symbol]</td>
</tr>
</tbody>
</table>
Wires are referred to by their layup; that is, the number of strands and diameter of each strand. For instance, 19/3.25 wire comprises 19 strands, each 3.25mm in diameter. Elements and alloys are denoted by their periodic table symbol, or similar abbreviation, as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Bz</td>
<td>Bronze</td>
</tr>
<tr>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>Mg</td>
<td>Magnesium</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>Sn</td>
<td>Tin</td>
</tr>
<tr>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td>HD</td>
<td>Hard Drawn (generally applied to copper)</td>
</tr>
</tbody>
</table>

A footnote with the reference *ibid* means it is referring to the same document as the previous reference.

Parts of the book which are new or amended since the last version are shown with a change bar (as left).

Items which have been deleted from the last version are marked with a deletion square (as left).
7. Basics of OLE

7.1. What is OLE?

*Overhead Line Equipment* (OLE) is a system used to deliver continuous electrical energy to a stationary or moving train, by means of a sliding contact between on-roof current collection equipment and a fixed overhead supply conductor. It is also known in the UK as OHL or OHLE. In Europe and the US, it is known as *Overhead Contact System* (OCS), and in New Zealand, as *Overhead Wiring System* (OWS). The generic term for the system is *Overhead Contact Lines*.

This book will use OLE, as it is the preferred term in the UK.

7.2. Unique Features of OLE

Unlike other power transmission systems, OLE is required to transmit high power\(^4\) to a stationary or moving load\(^5\) at a distance of several miles. The contact wire is therefore a twin system – it functions as both power transmission mechanism and sliding contact with the train.

![Figure 1: A shortened TGV train takes the world rail speed record on 3 April 2007](image)

The key requirement for any OLE system is to provide continuous power to the train. For this to happen there must be continuous contact between OLE and the pantograph (section 12.1). Loss of contact leads to degradation of energy transfer and unwelcome damage to the contact wire and pantograph due to *electrical arcing*\(^6\).

OLE is a very exposed system, being vulnerable to climate – especially wind, snow and ice; to wildlife – particularly birds; and also to pollution and vandalism. The mechanical and electrical forces imposed on OLE

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\(^4\) Up to 10MVA per train.

\(^5\) The current railway speed record is held by a French TGV unit, which reached 574.8km/h on 3 April 2007 travelling under modified and super-tensioned (40kN) 31kV OLE. Video is available online at [youtu.be/wflL5h6Rg8](https://youtu.be/wflL5h6Rg8).

\(^6\) The localised heating of the contact wire during arcing is known to locally reduce wire hardness, creating the conditions for fatigue cracking and failure. This can reduce the life of the wire by up to 50%. "Laboratory Assessment of Arc Damage in Railway Overhead Contact Lines with a Case Study on Copper-Silver and Low Oxygen Content Copper", Sunar, Fletcher, Beagles; 2020; IEEE.
by repeated pantograph passages and heavy starting traction loads are significant; and these make unplanned events much more likely than in conventional transmission lines. OLE systems must therefore be capable of withstanding frequent electrical fault conditions without degradation of performance. The system tends to be constrained by other railway infrastructure, particularly in the UK where it has been retrofitted to railways built in the 19th century with small clearances above the train.

![Figure 2: OLE and pantograph damage at 70km/h](image)

Due to the continuous contact requirements, the contact wire position is critical to successful operation. There is no redundancy in this part of the system; a second contact wire is not a practical proposition, from either an engineering or financial standpoint. If the contact wire strays outside defined position limits, the pantograph will usually damage a significant length of the OLE before the train comes to a halt.

OLE is above all else a combined electrical and mechanical system, and the requirements of each must be balanced in the design.

### 7.3. Advantages of the System

Electrification is the most effective form of traction power for trains in terms of efficiency, performance, whole life cost and the climate emergency. These advantages are a result of the basic laws of physics\(^7\). A 2020 study concluded that "for areas of the [UK] network with significant freight flows or long-distance high-speed services, electrification is the only technology currently able to support [the decarbonisation of] these service types. Analysis suggests that electrification is also the best whole life cost solution for more intensively used areas of the network." \(^8\)

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\(^7\) "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; section 5.1.

\(^8\) "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 4.
7.3.1. Power Capacity

All self-powered trains must store their own traction energy, and need a power plant to convert that potential energy into kinetic energy to make them move. A self-powered vehicle’s power and range is thus limited by the amount of energy it stores, and the capacity and efficiency of its power plant. The available space on a train limits the size of this plant. The fixed-capacity nature of all railways means that more space for energy storage and conversion equals less space for passengers and freight.

The above restrictions do not apply to electric trains, which can receive a large amount of energy whilst in motion; the amount of power is limited only by the specification of the electrification system and (during acceleration from rest) the available adhesion at the rail (section 11.1). Additionally electric trains are able to exceed their rated power for short durations in a way that is impossible for self-powered trains. This makes electric trains unique in their ability to provide high speed passenger and heavy freight transport.

7.3.2. Energy Efficiency

Electric trains are more efficient in their energy use since there is no energy conversion process other than that which takes place at the motor; the only losses are those from the generation, transmission and motor control processes. In addition, the regenerative braking capability (section 11.5) of an electric train increases its efficiency further, recovering up to 20% of the energy consumed. This means a typical electric traction unit has between 182% and 237% of the power of a comparable diesel unit, while requiring only one third of the energy.

For urban transit, trams are seven times as efficient at using energy as an equivalently loaded diesel bus, due to the difference between rolling resistance of steel-wheel-on-steel-rail and rubber tyres on tarmac, improved drive efficiency and lower weight.

7.3.3. Carbon Emissions

Surface transport is the highest carbon emitting sector of the UK economy. While rail emissions are only a small fraction of that total, railway traction accounts for the majority of those emissions. Electrification is the only form of traction power that can economically be used to decarbonate rail routes with significant traffic density, traffic frequency, train speed or journey distance. Electric trains can also be powered by whatever power source generates electricity, both now and in the future. In this way they can take advantage of significant carbon reduction in electricity generation, and concentration of emissions at a single source enabling more efficient control.

If their electricity is generated by renewables or nuclear power they also have net-zero emissions.
carbon emissions.

Electrification contributes further to emission reductions by driving modal shift. Road and air transport account for the bulk of transport emissions\textsuperscript{16}, and in the case of aviation and long-distance heavy goods vehicles, have no clear route to decarbonisation\textsuperscript{17}. Moving some of these journeys to rail is an essential part of any net zero strategy, and electrification has been shown over decades to produce a sparks effect\textsuperscript{18}, with a jump in customer numbers as soon as a route is electrified.

All infrastructure change creates embodied carbon; that is, the carbon emissions which the construction process generates through the production of steel, concrete and other activities. This carbon debt must be taken into account when assessing any proposed decarbonisation measure. A 2019 study\textsuperscript{19} concluded that electrification of a mile of two track railway would typically generate 313 tonnes of CO\textsubscript{2}e emissions, or 98 tonnes per Single Track Kilometre (STK). The UK network of 31091 STKs\textsuperscript{20} currently produces 1.788m tonnes of diesel-generated CO\textsubscript{2}e per annum\textsuperscript{21}, giving a payback period for the embodied carbon from electrification construction of 2.8 years\textsuperscript{22}. This demonstrates that electrification quickly becomes a positive decarbonisation measure.

### 7.3.4. Pollution Reduction

Combustion of diesel fuel, as currently happens in virtually all self-powered trains, produces sub-micron soot particulates (part of the PM\textsubscript{2.5} group of particulates\textsuperscript{23}), as well as Nitrogen Oxides (NO\textsubscript{x}) and aldehydes. Studies are increasingly showing that these emissions are associated with a range of chronic illnesses, including asthma, heart attacks and strokes. Across the world air pollution is believed to be responsible for one in ten deaths\textsuperscript{24}, with vulnerable groups such as young children and the elderly at particular risk. Short-term exposure to NO\textsubscript{x} can cause inflammation of the airways and increase susceptibility to respiratory infections and allergens; and it exacerbates the symptoms of those who are already suffering from lung or heart conditions, shortening their lives\textsuperscript{25}. Recent studies have found that enclosed railway stations have elevated PM\textsubscript{2.5} and NO\textsubscript{x} levels, and that even when brake dust and carbon strip (section 12.1) particulates are taken into account, electric trains produce less harmful pollutants than diesel trains\textsuperscript{26}. Matters improve further when - as is already the case for most European countries - coal-fired electricity generation is all but phased out, eliminating the particulates created during coal combustion.

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\textsuperscript{17} “Net Zero Technical Report”; May 2019; Committee on Climate Change; p140, p169.

\textsuperscript{18} “The Oxford Companion to British Railway History”, Simmons, Biddle; 1999; Oxford University Press; p144.

\textsuperscript{19} “Case study: Electrification Embodied Carbon Savings”; RSSB; 16 May 2019; accessed 13 February 2021. This figure does not include for enabling works such as bridge reconstruction, which can be expected to add a marginal amount to the CO\textsubscript{2}e figure.

\textsuperscript{20} “Network Rail Annual Return 2020”; Network Rail; accessed 13 February 2021.

\textsuperscript{21} “Table 6105 - Estimates of Passenger and Freight Energy Consumption and Carbon Dioxide Equivalent (CO\textsubscript{2}e) Emissions”; Office of Rail and Road; accessed 13 February 2021.

\textsuperscript{22} This estimate assumes that every STK of electrification removes a pro-rata amount of diesel traffic from the UK network. This is likely to be a conservative assumption, since electrification schemes are typically targeted at routes with the heaviest diesel traffic.

\textsuperscript{23} Particles with a mass median diameter of 2.5\(\mu\mbox{m}\).

\textsuperscript{24} “A Breath of Fresh Air: New Solutions to Reduce Transport Emissions”; January 2018; IMechE; p17.

\textsuperscript{25} “Clean Air Strategy 2019”; 2019; Department for Environment Food and Rural Affairs; p16.

\textsuperscript{26} “Air Quality in Enclosed Railway Stations”, Thornes et al; University of Birmingham; 2016; sections 2 and 5.
7.3.5. Economic Advantages

Electric trains have a number of key economic advantages over self-powered trains, again as a result of basic physics. This means electrification usually has a good whole-life business case on all but lightly used or short-length lines, regardless of any imperative to decarbonise or reduce pollution. The economic advantages can be summarised as:

- Higher acceleration\(^{27}\) and braking due to lower weight and ability to exceed rated power for short periods – meaning greater passenger capacity on routes with frequent stops and increased ability to recover from delays. Hydrogen and battery trains can only achieve this by sacrificing range;
- Substantially higher freight haulage capability than with diesel locomotives, and attendant reduced freight journey times\(^{28}\). Reduced freight point-to-point times also reduces speed differentials between freight and passenger, contributing to increased passenger capacity;
- Lower rolling stock capital cost\(^{29}\);
- Lower rolling stock operating cost, largely as a result of fuel and maintenance costs\(^{30}\);
- Lower rolling stock maintenance costs\(^{31}\,\,32\), due to the much smaller number of moving parts;
- Greater train reliability\(^{33}\), for the same reasons as above;
- Smaller fleet requirements due to increased reliability, since fewer trains are out of service for maintenance;
- Lower track maintenance costs\(^{34}\), driven by lower track forces from lighter power units;
- Reduced noise and vibration, improving passenger comfort levels.

Electrification also has economic benefits beyond the direct operational cost savings; the wider socio-economic benefits such as improved transport links should also be factored into the cost-benefit analysis for electrification schemes.

7.3.6. Advantages over 3rd and 4th Rail Electrification

Ground-mounted conductor rail systems form a significant minority of electrified railways worldwide, often as a result of the deployment of LV DC electrification prior to the development of train-borne rectification and control (section 11.2.3). However these systems are limited by current collection performance to about 160km/h, and are hazardous in unshielded top-contact form. Serious economic disadvantages arise from the need to provide more frequent and complex substations, as with DC OLE (section 10.5) - and so new conductor rail construction tends to be for extensions of existing systems rather than creation of new ones.

\(^{27}\) Typical rate of acceleration is 0.65m/s\(^2\) for DMU, 1.0m/s2 for EMU. "Study on Further Electrification of Britain’s Railway Network"; 2007; RSSB/Atkins; appendix D.

\(^{28}\) "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 5.5.31.

\(^{29}\) UK diesel vehicle capex is on average 12% higher than for electric vehicles. "Rail Value for Money Study – Rolling Stock Whole Life Costs – Final Report"; 2011; Arup; figs 2.10 and 2.11.

\(^{30}\) Typical operational savings for a single passenger vehicle are between £2m and £3m, based on a 30 year life. Applied to 80% of the UK fleet, this would equate to between £7bn and £1bn of annual savings. "Why Rail Electrification?", Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; appendix 3.

\(^{31}\) DMU maintenance costs across Europe are typically 40% higher than for an EMU. "European Benchmarking of the Costs, Performance and Revenues of GB TOCs – Final Report"; 2012; Civity; p65.

\(^{32}\) DMU maintenance costs worldwide are twice as high as EMUs. "Benchmarking identifies good practice in rolling stock maintenance"; 2006; Railway Gazette.

\(^{33}\) A new UK EMU has an average miles per technical incident of 26906, against 10272 for a new DMU – more than 2½ times as reliable; a midlife UK EMU is still almost twice as reliable as the most reliable equivalent DMU. "Understanding the Rolling Stock Costs of TOCs in the UK"; January 2015; Steer Davies Gleave; section 4.51.

\(^{34}\) Typical track wear and tear costs are 15% higher for diesel vehicles than for electric vehicles. "Network Route Utilisation Strategy - Electrification"; Network Rail; 2009; table 3.3.
7.4. Disadvantages of the System

Set against all of the advantages of OLE are a small number of disadvantages.

The disruption to existing services during construction of OLE on an existing railway corridor can be significant, and the lack of redundancy in the contact wire can cause significant constraints on the reliability of the railway if the system is not correctly designed, installed and maintained. Electrification of a route can lead to limitations on the use of diversionary routes at times of planned or unplanned disruption, although this is less of a constraint if the majority of the network is electrified.

The safety risks from high voltages require careful management, but should not be considered a disadvantage since the techniques and processes for doing so are well understood.

However the dominant disadvantage of OLE is the high capital cost of installation. Because of this, and despite the whole-life economic advantages (section 7.3.5), it has historically been difficult to gain funding for new electrification schemes, especially in the UK. Railway finances adhere to the timeless dictum that money ultimately comes from only two sources: the taxpayer and the fare payer. It is usually national or local government that authorises electrification schemes, and they will only proceed if two conditions can be demonstrably met:

- That there is a reasonable return on their citizens’ investment – in other words, that the capital outlay is paid for by reduced operational expenditure over a reasonable period of time;
- That the scheme can be built within the ceiling of available funding.

For this reason the focus of the planner, designer and installer must be to deliver a reliable system which minimises the whole life cost of the equipment (including maintenance and unplanned disruption costs), but not at the expense of an affordable capital outlay.
7.5. Efficiency and Rolling Programmes

The most effective way to minimise electrification capital cost is by means of a *rolling programme*; that is, a planned sequence of electrification schemes across a network, with a broadly constant volume of new electrification being delivered each year. This reduces costs in a number of ways:

- Continuity of work increases staff experience and skill over time, resulting in a highly-skilled workforce able to move from project to project;
- Processes, plant and materials can be refined over time, based on lessons learned from previous projects;
- Lower materials costs can be negotiated, based on economies of scale;
- Wastage of materials is avoided at the end of a project (section 20.2.4) since any surplus can be used on the next one;
- Competition for plant increases supply and lowers costs, as plant manufacturers and owners have greater confidence to invest in future work;
- Increased competition for design and installation contracts lowers costs, for the same reasons.

7.6. Alternative Traction Options

A number of energy storage technologies have been proposed as alternatives to electrification - in particular, battery and hydrogen. A 2020 study concluded that the overall feasibility of these technologies compared to electrification was as follows.

![Figure 4: Technical abilities of non-diesel traction technologies](image)

These options are studied in more detail below.

7.6.1. Battery Only Traction

Battery trains suffer from some of the same constraints as other self-powered trains - they must store their energy on the train, and that storage consumes space which, on capacity-limited routes at least, can eat into the available space for passengers or freight. There are currently few battery trains in operation worldwide, so

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35 “Traction Decarbonisation Network Strategy - Interim Programme Business Case - Executive Summary”; Network Rail; July 2020; p4
it is difficult to assess real-world operational experience. The following section draws on the experience gained in the automotive Electric Vehicle (EV) sector to assess some of the challenges that will have to be overcome before battery trains can take their place in the traction hierarchy.

The current best-in-class Lithium Ion batteries have an energy density around 7% that of diesel fuel, and this limits both range and speed. Current battery trains have a 200kWh capacity, but reserves to maximise battery life mean the useful capacity is 130kWh. Energy consumption is 1.7-2.2 kW/km, giving a range of 60 to 80km and a maximum speed of 100km/h.

The energy density of batteries is however rising, chiefly fuelled by R&D in the automotive sector. There are few further gains to be made in Lithium Ion chemistry, and the new chemistries under development are expected to make incremental gains. Even an optimistic estimate - doubling of energy density over the next 20 years - would mean an energy density of only one sixth that of diesel traction, and this will continue to be a significant limit on range and speed.

EVs typically consume only a small percentage of their battery capacity each day, before being charged again overnight, and the dominance of overnight trickle charging for EVs is the key to their long battery life. This is not the case for rail vehicles, where it is central to their economic use that they are diagrammed for journeys totalling hundreds of miles every day, with only short stops at the end of each journey.

This means that, unlike EVs, frequent rapid charging - taking the battery from 20% to 80% in under 20 minutes - is essential to the practical operation of battery rail vehicles. However rapid charging can cause significant battery heating, and this shortens battery life if used frequently. For this reason it is expected that the batteries on a Battery Electric Multiple Unit (BEMU) would need to be replaced several times during the life of the train, increasing whole life costs.

Battery train manufacturers are now working on charging technology that could recharge the battery in seven minutes using charging currents of 1000A, with significant on-board battery cooling provided to maintain battery life. But with an electric vehicle’s battery accounting for up to 20% of its total cost in 2020 and maybe 10% in 2035, the whole life economics of battery rail vehicles are not yet proven.

### 7.6.2 OLE-Battery Bi-Mode Traction

All of the above is predicated on a traction unit powered solely by batteries. In this configuration, the technology is only likely to be used on short, lightly-loaded routes where the electrification business case is harder to make. A promising alternative use for batteries is to provide supplemental power to a conventional electric traction

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36 “What Next for Vivarail?”, Shirres; Oct 2020; Rail Engineer.
37 Current estimates are that battery energy density will increase from 470Wh/litre today to 720Wh/litre in 2035, an increase of 53%. This compares with diesel fuel at 10.7kWh/litre. “Roadmap 2020: Electrical Energy Storage”; Advanced Propulsion Centre UK; 2020.
38 The average UK car journey length in 2019 was 8.4 miles. “National Travel Survey”; 2019; Department for Transport.
39 EV suppliers typically warrant that the battery will have at least 80% of its as-new range after eight years or 160,000km, regardless of duty cycle.
40 It is key to the long life of current rechargeable battery chemistry that they are not frequently operated above or below these values.
41 Charging a battery at a rate above 1C - that is, 1kW of charging rate for every 1kWh of capacity - increases heat stress which in turn increases battery ageing.
42 Currently a BEMU battery costs £400,000 per train. “What Next for Vivarail?”, Shirres; Oct 2020; Rail Engineer.
43 Current estimates are that battery pack costs will fall from $125/kWh in 2020 to $63/kWh in 2035. “Roadmap 2020: Electrical Energy Storage”; Advanced Propulsion Centre UK; 2020.
unit, so providing a last mile capability to move short distances onto non-electrified branch lines or into freight yards, before returning to the electrified network for the remainder of the journey. In this configuration, both the range and rapid charging issues are potentially resolved; depending on the duty cycle, the battery can be trickle-charged from the OLE while on the electrified network.

### 7.6.3. Discontinuous Electrification

It is also tempting to view an OLE-battery train as a means of avoiding the more expensive parts of conventional electrification - particularly the wiring of low overbridges and tunnels (section 12.13.1). In recent years this concept has become known as discontinuous electrification. This is defined as two distinct arrangements at difficult overbridges:

1. Installation of permanently earthed sections of OLE (section 10.12.2), with neutral sections and power switching either side of the bridge;
2. Omission of OLE altogether, with OLE terminated either side of the bridge and pantograph lower/raise operations either side of the bridge.

Crucially, discontinuous electrification is positioned as a permanent arrangement at multiple locations on a route, aiming to avoid costly enabling works at these locations.

Since OLE is its own power transmission system (section 7.2) and power must be fed to the other side of the discontinuity, lineside feeder cables (section 10.2.9) must be provided to bridge the gap. Power mode changeover is typically triggered by lineside balises or Radio Frequency Identification (RFID) means, adding both lineside and rolling stock complexity. Recent experience with operation of diesel/electric bi-mode trains in the UK shows that there are significant operational and infrastructure constraints on the placement of changeover zones; this makes it very challenging to have multiple discontinuities on all but low-speed routes. Additionally, option 2 above offers only very marginal clearance advantages over a voltage controlled clearance arrangement (section 10.8.1), which provide virtually all of the same benefits without the disadvantage of an electrification gap.

For all of the reasons given in the previous section, the concept is unproven; few railways around the world operate with multiple discontinuities between electrified sections, and none of those that have discontinuities use batteries to bridge the gap. Furthermore this approach does not work for routes with freight traffic, since power demand for freight is much higher, precluding the use of batteries.

These arrangements effectively swap the high capital costs of enabling works at low bridges for increased capital and operational costs elsewhere. These costs, which are yet to be determined with any accuracy, include:

- Increased capital cost of rolling stock;
- Increased maintenance cost of rolling stock;
- Increased capital costs of lineside 25kV cables through bridges;
- Increased complexity and maintenance cost of OLE (for neutral sections on graded approaches to permanently earthed bridges);
- Additional cost and complexity of lineside power changeover mechanism.

Discontinuous electrification also erodes one of the basic economic tenets of a cost-effective national railway system - that is, the ability to repurpose electric rolling stock around a network built on common standards, as traffic patterns change and train fleets age. This cascade process, where a new fleet displaces a mid-life fleet to a secondary route, is at the core of railway fleet economics. A train designed for a discontinuous electrification route must inevitably be designed with that route in mind, in terms of battery duty cycle at least. This locks the fleet in to that route for its whole life (unless a costly rebuild is contemplated) and prohibits the use of any
other rolling stock.

Discontinuous electrification is due to be implemented on the Valley Lines in South Wales in the early 2020s, and this project will be closely watched to see if it can provide lessons for wider adoption of the concept.

### 7.6.4. Staged Electrification

A more appropriate use of non-continuous electrification is as a planned temporary arrangement as part of a rolling programme of electrification. For instance, a long route being electrified may need a track remodelling in one area; since it is not efficient to electrify in advance of this work, a non-electrified gap can be left for a period and then filled after the remodelling has taken place.

### 7.6.5. Hydrogen Traction

Recent years have seen a surge of interest in the use of hydrogen as a low-carbon alternative to diesel fuel. Hydrogen can be stored on-board a rail vehicle as a highly-compressed gas\(^44\), and this this can be converted to electrical energy using an onboard fuel cell.

The energy density of hydrogen stored in this form is double that of a battery (section 7.6.1) but still only 14% of a diesel fuel tank. Current two-car hydrogen trains are able to store 188kg of hydrogen (6,300l per vehicle) and deliver 3200kWh to the motors once fuel cell and battery losses are taken into account\(^45\). This gives a range of 600-800km and a maximum speed of 140km/h; refuelling time is 15 minutes.

It should be noted that hydrogen trains still require a Lithium Ion battery - fuel cells work best when producing a broadly-constant output, and so the fuel cell charges the battery, which then drives the traction motors (section 11.4.1) in the same way as a battery train. Current production fleets in Europe carry the hydrogen in roof-mounted fuel tanks, but the more restrictive UK loading gauge means that storage within a vehicle body\(^46\) is likely to be needed, taking space that would otherwise provide additional seating. R&D on hydrogen is aiming to improve storage density by around 50%, and conversion efficiency by around 5%\(^47\). Regardless of the success of these efforts, the power capacity limitations rule hydrogen out for passenger trains above 160km/h and all freight.

An important difference between hydrogen and the diesel it seeks to replace is that hydrogen is not a naturally-occurring element; it must be synthesised, and should strictly be described as an energy vector rather than a fuel. Production currently takes place using steam reforming of hydrocarbons (usually methane) in large chemical plants, as it is almost entirely produced as part of a chemical process. The output is known as brown hydrogen, and the production process produces significant carbon emissions, making hydrogen produced in this way just as carbon-intensive as diesel. For hydrogen to be able to make a valid low-carbon case, it needs to be produced instead using electrolysis, with the electricity for the process produced using a renewable source such as wind, or excess electricity supply from a renewable source at times of low demand. This is known as green hydrogen.

The vector nature of hydrogen introduces another important consideration; that is, the requirements for hydrogen generation and distribution infrastructure. Centralised production would require the creation of a

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\(^44\) Current storage pressure is typically 35Mpa (5000psi).

\(^45\) "Fuel Cell Coradia iLint On Test"; 12 Jan 2018; Railvolution; accessed 27 Dec 2020.

\(^46\) This is expected to consume one third of one 20m vehicle on a four-car train. "Hydrogen Trains Coming Soon?", Shirres; Nov 2020; Rail Engineer; p33.

\(^47\) Ibid.; p32.
national grid for hydrogen storage and piping, as already exists in many countries for natural gas. With rail only ever likely to be a small part of the hydrogen market, and all foreseeable national capacity being needed for the essential task of decarbonising home heating, this model is unlikely to deliver for rail. It is more feasible to adopt a local production model, with electrolysers, compressors and storage tanks provided at a depot location. These could be supplied from the local electricity grid, producing hydrogen at times of low energy demand (typically night-time) when electricity is cheaper, helping with local grid demand management at the same time. This is essential to avoid high energy costs, since the low efficiency of the production and compression processes means it takes around three times as much electricity to power a hydrogen train as it does an equivalent electric train\textsuperscript{48}. A further step would be to generate renewable electricity locally, with a solar or wind installation close to the depot site.

With current hydrogen consumption rates a fleet of ten three-car trains doing 800km per day each would consume between 2000 and 3000kg of hydrogen. A 10MW electrolysis and storage facility would be needed to electrolyse and store two days fuel supply for this fleet, and this would occupy around 0.6 hectares\textsuperscript{49}; the plant would require significant hazard control measures. The capital cost of this facility currently equates to around £1.7m per train, but this could fall by 50\% as economies of scale take place\textsuperscript{50}. An installation of two or three 2.5MW wind turbines on site could produce sufficient electricity to electrolyse this amount of hydrogen.

Capital costs for the rolling stock are likely to be higher than that of an electric equivalent, and the additional energy generation and hydrogen processing infrastructure must also be taken into account when assessing costs.

Hydrogen is without doubt the most promising of the alternative fuels for the extremities of a network, where lightly-loaded lines may not have the bulk electricity supplies needed for electrification. As with battery trains, the whole-life economic case is not yet proven\textsuperscript{51}, but hydrogen trains have been trialled in Europe and wider adoption is likely. However for the reasons above it cannot be considered as an alternative to electrification of core mainlines\textsuperscript{52}.

\textsuperscript{48} “Traction Decarbonisation Network Strategy - Interim Business Case”; Network Rail; July 2020; section 5.6.60.

\textsuperscript{49} Based on calculations using data from Aberdeen hydrogen bus trial. “Data Sheet: Aberdeen, Scotland - Gaseous Hydrogen Fuelling Station for Buses”; 2017; BOC.

\textsuperscript{50} “UK Renewable Hydrogen Hub: Techno-economic and Environmental Assessment”; April 2017; Innovate UK; p26-28.

\textsuperscript{51} A 2020 study concluded that “The introduction of new battery and hydrogen rolling stock and the infrastructure they will require will be complex and will require new standards, operating procedures and products.” “Traction Decarbonisation Network Strategy - Interim Business Case”; Network Rail; July 2020; section 5.8.19.

\textsuperscript{52} Ibid.; section 4.
8. Development of OLE systems

The following sections give an overview of the history of OLE development. For a more detailed list of UK builds, see Appendix A.

8.1. Electric Beginnings

The first OLE systems were used with passenger trams in the last years of the 19th century. These generally consisted of a simple single wire (trolley or tram) system, suspended from poles and buildings, and fed at a low voltage. This was preferred to the previous attempts with 3rd rail systems, which gave rise to both reliability and safety problems in congested on-street areas.

The first thirty years of the 20th century saw these principles extended to mainline systems as the advantages of OLE over 3rd rail became clear. As volt drop losses increased with distance, voltages were increased to compensate. At the same time, more sophisticated suspension systems were required to maintain good current collection at increasing linespeeds (section 12.2). At this time the national grid had not been developed, so railways often had their own power stations feeding at a variety of voltages and frequencies.

Figure 5: 6.7kV AC twin catenary simple OLE on the London, Brighton and South Coast Railway, circa 1910

Experimental AC schemes were implemented for the Lancaster to Heysham (1908) and London Victoria to London Bridge (1909) schemes, both at 6.7kV, 25Hz AC. AC motor technology was not mature at this time, necessitating complex train-borne rectification equipment, which gave reliability problems of its own. AC traction did not make any further headway in the UK until after World War Two.

In the north of England the Newport – Shildon line, which featured heavy coal trains running over steep gradients, was electrified with 1500V DC OLE in 1915.

8.2. Mainline DC Growth

The barriers to using AC, coupled with the transmission limitations of DC current, meant OLE was only used for suburban and freight systems, where heavy electrical loads and short distances meant DC OLE made economic sense. In the UK, 1500V DC OLE was agreed in the 1930s as the national standard\(^{54}\). The Sheffield to Manchester and Wath route, which required very heavy coal trains to be hauled over the steep gradients of the Derbyshire peaks, was authorised for electrification in 1939, as was the Great Eastern Mainline (GEML) out of London Liverpool Street. However World War Two brought this, and all other electrification schemes in Europe, to an abrupt halt.

![Electric freight with 1500V DC OLE. Penistone, UK](image)

Both schemes recommenced after the war, but by now the railways’ priority was rebuilding their battered infrastructure rather than funding new schemes. The Wath scheme was completed in 1952, but was a pyrrhic victory, since within 6 years the DC standard was obsolete. The line survived until 1981, by which time it was an isolated system. The GE lines fared better due to their essential commuting status, eventually being converted to 25kV AC.

The story of OLE in the UK during the first half of the 20th century is a faltering one, but the rest of Europe installed a large amount of 1500V DC in the pre- and post-war years, and much of this network still exists.

8.3. AC Developments

The 1950s saw increased interest in AC OLE, driven by the emergence from the electricity supply industry of reliable industrial frequency technologies. This meant that high voltage, long-distance AC transmission – and by inference, inter-city OLE – was now feasible. Experiments with 50Hz AC traction had first been made as early as 1940 in Germany\(^{55}\). Across Europe, as the 1950s progressed the 1500V DC standard was dropped in favour of 25kV at AC industrial frequency; in the UK this was approved as the standard for future schemes (using

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\(^{54}\) Ibid., p263.

50Hz AC) in 1956\textsuperscript{56}.

The Lancaster to Heysham route, which had pioneered HV AC OLE in 1908, was converted from 25Hz to 50Hz in 1951\textsuperscript{57} to serve as a test bed for industrial frequency. These tests confirmed the choice as the right one. A further test scheme was installed between Colchester and Clacton in 1959. Various types of OLE were trialled, including simple and stitched equipment (section 12.2), but compound equipment was chosen as giving the best current collection at speed\textsuperscript{58}.

It was initially assumed that 25kV AC systems would require significant electrical clearances to existing infrastructure, and so 11" (275mm) was adopted as the standard air gap for bridges. In the UK this meant major reconstruction work, particularly for the many bridges in the vicinity of large stations, so for these areas a reduced voltage of 6.25kV was proposed, with 4" (100mm) clearances\textsuperscript{59}. Trains would be dual-voltage and switch between them on the move as necessary, using neutral sections each side of the bridge.

![Figure 7: 1500V DC on the GE; this was converted, first to 6.25kV AC and then 25kV. Gidea Park, UK](image)

Experience on the Great Eastern (GE) lines out of Liverpool St, where the 1500V DC lines were converted to 6.25kV AC, showed that there was excessive caution in the standard clearances. Reduced clearances, and later special reduced clearances (section 10.8) were added, so that 25kV could be adopted throughout.

The West Coast Mainline (WCML) electrification was the first large scale 25kV scheme in the UK; it was planned to have 6.25kV sections, but in light of GE experience was implemented fully at 25kV\textsuperscript{60}. The dual voltage locomotives which had been built for the route were modified as single voltage machines, and the 6.25kV areas were converted to 25kV.

\textsuperscript{56} “Electric Railways, 1880 – 1990”, Michael C Duffy; 2003; IEE; p321.
\textsuperscript{57} Ibid.; p273.
\textsuperscript{58} Paper; A D Suddards, T H Rosbotham, T B Bamford.
\textsuperscript{59} “Electric Trains in Britain”, B.K. Cooper; 1979; Ian Allan Ltd; p43.
\textsuperscript{60} “Electric Railways, 1880 – 1990”, Michael C Duffy; 2003; IEE; p322.
The first phase of the West Coast scheme was extremely successful in operational terms; it brought about a step change in service speed, and revived an image of high speed rail travel last seen in the 1930s. This was the first documented use of the term "sparks effect" (section 7.3.3).

However the railways were facing increasing pressure from an expanding motorways network, not to mention worsening finances, and when British Rail (BR) proposed a rolling programme of mainline electrification schemes, the Ministry of Transport made it clear that costs would have to come down.

BR responded with a wholesale overhaul in the design of OLE. The heavy, bespoke portal arrangements of the West Coast equipment were abandoned in favour of a new, lightweight, modularised, headspan-based metric system (the OLEMI – section 14.3). The first OLEMI system was known as Mark 3, and was further developed as Mark 3a; in this form it was used on the second phase of West Coast from Weaver Junction through to Glasgow in 1974.
8.4. High Speed Lines

Elsewhere in Europe, the possibilities for higher speed passenger trains using electric traction began to be explored. The French state railway SNCF began a series of experimental runs in the 1950s, culminating in a record-breaking run reaching 326km/h in March 1955. This used a modified 1500V DC system, with the line voltage increased to 1900V by means of mobile substations. The record stood until 1981. The tests showed the obstacles to be overcome if speeds over 300km/h were to become the norm. Frictional heat caused the pantographs to collapse; track damage was so great that derailment was only narrowly avoided.

Japan was the first country to build an electrified mainline railway from scratch. The Tokyo - Osaka Shinkansen (‘New Trunk Line’) opened in 1964. This was segregated from existing lines, and used 25kV 60Hz AC OLE rather than the 1500V DC used elsewhere in Japan. The line had no level crossings and was designed for continuous high speed with linespeeds of up to 210km/h.

France continued to develop their high speed system, and the Ligne à Grande Vitesse (LGV) concept was born. This would use dedicated high speed lines, high powered trains and a 50kV Auto Transformer system (section 10.4.3). Gradients were relatively steep, since the high power available meant that expensive embankment and cutting works would be minimised.

The first LGV between Paris and Lyon (TGV Sud-Est) opened in 1981. Since then, additional lines have been opened, and the concept has been exported to Germany (as the ICE), the UK (High Speed One) and worldwide.

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61 Ibid.; p389.

62 Footage of the run is available online at youtu.be/1KRMjAlpB0.
8.5. UK – APT and HST

In the mid-1960s BR began to investigate higher passenger speeds. Financial constraints ruled out LGV-style solutions, meaning any improvements would have to be delivered on existing routes. The newly-formed BR research division set themselves a target to achieve 250km/h speeds and a 40% increase through curves on the West Coast Mainline. The result was the Advanced Passenger Train (APT), which used active tilt to provide the required levels of passenger comfort through curves, as well as a host of other new technologies. Articulated bogies were used, where vehicle ends sat on a single bogie, thus improving ride quality. Two stage hydraulic/air brakes were used to improve braking performance. The pantograph was linked by chains to the bogie, thus countering the tilt of the train body.

Development of APT was prolonged – the gas turbine APT-E prototype ran until 1976, and the electric production model did not appear until 1978. While the project had obvious promise, many of the traditionalists in BR engineering were not convinced that the research division’s gamble would pay off. The APT programme also ran into trouble with the unions, since the prototype did not have a second seat for double-staffing.

The traction & rolling stock division were convinced they could push diesel technology to provide sustained high speed running, and began to develop the High Speed Train (HST) concept. This pushed diesel traction design to the limit to produce a 200km/h fixed length diesel train, for use on the Great Western Mainline (GWML).

The train surpassed all expectations and set the standard for high speed passenger services for decades to come. The HST took the world speed record for a diesel train, reaching 232km/h on 12 June 1973, a record not surpassed until 2002. The project was so successful that the HST build was extended to provide higher speeds on the East Coast Mainline (ECML) and Midland Mainline (MML). This effectively stalled the mainline electrification program – in the case of ECML, by 10 years, and GWML and MML by 40 years.

On 20 December 1979 an electric APT took the UK speed record from HST, reaching 259km/h. However the complexity of the train proved to be its undoing. Major teething problems were encountered when the train entered service in 1981, and this was compounded by some ill-advised press runs leading to bad publicity, and the worst weather seen in years that winter. By 1984 BR were on the point of solving the technical problems,
but political backing for the project had evaporated and funding was stopped.

Figure 12: APT tilting on neutral section tests. Murthat, UK

APT was ultimately a failure of political will rather than technology. The lessons learned were taken by Italian train builders, who developed the Pendolino concept, successfully used throughout Europe – and now, ironically, sold back to the UK as for use on the West Coast Mainline.

8.6. Privatisation, Famine and Feast

Electrification proceeded in the UK through the 1980s, albeit on smaller schemes such as St Pancras – Bedford and Colchester – Ipswich. BR was finally given the go-ahead in the mid-1980s to continue electrifying the ECML north of Hitchin, and this was completed in 1991. However, budgetary constraints meant the OLE on this scheme had a weak power supply, and the OLE design was prone to failure.

Infill schemes continued in the 1990s, with Cambridge to King’s Lynn, Carstairs to Edinburgh and London to Heathrow Airport all completed. A significant milestone was the opening of the Channel Tunnel, operating at 160km/h with OLE. However privatisation had broken the link between infrastructure capital cost and train maintenance saving which was vital to justify the initial cost of electrification schemes. The splitting of rolling stock procurement, rolling stock operation and infrastructure ownership led to a huge increase in diesel procurement, as no organisation would benefit from the whole life advantages of electric traction.

By the early years of the 21st century the only major schemes in progress were the West Coast upgrade, and the Channel Tunnel Rail Link (CTRL), which finally brought true high speed (300km/h) running to the UK. Section 1 of CTRL opened in 2003, and section 2 into London was opened in 2007. This line was subsequently renamed High Speed One. On 30 July 2003, a Eurostar test train took the UK rail speed record from the APT, reaching 334.7km/h (208mph) on section 1 of CTRL.
The middle part of the 2000s saw the beginnings of renewed interest in OLE in the UK, as a surge in oil prices, increasing environmental pressure, and new diesel emissions regulations all affected the economics of diesel traction. In 2010, with both the HST and the associated signalling systems approaching life-expiry, the UK government committed to a new programme of electrification on the GWML, as well as the Midland Mainline and routes in East London, the West Midlands and the North West. Meanwhile, the Scottish government authorised multiple schemes in the central belt. Altogether this committed the industry to deliver over 2,400 STKs of new electrification within a single five year Control Period.

While many of the later schemes were delivered on time and within budget, most of the early ones fell victim to the inevitable problems that come with trying to deliver large volumes of a type of work not undertaken for
decades previously. The most high profile of these, the Great Western Electrification Programme (GWEP), ran heavily over programme and budget, resulting in cutbacks to the extent of the scheme, as well as cancellation of large parts of the Midland Mainline scheme in a bid to rebalance Network Rail’s budget.

8.7. Decarbonisation and Renaissance

As the industry learned from the failures and began to deliver schemes on time and budget, the climate emergency was increasingly impinging on policy-makers’ thinking. In 2019 Network Rail was asked to deliver a plan for making UK rail carbon-neutral by 2050. With diesel traction accounting for a large majority of carbon emissions and rail being the only form of transport with a proven route to carbon neutrality, this put electrification firmly back on the agenda. In 2020 Network Rail delivered the Traction Decarbonisation Network Strategy (TDNS) report\(^\text{63}\), which recommended over 11,000 STKs of new electrification over a 30 year period, taking the proportion of the UK network electrified from around 46% to over 80%\(^\text{64}\).

At the time of writing it appears that politicians have begun to grasp the urgency of the issue and commit to a rolling programme of electrification; the Scottish government has embarked on a plan to fully decarbonise Scotland’s railways, and the UK government has committed to “an ambitious, sustainable and cost-effective programme of electrification”\(^\text{65}\) for England and Wales, based on the TDNS.

\(^{63}\) “Traction Decarbonisation Network Strategy - Interim Business Case”; July 2020; Network Rail.

\(^{64}\) As measured using STKs.

\(^{65}\) “Decarbonising Transport - A Better, Greener Britain”; 14 July 2021; Department for Transport; part 2a.
9. Categories of OLE System

The parameters of an OLE system must be matched to the railway to which it is to be applied. OLE systems fall into one of five broad categories.

9.1. Tram Systems

Trams are mass transit systems, used to move large volumes of people over relatively short distances at relatively low speeds (up to 80km/h), usually in and out of urban centres. These systems feature on-street running, tight radius curves, steep gradients, short headways between trams and line of sight driving (i.e. no signalling except at highways interfaces). They are usually of post-war vintage.

Tram OLE system design is driven by the need to ensure the safety of the public, and by the many interfaces with buildings and highways. The systems are low voltage (usually 750V DC) and are often split into on-street and off-street equipments; the former being characterised by high contact wire, fixed termination tramway equipment (sections 12.2 and 12.3) and support from buildings, and the latter by a more conventional system with catenary and auto-tensioning. Support assemblies are very light, and double insulation (section 10.10.2) is used to prevent stray currents from entering buried services.

![Figure 15: Typical street-running tram with building-suspended OLE. Birmingham, UK](image)

9.2. Trolley Systems

Trolley buses also provide mass transit, and are used to provide low-pollution electrified public transport without the high cost and disruption of laying rails in city centres. The system consists of an unguided trolley bus controlled and steered by a driver in the same way as a conventional bus, but powered via trolley OLE (section 15) which is usually suspended from adjacent buildings.
Uniquely for an OLE system, the lack of running rails means that traction current cannot return to the supply point using the rail. Therefore the OLE is a double pole system, with outward and return contact wires insulated from earth and each other. These provide both circuit legs, and a pair of trolley poles (section 15.1) on top of the trolley bus collect and return traction current. The double pole arrangement leads to additional insulation complexity wherever routes converge or diverge.

Trolley bus systems are popular in continental Europe and elsewhere, and share many common features with tram systems. In some cities such as Bern the two types of transport run on a common support system.

9.3. Light Rail Systems

Light rail systems are a step up from trams. They are also mass transit systems, situated in and around urban centres, but they do not feature on-street running, and share many of the characteristics of heavy rail, such as fixed signalling. Speeds are usually below 120km/h.

For these systems, supply voltages are higher (1.5kV DC or 25kV AC), and the OLE is often fixed termination, with simple catenary (section 12.2). Structures and assemblies are lightweight, and headspans (section 12.10.7) are often used. The Tyne & Wear Metro is an example of such a system.

Figure 16: Trolley bus system showing complex double pole insulation and tight radius curve. Lucerne, Switzerland
9.4. Mainline Systems

Mainline systems form the bulk of the OLE railway route mileage worldwide. These systems are mainstream traditional railways; speeds may be anywhere up to 200km/h, and traffic may be heavy and frequent, with a mix of passenger and freight. The railway may date from Victorian times, the OLE having been superimposed at a later date.

Standard supply voltages are 1.5kV or 3kV DC, and 15kV or 25kV industrial frequency AC (25kV being standard for all systems since the 1960s). OLE is either simple or compound auto tensioned (section 12.2 and 12.3); assemblies are heavier, and portal (section 12.10.6) or headspan (section 12.10.7) structures may be used. Fixed termination equipment is often used in sidings and terminal stations.

9.5. High Speed Systems

Mixing passenger services with slower moving freight at speeds above 200km/h is neither practical nor safe. For this reason, high speed systems are usually dedicated to passenger services; the high power available often means steep gradients are used, reducing construction costs. These lines are usually less than 40 years old, and built with large radius curves, generous OLE clearances (section 10.8) and no OLE gradients (section 12.13.1). Service speeds are typically 300km/h or 350km/h.

The standard supply voltage is 25kV industrial frequency AC, usually with a transmission voltage of 50kV and an Auto Transformer system (section 10.4.3). Good current collection becomes paramount; OLE is either sagged simple, stitched simple or compound (section 12.2). Assemblies are lightweight, and structures are a mix of portals and cantilevers (section 12.10).
Figure 18: Typical high speed railway - Class 395 on High Speed One. Medway, UK
10. Electrical Principles

10.1. Supply Voltages and Currents

10.1.1. Transmission and Supply Voltages

*Transmission Voltage* is the voltage at which energy is transmitted to the train’s location. *Supply Voltage* is the voltage at which the train is supplied with energy.

For the majority of systems, the transmission and supply voltages are the same. However, some high speed lines use a higher transmission voltage to avoid excessive volt drop losses and thus provide more power at the train.

A variety of supply voltages are used around the world, due to a combination of historical and operational factors. 750V DC is standard for tram systems, and is chosen to minimise safety issues in public areas. 25kV AC, at a frequency equal to the country’s industrial supply frequency (50Hz in the UK), is used for the majority of new mainline and all new high-speed builds. Most countries (with the notable exception of the UK) have a legacy network of 1500V DC OLE, and Northern Europe has a sizeable 15kV AC 16.7Hz network.

It should be noted that the supply voltage is not a single constant value, since volt drop losses, magnitude of load in section and other factors affect the supply voltage at the train. For instance, below are the allowable voltages for UK 25kV AC systems.

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 kV</td>
<td>Minimum voltage at which a train should continue to operate for not more than two minutes without being damaged (for existing electrified routes only).</td>
</tr>
<tr>
<td>14 kV</td>
<td>Minimum voltage at which a train should continue to operate for not more than ten minutes without being damaged (for existing electrified routes only).</td>
</tr>
<tr>
<td>17.5 kV</td>
<td>Minimum voltage at which a train should continue to operate for not more than two minutes without being damaged (for new electrification schemes).</td>
</tr>
<tr>
<td>19 kV</td>
<td>Minimum at which train equipment should operate continuously</td>
</tr>
<tr>
<td>22 kV</td>
<td>Mean useful voltage at the pantograph for routes with speeds ( \leq 200 \text{km/h} )</td>
</tr>
<tr>
<td>22.5 kV</td>
<td>Mean useful voltage at the pantograph for routes with speeds ( &gt; 200 \text{km/h} )</td>
</tr>
<tr>
<td>25 kV</td>
<td>Nominal system voltage</td>
</tr>
<tr>
<td>27.5 kV</td>
<td>Maximum voltage at which train equipment should operate continuously</td>
</tr>
<tr>
<td>29 kV</td>
<td>Maximum voltage at which a train should continue to operate for not more than five minutes without being damaged</td>
</tr>
</tbody>
</table>

Each system will have a line voltage performance specification in this way, and the OLE system design is tailored to meet this.

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66 GLRT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 2, December 2019; RSSB; appendix D, table D.1.
10.1.2. Supply Current

The supply current is dependent upon the train power characteristic and the number of trains in section at any one time. For Low Voltage (LV) DC systems, the supply current is relatively high.

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Typical Train Starting Current Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>750V DC three car tram</td>
<td>~1100A</td>
</tr>
<tr>
<td>750V DC train</td>
<td>~3000A</td>
</tr>
<tr>
<td>1500V DC train</td>
<td>~1500A</td>
</tr>
</tbody>
</table>

For AC systems, the higher voltage available means lower supply currents.

<table>
<thead>
<tr>
<th>Train Type</th>
<th>Typical Train Starting Current Draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kV AC passenger train</td>
<td>~200A</td>
</tr>
<tr>
<td>25kV double headed freight train</td>
<td>~500A</td>
</tr>
</tbody>
</table>

Of paramount importance is the maximum fault current – the highest current which will flow under fault conditions. The entire OLE system must be designed to withstand many such faults over the lifetime of the equipment, without degradation of the components. For UK classic 25kV systems (section 10.4.4), the maximum fault current is 6kA. For new auto transformer systems (section 10.4.3), an increased level of 12kA or 15kA is generally specified.

Figure 19: Ends of contact wire which has parted during an undetected 25kV fault

10.1.3. AC Supply Principles

AC systems do not require rectification equipment, and AC electrical arcs are easier to extinguish when they cross zero volts, which means they can use higher voltages than DC. The resultant percentage volt drop is much lower, and so feeder stations can be further apart than for DC systems – for a standard 25kV feeding system, feeder stations are 40 to 60km apart. This eliminates the requirement for a separate HV feeding network.

Supplies have traditionally been obtained at each feeder station from the 132kV Distribution Network Operator (DNO). 25kV is obtained through 132/25kV transformers supplied by the DNO. These are often duplicated to give a backup supply or redundancy. These transformers are usually procured by the railway but owned and maintained by the DNO. They may be sited at a DNO compound alongside the railway feeder station, or sited
at a remote DNO site with 25kV cabling between the two.

New UK installations are now taking their supplies from the 400kV National Grid Company (NGC) system, which can withstand a much greater load imbalance and therefore provide much greater power capacity (section 10.4.3). By the mid-2020s it is possible that mainline rail will be the biggest single consumer of electricity in the UK.

The single phase supply taken from the three phase system at each feeder station creates an unbalanced load (or phase imbalance) on the Electricity Supply Industry (ESI) system. The ESI imposes contractually agreed limits on its customers on the total imbalance, and the railway is usually the biggest single contributor to this imbalance. For example, the ESI UK limits are 1.5% on the grid or DNO\(^67\); and 0.5% maximum contribution by the railway. This is one of the key reasons for moving to a 400kV-derived supply for high power railways.

![Figure 20: Principles of feeding a single phase railway from a three phase ESI\(^68\)](overhead_line_electrification_for_railways_6th_edition_2021_27.png)

To help limit the imbalance, adjacent feeder stations use different phase combinations; for instance feeder station 1 uses blue-yellow, feeder 2 uses yellow-red, feeder 3 uses red-blue. Direct connection of these adjacent systems would be catastrophic, so a short section of dead OLE – a neutral section – is used to keep the phases electrically separate. Trains shut off power before the neutral section, usually by means of an automatic trip, and coast through the neutral section before the power is switched on again (section 12.6.3). This configuration is single end fed, with all power coming from one supply point, and uses tee-feeding, with each feeder station supplying power in two directions.

Some administrations are now using Static VAR Converters (SVCs) or Static Frequency Converters (SFCs) to eliminate national grid imbalance and the need for neutral sections. SVCs are solid state devices that provide load balancing and harmonic reduction. SFCs convert three phase AC into single phase AC with a high level of efficiency, so allowing a grid connection to be made at a lower voltage such as 132kV or even 33kV, so potentially lowering the connection cost. When used at concurrent locations along a route - meshed feeding - the balanced nature of the SFC output means there is no requirement for neutral sections between them. However, due to their solid state nature, SFCs cannot be driven beyond their rated capacity - if this occurs they will shut down as a precaution against damage. This contrasts with a conventional feeder station, which is typically able to

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\(^{67}\) This figure can be much lower depending on the robustness of the grid at a particular location. For instance the UK High Speed 1 grid connection has an imbalance limit of 0.1%, meaning load balancing technology must be installed at the feeder stations.

\(^{68}\) This diagram is necessarily simplified; in practice successive feed connections are unlikely to be taken from a single ESI circuit.
operate at 200% of its rated capacity for up to two hours.

Other administrations – notably Russia – use three phase transformers between grid and railway to reduce the imbalance.69

The OLE between feeder stations is electrically split into *sections* and *subsections*, allowing sections of OLE to be isolated during planned maintenance or emergency situations. Each running line is electrically separate from the others. For classic feeding, sectioning is maintained at intermediate locations called *Track Sectioning Cabins* (TSCs) or *Track Sectioning Locations* (TSLs). These are the equivalent of the Track Paralleling Hut on a DC railway (section 10.5), and help keep the system impedance down by paralleling all OLE circuits together. The *midpoint TSC* (MPTSC) – so called because it is midway between feeder stations – includes a neutral section which keeps the phases at adjacent feeder stations apart.70

![Diagram of OLE with TSCs and MPTSCs](image)

**Figure 21: Typical feeding arrangements for classically-fed AC OLE**

Typical spacings for 25kV classic feeding are:

- Feeder Station to Feeder Station – 40 to 60 km;
- Feeder Station to midpoint TSC – 20 to 30 km;
- Feeder Station to TSC – 10 to 15 km.

Spacings are determined by the traffic to be handled, the train performance requirements and the electrical characteristics of the overhead and supply systems. These considerations result in an optimum spacing which it is not often possible to achieve in the real world, and shorter sections are often used to locate the feeder stations at strategic points such as junctions or route intersections. Feeder Stations are usually situated in close proximity to grid substations in order to avoid the high cost of long incoming feeds.

AT systems work on similar principles, but the equivalent of TSCs and MPTSCs are known as *Auto Transformer Sites* (ATS), *Sectioning Auto Transformer Sites* (SATS) and *Midpoint Auto Transformer Sites* (MPATS).

Each feeder station also has a neutral section, allowing the phase split to be moved up and down the railway in emergency feeding conditions. The loss of one incoming grid feed is known as *first emergency feeding* or *N-1 feeding*; the infeed circuit breaker at the feeder station is opened, the *bus section breaker* closed, and the remaining grid feed now supplies the railway in both directions, increasing the feeding distance and load. The system is usually designed to maintain compliant voltage levels in this scenario.


70 TSCs which are not at the midpoint are sometimes differentiated by the term *Intermediate TSCs* (ITSCs).
The loss of an adjacent feeder station grid infeed results in second emergency feeding or N-2 feeding; in this scenario the midpoint bus section circuit breaker is closed, allowing the feeder station to feed all the way to the adjacent faulty feeder station. Under this scenario voltage regulation may be degraded, and service levels may be reduced.

10.2. AC Supply Equipment

10.2.1. Substation Site Formats

Substation compounds are unstaffed, and take a number of different forms. Until the 1970s the standard format was a fully enclosed brick building housing all the circuit breakers (section 10.2.7), protection (section 10.7.1) and control & monitoring (section 10.7.3) equipment. However this format needed costly civil engineering, so alternatives were sought.
In the 1970s the modular steel housing format was developed; this used a steel building module of standard section, typically housing one circuit breaker, so that multiple modules could be bolted together to form a substation.
However this method still required significant foundation work, and so in the 1980s the building was done away with altogether, in favour of Structure Mounted Outdoor Switchgear (SMOS). This placed all the circuit breakers in special outdoor housings, mounted on OLE structures with a bare aerial busbar. The control & monitoring equipment was contained in a small building.

However this type of installation created its own problems; water ingress has occurred in circuit breakers, particularly in regions prone to bad weather. In the 1990s the SMOS concept was replaced by the containerised building concept, where a complete substation (apart from the transformers) is fitted out in a factory environment and delivered to site in a steel building. This remains the preferred format in the UK, either with indoor switchgear, or more recently with the containerised building housing control equipment for an improved SMOS arrangement.
10.2.2. Supply Transformers

Supply Transformers are used to step voltages down from grid connections at 400kV, 275kV or 132kV to the supply voltage.

400kV Super Grid Transformers (SGTs) are typically either an Oil Natural Air Forced (ONAF)\textsuperscript{71} design, or an Oil Forced Air Forced (OFAF)\textsuperscript{72} design.

132kV supply transformers are typically of a conventional Oil Natural Air Natural (ONAN)\textsuperscript{73} design. Off load tap changing of \(\pm2\%\) or \(\pm5\%\) is normally provided to allow the output voltage to be adjusted; other transformers are fitted with remotely controlled on-load tap changers to allow this adjustment to be made in service. Typical supply transformer sizes in the UK are 80, 88 and 104MVA for a 400kV to 50kV Auto Transformer (section 10.4.3) feeding supply, and 25 to 26.5MVA for a 132kV to 25kV classic supply (section 10.4.4).

![Grid feeding site with 400kV to 50kV Super Grid Transformer on right. Didcot, UK](image)

Where AC supplies are derived from networks operating at voltages lower than 66kV (such as 33kV or 11kV) the transformers are usually purchased by the railway infrastructure owner.

10.2.3. Auto Transformers

Auto Transformers are used to provide 50kV Auto Transformer (section 10.4.3) feeding, and are divided into two types.

Auto Transformers at feeder stations in the UK are typically sized at 80, 88 or 104MVA (oldest to newest). These are of the ONAN type, and have on-load tap changers. Auto Transformers at lineside AT sites remote from feeder stations are typically 15MVA and are also of the ONAN type.

\textsuperscript{71} This denotes that the insulating/cooling oil circulates naturally without any forced means, but air cooling uses fans.

\textsuperscript{72} Both oil and air are circulated, the former by means of pumps.

\textsuperscript{73} Oil circulates naturally, and air cooling is also by natural convention around the radiator fins.
10.2.4. Isolating Transformers

Isolating Transformers are 1:1 current transformers, used at the interface between AC and DC electrified railways (section 10.11.1). Power ratings are up to 5MVA, and due to the presence of DC voltages, the transformer uses an air gapped core rather than the more usual continuous core to prevent core saturation from occurring.

10.2.5. Auxiliary Transformers

Auxiliary supplies are used to feed local Low Voltage (LV) equipment or as a backup to other supplies, and are taken from the busbar at a substation, or directly from the OLE at a convenient lineside location. Auxiliary supplies can be for:

- Signalling Supplies (typically 650V or 400V);
- Battery charging (typically 110V) for safety-critical substation equipment (section 10.2.8);
- Operation of substation switchgear;
- Lighting and heating for the substation.

These supplies can be derived from the traction supply by means of step down transformers, or direct from a DNO feed. Auxiliary transformers are matched to the load that they feed, and sizes can be anything up to 450kVA.
10.2.6. Transformer Protection

Many administrations require oil-filled transformers to incorporate a means to mitigate the environmental damage done if the oil escapes in the event of a transformer failure. This typically takes the form of a concrete bund incorporated into the transformer footing, big enough to house 110% of the total volume of oil in the transformer tank (to allow for water collection from rainfall). These often have a smart bund pump fitted, which will pump excess water from the bund and also detect the presence of oil and raise an alarm.

10.2.7. AC Circuit Breakers

_Circuit Breakers_ are designed to interrupt the traction supply during fault conditions or for routine maintenance. They must be capable of closing and opening (_making_ and _breaking_) with both the normal operational currents (_load current_) and the much higher currents experienced during a fault. They must be able to do this many times over their life without experiencing degradation of the electrical contacts. Of particular importance is the ability to quickly extinguish the electrical arc which forms as the contacts move apart.

When discussing insulation materials in circuit breakers it is important to differentiate between the medium used for the arc chamber and that used to insulate the live parts of the circuit breaker from the earthed casing.

AC circuit breaker technology has advanced significantly in the last 50 years, and this is reflected in the range of circuit breaker types on the railway. In historical order of installation, they are:

- Oil insulated;
- Air insulated;
- Vacuum insulated;
- Sulphur Hexafluoride (SF$_6$) insulated for both the arc chamber and general insulation;
- Hybrid – vacuum for the arc chamber and SF$_6$ for general insulation;
- Air insulated (again).

_Oil Circuit Breakers_ (OCBs) were used for installations until the 1970s. Oil provides a good electrical insulator and will extinguish the arc quickly while dissipating the heat generated. However, they are heavy and bulky, and are not able to clear faults quickly, while repeated operations contaminate the oil with carbon deposits. These further degrade performance, meaning regular maintenance – which is messy and time-consuming – is required.
**Vacuum Circuit Breakers (VCBs)** were first used in the 1970s. Their simplified mechanical arrangement means they were thought to be more reliable than OCBs, giving improved interrupting capacity, increased contact life, and requiring less maintenance. They are also significantly quieter and smaller than OCBs, and require less maintenance. In this incarnation a vacuum was used for both the arc chamber and for general insulation.

**Sulphur Hexafluoride (SF$_6$)** breakers were introduced because the vacuum in VCBs was proving hard to maintain, with frequent leaks occurring. Initially SF$_6$ was used for both insulation and arc-extinguishing purposes, but it was found that under arcing conditions the gas breaks down into acidic elements which damage the breaker.

More recent SF$_6$ designs have used the gas for insulation only, with a vacuum used for extinguishing the arc. However SF$_6$ is considered to be the most potent greenhouse gas to enter our atmosphere, and the search is on for a suitable replacement. Some circuit breakers use Nitrogen rather than SF$_6$ as the insulation medium for this reason.

Recent developments have looked at the use of resin, or even a modern form of the oil-filled circuit breaker. New UK installations are currently using *Air Insulated Switchgear (AIS)*, with air used for general insulation and a vacuum retained for the arc chamber. This requires more space than SF$_6$ or full vacuum types, but is more reliable and emits no damaging gases.

### 10.2.8. LV DC Supply Equipment

Substations are typically provided with a local LV DC supply, and the control & monitoring and protection systems (section 10.7) are powered by this supply. This allows the safety-critical systems to continue to function in the event of a failure of the LV AC supply (section 10.2.5), preventing loss of control of the substation.

The DC supply comprises a set of batteries, charged from the LV AC supply. The batteries then feed the SCADA and protection systems - in the UK at 48V DC. In the event of an interruption to the AC supply, the batteries have sufficient capacity to feed the equipment for several hours.

### 10.2.9. AC Cables

Incoming 400kV or 132kV supplies from the ESI are typically delivered to the railway feeder stations through 400-500mm$^2$ two-core *concentric pressure* cables. The same type of cable is also used where connections are required between railway feeder stations.
Generally the cables are of the oil-filled type, with some being gas-filled. This latter type has the advantage of a lower charging current, and is favoured for tunnel use. Connections from the switchgear to the 25kV overhead contact system are usually formed of 25kV single core solid type cables. All of these cables must be carefully routed to prevent damage to the insulation; the cable will typically be laid in protective troughing, a minimum bend radius is specified\(^\text{74}\) and additional protection measures may be specified as the cable transitions from trough route onto a mast. HV cables experience large electromagnetic forces during short circuit conditions, and this will result in physical movement and damage unless the cable is mechanically restrained at regular intervals\(^\text{75}\).

The transition from insulated cable to bare wire requires a specialised assembly known as a sealing end, which facilitates connection of a bare lugged wire while sealing the insulated cable against water ingress or damage. These connections are built in the field, and the process requires skill and care\(^\text{76}\); they must be electrically pressure tested (section 21.3) to ensure that the insulation strength is maintained.

\(^{74}\) For 400mm\(^2\) cable, minimum bend radius is typically 1.5m.

\(^{75}\) The forces generated between parallel cables during a short circuit are proportional to the square of peak current and inversely proportional to distance between the cables. IEC 61914:2015 “Cable cleats for electrical installations”; 28 November 2015; International Electrotechnical Commission. Video of HV cable movement under short circuit conditions is available online at [youtu.be/eWPpGtOtK8](https://youtu.be/eWPpGtOtK8).

\(^{76}\) Installation video is available online at [youtu.be/rwIqHW9HmYA](https://youtu.be/rwIqHW9HmYA).
10.3. AC Sectioning Principles

Sectioning is carefully chosen to give the ability to isolate any OLE section, and is matched to the normal and perturbed working train service patterns.

Crossovers are usually provided to allow trains to transfer from the normal running line to the *wrong direction* line under *perturbation conditions*, which can be for planned maintenance or to deal with unplanned events. Traditionally in the UK insulators have been placed in the OLE (section 12.18) to create subsections which are bridged by normally-closed isolators (section 12.7). When these are opened they allow the OLE to be isolated at a fault or for planned maintenance. The train then runs wrong direction around the isolated subsection.
A serious disadvantage of this arrangement is that the Points of Isolation are not at the same location on both tracks. This leaves a residual hazard (section 18.12) when one track is isolated; the other remains live and this gives rise to an electric shock risk for workers.

New electrification in the UK is now using parallel isolation points; these also allow the whole junction to be isolated for maintenance, but are less flexible under perturbed working.

Isolators have traditionally been manually operated, requiring switching on site, but remotely operated motorised isolators (section 12.7) are increasingly used.

### 10.4. AC Feeding and Immunisation Methods

The first OLE systems used the OLE to transmit power to the train, and one or more running rails to return current to the supply point. Since the rails and sleepers form a conductive path to earth, a portion of the return current will flow via the general mass of earth.

In AC systems this was found to be unsatisfactory, due to the large electromagnetic (EM) field created around the OLE. This drives inductive coupling which creates particular problems of Electromagnetic Interference (EMI) for safety-critical lineside signalling and telecoms cables, as well as third party cables. This means that on any AC
electrified railway Electromagnetic Compatibility (EMC) must be carefully managed, starting with minimisation of EMI at source.

Any conductor carrying current will generate a magnetic field whose strength is proportional to the current, and this field induces a voltage in any nearby cables which is proportional to the magnetic field strength seen by that cable and the length of the cable, in accordance with Faraday’s Law. The proportion of return current flowing in the rails (as opposed to via earth) decreases exponentially with distance from the supply point, and this current is shared between the running rails as a result of cross bonding (section 10.10.1). For this reason each rail generates a much weaker EM field and so the OLE EM field dominates, creating an induced voltage in any lineside cable. This longitudinal voltage will drive a current that is able to form a circuit via the capacitance of the lineside cable to earth. If the lineside cable has an outward and return conductor (typically formed as a twisted pair) then small variations in the longitudinal voltage will create a transverse voltage between the conductors. This voltage appears as noise on the cable and creates interference in telecoms systems. Inductive coupling can also affect sensitive magnetic systems in nearby universities, factories and hospitals.

Figure 38: Induced currents in lineside cables with non-immunised OLE

Various techniques have since been adopted to manage this risk.

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77 NR/GN/TEL/31106 "Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables"; Issue 1, 2009; Network Rail; section 6.3.

78 A 200A train load with 10km of parallel lineside cable and no mitigation will induce a longitudinal voltage of 154V in the cable. Ibid.; section 7.1.1.

79 Ibid.; section 6.6.
10.4.1. Classic Feeding – Return Conductors Only

Where current-carrying conductors interact, the relative direction of the currents determines whether the magnetic fields add or subtract from one another. At any point the magnetic fields can be summed to determine the resultant magnetic field. This interaction is exploited by the Return Conductor (RC) system.

The RC runs parallel to the OLE, at approximately the same height, and positioned over the lineside. The RC is insulated from the OLE masts and bonded at regular intervals to the running rail, so providing a measure of current sharing\(^80\). Because the current in the RC flows in the opposite direction to that in the OLE, and is at equal height, the magnetic field produced by the RC will act to reduce the field produced by the OLE at ground level by around 50%. However, the currents and therefore the fields are not equal, and there is still the potential for interference.

Figure 39: Reduced induction in lineside cables with Return Conductor\(^81\)

\(^{80}\) Around 35% of return current will still flow via earth, and a 200A train with 10km of parallel cable will induce around 76V. Ibid.; section 7.1.2.

\(^{81}\) Cable capacitance and cable return flow are omitted on this and all subsequent immunisation diagrams for clarity.
10.4.2. Feeding – Return Conductors and Booster Transformers

To maximise cancellation of the magnetic field it is necessary to transfer all of the return current from the rail to the RC. This is achieved by means of a Booster Transformer (BT). A BT is a 1:1 ratio current transformer, with the primary winding connected in series with the OLE so that traction current is routed through it. The secondary winding of the BT is connected in series across an electrical break in the RC. The current in the primary induces an equal and opposite current in the secondary winding, and so drives current in the RC; and this current can only come from the rail at a bond connection midway between BTs called the midpoint connection (MPC).

This system ensures that almost all return current moves from rail to RC. Since the current in OLE and RC are now approximately equal and opposite, the magnetic fields at ground level largely cancel each other out, and so the BT/RC system provides a large measure of immunisation for lineside cables.  

Figure 41: Midpoint Connection from RC to traction return rail. Edinburgh, UK

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82 “Report on the Application of the Control of Electromagnetic Fields at Work Regulations 2016”, Rafi, Gavrilakis, Hayes; 2016; Atkins/RSSB; appendix A.

83 A 200A train with 10km of parallel cable will induce around 12V. NR/GN/TEL/31106 “Overview of Electromagnetic Coupling between Traction Systems and Telecommunications Cables”; Issue 1, 2009; Network Rail; section 7.1.3.
Figure 42: Booster Transformer arrangement for OLE

Figure 43: Minimised induction in lineside cables with Return Conductors and Booster Transformers
Booster Transformers are typically located every 5km, and OLE overlaps (section 12.4) are used as a convenient point for a break in the OLE.

Booster transformer systems have two major disadvantages: the transformers require regular checks, particularly for contamination of the insulating oil; and they increase the impedance of the system, thereby limiting the power capacity.

The BT/RC arrangement has been used widely across Europe, Asia and the UK, but there remain a large number of legacy RC only routes.
10.4.3. Auto Transformer Feeding

There are practical limits to the amount of power that a classic feeding system can deliver as volt drop losses increase. In particular, the move to higher passenger speeds requires a system with much higher power availability. The Auto Transformer (AT) system was pioneered at Philadelphia in the US in the early 20th century, using 36kV transmission and 12kV supply. It was then used on the Shinkansen at 60kV:30kV, before being introduced in Europe for TGV routes at 50kV:25kV. This is now the standard configuration for new high speed lines, and the details below are based on this configuration.

In any electrical circuit with a fixed load, power is proportional to $V^2$, and so there is more power available in a 50kV system than in the classic 25kV feeding system. Alternatively, since the current is halved for the same power, the same electrical load can be serviced with fewer feeder stations spaced further apart.

At the heart of the system is the Auto Transformer itself. This transformer works differently to a conventional one, since it has only one winding wound onto a laminated core. This primary winding is divided in two by taking a secondary centre-tap at the midpoint of the winding; this means that a part of the winding is common to both primary and secondary sides. The primary current flowing in the primary winding creates an electromagnetic field in accordance with Faraday’s Law, and as with any transformer this creates an electromotive force (voltage) in the half of the winding connected to the secondary, that drives a secondary current in the opposite direction to that of the primary current, in accordance with Lenz’s Law. So when under load, part of the load current through the winding is obtained directly from the supply, and the rest is driven by the action of the transformer.

Figure 46: Basic Auto Transformer operation showing loop currents

Figure 47: Auto Transformer arrangement for OLE, showing loop currents for a train drawing 1 amps. Shaded region represents previous figure
The system is supplied from a 25kV-0V-25kV centre-tapped voltage transformer, with the OLE fed from one half of the winding at +25kV, and an Auto Transformer Feeder or ATF (also known as an Auxiliary Feeder or AF) fed from the other half at -25kV. The traction return rail (section 10.10.1) is connected to the 0V centre tap.

The auto transformers are arranged in parallel along the railway, with the OLE fed from one end of the primary winding at +25kV, and the ATF fed from the other end at -25kV. The traction return rail is connected to the centre tap. The secondary winding is formed from the section of winding between the OLE and traction return rail.

The primary current, driven by the 50kV primary circuit, is supplied along the OLE to the AT and returns via the ATF. Ignoring volt drop in the system, the paralleled ATs all have the same 50kV primary voltage. Since the primary winding has twice as many turns as the secondary, the primary current drives a secondary current which is twice as large and moves in the opposite direction. The secondary circuit of each AT is therefore able to deliver twice as much current to the train as that which flows in the primary circuit, but at a voltage of 25kV. This is an essential requirement of any AT system, which must interface with classically-fed systems (section 10.4.4) and 25kV trains.

Meanwhile the current in the OLE is the sum of the primary currents of all ATs in parallel, plus the secondary current required by the train; and the current in the ATF comprises only the sum of the primary currents. This allows the ATF to carry out a similar immunisation role to the Return Conductor. AT sites are typically located every 5 to 10km, and can be thought of as acting as proxy feeder stations which take a supply from a 50kV ring and transform it to 25kV.

Figure 48: (top to bottom) Magnetic field strengths with 100A train load; midway between Auto Transformers, and at an Auto Transformer85

The additional 25kV ATF conductors create additional design challenges, since 25kV clearances must be

85 Ibid.; section 7.1.4.
maintained for ATF to earth, but also 50kV clearances for ATF to OLE. This can be a particular problem through limited clearance overbridges and stations.

The AT system is widely used on high speed systems worldwide, and in the UK it is installed on HS1 and GWML. It has also been retrofitted to the WCML and ECML to increase power capacity, and new retrofitment is under way on the GEML.

10.4.4. Boosterless Classic Feeding

In recent years the BT/RC system has been deprecated in the UK, in favour of **boosterless classic feeding**. This arrangement removes all booster transformers and return conductors in favour of a simple out-and-back feeding arrangement. Immunisation is instead provided by means of a Return Screening Conductor (section 10.4.5).

10.4.5. Mutual Screening and Return Screening Conductors

The **Mutual Screening Conductor** (MSC) and **Return Screening Conductor** (RSC) systems exploit another feature of electromagnetic fields interacting with conductors. Both take the form of an insulated cable placed immediately next to the cable which requires immunisation – usually in the signalling trough route.

When used as an MSC, this cable is earthed – in the UK, this is done every kilometre using a $4\Omega$ earth connection. The EM field created by the OLE then acts on the MSC, setting up a magnetic field which opposes that of the OLE in accordance with Lenz’s Law. Current will then begin to flow in the MSC, in the opposite direction to the current in the OLE. The MSC cable size is chosen with a larger cross sectional area than the lineside cables to provide a lower impedance, so the AC induced current in the MSC will be correspondingly higher than that in the lineside cable.

![Figure 49: Reduced induction in lineside cables with Mutual Screening Conductor](image_url)

The induced current in the MSC then creates its own magnetic field in the trough route which induces a voltage
in the lineside cable; one which opposes that induced by the OLE. This works provided that the MSC has low impedance to earth, and is physically close to the lineside cable.

MSCs in the UK are typically PVC sheathed 19/4.22 aluminium cable (section 12.16.5). This provides a screening factor of about 0.69, meaning the voltage induced on the LV cable is reduced by 31%. Although the current induced by the MSC is lower than that induced by the OLE, the reduction can sometimes be sufficient to remove the safety risk.

The disadvantage of the MSC is that it needs earth farms at regular intervals along the railway, and provides only limited screening. The RSC operates in the same way as an MSC, but is instead connected to the traction bonding system, typically at the cross bond locations (section 10.10.1). This removes the expensive earth farm requirement and provides significantly better screening than an MSC – for example the same 19/4.22 Al cable provides a screening factor of 0.33, reducing the induced voltage by 66%.

Figure 50: Minimised induction in lineside cables with Return Screening Conductor

RSCs are now being used in the UK with Boosterless Classic (section 10.4.4) and AT feeding (section 10.4.3) systems. Although the ATF in an AT feeding system provides a measure of EM cancellation, an RSC is also used to allow lineside circuit lengths to be significantly longer.

10.5. DC Supply Principles

DC systems have historically been constrained to lower supply voltages (up to 3kV) due to the expense and availability of rectification equipment (which converts AC current to DC), and the difficulty in breaking DC fault current. This means the system suffers from a large volt drop as a percentage of the supply voltage, and substations must be placed closer together (1.5km to 6km apart). The cost of providing a direct feed from the DNO at each location would be prohibitive, so mainline DC railways usually have a dedicated HV trackside feeder system to provide power to the substations. These feeder rings are typically at 66, 33, 22 or 11kV, fed
from a 132kV DNO infeed. The HV supply is then transformed down and rectified at each substation to provide power to the railway. The rectifier is fed with all three phases, meaning there is no imbalance on the DNO supply or requirement for neutral sections, and is usually of the 6 or 12 pulse type, to minimise the ripple voltage which is a feature of all rectifier outputs. The removal of any phase imbalance allows DC systems to be double end fed, which helps to raise voltages midway between substations. DC substations have outputs varying from 1MW (for tram systems) to 10MW (for mainlines)\textsuperscript{86}. Regenerative braking is only possible on DC systems with the addition of a DC to AC inverter (section 11.5) in parallel with the rectifier.

Many mainline DC systems also have traction feed wires; these run at the same voltage as the OLE and connect to it at regular intervals. They are usually suspended from the OLE structures and help to reduce the system impedance and raise line voltage.

Tram systems are usually compact enough not to require HV feeder rings, which would in any case be difficult to safely configure in busy street environments. They do however usually have traction feed cables buried in lineside ducts for safety reasons, and brought up the mast at regular intervals to connect to the OLE.

10.6. DC Sectioning Principles

Switching is carried out at intermediate Track Paralleling Hut locations. These help keep the system impedance down by paralleling all tracks together.

10.7. Protection, Monitoring and Control

10.7.1. Fault Protection

OLE systems are vulnerable to a large number of faults. These faults result in currents that are much larger than those caused by normal operation, causing considerable damage if the supply is not quickly disconnected. To prevent this damage an electrical protection system is used to clear faults by opening the circuit breakers feeding into the section.

Any system of protection should:

• Be able to differentiate between load current and fault current;
• Be sufficiently sensitive to detect a fault in its early stages;
• Be very reliable in operation – the simpler and more robust the design the better;
• Discriminate between currents fed to faults within the electrical section being protected, and current passing through to a fault in another section.

This section focuses on fault protection of an AC system.

10.7.2. Classic Protection

Classic protection has been used on all but the most recent electrification schemes. In this configuration OLE is split into sections that are fed from a single phase, single end-fed AC supply (section 10.3). Each feed is routed through a circuit breaker.

Attached to the feed by means of a Current Transformer (CT) and Voltage Transformer (VT) is a protection relay which looks continuously for faults, by measuring both voltage and current, and then calculating the impedance of the section that it is feeding. This is known as impedance or distance protection. It exploits the fact that fault current will usually flow through several circuit breakers between the fault and the feeder station, thus giving the opportunity to provide time delayed backup protection. The system is also impervious to voltage fluctuations, which would fool a simpler overcurrent-based protection system and cause nuisance tripping. Importantly, a distance relay will only detect fault current flowing in one direction.

Distance protection in the UK is configured with three zones of protection:

• Zone 1 is set to trip instantaneously, and is set to the impedance of the initial section less a calculation tolerance - so that zone 1 typically detects faults up to 85% of the way along the protected section;
• Zone 2 sees approximately 70% of the adjacent section and has a small time delay;
• Zone 3 sees all of the following section with a larger time delay.

To understand how this works, consider a two track railway consisting of three electrical sections, each protected separately and capable of isolation by a circuit breaker at each end of the section:

Figure 52: Alstom P40 distance protection relay

Figure 53: Detection of a fault using distance protection
During a fault the impedance ($Z$) of the faulted section will be significantly lower, since $Z = V/I$ and $I$ is now fault current rather than traction current.

The fault at $F$ is a section fault relative to Section C, but a through fault relative to Sections A and B. Thus the protective devices on Sections A and B should not trip their respective circuit breakers, whilst the protection on Section C should detect the lower impedance and open its circuit breaker.

If circuit breakers C2 and C4 do not clear the fault within the specified time, then the protection on section B will cause circuit breakers B1 and B2 to trip. Similarly, circuit breakers A1 and A2 will trip if all the affected circuit breakers in section B do not.

In addition to impedance protection, *overcurrent* and *undervoltage* protection may be provided. Overcurrent protection is typically provided using an *Inverse Definite Minimum Time* (IDMT) relay. The speed with which this relay operates is inversely proportional to the magnitude of the overcurrent - an ideal characteristic for overcurrent protection - but like all electromagnetic devices, it has a minimum operating time.

**Figure 54: Inverse current-time relationship for IDMT relay**

10.7.3. **Classic Control and Monitoring**

The circuit breakers at feeder stations, TSCs and AT sites are under the control of the *Electrical Control Room* (ECR). This is a control centre which supervises operation and maintenance of the OLE and the power & distribution system. A telecommunication system known as *Supervisory Control and Data Acquisition* (SCADA) is used to monitor and control circuit breakers remotely.

Traditional railway SCADA uses a *Time Division Multiplex* (TDM) system which polls the SCADA *outstation* or *Remote Terminal Unit* (RTU) at each feeder station in turn, interrogating the state of each circuit breaker. Any change in state or alarm is relayed back to the ECR. Similarly the ECR can send an instruction to a particular circuit breaker to open or close in the event of a fault or maintenance. The *Electrical Control Operator* (ECO) is therefore able to monitor and control the whole system from a set of display screens at a central terminal. Motorised isolators and/or load break switches (section 12.7) under ECO control may also be provided at key locations if fast perturbation management is required.

**Figure 55: ECR display screens. Melbourne, Australia**
10.7.4. IP-Based Control and Monitoring

TDM-based SCADA is now being superseded by a computer-based system using Internet Protocol (IP) based networks and computer outstations in each substation. These sites are capable of communicating with each other to determine and clear faults, without needing direction from the central ECR software; instead the control and monitoring is carried out at a local substation-to-substation level. This is done by means of Generic Object Oriented Substation Event (GOOSE) messages.

This system is captured in a new European standard[^1], and is now being used to significantly improve the detection and clearance of faults, while reducing switchgear costs.

![SCADA outstation. Hayes, UK](image)

10.7.5. Rationalised Auto Transformer System Protection

The classic protection system (section 10.7.3) was borne out of the necessity for each substation to be self-sufficient in detecting and clearing faults. The ability of IP-based substations to communicate with each other - without reference to the ECR - has recently led to the development of the Rationalised Auto Transformer System (RATS) protection scheme.

This is currently only used on auto transformer (section 10.4.3) systems in the UK, taking advantage of the tee feeding at AT sites to work in a radically different way to classic protection schemes.

Faults are cleared in a four step process:

- Detect fault within the protected feeding area;
- Open all circuit breakers for all lines and all electrical sections - both OLE and ATF;
- Open load break switches (section 12.7) feeding the faulted section;
- Reclose all circuit breakers (other than those directly feeding the fault) and resume normal feeding on unfaulted sections.

By adopting these principles, the number of circuit breakers in the system is significantly reduced - outgoing feeders at the AT sites are fed using cheaper load break switches rather than circuit breakers.

In the two track section above, a total of 8 load break switches are provided. If a fault occurs at F, within the first 50ms, the fault is detected. Between 50ms and 150ms, all feeding circuit breakers - A1 to A4 - are opened. Both tracks and ATFs are now isolated.

With all current flow stopped, it is safe to open the load break switches feeding the faulted section, B3 and C3; these switches cannot break fault current, which is why it is necessary to open all circuit breakers first. Fault isolation occurs between 150ms and 5s after the fault has occurred.

With the faulty section isolated, circuit breakers A1, A2 and A4 are now reclosed and railway operation is restored within 5s of the fault occurring. The whole process is fully automated and does not require ECO intervention.

While having some clear advantages over classic protection schemes, RATS does rely on sophisticated and specialised logic in the IEC61850 code, requiring a significantly different skill set to traditional protection systems. The system also results in an entire railway being isolated for a short period before service is restored.

Work is now under way to apply the cost-saving principles of rationalised protection to new boosterless classic (section 10.4.4) electrification schemes in the UK.
10.7.6. Interlocking

The power supply system is provided with interlocking at both a circuit and system level, to protect the electrification system from operational errors, and to help ensure safety and reliability.

At the circuit level, both electrical and mechanical interlocking is provided within each substation; depending on the choice of switchgear (section 10.2.7), the interlocking ensures that equipment is operated in the correct sequence - for instance, to prevent an earth switch being closed onto a closed (and so potentially live) circuit breaker. A mechanical interlock provides a physical barrier preventing this occurring, whereas an electrical interlock is a control circuit that prevents the operation being carried out.

At the system level, interlocking is provided to assist with operation of the system, but also to ensure safety between the ESI electrical system and that of the railway. For instance at a typical feeder station with two incoming ESI supplies, a two out of three interlocking is applied to the incoming circuit breakers and to the bus section that separates them (section 10.1.3). This permits any two of the three circuit breakers to be closed at any point in time, so preventing the incoming supplies being connected together through the busbar and potentially overloading and damaging both the ESI and railway systems. Bus section circuit breakers are also provided with dead bus switching which only permits the bus section circuit breaker to be closed if one of the busbars is de-energised; this is an additional barrier to accidental connection of the two incoming circuits.

Figure 58: Two out of three interlocking; the first three scenarios are permitted, but the fourth is not

Additionally, the ESI disconnector cannot be operated without opening the railway incoming circuit breaker; this is achieved either by the physical transfer of a key between representatives of the two companies on site, or operation of an electrical interlock releasing the disconnector.

All of these systems are collectively designed to prevent connection of different grid supplies by ensuring switching is only carried out in a specific order, with disconnection of one circuit occurring before connection of the second one. Not all switches within the system are interlocked, but additional safeguards are provided by placing control of all switching under the ECO (section 10.7.3). Collectively these measures help provide safe and reliable operation of the power system.

10.8. Electrical Clearances

Since it is not possible to provide insulated conductors in an OLE system, it is essential for safety and reliable operation to keep all live OLE parts a sufficient distance from other infrastructure, so that flashover is prevented. For this reason two sets of air gap clearances are defined. The static electrical clearance is the clearance which must be achieved under permanent (static) conditions. The passing electrical clearance is a smaller clearance which must be maintained for a short duration as the train passes or another non-permanent event occurs.
This smaller clearance is justified by the lower risk level in a short-duration event.

These clearances are set for a particular system voltage, based on the insulation coordination for the system. This involves selection of the right level of insulation strength to provide protection against both supply voltages and transient overvoltages, such as those experienced during lightning strikes. The lightning impulse withstand voltage is typically an order of magnitude higher than the supply voltage, and is also the determining factor in the size of insulators (section 12.18).

It is usual to have several categories of static and passing clearance in recognition of the different circumstances which may apply. For instance, historically UK standards defined four clearance categories;

- **Enhanced Clearances**, used wherever practicable;
- **Normal Clearances**, used where enhanced clearances cannot be attained;
- **Reduced Clearances**, only to be used with the consent of the infrastructure owner when normal clearances cannot be attained;
- **Special Reduced Clearances**, only to be used with the consent of the safety authority when reduced clearances cannot be attained.

The reduced level was introduced in 1962 based on operational experience and experimental findings; and the special reduced level was introduced in 1974 based on further testing and the introduction of a stress-graded bridge arm (section 12.10.9).

The historical standards for the various voltage standards used in the UK prior to 2015 were as follows:

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Clearance</th>
<th>Enhanced</th>
<th>Normal</th>
<th>Reduced</th>
<th>Special Reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>750V DC</td>
<td>Static</td>
<td>≥75mm</td>
<td>75mm</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥25mm</td>
<td>25mm</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>1500V DC</td>
<td>Static</td>
<td>≥500mm</td>
<td>150 – 499mm</td>
<td>100mm</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥500mm</td>
<td>≥100mm</td>
<td>99 – 80mm</td>
<td>N/A</td>
</tr>
<tr>
<td>25kV AC</td>
<td>Static</td>
<td>≥600mm</td>
<td>270 – 599mm</td>
<td>269 – 200mm</td>
<td>199 – 150mm</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥600mm</td>
<td>≥200mm</td>
<td>199 – 150mm</td>
<td>149 – 125mm</td>
</tr>
</tbody>
</table>

For AC systems this standard has been superseded by a new Group Standard which introduces three levels of insulation; reinforced insulation (equivalent to the old enhanced level) provides the highest level of protection, basic insulation provides an acceptable level, and functional insulation (equivalent to the old normal level) provides a level which must be supported by a risk assessment. The old reduced and special reduced levels are

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88 Insulation coordination in European systems is specified in BS EN50124-1:2017 “Railway Applications – Insulation Coordination Part 1: Basic requirements - Clearances and Creepage Distances for all Electrical and Electronic Equipment”; 31 March 2017; BSI; section 5.2.

89 A typical lightning withstand voltage for 25kV AC systems is 200kV. If an air gap or insulator breaks down under lightning strike conditions, the resulting arc will allow traction fault current to flow.

90 GERT8025 “Electrical Protective Provisions for Electrified Lines”; Issue 1, October 2001; RSSB; section B4.6.2.

91 “Railway Electrification: 25kV a.c. Design on B.R.”; 1988; Director of Mechanical & Electrical Engineering, British Railways; section 4.2.

92 HS(G)153/4 “Railway Safety Principles and Guidance, Part 2, Section C: Guidance on Electric Traction Systems”; 2005; HSE; section 43.

93 Ibid.

94 GLRT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 2, December 2019; RSSB; section 2.1.8.1 and table 5.
not formalised but remain available in extremis, subject to an appropriate risk assessment and implementation of mitigation measures.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Clearance</th>
<th>Reinforced Insulation</th>
<th>Basic Insulation</th>
<th>Functional Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>25kV AC</td>
<td>Static</td>
<td>≥600mm</td>
<td>370 – 599mm</td>
<td>270 – 369mm</td>
</tr>
<tr>
<td></td>
<td>Passing</td>
<td>≥200mm</td>
<td>≥200mm</td>
<td>≥200mm</td>
</tr>
</tbody>
</table>

Where reinforced insulation cannot be provided, such as at low overbridges, a section of contact wire typically replaces the catenary. This minimises the chance of wire stranding in the event of a flashover. This wire is known as catenary.

![Catenary wire damage caused by electrical arcing. Rayleigh, UK](image)

**Figure 59:** Catenary wire damage caused by electrical arcing. Rayleigh, UK
10.8.1. Voltage Controlled Clearances

It is possible to reduce air gap clearances further at overbridges by providing overvoltage protection by other means, reducing the air gap to a level sufficient to withstand the supply voltage. This can be achieved using a Surge Diverter (also known as a Surge Arrester). This device is a type of Non-Linear Resistor, and is connected between the OLE and traction earth at the OLE structure either side of an overbridge which requires small air gaps. At normal operating voltages it is an insulator and prevents current flowing to earth. However if the voltage in the system reaches the threshold (typically set at 300% of the supply voltage) the surge diverter becomes a conductor, allowing current to flow safely to earth rather than arcing across the air gaps in the system. A trip counter provides information on the number of overvoltage events, and a drop-out fuse link connected between the surge diverter and traction earth provides a visible disconnection in the event that surge current exceeds the capacity of the device.

This approach to reducing air gap clearances at overbridges is now in use in the UK\textsuperscript{96}, and has the potential to reduce the number of bridge reconstructions and/or track lowers (section 18.7) required for new electrification schemes. The resulting small air gap clearances are however vulnerable to being bridged by birds or debris, and additional measures are provided to prevent flashover in these circumstances. These include:

- Use of a bridge arm with a fully insulated head;
- Application of a special insulated coating to the length of the bridge soffit over each wire run;
- Application of an insulating plastic cover on the contact wire.

Air gaps using this combination of measures are known in the UK as Voltage Controlled Clearances, to differentiate them from clearances provided using conventional air gaps. It is possible to have passing clearance values as low as 20mm when using these measures, but their use requires careful design and a detailed risk assessment.

10.9. Safety Protection

The sliding contact function of OLE means that protection by insulation is not practical when it comes to protecting the public from the risk of electric shock. Instead protection by separation\textsuperscript{97} is extensively used. This means maintaining minimum distances between places that people can access – standing surfaces – and all live parts. These safety separations are considerably larger than the electrical clearances for a given system. For instance, the minimum safety separation between a standing surface and fixed live parts\textsuperscript{98} for 25kV AC lines in the UK was for many years 2.75 metres. This has now been increased to 3.5m.

\textsuperscript{96} The first location in the UK to be permanently energised using surge diverters is at Cardiff Intersection Bridge, where constraints above and below the track made reconstruction or track lowering uneconomic.

\textsuperscript{97} This type of protection is known in European standards as protection by clearance, but in this book “clearance” refers to air gap distances between two objects rather than between objects and people.

\textsuperscript{98} In the UK the whole length of an insulator is considered to be live. Other administrations consider the limit of live parts to be halfway along the insulator. NR-L2-ELP-27715 “Overhead Contact System Design Specification Module 4: Electrical and Mechanical Clearances and Separation”; Issue 3, September 2018; Network Rail; section 6.1.2.
Where it is not possible to provide protection by clearance, protection by obstacle is instead provided. The obstacle must meet predefined standards in terms of ingress protection and height, depending on where the standing surface is in relation to live parts. Solid floors are typically mandated for walkways over live parts to prevent objects or liquids coming into contact with the OLE.

For standing surfaces above OLE, such as overbridge parapets, an alternative to the fixed height approach is to specify a minimum taut stringline distance between the standing surface and live parts. This notional string line has one end placed on the standing surface, and is then pulled tight while being passed over the obstacle and toward the live parts.

It should be noted that the term "live parts" includes the pantograph itself. Due to the position and width of the pantograph, this can often be the most extreme part of the live envelope; it is important to consider this in the OLE design for both clearances and separations through overbridges, stations, signals and other infrastructure. In the UK pantograph live parts are only permitted to breach the 3.5m separation distance if a site-specific risk assessment has determined that the safety risks have been mitigated.

### 10.10. Earthing and Bonding

At its simplest, traction bonding provides the negative half of the traction circuit, with OLE providing the positive half. However, this in itself is not sufficient to provide a safe system. *Traction earthing and bonding* is the collective term used to describe a set of arrangements designed to:

- Provide a low impedance path for traction return current and fault current;
- Allow faults to be detected and cleared quickly;
- Keep the potential of exposed metalwork within safe limits;
- Eliminate touch potentials and step potentials.

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100 For instance European Standards permit the use of a vertical barrier with up to a 12mm² mesh for live parts alongside a standing surface in a restricted area, but mandate a solid wall up to a specific height for the same situation in a public area. Ibid.; section 5.3.

101 For 25kV AC systems in Europe, the voltage of exposed metalwork should not exceed 60V for any period >300s, and not exceed 645V for more than 200ms. Ibid.; table 4.
*Step potentials* arise during fault conditions, or when current is allowed to flow to earth. During these conditions, the system earth electrode may be subject to a rise in potential. This will create a potential gradient in the surrounding ground, the potential reaching true earth or zero at some distance from the earth electrode. Step potential is the potential difference between a person’s feet caused by this potential gradient.

*Touch potentials* arise where a metal service connected to another earth system (such as a level crossing barrier motor supplied from the DNO) is adjacent to OLE. In this situation, a person may be able to simultaneously touch the two earth systems (such as an OLE mast and an equipment cabinet). The two earths may be at different potentials, and so a current will flow through any person simultaneously touching both.

Both these situations give rise to unacceptable safety hazards, and so the earthing and bonding design must ensure these potentials are kept at acceptable levels.

### 10.10.1  AC Earthing and Bonding

AC systems are characterised by the creation of a distributed earth system using the general mass of earth; this is formed by using each OLE structure foundation as an earth connection. This system helps to keep the rail potential low in the event of a fault. The OLE structures are connected together by being bonded (along with earth wires) to the *traction return rail*, which may be one or both rails of each track (depending on the signalling system being used). This ensures that a fault on the structure will be cleared quickly. In electrical installation terms the earthing system is a *TN-C* type – that is, the *Circuit Protective Conductor* (CPC) and the *neutral conductor* functions are provided by a single shared set of conductors.

Other railway infrastructure is typically bonded to traction earth, to take account of the possibility that assets...
which lie within the Overhead Contact Line Zone (OCLZ) and Current Collection Zone (CCZ)\(^{102}\) may become energised under OLE mechanical failure conditions. These faults will create a safety risk if not cleared quickly – in particular, signal structures and metal bridges are usually bonded to traction return. Additionally, OLE can induce unsafe voltages in adjacent metalwork without direct contact, as described in section 10.10. This particularly affects long continuous lengths of connected metal such as lineside fencing.

For these reasons all exposed metalwork within the equipotential zone is generally bonded to traction earth, to ensure that no dangerous potentials can arise.

An important factor governing AC bonding design in mainline railways is that the main function of the rail is often not traction bonding. The primary purpose is the guiding of trains, but it is also used by those signalling systems which use track circuits to detect the presence of a train. For these systems the track is electrically sectioned by means of Insulated Block Joints (IBJs), also known as Insulated Rail Joints (IRJs). A voltage is placed across the rails at one end of the track circuit, and a relay detects the voltage at the other end. A train axle shorts the circuit, and this shorting is detected and allows the signalling system to locate a train. Track circuits have their own bonding system, and so the traction bonding must be integrated with the signalling bonding. Track circuits which use IBJs are known as single rail track circuits; where these are used, one rail of each track is designated the traction return rail - (although confusingly it also carries track circuit current and so would be better described as a common rail) and the other is reserved for signalling use only. Double rail track circuits (also known as jointless track circuits) eliminate the use of IBJs - which can pose reliability problems - by using high frequency AC voltages. For these types of track circuit both rails are used for signalling and traction currents, allowing the use of double rail traction return. Where no track circuits are present - in axle counter areas or sidings with no train detection - double rail traction return is also used.

For these reasons all exposed metalwork within the equipotential zone is generally bonded to traction earth, to ensure that no dangerous potentials can arise.

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\(^{102}\) The OCLZ is the zone within which broken conductors may fall; the CCZ is the zone which a damaged pantograph may intrude into.

\(^{103}\) Ibid., figure 1. In the UK \(S_{11}\) is defined as 6.8m, \(Y\) is defined as 1.4m, and \(X\) is defined as the lesser of 5.2m or the distance to the OLE structure. GLRT1210 "AC Energy Subsystem and Interfaces to Rolling Stock"; Issue 2, December 2019; RSSB; section 3.2.1.1.
AC railways use the traction return rails to form the core of the AC bonding system, and are typically configured to provide a path to earth of less than 1Ω impedance – this is known as traction earth. All of the conductors in the circuit – both live and earth – play a part in setting this impedance, so any significant change to the OLE configuration will also have an impact on impedance and therefore protection settings (section 10.7.1).

Bond connections are typically made using PVC-sheathed aluminium cable (section 12.16.5). Connections to the traction return rail use a crimped lug, which connects to a through-bolt in the web of the rail; a special compression bushing is fitted into the drilled hole, to maintain the strength of the rail, protect against the formation of cracks and provide a flat face for a good electrical connection.

The physical configuration of the bonding system is based on a set of simple principles.

Traction rail continuity must be provided at all locations, so that any train has a minimum of two paths for traction return current to flow; direct to the supply point, and in the opposite direction to the nearest cross bond location, and then back via another path. This is guaranteed by placing continuity bonds across any interruption in the traction return rail, such as expansion joints (where a gap in the rails is provided for thermal expansion).

Continuity must also be ensured where the traction return rail swaps sides, a situation frequently required in track circuited railways. In this case a transposition bond is placed across the IBJs which form the transposition point.

Transposition bonds are also a necessary feature at turnouts in track circuited systems, where IBJs are necessary to prevent the turnout geometry from shorting out the two rails.

Low impedance is essential, and is attained by bonding the traction return rails together at frequent intervals. For instance, in the UK AC railways are provided with cross bonds which connect all traction return rails (and any earth wires), typically every 400m. These locations are coincident with DEPs (section 10.12) to provide a secure path to earth in the event of inadvertent re-energisation during an isolation.

Impedance is further reduced by connecting all of the OLE structures to the traction return rail, either directly or via an aerial earth wire. This provides two important features: firstly the foundations form a distributed earth farm, tying the whole system to earth potential; and secondly, it provides a direct connection for fault current in the event of an insulator or similar failure at a structure.

Jointless track circuits are prone to interference from traction fault current, so OLE systems which are co-located...
with this type of track circuit are provided with an OLE earth wire. This is connected to the traction return rail at cross bond locations by means of an impedance unit, which is a low-pass electrical filter that allows traction current to pass while blocking the track circuit frequency.

These are also provided at transposition bond locations and the interface between jointless and conventional track circuits. The OLE structures are then bonded to the earth wire rather than direct to the traction return rail. The earth wire may be buried, but is usually aerially suspended between structures for security.

Bonds are also provided at all feeding and sectioning points to connect the traction return rails and the neutral busbar at the feeder station, ATS or TSC. This forms the main path for traction return current to leave the rails, and as such these cables can give rise to dangerous voltages if disconnected. For this reason in the UK they are designated and marked as red bonds, meaning they should not be disconnected without an isolation.

Some bonds have a dual function, providing both traction continuity and track circuit continuity. These bonds are designated yellow bonds in the UK and marked as such.

All of these ground-level bonds are vulnerable to damage from track maintenance tamper vehicles, and regular inspections are required. In the UK spider plates are increasingly used to allow easy cable replacement.

These features collectively provide the backbone of traction bonding of any AC electrified railway. However this in itself does not provide a safe system since a large number of other assets and systems must also be protected by being bonded to traction earth. These include:

- Overbridges and underbridges;
- Station ironwork and metal canopies;
- Signalling structures;
- Level crossing barriers;
- CCTV and radio masts;
- LV power supplies for signalling, points heating, stations and level crossings;
- Metallic fencing;
- Crash barriers;
- Metal bridge parapets;
- Any other substantial exposed metalwork.
It is often not desirable to connect LV equipment to traction return. For instance, LV equipment connected to a DNO earth will not tolerate large OLE fault currents; additionally, the two earth systems may be at different potentials, allowing current to flow between them.

In this case, it is important to locate this equipment away from the OCLZ and a sufficient distance from traction bonded equipment that touch potentials may not arise. If this is not possible, an insulating shroud or earth gapping may be required instead.

Bonding at stations requires special care, since LV systems bonded to traction earth may experience current levels during fault conditions which their CPCs are not sized to cope with. Segregation of HV and LV is often not practical, with OLE structures and LV-connected services in close proximity; in which case the LV earth system will be bonded to traction earth via a green bond at one controlled point, with or without LV earth gapping elsewhere.

Long metallic assets running parallel to the OLE - such as fences and metal pipes - are typically gapped or provided with a non-metallic section every 200m to prevent induced voltages (section 10.4) from reaching hazardous levels.

Overline structures often have small electrical clearances (section 10.8) and so require special measures to mitigate the increased risk of flashover. In the UK non-metallic bridges with electrical clearances of less than Reinforced Insulation level are provided with Conductive Assemblies (also known as Flashover Strips). These copper strips are placed on the bridge underside in line with the OLE and bonded to traction earth. Any flashover will generally migrate to the conductive assembly as the lowest impedance path, resulting in the fault being detected and protecting the vulnerable concrete from arcing damage. Metallic bridges are bonded direct to traction earth and so do not need flashover strips.

For those items which are to be bonded to traction earth, the choice over the bonding configuration depends on the specifics of the system and administration preferences. Some administrations choose to nodal bond these items to traction return. This ensures that all fault current will flow along a well-defined single path to earth.

Figures 70, 71, and 72 illustrate these concepts with diagrams and photographs.
Alternatively the systems can be mesh bonded, providing multiple paths for fault current to flow. This has the advantage of reducing the fault impedance when compared to nodal bonding, but there is naturally less control over how much current flows in particular paths. Mesh bonding is particularly useful in stations, where it can be difficult to separate traction and LV return systems.

Sometimes structures need protection from AC traction current. In this case, secondary insulation may be used. This is an additional level of insulation inserted between the primary insulation and the mass of earth. A connection to traction return is made between the two sets of insulation, and this captures any fault current, preventing it reaching the general mass of earth.

This method is used to provide an additional level of protection against flashovers – for instance, at sensitive overbridge locations or heritage structures where AC stray currents are to be avoided.

Special measures are required at the limits of electrified railways, to protect the adjacent non-electrified lines. This typically takes the form of single or double IBJs in all rails, to block any traction current from leaving the system. Similar precautions are also needed at locations where flammable substances may be present, such as at oil or gas loading depots. It is often not safe to directly bond oil or gas pipes passing over the railway or to extend the equipotential zone to cover them, due to the risk of traction current flowing into the pipe.
Figure 76: Bond connections for a typical mesh-bonded railway
10.10.2. **DC Bonding and Stray Currents**

Earthing and bonding principles for DC systems differ than those for AC systems. This is because DC stray currents can be especially damaging to the running rails, as well as to metal services and foundation reinforcement – because of the phenomenon of *cathodic corrosion* (also known as *galvanic corrosion*). This occurs when current flows continuously between dissimilar materials – for instance from a metal into adjoining soil. The metal is corroded, eventually to such an extent that a hole may appear – a particular issue with metal services adjacent to the DC supply point. The volt drop within the traction return system means that current will naturally flow from the rails to surrounding ground near the train, and back into the rails near the supply. Any metalwork in the path of these flows - such as masts, foundations, bridge metalwork, reinforcing bars, water and gas pipes - are vulnerable to damage.

![Figure 77: Secondary insulation protecting a sensitive viaduct; note connection to earth wire (which is insulated from the structure). Kentish Town, UK](image)

These problems mean that on DC OLE the earthing system is entirely different to that of AC systems. The entire OLE system is insulated from the general mass of earth, so that stray currents cannot leave the system.

![Figure 78: DC stray current flows in a DC OLE system without mitigation](image)
DC tram systems typically use two levels of OLE insulation – double insulation\textsuperscript{104} – to protect people from electric shock and street-level assets from the effects of stray currents. OLE structures are not bonded to rails and so are protected from corrosion.

Figure 79: (l-r) Foundation damage due to effects of stray currents on reinforcing bars, and replacement with secondary insulation to prevent DC current flowing into foundation (arrowed). North London, UK

The lack of a system earth can lead to unacceptable voltages between the rails and exposed metalwork under high train load or fault conditions, and some systems counteract this by installing short circuit devices at stations to temporarily disconnect the supply\textsuperscript{105}.

Figure 80: Double insulation (red insulators and top tie parafil rope) on tram cantilever. Manchester, UK

The question of how to insulate the return half of the circuit (the track) is more problematic; for a variety of reasons there is no one standard approach to this problem, but the available solutions can be grouped into three categories.\textsuperscript{106}

\begin{itemize}
\item \textsuperscript{104}BS EN50122-2:2010 incorporating corrigenda February 2011 and March 2011 "Railway applications - Fixed installations - Electrical safety, earthing and the return circuit, Part 2: Provisions against the effects of stray currents caused by d.c. traction systems"; 31 March 2011; BSI.
\item \textsuperscript{105}“Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance”, Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p68.
\item \textsuperscript{106}“Stray Current Control – An Overview of Options”, N. Dekker; 1999; IEE; Section 1.
\end{itemize}
The first option – **fully insulated earthing** – provides insulation immediately below the rails, and bonds the rails to local earth at each substation. Thus the rails are intended to be the only path for return current. Maintenance of the rail insulation is essential to successful operation of this system.

In railways with a reinforced concrete trackbed, this system is often provided with a form of secondary protection – a **stray current collection** mat – in case of failure of the rail insulation. The steel reinforcing bars within the top layer of the trackbed are tied together to maximise its conductivity relative to the conductivity of those to ground. An additional parallel return cable may be bonded to the reinforcing bars to reduce resistance further.

There is some debate as to whether this secondary measure is effective at limiting stray current leakage. Older installations included a diode between the stray current collector and the substation earth, but this was found to cause much higher secondary stray currents to flow, resulting in high levels of corrosion at the rail. As a result the use of diodes in this way is now deprecated in European Standards\(^\text{107}\).

![Figure 81: Fully insulated earthing and stray current collection mats on DC OLE](image)

The second option – which is now being installed in many tram and metro systems – keeps the rails insulated and connected to the rectifier, but removes the earth connection at the substation, resulting in a **floating return**. Theoretically this reduces the likelihood of earth leakage since no direct path to the substation is provided for stray current, but the disadvantage is that any stray current that does reach ground is no longer under control. Many systems use this in conjunction with a stray current collection mat.

The final option – one which has been widely adopted by historic DC systems – is to have no specific control measures at all. Any rail insulation exists purely to reduce vibration and sleeper damage, and the electrical insulation properties are incidental. Some railways, such as the DC lines between London Euston and Watford, are able to operate satisfactorily in this way due to the geography and specifics of the feeding system\(^\text{108}\), while others will experience ongoing corrosion problems due to the absence of mitigation methods.

### 10.11. Dual Voltage Areas

There are many locations where AC and DC electric railways meet, including:

- AC and DC systems coming into proximity at a complex location, such as a tram-train interchange;
- Separate AC and DC railways running in parallel on a transport corridor or at a station;

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\(^{108}\) “Stray Direct Current – a View from the Main Line”, F. Waterland; 1999; IEE; section 2.
• Separate AC and DC railways crossing, either at grade, overline or underline;
• Voltage conversion within a single railway, with trains switching from AC to DC and vice versa at a voltage switching location;
• A single railway carrying both AC and DC electrification in parallel – usually meaning AC OLE and DC 3rd or 4th rail.

![25kV AC/750V DC changeover. Drayton Park, UK](image)

We have seen that the bonding arrangements for AC and DC electrification are in opposition to each other, and this poses special problems whenever the systems meet. While in theory each system can affect the other in undesirable ways, in practice – and often depending on the standards applied when the first system was built – one system can usually be considered the cause and the other the victim\(^{109}\). The level of interference is largely determined by the configuration of the traction systems involved, which adds another level of complexity\(^{110}\). AC systems will produce interference via inductive coupling, and to a much lesser extent can also interfere via capacitive coupling; meanwhile DC systems will typically export cathodic corrosion to surrounding systems. Problems can multiply when the signalling systems of the respective systems are included – immunisation against AC being no protection against DC, and vice versa.

\(^{109}\)“Consequences of DC Components in AC Railway and their Elimination”, Midya, Thottappillil, Schütte; 2007; Uppsala University.

\(^{110}\)“Stray Direct Current – a View from the Main Line”, F. Waterland; 1999; IEE.
The particular geometries of the interaction play a part in determining the effects, and make modelling of the problem much harder. There is no single perfect solution to the interaction of AC and DC systems – each situation must be assessed and modelled, and an appropriate solution found\textsuperscript{111}. All of the available solutions involve compromises, and are best described as controlling the problem, rather than eliminating it. It is much harder to design immunisation problems out of a system after it is built, and so wherever possible the solutions should be incorporated during the original construction.

A full description of the potential solutions is beyond the scope of this book, but the following sections describe solutions which have been used to greater or lesser effect, and their respective advantages and disadvantages. A list of UK locations with dual voltage electrification, and their mitigation measures, can be found in Appendix B.

10.11.1. DC Transition - Isolating Section in AC

This solution is relevant at a transition between an AC and a DC system on a single set of tracks. Here the requirement is to permit changeover from AC to DC and vice versa, allowing for continuous operation of trains, while protecting vulnerable lineside LV systems and OLE structures from the effects of stray currents. IBJs (section 10.10.1) are used to prevent the flow of DC current from the rails into an AC area, or vice versa. It is necessary to provide two sets of IBJs, sufficiently far apart that the longest train (electric or otherwise) cannot bridge both sets; otherwise each train would connect AC and DC areas together, and undesirable currents would flow through the train body\textsuperscript{112}.

However this arrangement still requires a means to be provided for traction current to return from an electric train to the power supply. The means of doing this depends on the specifics of the interfacing electrification systems.


\textsuperscript{112} Ibid; appendix A.
The first option places the isolating section in the AC-only railway. Section insulators (section 12.6.1) are placed directly over the IBJs, and isolating transformers (section 10.2.4) are used to transmit power to an AC train beyond the IBJs. The OLE earth wire is segregated and all OLE structures bonded to the adjacent earth wire section. The system is analogous to an airlock, allowing continuity of AC traction current to the train but blocking DC current, which cannot flow across the transformer interface.

The following diagrams depict transfer from an AC OLE system to a DC conductor rail system, but these methods can equally be applied to AC OLE to DC OLE transfer, when combined with a suitable neutral section (section 12.6.3).

This option has the advantage of being simple, with no moving parts or control system required. However care is needed in the design of earthing and bonding to ensure that the OLE structures and bonding do not provide a path for current to bypass the isolating transformer. For this reason, complex track layouts, station areas and overbridge locations are best avoided.
A simplified version of this configuration removes the section insulators and provides continuous OLE into the isolating section, and then connects resistors across the IBJs, with a resistance value that ensures the volt drop does not cause electric shock risk or damage to trains. This reduces stray currents rather than eliminating them, but can work if DC voltages, AC traction currents and AC fault currents are all low.

A further variation replaces the resistors with bandpass filters – consisting of capacitors and inductors – which block DC current but allow the AC traction frequency current to flow unimpeded. Spark gaps (section 10.11.3) are provided to protect the capacitors in the event of a short circuit. This solution needs very careful design, since ageing of the filters, harmonics and over-voltages can all damage the equipment or cause unsafe voltages to arise.

10.11.2. DC Transition - Isolating Section in DC

Alternatively, where an AC OLE railway interfaces with DC conductor rail, the isolating section can be placed in the DC system. The two sets of IBJs are retained, and the conductor rails are gapped coincident with the IBJs. DC contactors are used to temporarily bypass the gaps and IBJs when trains are passing. The contactor operation is triggered by the train detection system, and is configured so that the contactors at each end of the isolating section are never closed simultaneously. It thus provides a similar airlock approach to that of section 10.11.1, but by mechanical rather than electrical means.

This system is effective, but adds complexity and significant maintenance of the contactors and control equipment. Stray current monitoring is typically provided for this configuration.
10.11.3. Shared AC and DC Lines

Lines which are provided with both AC and DC electrification on a single set of tracks – usually AC OLE and DC 3rd or 4th rail – present a particular problem since the segregation methods outlined in previous sections cannot be used. The principles of AC bonding (section 10.10.1) are completely at odds with normal provisions to prevent DC stray currents from flowing in other metallic systems, whether it be the OLE itself, an LV station supply or a steel bridge.

A number of different approaches are available, which may be more or less effective depending on the specifics of the situation.

The first option is to maintain AC bonding principles as per section 10.10.1, with special measures taken to limit the magnitude of DC stray currents. This could include a DC substation which only feeds the dual voltage area, with conductor rails and running rails isolated from the remaining railway; reducing the volt drop in the DC return circuit, using parallel return cables or additional rails in the return circuit to reduce the resistance; and bonding railway metalwork such as station and bridge metalwork to traction return as close to the DC substation as possible.

Alternatively, AC bonding principles can be maintained as per section 10.10.1, with special measures taken to limit the impact of DC stray currents. This could include reinforcement of bonding conductors and earth wires; a specially-designed DC substation at the AC/DC changeover point to keep DC rail voltage at zero or a negative value; and segregation of earths of third party assets from the rails.

Finally, devices such as spark gaps or non-linear resistors can be placed between bridge and station metalwork and the traction earth; these prevent DC from flowing into the asset, but allow AC fault current to flow across the device. These devices are not trouble-free; spark gaps can weld themselves closed, and non-linear resistors are hard to use in high fault current situations.

10.12. Earthing for Construction and Maintenance

10.12.1. Temporary Earthing Arrangements

Temporary earths are required to protect staff against inadvertent re-energisation and induced voltages (section 10.4) during construction and maintenance activities on or near to the OLE. The primary level of protection is provided by one or more Circuit Main Earths (CMEs); these are connections between the OLE and traction earth at each location on the circuit where inadvertent re-energisation could occur as a result of human error (such as reclosing a circuit breaker or misrouting an electric train into the section). The function of a CME can be provided either using portable earth cables, or via an earthing isolator (section 12.7.1). In the former case earthing stalks and/or line guards are provided on the OLE for these connections.
A section of OLE being protected by CMEs at either end may be sufficiently long that induced voltages could lead to hazardous touch potentials. For this reason Designated Earth Points (DEPs) are also provided every 400m between the CMEs. These can also be provided by means of earthing isolators, but are more commonly provided for with portable earths.

In the UK, construction earths (blue) are differentiated from maintenance earths (orange).

10.12.2 Buffer Sections and Permanent Earths

It is often necessary, for the protection of staff during a longer period of OLE construction works, to permanently earth a section of OLE using a Permanently Earthed Section (PES).

This is done by isolating the section of OLE from the live sections around it, and installing permanent earths at the limits of the section. Construction earths close to the start of the PES then form the safe limits of work for construction staff.
Figure 92: Permanent earthing connections. Newbury, UK
11. Electric Traction

A full description of the operation of electric traction is outside the scope of this book, but the following section provides an overview of the process by which an electric traction unit - whether it is a locomotive or EMU - converts electrical energy collected from the OLE into useful mechanical work at the rail. The examples used are generally for 25kV AC traction.

11.1. The Ideal Traction Unit

The key feature which gives rail-guided transport its efficiency advantage over other forms of land transport is the low rolling resistance offered by the small steel-to-steel wheel-rail interface\textsuperscript{113}. However this low-friction interface is the sole means for converting the rotary motion of the motored wheels into forward movement, and so the adhesion of this interface - defined as the ratio of force that can be applied to the rail without the wheel slipping to the weight applied over the wheel - is the limiting factor on power transfer and acceleration, as well as braking force. Actual adhesion levels vary widely, from 10-20\% in damp conditions to 20-40\% in dry weather with uncontaminated rails\textsuperscript{114}.

![Figure 93: Tractive effort/speed curve for electric traction](image)

The other factor that determines the tractive effort\textsuperscript{115} of the traction unit is the proportion of the unit mass carried on the motored axles; the greater the mass, the greater the torque that can be applied to the wheels before they reach the adhesion limit and slip. For this reason the only practical way to increase acceleration rates for rail vehicles is to increase the number of motored axles; and this is what gives EMUs an advantage on high-capacity urban railways. For instance, an acceleration rate of 1.0m/s\textsuperscript{2} for a traction unit with 20\% adhesion would require 50\% motored axles, and 1.5m/s\textsuperscript{2} would require 75\% motored axles\textsuperscript{116}. However more motored axles means more weight, more control equipment, higher capital cost, increased maintenance and higher track forces; and so electric rolling stock specification involves balancing the required performance with

\textsuperscript{113} "Overview of Electric Railway Systems", Schmid, Goodson, Watson; 2015; IET; p2.
\textsuperscript{114} "Managing Low Adhesion"; 6th edition, January 2018; Adhesion Working Group; section 2.
\textsuperscript{115} Starting tractive effort is the tractive force that can be generated at a standstill. This figure determines the maximum train weight that a locomotive can set into motion. Maximum tractive effort is the highest tractive force that can be generated under all conditions. In most cases, maximum tractive effort is developed at low speed and may be the same as the starting tractive effort. Continuous tractive effort is the tractive force that can be maintained indefinitely, as distinct from the higher tractive effort that can be maintained for a limited period of time before the power transmission system overheats.
\textsuperscript{116} Ibid; p2.
these constraints. Most modern EMUs are specified with 50% motored axles.

The traction motor drives each motored axle, and its function is central to the correct operation of any traction unit. Regardless of the control or motor technology involved, the ideal traction unit should initially provide a constant tractive effort which is set close to - but never exceeds - the specified limit of adhesion. This is the constant torque zone (from v=0 to v=V₁ in the graph above). In practice the constant torque level is normally set well below the limit of adhesion in good conditions.

The natural power limit of the motor means that it is not possible to maintain a constant tractive effort at higher speeds, since power = speed x torque; once the motor voltage has reached its maximum value, the back EMF created within the motor must be controlled by reducing the magnetic flux; so from V₁ to V₂ the traction unit enters the constant power zone and torque falls with the inverse of speed. This begins to limit the ability of the traction unit to accelerate. As speed increases further, the aerodynamic drag on the train increases, and overtakes the (broadly constant) rolling resistance to become the dominant retarding force. This is particularly important when specifying high-speed rolling stock (section 9.5).

Beyond V₂ the traction unit enters the constant voltage zone, where torque and power reduce while retarding forces continue to increase. Eventually the retarding forces reach a magnitude equal to the tractive effort of the unit; this point is known as the balancing speed (V₈), which for a given track gradient, cannot be exceeded without reducing the trailing load of the train. For this reason the design of the traction unit must take into account the required maximum speed, the required passenger or freight load, and the gradient characteristics of the route it is required to run on.

11.2. The DC Traction Era

Until relatively recently, electric traction was dominated by the series DC motor, with control using resistors and contactors. This approach was developed during the era of DC electrification (section 8.2) and was continued into the AC electrification era (section 8.3) with suitable adaptations.

11.2.1. Series DC Motor

The series DC motor comprises a stationary stator (colloquially known as the field) carrying a series of windings which generates an electromagnetic field, and a rotating rotor or armature which has a similar set of field-generating windings, each winding set at a different angle around the shaft. The two are connected in series - hence the name - through the commutator. This is formed of spring-loaded carbon brushes attached to one end of the stator, which press down on copper segments attached to the end of the armature. Different segments are connected to different armature windings, thus ensuring that different windings are energised as the armature rotates.
The windings are arranged in such a way that when fed with DC current, the EM field (section 10.4) generated by the armature is always out of alignment with that of the stator; this misalignment of fields ensures that the electromagnetic fields are always opposing or attracting each other, so generating a rotational force which spins the motor. DC series-wound motors have a high starting torque which falls with speed, making their electromechanical characteristic ideal for use in accelerating a vehicle from rest, where a high torque is required.

The dominance of this form of motor until recently was largely a function of the availability of suitable control equipment in the pre-solid-state age. The major disadvantages of this type of motor are the need for frequent replacement of brushes along with cleaning of the commutator\textsuperscript{117}, and the loss of energy in the associated resistance control mechanism (section 11.2.2); although this was later solved by using solid-state control (section 11.3).

11.2.2. Resistor and Contactor Control

It is not possible to start a DC motor at full voltage, since the resistance of the stationary motor is negligible and applying full voltage would lead to a short circuit. Therefore, traditional DC control systems in the DC electrification era used resistors which were switched into the circuit for low-speed control, and then progressively switched out as speed increases. This must be done as quickly as possible, since resistors waste energy, produce large amounts of heat, and will burn out if used excessively.

\textsuperscript{117}This typically involves grinding or turning the commutator to ensure it remains round as well as clean, and this is often done with the commutator in situ. Brushes generally last 6-12 months, depending upon commutator condition motor design. Motor overhaul takes place at between 2 and 10 years, depending upon how quickly the commutator wears down and becomes out-of-round. Many UK fleets grind the commutator while in place on the vehicle, and this gives an overhaul life in excess of 5 years.
For this reason, the voltage across each motor is also reduced at slow speeds by connecting the traction motors on the traction unit in series with each other and with the resistors. As speed increases, the motors generate a back EMF which increases their resistance, and so the resistors are progressively switched out using electro-pneumatic contactors, controlled by the LV control circuitry on the traction unit.

From the 1960s camshaft control became popular; in this system a series of contactors are all operated by a single camshaft, giving space savings over the individual contactor system, thus allowing more steps to be made and providing smoother operation. As the train accelerates the camshaft turns one step at a time, each turn shorting out specific resistors.

Once all of the resistors are removed from the circuit, further acceleration is achieved by switching the motors from series to parallel supply, so that each traction motor has the full supply voltage; at the same time, the resistors are restored to the circuit. This process is known as *rheostatic acceleration*. As speed increases further, the resistors are again progressively switched out by means of contactors.
The back EMF can be reduced further by a process of field weakening, where current is diverted away from the motor winding, thereby reducing the electromagnetic fields. This is the final stage of the process before the ultimate balancing speed is reached.

By the zenith of the DC motor era, this process had been fully automated; each time the speed increased and current fell, the control circuitry would switch out a section of resistance, a process known as notching. As train speed increased, current reduced until the next notch is activated; current then rose sharply, and the cycle would repeat. This occurred through the series, parallel and finally field-weakening stages, and in doing so kept the traction current approximately constant between tight boundaries.

For EMUs the system would also respond to higher trailing loads by increasing the target current to maintain acceleration at the same value. Since locomotives hauled a much wider variety of loads, this level of automation was not possible, so the driver would typically control traction current limit by monitoring the ammeter, with an overcurrent device stepping in only in extremis. This approach worked because drivers were aware of the short- and long-term thermal limits of the locomotive; later locomotives (such as the UK class 90) added electronic control which could measure and predict motor temperature, and reduce current accordingly.

However DC motor traction (without onboard voltage transformation) ultimately struggled due to a hard limit on supply voltage; since voltage is proportional to speed, maintaining high torque levels across the speed range required higher voltages, which in turn demanded larger insulation layers around live parts of the motor. This required a larger motor carcass, but the available space between wheelsets and below the vehicle floor prevented this.

### 11.2.3. Adaptations for AC Electrification

The desire to move to higher voltage AC OLE (section 8.3) reignited the debate over the best motor technology to use. Some administrations experimented with series DC motors but found that when AC currents were fed through the motor brushes and commutator, the momentary short-circuiting that is inherent to the design led to induced voltages and high currents. This transformer effect produced significant arcing at the brushes as they break the current flowing to the armature. The phenomenon, which does not occur with DC current, significantly increased wear on the commutator. The effect is proportionate to the frequency of the AC current, so some administrations - notably Germany - adopted a lower OLE frequency, necessitating the installation of rotating motor-generator pairs in substations to convert from industrial frequency to railway frequency. These measures reduced the impact but did not eliminate it. The lower frequency also

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118 “Electric Trains in Britain”, B.K. Cooper; 1979; Ian Allan Ltd; p18.
119 Ibid.; chapter 2.
120 Germany adopted 16 2/3 Hz for all of its early electrification schemes, and these remain in operation today.
necessitated larger supply transformers (section 10.2.2), to avoid them being driven into magnetic saturation.

In order to alleviate this problem, the French began to experiment with DC motors fed from AC OLE at industrial frequency, but with the AC voltage stepped down to the required level by a transformer in the traction unit before being converted to DC - albeit with a significant ripple - by means of a mercury-arc rectifier\textsuperscript{121}. This was the first time these devices had been used on a moving vehicle.

\textbf{Figure 99:} (l-r) Air-cooled steel tank mercury arc rectifier\textsuperscript{122} for class 81 locomotive, Glass bulb mercury arc rectifier in use at a substation; Laxey, Isle of Man

Rather than using inefficient resistance control, the traction transformer was provided with a tap changer which permitted the output voltage to be varied over a wide range. This gave the added advantage of allowing the DC motors to be permanently connected in parallel, eliminating some of the contactor complexity and also improving performance during wheelslip conditions. Resistors continued to be used for the field-weakening stage.

This arrangement was successful in comparison with the previous approach, and was adopted for the UK AC electrification trials between Lancaster and Heysham (section 8.3) and all subsequent UK schemes. However the reliability of mercury-arc rectifiers on moving vehicles was poor, and so they gave way to solid-state designs as soon as the technology was available - firstly using germanium diode rectifiers, and then later silicon diode rectifiers. At this point the solid-state devices were still controlled by tap changers, and in this configuration proved very reliable. In this form the DC traction system powered the first generation of AC electrification locomotives and EMUs\textsuperscript{123} up to the mid 1970s. Rectification was via a standard 4-pulse bridge rectifier, meaning a larger ripple voltage than that provided by lineside rectifiers (section 10.5); and so a large smoothing choke was connected across the output to reduce this ripple for the DC motor.

\textbf{11.3. The Thyristor Control Era}

The shortcomings of the DC system - the wasted energy in the resistors, the large number of moving parts in the contactor system, and the need for maintenance and replacement of motor brushes - meant that the coming

\textsuperscript{121} For more information see en.wikipedia.org/wiki/Mercury-arc_valve.

\textsuperscript{122} Three of these were fitted in each locomotive, but were eventually replaced with silicon rectifiers. "AC Electric Locomotives of British Rail", Webb, Duncan; 1979; David & Charles; p26.

\textsuperscript{123} UK EMUs as far as class 305, and locos of classes 81-85 were built with mercury-arc rectifiers and quickly converted. Classes 306 and 307 were built for 1500V and later converted to 25kV with germanium rectifiers.
of the power electronics age was bound to result in adoption of a more efficient system.

The development of the thyristor to the level of power electronics in the mid-1960s offered the first possibility of stepless AC voltage control, and the elimination of resistors and tap changers. A thyristor acts as an electronic switch; in its passive state all traction current is blocked, but if a pulse is applied to the gate, it begins continuously conducting from the anode to the cathode - as with a diode - until the current through it drops to near zero. This makes the thyristor ideal for controlling an AC waveform, which reverses polarity every half cycle, thus commutating the thyristor and halting conduction.

Once the thyristor is triggered to the on state, it is latched and will not switch off - even if the gate voltage is removed - until traction current passes through zero at the end of the half cycle. The thyristor therefore controls the Root Mean Square (RMS) traction voltage by providing phase angle control - the resulting power controller is known as a phase angle converter. The switch-on time of the thyristor is controlled to let a set proportion of the AC waveform through, the phase angle (or position along the waveform) varying from zero from 100%, where the full waveform is let through. Most inverters use full wave rectification, rectifying both positive and negative half of the waveform, since this reduces the ripple seen by the motor.

Thyristors perform this function with low losses compared to traditional control methods, and can carry currents in the order of hundreds of amps. Switching is a much more efficient way of converting a voltage than using resistors or amplification, since the voltage is either fully blocked (almost no current flowing) or fully flowing (almost no volt drop) through the thyristor.

In the UK thyristors were first used for phase angle control of DC motors; this happened very late relative to other European countries, with British Rail preferring to wait until the technology had matured and EMC issues were understood.

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124 For a given AC voltage, the RMS is the voltage that would provide the same level of power as for the same DC voltage; it is always lower than the peak AC voltage.

125 Typical forward volt drop for an individual thyristor is in the region of 1V. This effect does however make it much more difficult to use a thyristor to synthesize an AC waveform from a DC supply, generally requiring a separate commutation circuit comprising a capacitor and a second thyristor to temporarily cut the power to the main thyristor.

126 A prototype EMU class 302 with thyristor phase angle control operated in the late 1960s, but EMU classes 314 and 315 and the unique class 87/1 prototype were the first to adopt this approach in service.
The development of thyristor voltage control also meant that for the first time it was possible to use a three-phase brushless AC motor (section 11.4.1) in a railway traction context. Groups of thyristors could be arranged in such a way as to convert DC voltage to three-phase AC voltage, while controlling the magnitude of the output RMS voltage. This arrangement, known as an inverter, lies at the heart of the transformer/rectifier/DC link/inverter architecture described more fully in section 11.6.

The first three-phase thyristor-controlled locomotive appeared in the 1960s as an experimental machine. It was not successful, probably due to the early silicon thyristors not being able to withstand the high voltages required, coupled with an insufficient understanding of surge voltages and harmonics. After extensive development throughout the 1970s, from 1979 onwards thyristor-controlled traction units with AC motors began to enter service in several countries; in the UK the first thyristor testbed locomotive entered regular service in 1976, but squadron fleets of EMUs did not appear until the early 1990s.  

A significant disadvantage of the basic thyristor is the inability to switch traction current off at will; once triggered, the control system must wait for the AC waveform to pass through zero before current is blocked and control can be reasserted. The Gate Turn-Off (GTO) thyristor was a development of the device, allowing the flow of traction current to be blocked again within the half cycle, by the action of applying a negative voltage at the gate.

![GTO switching cycle](image)

This meant that for the first time, it was possible to have complete control over the voltage level within the AC cycle, and significantly reduce the number of devices needed while delivering significantly more power. From the mid 1980s, GTO traction packages rapidly took over from the basic thyristor type, and GTO-controlled EMUs first appeared in the UK in 1987. GTO traction units are instantly recognisable by their distinctive rapidly-rising-and-falling sound, created by the relatively low-frequency switching of the PWM (section 11.5).

GTOs have now been superseded by the IGBT, which is described in section 11.5.

11.4. The Modern Era

The following sections describe the technology found in new-build electric traction units today, whether fed from AC or DC OLE.

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127 As before, the introduction of three-phase AC motors came late to the UK, the first trains in fleet service being EMU classes 323 and 465, using GTO thyristors.

128 The class 319, which uses DC motors fed from either a 25kV AC OLE or 750V third rail supply. On these units the AC supply is rectified to DC (mimicking the third rail supply) before being fed to a chopper, a simple inverter which produces a pulsed waveform using GTO thyristors. This enables a variable voltage supply from the DC supply, without the losses that resistors would entail.
11.4.1. The Asynchronous Three-Phase AC Motor

The development of solid-state control electronics means that the DC series motor has largely been superseded by the **asynchronous three-phase induction motor**\(^{129}\). This type of motor has three windings in the stator (formed of insulated copper wire) which are connected to a three-phase AC supply in such a way that the phases rotate synchronous with the supply, with a 120° spacing. The rotor has no winding, brushes or commutator and is not supplied with electricity; instead a series of heavy copper conductor bars are arranged around the spindle and almost parallel to it\(^{130}\), and are short-circuited by end rings at each end of the rotor. This arrangement is also known as a *squirrel cage*. Both rotor and stator are provided with laminated steel cores to reduce hysteresis and losses.

As three-phase AC current is supplied to the stator, a rotating three-phase EM field is set up which cuts through the squirrel cage, inducing a voltage. Since the conductor bars and end rings form a circuit, current begins to flow in accordance with Lenz’s Law (section 10.4) just as it would in a transformer; and this in turn sets up an EM field in the rotor which reacts against that of the stator and begins to turn the rotor in the same direction as the rotating stator field. The rotor will accelerate until the torque generated matches the applied load, and since rotation at the speed of the stator field would result in no induced current, the rotor always lags (or *slips*) somewhat behind it - it is *asynchronous*. The rotor speed must always be less than the stator field speed, and the difference between the two depends on the load on the motor.

\[
\begin{align*}
\text{TORQUE} & = \text{PULL-OUT TORQUE} \\
\text{SPEED} & = V_s \\
\text{OPERATING POINT} & = \text{STABLE} \\
\text{UNSTABLE} & = \text{TORQUE}\text{.}
\end{align*}
\]

![Figure 103: Torque/speed graph for three-phase asynchronous motor](image)

It can be seen from the above graph that the asynchronous motor only has a small operating range, between the maximum torque and zero torque at the synchronous speed. This is typically only about 3% of the total speed range, meaning asynchronous motors are effectively constant speed for a given supply frequency. This type of motor can still provide variable speed for railway traction, but only by constantly varying the motor supply frequency, to keep the operating point within the stable operating range and move along the required tractive effort/speed curve as train speed increases.

The starting torque of the motor must be greater than that required to begin moving the train; this is achieved by supplying the motor with a low frequency, increasing the starting torque compared to that achieved with a fixed frequency. As the train accelerates, the motor moves into the stable zone, and at this point the *Variable*

\(^{129}\) The DC motor remains in use in some diesel locomotives such as the UK class 66, due to its inherent simplicity and reliability.

\(^{130}\) A small skew is usually introduced to reduce magnetic hum and avoid the motor stalling.
Voltage Variable Frequency (VVF) inverter (section 11.5) will begin to increase the motor supply frequency, which can be varied from near zero to around 140Hz. The motor supply voltage is also varied to ensure that motor current is kept below the maximum rating, particularly during the acceleration phase; and the inverter will also reduce the voltage to reduce losses as the required torque reduces.

![Figure 104: Varying supply frequency of asynchronous motor in a traction unit](image)

The asynchronous three-phase motor has key advantages over the DC series motor:

- Removal of the commutator and brushes means the unit can be sealed\(^{131}\) and is effectively maintenance free\(^ {132}\), as well as being cheaper to manufacture;
- For a given power output, asynchronous motors are up to 20% smaller than their DC equivalent, mainly due to the lack of commutator;
- The lack of copper on the rotor reduces the weight of the motor;
- The asynchronous motor can easily be powered and controlled using solid-state power electronics packages, which can ultimately be fed from either AC or DC OLE;
- It is easier to drive an asynchronous motor to a higher speed using an inverter; an equivalent size DC motor will run out of torque at high speeds, even with field weakening (section 11.2.2).

The asynchronous three-phase motor has provided train manufacturers with the ability to develop a modular train traction package, with the majority of components remaining the same\(^ {133}\) regardless of the supply voltage; and so variants of the same train can be produced to work with AC OLE or DC OLE (or indeed 3rd rail) at a variety of voltages. This provides obvious cost and manufacturing efficiencies, and has consolidated the asynchronous motor as the dominant form of rotating machine for electric railway traction.

### 11.4.2. The Synchronous Three Phase AC Motor

The stator of a synchronous three-phase AC motor has similar construction to the asynchronous variant, but requires brushes and slip rings (rather than a commutator) to supply electric current to the rotor, which unlike a squirrel cage has windings. While the rotor appears similar to that of a DC motor, the windings are simpler and carry far less current. The motor still requires a variable frequency supply for traction purposes.

The synchronous motor thus has the advantage of natural commutation, but still requires a variable frequency supply as with the asynchronous variant. Synchronous motors are larger than asynchronous ones for a given

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\(^{131}\) Many traction motors have air blown through them for cooling, and so cannot be totally sealed. This cooling gives a higher rating for a given motor size.

\(^{132}\) Bearing replacement after 5 to 10 years of service is broadly the only maintenance required for an AC motor.

\(^{133}\) The requirement to fit specific additional components to manage EMC (section 10.4) on UK trains, such as chokes fitted to 3rd rail EMUs, has prevented the complete standardisation of the design.
power output, and require brush replacement and slip ring maintenance. Synchronous AC motors have been used on multiple generations of French TGV trains (section 8.4), but have not found favour more generally.

11.4.3. Traction Motor Configuration

On an electric locomotive every axle is usually motored; 2-bogie 4-axle locomotives with 4 motors (known as Bo-Bo configuration) are popular for passenger services, while 2-bogie 6-axle locomotives with 6 motors (Co-Co configuration) are generally used for heavy freight services where higher tractive effort (section 11.1) is needed. For EMUs, the number of motored axles is matched to the required acceleration level.

Early electric traction units often used a single motor driving multiple axles through connecting shafts or rods. This created complexity, and so as traction motors reduced in size they were instead mounted directly within the bogie frame between the wheels. In this arrangement, each motor powers only one axle.

There are two principal ways to suspend a traction motor for this direct drive arrangement. The first is the nose-suspended configuration, where the motor is attached to the bogie frame at a single point, with the axle itself providing the other support point; the motor rests on a suspension tube, which surrounds the axle and is supported on it via bearings. A direct gear connection is provided between the motor spindle and the axle. This arrangement means that a portion of the motor weight is unsprung mass borne directly on the axle, and this can cause high track forces.

Figure 105: Nose-suspended AC traction motor on a UK class 455/8 EMU bogie - nose suspension on right, suspension tube on left

The second option is to mount the motor on the bogie frame, with a flexible coupling or quill drive used to account for the movement of the wheelset relative to the bogie frame. This results in a reduction in unsprung mass, since only part of the gearbox mass remains supported on the axle.

Other traction units go further by having the motor mounted on the vehicle body, with a long cardan shaft allowing for the additional movement between body and wheelset\textsuperscript{134}. This completely removes the unsprung mass, but at the cost of some additional complexity in the coupling.

\textsuperscript{134} Examples in the UK include the class 91 locomotive and class 390 high-speed EMU.
11.4.4. **Traction Motor Cooling**

Traction motors produce large amounts of heat, and so must be actively cooled. On most EMUs, the motor fan is mounted on the motor shaft, providing cooling which is directly proportional to speed. Since EMU motors spend proportionally less time at low speed, this gives the best cooling compromise without additional equipment. Locomotives generally have a separate *motor blower*, due to the increased amount of time they spend operating at low speeds and high torque.

Motors designed to be inverter-controlled (section 11.5) are designed and cooling-rated for operation at a wider range of frequencies than would otherwise be the case; the windings and cooling system will also be rated for slightly increased losses arising from inverter operation, depending upon the amount of distortion in the inverter output sine wave.

11.5. **Traction Power Control and the Inverter**

The use of the asynchronous AC motor for traction purposes is only possible if both the voltage and frequency of the three-phase AC input can be continuously varied, to keep the motor speed in the stable zone and the torque matched to the load (section 11.4.1); and so the controller must be capable of producing a VVVF three-phase AC supply. This is produced by an *inverter*, which takes a low voltage DC input\(^\text{135}\) and inverts it to a three-phase AC output.

The GTO (section 11.3) has now been superseded by the *Insulated Gate Bipolar Transistor* (IGBT) in most modern traction inverters. The IGBT is a combination of a *Field Effect Transistor* (FET) and a *bipolar transistor*. It behaves similarly to a conventional bipolar transistor, but the base current required to drive the device is significantly reduced. It can be switched at frequencies three to four times higher\(^\text{136}\) than a thyristor, and does not require

\(^{135}\) Typically 800V, although other voltages are used; for example, traction designed for 1500V DC overhead systems will feed the 1500V directly into the inverter, which will be constructed with higher voltage silicon.

\(^{136}\) Typical switching frequency for IGBTs is 1500Hz.
the same complex drive circuits to trigger and turn off the device.

The increase in switching frequency allows smaller inductors and capacitors to be used in the inverter design, as the higher frequency means less energy is required to be stored between cycles\(^\text{137}\). The IGBT also makes it easier to provide EMC (section 10.4) since a wider choice of operating frequencies means track circuit frequencies (section 10.10.1) can be avoided more easily.

IGBTs are used to convert DC to AC within an inverter using the technique of *Pulse Width Modulation* (PWM), itself a development of the basic thyristor method (section 11.3). This approach approximates an AC waveform using a DC input, by switching the supply on and off for varying periods of time in a precise way to produce a series of rectangular pulses. If a voltage of 1V is supplied for 0.5ms, and then switched off for 0.5ms, then the average voltage is 0.5V. For higher voltages, the IGBTs are left on for longer; for lower voltages, left off for longer. This technique is also known as chopping.

**Figure 107: Pulse Width Modulation - switching a DC input to form an AC output**

By varying the time periods - but not the voltage - in this way a sinusoidal waveform can be approximated by the inverter. Output frequency can be varied\(^\text{138}\) by shortening or lengthening the time between the V=0 crossing points of the output waveform. PWM is particularly suited to control of motors, which have inertia and so are able to overcome the discontinuities in the supply; however it is essential that the switching frequency is high enough that the sinusoidal output is relatively smooth.

For a three-phase AC VVVF, each inverter comprises comprising six IGBTs and six diodes. An inductor and capacitor are also provided to smooth the output to more closely approximate a sine wave. Each IGBT is switched using control electronics which monitor motor speed, current and voltage as well as the required power output being demanded by the train driver.

\(^{137}\)IGBTs are at least 5-6% more efficient than GTOs.

\(^{138}\)Output frequency is typically 0-70Hz for two pole motors, and 0-150Hz for four pole motors.
The switching frequency of the traction inverters is visible at the traction transformer and subsequently at the OLE; a single traction inverter will typically be configured to present an apparent switching frequency of 1500Hz at the transformer, although the actual frequency of the individual devices within the inverter may be different. The individual inverters on a traction unit are often synchronised and interlaced together, so that the OLE will see an apparent switching frequency of 3000Hz. The frequencies, and their harmonics, will be chosen as part of the EMC strategy so that they do not interfere with track circuits or any other part of the signalling system.

The harmonics produced by the controller are further minimised by ensuring that the frequency is high enough that the ripple between each waveform - the Total Harmonic Distortion (THD) - is small, and then chokes are used to smooth the output. The motors must be thermally rated to work with the marginally higher ripple current.

A key feature of this arrangement is that current is also able to flow from the motor back through the inverter, making the device compatible with regenerative braking. This is provided to reduce energy usage, turning the motor into a generator and using the retarding force to slow the train as the magnetic flux lines of the stator are
cut by the rotor (section 11.4.1). The process converts the kinetic energy of the train into electrical output from the motor-generator, which flows back through the inverter, DC link, rectifier (which now acts in reverse as an inverter) and pantograph before reaching the OLE to be used by another train in the electrical section.

It is essential that any regenerative traction unit is able to monitor the OLE line voltage before attempting to regenerate to it; since otherwise a section of OLE has been isolated (section 10.12.1) could inadvertently be re-energised by the traction unit, creating an electric shock hazard. A VT (section 11.8) is used for this purpose.

11.6. AC Electric Traction Architecture

The development of the three-phase inverter and AC asynchronous motor traction system has resulted in a standard traction architecture which now dominates the electric rolling stock market. While the concept is standard, the detailed implementation will vary to meet the specific demands of the route or region.

![Figure 110: Typical traction architecture for an AC OLE traction unit fed from AC OLE](image)

Traction current from the pantograph (section 12.1) passes through a roof-mounted VCB and other roof-mounted equipment (section 11.8) and into the primary winding of the traction transformer, which is typically mounted below floor level between the bogies. Traction units fed from DC OLE will instead have a High-Speed Circuit Breaker (HSCB) to break the higher traction currents.

The traction transformer is provided with multiple secondary windings (although only the winding providing traction power is known as such). This produces low voltage AC traction power at around 800V. The remaining secondary windings are confusingly known as tertiary windings and typically produce 230V, which is then used to power cabin heaters and other electrical systems on the train.

For traction units fed from AC OLE, the traction power is then fed through a rectifier to produce around 800V DC. This DC section of the circuit is known as the DC link; its importance lies in the fact that the system from this point onwards can be fed from either AC or DC voltage of any magnitude. The use of a controlled rectifier means the DC link voltage is very tightly controlled, and not dependant upon the wide variations in OLE line voltage (section 10.1). The DC link feeds the main traction inverters, which in turn feed the asynchronous motors. Compressors, motor blowers (section 11.4.4), cooling fans and battery chargers are usually fed from an auxiliary inverter connected to the DC link.

For traction units fed from AC OLE, a controlled auxiliary rectifier is usually provided to charge batteries and supply a DC control voltage for all control gear and lighting on the train. For UK EMUs this can be shared with
other units in *multiple working*, allowing rescue of a failed unit using normal driving controls.

This architecture permits the development of modular train formats, which can be produced to work with AC OLE, DC OLE or 3rd/4th rail, simply by varying the transformer module (for HV fed trains) or by omitting the transformer and rectifier (for LV DC fed trains). The rectifier and inverter are often combined into a single traction package. EMUs typically duplicate this architecture, except for the pantograph and main transformer; the doubling of auxiliary circuits means they will continue to be powered even if a single inverter fails.

Examples of UK traction architectures from the 1960s to the present day are as follows:

<table>
<thead>
<tr>
<th>Class</th>
<th>Traction Characteristics</th>
<th>Electric Braking Characteristics</th>
<th>Auxiliaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 310, 312 (4-car, 1965-1978)</td>
<td>Transformer tap changer voltage control, silicon rectifier; 4x 200kW series DC motor; 25% of axles motored</td>
<td>None</td>
<td>Tertiary winding on main transformer</td>
</tr>
<tr>
<td>Class 313 (3-car, 1976)</td>
<td>Rectifier, camshaft based resistance controller, DC series wound motors; 8x 82kW series DC motors; 66% of axles motored</td>
<td>Rheostatic (potential to re-use heat in saloon)</td>
<td>Using motor-alternator set to generate three-phase AC</td>
</tr>
<tr>
<td>Class 317-322 (4-car, 1981-1990)</td>
<td>Thyristor phase angle controller; 4x 187kW series DC motors; 25% of axles motored</td>
<td>None</td>
<td>Tertiary winding on main transformer</td>
</tr>
<tr>
<td>Class 323 (3-car, 1992)</td>
<td>GTO-based controlled rectifier and inverter; 8x 145kW AC asynchronous motors; 66% of axles motored</td>
<td>Rheostatic, regenerative</td>
<td>Heating via tertiary winding on main transformer; AC auxiliaries via tertiary winding and inverter</td>
</tr>
<tr>
<td>Class 365 (4-car, 1994)</td>
<td>Rectifier, GTO based inverter; 8x 157kW AC asynchronous motors; 50% of axles motored</td>
<td>Rheostatic</td>
<td>Heating via tertiary winding on main transformer; AC auxiliaries via tertiary winding and inverter</td>
</tr>
<tr>
<td>Class 357, 375 (4-car, 1999)</td>
<td>IGBT-based controlled rectifier, inverter; 6x 350kW AC asynchronous motors; 38% of axles motored</td>
<td>Rheostatic, regenerative</td>
<td>Heating via tertiary winding on main transformer; AC auxiliaries via inverter</td>
</tr>
<tr>
<td>Class 350, 360 (4-car versions, 2002-2004)</td>
<td>IGBT-based controlled rectifier, inverter; generally 8x 250kW AC asynchronous motors; 50% of axles motored</td>
<td>Rheostatic, regenerative</td>
<td>Heating via tertiary winding on main transformer; AC auxiliaries via inverter</td>
</tr>
</tbody>
</table>

Traction ratings are nominal, and may include additional peak ratings, particularly for DC motors.
11.7. Transformer and Rectifier Cooling

Traction transformers are typically encased in a large tank of silica-based oil, and are usually of the Oil Forced Air Forced (OFAF) (section 10.2.2) type; although some BR-era fleets use Oil Forced Air Natural (OFAN)\textsuperscript{140} cooling.

Traction rectifiers are typically water-cooled, since this permits better temperature control, and requires less space than an air-cooled rectifier, which requires a large heatsink. Some older fleets do however use air-cooling by simple convection.

11.8. Traction Busbars and Roof Mounted Equipment

A number of items of electrical equipment are positioned on the train roof and fed directly from the pantograph. These include:

- The VCB (section 11.6) to clear faults on the train;
- A VT (section 10.7.2) connected directly to the pantograph to allow the traction control system to measure the voltage before closing the circuit breaker. It is also used to synchronise the inverter to the incoming AC waveform and for energy metering purposes;
- A CT to measure current for inverter feedback, overcurrent detection, detection of earth faults in the transformer (with a corresponding CT on the transformer outgoing cable) and for energy metering purposes;
- A surge diverter (section 10.8.1) to protect the traction unit from overvoltages;
- An earthing device to earth the traction circuits during maintenance when the pantograph is lowered.

\textsuperscript{140}This denotes that the insulating/cooling oil is circulated by pumps, but external air cooling is natural without any forced means.
The VT can play several roles, depending upon the traction system design; as well as measuring the line voltage, it is often used to provide a precise reference voltage for traction package synchronisation purposes (section 11.5) rather than relying on a voltage measurement at the traction transformer (section 11.6), where lag may be occurring.

Modern electric trains often have distributed traction, where a single raised pantograph supplies power to traction motors across several vehicles, usually at both the HV and LV levels. A typical high-speed EMU has a roof-mounted HV busbar connected to the output of the VCB of each of the two pantographs, and carried along the roof by a single core 25kV insulated cable (section 10.2.9). Inter-vehicle HV connections are provided using sealing ends at each vehicle-end, and a flexible cable. Each transformer then feeds traction motors across multiple vehicles, via LV cables running within the vehicle body. Inter-vehicle connections for the LV busbar are provided using flexible cable harnesses on the body ends.

This system allows the minimum number of pantographs to be raised, maximising dynamic performance (section 12.1.2), while still providing all of the benefits of distributed traction, and the flexibility to switch...
to the second pantograph when needed. Distribution purely using LV is impractical since it would require a large transformer and heavy cables.

11.9. Automatic Power Control

AC tractions units usually operate on routes with neutral sections (section 12.6.3) and where this is the case, most administrations mandate that traction units are provided with some form of Automatic Power Control (APC) to ensure that traction power is switched off on approach to the neutral section, and restored beyond it.

In the UK the standard arrangement is a reed switch - or more recently, an equivalent device with no moving parts - fitted to one side of one bogie of each traction unit, usually the one close to the pantograph. This detects the magnetic field created by a sleeper-end APC magnet, and operates the VCB (section 11.6). It is also possible to use a balise to achieve the same function, as is the case on the forthcoming Crossrail and HS2 routes in the UK. The driver will remove power demand from the train before the neutral section is reached, to ensure a smooth ride and less wear on the circuit breaker for older trains; and signage (section 13.2.1) is provided as a reminder to the driver. However some administrations do not provide APC equipment on electric trains, and rely solely on the driver to remove power before entering the neutral section.

![Figure 113: (l-r) APC magnet receivers on UK EMUs; old pattern, and new pattern](image)

11.10. Train Bonding

From an electrical safety perspective, trains are treated no differently to conductive infrastructure, in that exposed live parts must be connected to earth to manage the electrical risks (section 10.10), and to provide a path for traction current to safely leave the vehicle and enter the traction return rail(s) (section 10.10). For this reason the various elements of the train which run on bearings, such as the bogies, have bonding connections across the moving joints to ensure that traction and fault current can safely reach the traction earth through the wheels. It is important to ensure that no traction current passes across the wheel bearing races, since micro-arcing across this interface causes damage that significantly reduces the bearing life. Bearings are often deliberately insulated to eliminate this possibility.

The means of achieving bonding on a vehicle is however complex, especially with DC units. While AC units typically return currents on the same vehicle as the pantograph, with relatively small currents (section 10.1.2), DC units have much higher currents and so the bonding will be designed to return this via multiple routes within the vehicle.

The vehicle bonding design must also mitigate the risk of traction current for other trains flowing through parallel paths within the vehicle, rather than staying in the traction return system (section 10.10). The non-live side of the motor is connected by traction cables to axle brushes, which provide an electrical connection to the axle, permitting traction current to pass into the traction return rail. These cables are kept separate from...
equipotential bond cables within the vehicle to prevent parallel paths being created.

The equipotential bonding on a vehicle typically adopts one of two options:

- A nodal bonding approach, ensuring the train cannot create parallel paths, using insulators on couplings and bogie components to guarantee a single equipotential bonding zone for the body, and providing a return path through one axle on one bogie only;
- A mesh bonding approach, accepting that parallel paths may exist, and ensuring that all equipotential bond components are capable of taking the largest current that can flow through the train, for instance if it stops over an IBJ. This may involve large bonds between vehicles, or even resistors fitted in some bonding cables.

11.10.1. Electrical Protection

Electrical protection is provided on traction units so that wherever possible, electrical faults on the train are isolated locally, and so do not trip the electrical protection on the OLE (section 10.7.1). The main protection device is the VCB (section 11.6), which will trip in the event of:

- Overcurrent or earth leakage fault;
- Incorrect voltage or frequency;
- Detection of gases in the transformer oil;
- Excess electromagnetic emissions;
- Some overheating conditions.

11.11. Pantograph Configuration

The pantograph (section 12.1) is positioned on the roof of one of the vehicles so that the vertical axis of the pantograph head is as close as possible to the bogie pivot point; this ensures that the pantograph is always over the track centreline, to eliminate any throw caused by the vehicle movement around curves. The vehicle carrying the pantograph often has one or more of the following measures applied, to minimise sway (section 12.13.2) caused by the roll of the vehicle:

- Slightly stiffer suspension;
- Stronger anti-roll bars;
- More restrictive suspension stops.

The pantograph raising mechanism relies on a steady supply of air from the vehicle’s compressor. If the train has been out of use for any length of time, there may not be any compressed air available. Traction units therefore carry a small battery-powered compressor to provide air to the pantograph, sufficient to raise the pantograph before the main compressor can be started.

_Tilting trains_ present a special challenge for pantograph operation, since the pantograph must remain parallel to the track even as the vehicle body tilts. This is typically achieved by placing the whole pantograph frame on rollers, which move in the cross-track plane on a curved track. A motor controls the movement of the frame, and is linked to the tilt controller so that any movement of the vehicle body is matched by an equal and opposite movement of the pantograph frame.
Figure 114: Tilting Brecknell Willis HS-A pantograph on UK class 390
The key interface to be considered in OLE design is that of the contact wire and pantograph (or pan). It is the pantograph which collects traction current from the OLE, and it is so-called because of the parallel linkage used to maintain a level pantograph head.

![Typical mainline pantograph](image)

This linkage ensures the head is always parallel with the contact wire. The pantograph is maintained on the wire by an upward force generated by an actuator (which is generally a pneumatic cylinder, although historically has been a mechanical spring). This raises the lower arm, and the upper arm is raised either by an external bar linkage, or by an internal 4th bar which pulls a set of chains around a cam at the knuckle. This approach has the advantage of minimising aerodynamic disturbance from external links. The actuator also acts as the primary suspension for the system. Secondary suspension is usually provided on pantograph heads designed for mainline railways, and some high speed pans provide tertiary suspension. Secondary and tertiary suspension can be provided by a variety of means, from torsion bars to radial arms or plunger springs.
The head itself is designed to be of low mass to reduce inertia, and typically supports one or more rows of carbon strips; these form the interface with the contact wire. Carbon is used because it has good electrical and thermal conductivity, is self-lubricating, and has a much lower hardness than the contact wire. This means that most of the frictional wear is taken by the carbon strips rather than the OLE (it being far easier and cheaper to replace the carbons than the contact wire). Many administrations, including the UK, impregnate the carbons with copper (and historically, lead) flakes to improve its conductivity. In the UK up to 35% impregnation by weight is permitted. A set of carbon strips will typically last 80,000km before needing replacement.

The dynamic performance of the pantograph is partly a function of the unsprung mass of the elements between the secondary (or tertiary) suspension and the contact wire; the lower the mass, the better the ability to absorb small changes in contact wire position. Modern high speed pantographs reduce this mass even further by separating the horns from the head and placing them below the suspension. This is known as a floating head pantograph.

In many mainline and high speed pantographs the carbons are glued into an air channel, which is connected to a compressed air circuit. In the event of loss or excessive wear of a carbon strip, air pressure is lost and the pantograph Auto-Drop Device (ADD) lowers the pantograph, thus reducing the chances of damage to the OLE. Modern pans have a fast-drop capability to further reduce the risk of damage.

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142 Some low speed pantograph designs use a metallic strip instead.
All pantographs have a specified *operating range*; that is, the vertical distance over which they will safely operate, with a mechanical behaviour that is broadly the same. Those with an auto-drop mechanism will generally also retract if the pantograph exceeds the upper operating limit.

The pantograph to contact wire interface is a complex one, comprising as it does three interacting dynamic systems (the pantograph, the OLE, and the train) each with various modes of movement.

The pantograph itself can be approximately modelled as a *spring-mass-damper system*. In simple terms, the pantograph is arranged to exert an upward force on the contact wire - the *contact force*. This is ideally a constant force, but several factors prevent this in practice. Aerodynamic effects on the pantograph are different depending on speed and whether the pantograph is *knuckle leading*.

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144 BS EN50367-2020 “Railway Applications - Fixed Installations and Rolling Stock - Criteria to achieve Technical Compatibility between Pantographs and Overhead Contact Line”; August 2020; BSI; figures A.6, B.6, B.3.

or trailing. This can be partially overcome on modern pans by means of tuned aerofoils on the knuckle and/or head, and/or tabs on the horns to counteract the aerodynamic lever effect on the head.

![Diagram](image1.png)

**Figure 119: Different contact force depending on pantograph direction**

The contact force also varies somewhat with wire height, due to the mechanical arrangement of the pantograph linkage and actuator. Additionally, the friction of the knuckle itself can lead to varying force due to hysteresis, depending on whether the pantograph is rising or falling.

![Image](image2.png)

**Figure 120: Brecknell Willis HS-P Mk1 pantograph with knuckle aerofoils and head tabs (arrowed). Kings Cross, UK**

In Europe the design of pantograph-OLE interface is governed by the *Technical Specifications for Interoperability* (TSIs), as transposed into European Standards, and these specify that a compliant AC OLE/pantograph system for up to 200km/h linespeed will have a contact force distribution such that the mean contact force ±3σ (3 standard deviations) is always between 0 and 300N. Static contact force is generally set at 70N or 90N at the pantograph. As dynamic contact force is added, higher forces will be seen at discrete features, and forces up to around 350N can be accommodated without risk of damage.

Pantographs at the front of a train experience higher levels of air turbulence, due to the nose of the train pushing

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146 On high speed systems, this problem is overcome by providing OLE at a constant contact wire height.

147 The UK has now left the European Union and so the TSIs have ceased to apply. Their content has been transposed into the National Technical Specification Notices (NTSNs).

148 BS EN 50119:2020 “Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; April 2020; BSI; section 5.2.5.2.
air around it. Airflow at the rear of the train tends to be smoother, so many administrations run their medium and high speed services using the pantograph at the rear of the train set, with the front one out of use in normal operation. This has the added advantage that in the event of a dewirement, the events will generally occur behind the front pantograph, leaving it undamaged and able to power the train after an incident.

### 12.1.1. Types of Pantograph

The UK currently has 11 different types of pantograph in active use; six on the mainline, 2 tram/metro types, and 3 which are confined to High Speed One (section 8.4). A full list can be found in Appendix C.

Early pantographs used a diamond linkage configuration (see figure 6 for an example), and later the cross-arm type was adopted; but a more sophisticated mechanical linkage design allowed parallelism to be maintained with a more responsive single arm. In the UK this began to overtake the cross-arm design when the Stone-Faiveley AM/BR pantograph was introduced in 1959.

British Rail subsequently went into partnership with Brecknell Willis to develop a new single arm pantograph which would (after several iterations) be capable of reliable operation at speeds of 225km/h. The resulting Brecknell Willis High Speed pantograph became the template for most mainline railway pans in the UK, which all conform to the BR head profile shown in section 12.1.

The exception is on High Speed One, where a series of Faiveley high speed pans are used. These are matched to the French pattern OLE system on that route, having previously been used on TGV trains. HS1 pans use a different geometry with insulated horns, and have different dynamic characteristics. For this reason the HS1 pantographs are not permitted to run on UK conventional routes.

For the lower speeds of tram and metro systems it is not necessary to have the sophistication of secondary suspension or aerodynamic balancing, and so simpler pantograph designs are used.

Engineering development is now focused on active pantographs, where the contact force is measured many times a second and fed back to a controller which varies the actuator force. The Faiveley CX pantograph used in the 2007 speed record used this principle.

### 12.1.2. The Pantograph-OLE Interface

The contact force from the pantograph creates a vertical displacement on the contact wire – uplift. When the train is moving this uplift combined with the along track movement creates a mechanical wave in the contact wire. In simplified terms the pantograph can lose contact with the wire if the train catches up with the wave it creates. Since the speed of the wave is proportional to the square root of the wire tension, the OLE system designer will set the contact wire tension so that wave speed > 1.4 x maximum train speed. For higher speed systems this increased mechanical tension becomes a key constraint on the selection of conductors (section 12.16) and control of mechanical forces in line fittings (section 12.17.1) and OLE structures (section 12.10). Actual performance is however much more complex, due to higher order wave harmonics. These are affected by parameters such as presag (section 12.2), dropper spacing and discrete features in the wire.

A key factor in the system performance is the elasticity (measured as uplift per unit of contact force) of the OLE. Ideally this would be uniform throughout the system – however in reality the elasticity is less at the OLE

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149 Invented by Louis Faiveley in 1955.
150 For more information on the development of the BWHS pantograph visit Dave Coxon’s train testing site at www.old-dalby.com/HSCCP.htm.
structure, due to the support arrangement on the catenary restraining the system, than at the midspan between structures.

Therefore the OLE system designer will match the elasticity differential in the system to the performance requirements. The higher the linespeed, the lower the required elasticity differentials (section 12.2). For high speed systems, the absolute elasticity must also be controlled, to counteract the increased dynamic contact force and keep uplifts within the available movement of the OLE.

All mainline and high speed systems have a maximum free uplift capability - that is, the degree of uplift that registration arms (section 12.13.2) and other components must cater for. This is usually set to twice the value of the maximum design uplift derived from measurement or modelling, to provide a factor of safety\textsuperscript{151}. Free uplift values for UK mainline systems vary from 160mm to 300mm.

![Figure 121: (clockwise from top) Pantograph head damaged by OLE defect, close-up of chipping, top view of chipping (arrowed)](image)

Trains with multiple pantographs pose a further problem; the wave travelling backwards from the front pantograph can interfere with current collection at the rear pantograph. OLE systems designed to run with multiple pantographs at high speed therefore require particular care in the selection of tension and droppering.

A further problem is that of hard spots; any component attached to the contact wire - such as a dropper clip (section 12.16.4) or registration arm (section 12.13.2) – reduces the elasticity locally, and each hard spot will

\textsuperscript{151} BS EN 50119:2020 “Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; April 2020; BSI; section 5.10.2.
reflect a portion of the wave back towards the train. Excessive hard spots will lead to loss of contact at the pantograph, and can cause damage to the carbons which then create a vicious circle of OLE/pantograph damage.

Conversely, an over-tensioned z-dropper (section 12.10.11) can lead to hogging which will also affect dynamic performance.

![Image 122: Loss of contact and arcing caused by poorly adjusted dropper](image122.png)

Heating effects can be significant at the pantograph/contact wire interface – a particular issue when the train is stationary and aerodynamic cooling is not available. For this reason trains may have limitations on their power consumption when at rest. The contact area must be set according to current requirements, and DC pantographs (needing higher currents) have either a larger contact area with multiple carbon strips, or use multiple pans.

![Image 123: Brecknell Willis DC pantograph with four carbon strips](image123.png)
12.2. Suspension Arrangements

Various suspension systems have been developed for the different performance requirements of OLE.

At its simplest, OLE can consist of a contact wire suspended directly from support structures. This is known as tramway or trolley OLE.

![Figure 124: Tramway OLE](image)

Although simplest in terms of engineering, the elasticity is zero at the support point and very high at the midspan; and since there is no support to the contact wire between structures, spans are typically limited to 40m. For these reasons, it is suited only to very low speed (≤30km/h) lines for tram networks and heavy rail sidings.

The tram system can be improved by the addition of a stitch (also known as a bridle). Here the support is transferred to the stitch wire, which in turn suspends the contact wire. The length of stitch may be varied for the particular system.

![Figure 125: Stitched tramway OLE](image)

The stitch creates some elasticity at the support, and this type of suspension is often used on tram systems, giving good current collection up to 80km/h.

The next step is to create a suspension wire running the whole length of the system. This is the simple catenary system – so called because a wire suspended in space describes a catenary curve under gravity. The contact wire is suspended from the catenary by vertical droppers.

![Figure 126: Simple catenary OLE](image)

Technically a suspended wire describes a cosh curve rather than a true catenary, but the differences are very small.
This system gives better elasticity at the support and is the simplest system adequate for mainline railways. For this reason it is widely used around the world, and gives good current collection up to 120km/h. It also provides the additional cross section necessary for delivering increased traction current.

Above this speed there are three options available. The first option modifies simple equipment to use a *presagged* contact wire. Rather than keeping the contact wire flat across the span, a deliberate amount of *sag* is introduced between the first and last droppers – typically of 1/1000 or 1/2000 of the *span length* (the distance between structures).

![Figure 127: Presagged simple catenary OLE](image)

The purpose of the presag is to compensate for the greater elasticity at the midspan, since the uplifted contact wire position at midspan is closer to the uplifted position at the support. This system has found favour in the UK and France, and works at all speeds – this system powered the current rail world speed record holder (section 7.3).

It is also possible to introduce a stitch wire into simple catenary. The tension in the stitch can be set so as to increase the elasticity at the support and so reduce elasticity differential even further.

![Figure 128: Stitched simple catenary OLE](image)

This system is favoured on high speed lines in Germany, where it is used for speeds up to 300km/h. Some German stitched systems also have presag. The UK trialled stitched equipment in the late 1950s, but it was subsequently removed on all but the Brown Boveri system (section 14.2.5).

A further development is the introduction of a third wire – the *auxiliary catenary*. This gives us the *compound catenary* system.

![Figure 129: Compound catenary OLE](image)

This also gives very low elasticity variation, and many of the first mainline systems in the UK were compound.

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It has since fallen out of favour in the UK due to the complexity and maintenance requirements. Elsewhere in the world it is still widely used, notably in Japan, where the Shinkansen lines (section 8.4) make extensive use of compound equipment at speeds up to 300km/h.

12.3. Tensioning Arrangements

OLE must be tensioned to maintain the contact wire height under gravity. Contact wire tensions run from 8kN for slow speed systems, right up to 40kN (used for the world speed record attempt). Typically, mainline systems run between 10 and 20kN.

The tensioning arrangements must take account of the expansion and contraction of the wires with varying temperature. Each system has a defined temperature operating range, and a complete length of OLE (or wire run) will expand and contract as much as 1.5 metres over a typical range. This has a major effect on tensioning arrangements.

The simplest system is known as Fixed Termination (FT). Here the catenary is fixed and tensioned at every structure. The contact wire is tensioned at each end, and allowed to expand and contract in between, but is restrained by the droppers attached to the catenary.

As temperature increases, the contact wire will sag between structures. As it decreases, the contact wire will hog. This change in profile will affect the system dynamics; for this reason, FT systems are not suited for higher speeds, and are generally only used on tram and sidings systems.

Care must be taken when designing FT systems to ensure that all fittings can withstand the maximum tension in the system. FT cantilevers are configured to pivot in the vertical plane, so that tension changes do not stress the cantilever frame, while using the frame weight to prevent large tension differences between spans.

The standard system for medium and high speeds is the Auto Tensioned (AT) system. Here the catenary is fixed only in the centre of the wire run at the midpoint anchor; the whole system is free to move around this fixed point. Constant tension is provided by a tensioning device – traditionally by a set of balance weights attached to the catenary and contact wire.

For example, modern UK mainline systems are designed to operate in an ambient air temperature of -18°C to +40°C.
Mechanical advantage of 3:1 – or for higher tensions, 5:1 – reduces the size of the weight stack required, and is provided via *pulleys* or *drumwheels*. The weights travel up and down the mast as the system expands and contracts. A single set of weights can tension both contact wire and catenary, but modern mainline and high speed systems typically have independent tensioning of the two wires.

Balance weights are a significant hazard in the event of a dewirement – without a means of stopping the fall of the weights, they can be a hazard to staff and to passing trains, and (for independently tensioned systems) cause further OLE damage via dropper breakage.
For this reason modern balance weight assemblies use a drumwheel which includes an anti-fall mechanism; usually a simple toothed wheel which engages with a ratchet stop in the event that tension is lost. This prevents further fall of the weight stack. Balance weights on tram systems are usually configured to travel inside the support mast to avoid these issues and prevent vandalism.

Balance weights are simple and robust, but for mainline railways where reliability is critical and maintenance access limited, they suffer from a number of disadvantages. The need for vertical travel means they must be placed on a mast, and for multi-track railways this means the OLE on inner tracks must be routed out to the mast; either using a set of right angle pulleys at a portal, or by threading the wire run directly through the outer track OLE to the mast. The former system introduces complexity and failure modes, and the latter means that wire runs are interconnected and no longer have mechanical independence. Weight theft can also be an issue when metals prices are high.

A recent development is the use of spring tensioners instead of balance weights. These maintain a constant tension by using a mechanical spring. Since a spring applies a force in accordance with the equation $F = kx$, the tension would ordinarily vary with the spring extension. To eliminate this, a shaped cam is used to provide a constant force. The tensioners are often placed over the track for ease of maintenance access using rail-mounted plant. Spring tensioners come in varieties which use a helical spring, and a more compact arrangement using a spiral torsion spring.

All tensioners have an efficiency of less than 100%, caused by the friction within the tensioner mechanism. Tensioner efficiency should be at least 97% for good performance.
Whatever tensioning device is used, along track movement is provided for at intermediate structures by pulleys, flexible links or pivoted cantilevers. Only the catenary supports closest to the midpoint anchor can be directly clamped. The tension is not entirely constant, varying slightly due to the drag caused by cantilevers pivoting the wire away from the neutral temperature position. However with good design, the tension variation can be kept below 3%. Cantilevers in AT systems pivot in the horizontal plane so as not to unduly influence the contact wire profile, and so it is important to limit stagger change as the rotation of the cantilever moves the wire away from its design position.

Other tensioning devices are sometimes substituted, such as gas systems where space is restricted. These have the disadvantage that their travel is proportional to the change in gas pressure, and therefore ambient temperature rather than wire temperature (which can be significantly higher or lower). They cannot therefore provide a constant wire tension.

Some administrations, including the UK, have experimented with hybrid systems, with auto-tensioned catenary and fixed termination contact wire, or vice versa. These arrangements were shown not to provide good performance and are not used in modern systems.
12.4. Tension Lengths and Overlaps

The length of a wire run is limited due to the maximum drag and stagger change requirements detailed above – as well as practical considerations such as maximum wire length on the wire drum (section 20.12). OLE is therefore split into tension lengths (also known as wire runs). Turnouts and crossovers are provided with their own wiring (section 12.5), and due to the shorter length of OLE needed are often provided with a half tension length comprising a tensioner (section 12.10.10) at one end, a fixed anchor at the other, and no midpoint anchor (section 12.10.11).

At the end of each tension length (or half tension length) arrangements must be made to transfer the pantograph from one tension length to the next. This transfer arrangement is known as an overlap. At its simplest, an overlap is a purely mechanical arrangement. However, it is also a convenient place to create an electrical break in the OLE for sectioning purposes.

Figure 139: Tension Lengths, Overlaps and Midpoint Anchors

The overlap type is defined by two parameters; the number of spans of parallel running; and whether it is uninsulated (also known as a construction overlap) or insulated.

An insulated overlap takes advantage of the fact that each wire run has a zone where it is out of running (not in contact with the pantograph). At this point insulation can be inserted in each wire without the complication of an in running type insulator. An isolator (section 12.7) or booster transformer (section 10.4.2) may then be connected around the electrical break.

It is important when configuring overlaps to ensure that electrical continuity is provided (through uninsulated overlaps) and that all wire run sections are at the same electrical potential (for insulated overlaps). This is achieved by applying flexible jumpers between wire runs. For electrical continuity current carrying jumpers are used, and these are generally duplicated to provide redundancy. For voltage equalisation equipotential jumpers are used.

Figure 140: (l-r) Jumper types; current carrying, equipotential, C-jumper

A third type of jumper, the C-jumper, is used to provide current sharing between contact wire and catenary in systems which do not have current carrying droppers (section 12.16.4).

\[155\] For example, UK mainline systems have length limits varying from 1500m to 1970m.
It should be noted that, when used as an electrical break for a booster transformer, a train brought to a stand in the overlap will short out the booster transformer. This can lead to arcing and contact wire burnout, and for this reason overlaps are placed carefully relative to signals.

12.4.1. **Single Point Overlap**

The simplest form of overlap is the *single point*; this has a single point of transfer, with no spans of parallel running.

![Figure 141: Uninsulated single point overlap](image1)

This arrangement is only suitable for low speeds on tram and siding systems, due to the relatively hard spot and short length of the transfer zone.

12.4.2. **Single Span Overlap - Conventional**

Higher speeds are achievable using a *single span* overlap. This has a single span of parallel running. The pantograph is transferred gradually from one wire run to the other; within the parallel running section, it is in contact with both. The out of running contact wire is set 300-500mm above the in-running wire at the structures depending on the system parameters.

![Figure 142: Uninsulated single span overlap](image2)
The single span overlap is used worldwide, and is the standard for UK heavy rail up to 200km/h. To confuse matters, many reference sources refer to this arrangement as a three span overlap.

12.4.3. Single Span Overlap – Without Anchor Spans

A recent development in the UK is to remove the anchor spans from the single span overlap and terminate each wire run at the end of the overlap span. Without careful design this would result in poor pantograph dynamics, but it is possible to adopt a very specific vertical profile, using the natural rise or circumflex of the contact wire to ensure good parallel running. A pulley is mounted below the spring tensioner (section 12.3) to ensure that the height of the terminating contact wire remains constant. This arrangement has been proven for speeds up to 200km/h but requires careful setup and maintenance.
12.4.4. Multiple Span Overlaps

For higher speeds, the increased elasticity variation created by the wire being lifted out of running, and waves being reflected back from the anchor (section 12.10.10), become barriers to good current collection. Therefore the number of spans of parallel running is increased. High speed OLE typically uses two span overlaps.

**Figure 146: Uninsulated two span overlap**

**Figure 147: Insulated two span overlap**

This system is used on European high speed lines at up to 300km/h. Some high speed lines use three, four or even five span overlaps.

12.4.5. Overlaps in Multi-track Areas

Wiring of overlaps and crossovers becomes more complex in multi-track areas, particularly on systems which exclusively use tensioners on masts; it becomes necessary to extend the conductors on inner tracks through those on the outer tracks to reach a mast. This is most easily done by merging the wire run conductors into a single wire, known as a *tail wire*. This is done using an equalising plate (section 12.17.1) and allows the wire run to pass between the catenary and contact wire of the outer track(s).

**Figure 148: Tail wire (shaded red) splitting into full equipment. Peterborough, UK**
12.5. Turnout and Crossover Wiring

Special arrangements are required where tracks diverge, converge or cross, to ensure continuity of current collection and minimise dewirement risk. A second wire run is required to service the crossover, and introducing this additional contact wire brings with it the risk of hookover, where the contact wire enters the space at the end of the pantograph (section 12.1), and then gets underneath the pantograph head with catastrophic results. This risk rises with speed, and is exacerbated when the pantograph raises the in-running contact wire, since the second wire does not rise at the same time.

![Figure 149: Hookover risk for different wire/pantograph interactions](image)

Even if hookover is avoided, incorrect turnout wiring geometry can lead to contact wire side wear, caused by the wire repeatedly running up the pantograph from the end of the horn and wear strip. Side wear often leads to early failure of the wire or dewirement when a pantograph strikes a fitting.

![Figure 150: (l-r) Contact wire side wear in progress, side wear at a turnout (arrowed), close up of side wear threatening jumper clamp](image)

12.5.1. Fitting Free Zone

To minimise this risk, European systems adopt the concept of the Fitting Free Zone (FFZ). This zone encompasses the space around the end of the pantograph, including the horns. The goal is to ensure that no contact wire clips or clamps (other than dropper clips, which are unavoidable) enter the space at the end of the pantograph. This minimises the risk of damage from a fitting bolt if a contact wire is not completely vertical, during the period when it runs up from the horn area onto the contact strip.

Fittings which are excluded from the FFZ include:

- Registration arms (section 12.13.2) - it is permissible for the arm to cross the FFZ, but the contact wire clip should be outside the zone;
- Section insulators (section 12.6.1);
- Jumper connections (section 12.4);
- Tensioned connectors (section 12.4);
- Out of running contact wires (permitted but not preferred).

The FFZ begins horizontally at the point where the pantograph head begins to curve downwards, and ends a short distance beyond the end of the horn to allow for sway (section 12.13.2). Vertically, it typically extends...
from a distance above the pantograph plane equal to the free uplift (section 12.13.1) to the same distance below it. Once defined, the FFZ is applied to standard turnout geometries and used to develop the permissible wiring geometry to be used.

Fitting free zones are defined for OLE systems in most countries in Europe, but are not defined or used in the UK, with the exception of the recently-introduced GEFF (section 14.4.2) and Series 1 (section 14.4.4) systems.

![Figure 151: (l-r) Series 1 Fitting Free Zone around GB profile pantograph, and zone applied to a UK 40mph Ev geometry crossover](image)

### 12.5.2. Turnout Control Structure

At the core of the turnout arrangement is the control structure; an OLE structure placed at a specific point in relation to the turnout. In Europe the position of the control structure is determined using the fitting free zones as the starting point; but in UK systems it is predefined for specific OLE systems based on the distance between the stock rail and switch rail of the turnout - the toe opening.

![Figure 152: Toe opening for a turnout](image)

Some systems place the control structure at a toe opening of between 180mm and 330mm (with a nominal

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156 All turnout diagrams in this section are stretched 10x in the cross-track direction for clarity.


158 M.01.340 "Fitting Free Zone"; Rev C, 2012; Network Rail/Furrer+Frey.
value of 200mm\textsuperscript{159}, and others 200mm to 350mm (nominal value 300mm)\textsuperscript{160}.

The following sections set out the various ways that turnout wiring and control structures can be arranged, and are illustrated using typical UK turnout geometry and fitting free zones.

12.5.3. Low Speed Tangential Method

The simplest way to wire a turnout is to use an additional wire run for the turnout, with no connection between the two wire runs and pantograph transfer at the control structure.

![Figure 153: Low speed tangential crossover wiring](image)

This is satisfactory for low speeds, and is used extensively on trams systems and in heavy rail sidings. Fitting free zones are not required for low speed situations as the uplift (and therefore hookover risk) is negligible.

12.5.4. Cross Contact Method

One method used to minimise the hookover risk at higher speeds is to use a cross contact arrangement. In this case the two wire runs cross, and a cross contact bar is provided at the contact wire crossing point, which is set inboard of the control structure - but outside of the fitting free zone - by careful staggering. The cross contact bar ties the two wires together while allowing for along-track movement. The most frequently used wire (usually the mainline) is placed below the second (usually crossover) wire; this ensures that the wire run which is not in contact with the pantograph follows the lifted wire, so that hookover risk is minimised.

![Figure 154: Traditional cross contact crossover wiring with mast anchors](image)

\textsuperscript{159} 141667-FAF-MAN-EOH-000002 "UK Master Series - Allocation Design Manual"; Issue 1.8, 2017; Network Rail; section 13.11.

This configuration (and all the subsequent ones in this section) creates a mechanical connection between the two wire runs, so it is important to consider relative along-track movement (section 12.3) of the two conductors and ensure that it remains within the limits imposed by those connections. For this reason, the fixed anchor end of the crossover wire run location should be located close to the midpoint anchor (section 12.10.11) or fixed anchor of the mainline wire run.

![Diagram of wire runs and connections]

The cross contact arrangement was the UK standard from the introduction of OLEMI equipment (section 14.3) in the 1970s onwards. At this time the fitting free zone concept was not used in the UK, and so turnouts which use OLEMI geometry often place fittings close to, or even within, the fitting free zone.

Figure 155: (top to bottom) Traditional cross contact bar general arrangement, Siemens cross contact assembly with T-bar detail
Figure 156: OLEMI standard cross contact geometry (with mast anchors) relative to fitting free zone for a 40mph Ev crossover

More recent systems such as Series 1 (section 14.4.4) and UKMS (section 14.4.5) adopt different toe openings and staggers, and keep fittings outside of the zone.

Figure 157: UKMS standard cross contact geometry (with mast anchors) relative to fitting free zone for a 40mph Ev crossover

The cross contact system has been used extensively in UK heavy rail - although the cross contact bar can cause a hard spot if poorly designed, leading to fatigue of the bar, and the bolts for the bar have a tendency to loosen and fail. For this reason use in the UK is now limited to speeds below 160km/h or where there is no practical alternative. Cross contact has however been successfully used in Europe with a specially-designed T-shaped cross contact bar and appropriate dropper.

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161 Toe opening zone shown in this and subsequent drawings in blue hatching. Turnout staggers are +350/-230mm relative to relevant track, structure placed at 200mm toe opening. UK1/006/202 "Crossover Arrangement for Cantilevers (Mk1)"; Rev 05, 2003; Network Rail. Note that the cross contact bar is clear of the FFZ, but the crossover wire run registration point is close to the FFZ.

162 Geometry is as previous diagram, except that crossover staggers are +320. MS/B06/B02/A3 "Crossed Contacts Crossover General Arrangements"; Rev 01, 2017; Network Rail. Note that the registration point is now clear of the fitting free zone.
Modern UK systems have moved away from the cross contact arrangement for the reasons given above, and instead adopted a more sophisticated form of tangential arrangement.

The first system to do so was UK1 (section 14.3.7), used for the West Coast Route Modernisation. This used a specific droppering arrangement and a span where the two wire runs are in parallel on the lead up to the control structure, to ensure that the pantograph picks up the crossover wire run without hookover risk.

The UK1 tangential system, though effective, was felt to be overly-complex and hard to set up and maintain. For this reason, the latest Series 1 (section 14.4.4), Series 2 (section 14.4.3) and UKMS (section 14.4.5) designs instead use a simple tangential arrangement with one, or preferably two, spans of parallel OLE before the control structure, and cross-droppering (section 12.5.7) at the turnout. Anchoring is usually provided on a portal boom (section 12.10.10) thus keeping the crossover wire run over the pantograph and further minimising hookover risk.
The staggers in the above arrangement are positioned between the two track centrelines; this minimises hookover risk as a pantograph approaches the turnout in the trailing direction on either the through route or the crossover. Modern pantographs have sprung heads (section 12.1) and this feature is exploited by the wiring geometry; the stagger is such that the contact force pushes the side of the head near the incoming wire downwards, rolling the whole head (on a fixed head pantograph) or the carbon carrier only (on a floating head pantograph), and so moving the horn and/or wear strip away from the second wire.

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163 141667-FAF-MAN-EOH-000002 "UK Master Series Allocation Design Manual"; Issue 1.8, 2017; Network Rail; fig. 13.2.

164 Turnout staggers are +100/-100mm relative to relevant track, structure placed at 300mm toe opening. MS/B06/B01/A3 "Crossed Contacts Crossover General Arrangements"; Rev 01, 2017; Network Rail. Note that this drawing erroneously shows the staggers as -100/-100mm.
12.5.7. Cross-Droppered Method

Modern cross contact and tangential methods both use cross dropping. This entails dropping the mainline catenary to the crossover contact wire (and vice versa) in the vicinity of the turnout, to help both wire runs to rise and fall together as the pantograph passes. This system has been used in recent UK turnout wiring at speeds up to 200km/h.

It is not possible to use normal dropper clips for inclined dropping, as the inclination of the dropper would lead to twisting of the contact wire, and potential contact between the pantograph and the dropper clip; instead an inclined dropper clip is used, which has an offset fitting so that the load axis of the dropper intersects the contact wire, keeping the clip upright.

12.5.8. High Speed Three Wire System

All the systems described so far use a single wire run on the crossover itself. Since the running lines generally have separate electrical sections (section 10.3), this means a section insulator (section 12.6.1) is required at the midpoint of the crossover. Some high speed routes have high speed turnouts, where the dynamic performance
of a section insulator would be unacceptable.

They therefore use two wire runs on the crossover, allowing the use of an insulated overlap (section 12.4.2) on the crossover to achieve the necessary section break. At these speeds a smooth run-up and run-off of the pantograph between the wire runs is essential, and a number of different configurations are in use to achieve this. Some systems adopt a specific vertical profile for the middle of the three wire runs, meaning it acts as a guide wire and keeps a through-running pantograph out of contact with the inner third wire run. This improves dynamic performance and reduces hookover risk.

![Figure 164: Typical high speed three wire crossover wiring](image)

This means that a **triple cantilever** is needed at the control structure, and transfer is achieved by careful positioning of the three wires. This arrangement is not common in the UK, but is used on High Speed One and will be used on the future **High Speed Two** line.

![Figure 165: High speed triple cantilever. Stratford, UK](image)

### 12.6. Other Electrical Break Devices

#### 12.6.1. Section Insulator

Although overlaps are used wherever possible to create section breaks, there are times when additional breaks are required for switching and sectioning at locations away from overlaps. At these locations, a **Section Insulator** (SI) is used. This is a set of insulators spliced into the contact wire and catenary, while

![Figure 166: Plan view of typical skidless SI](image)
allowing the pantograph to pass over it. A standard insulator is used in the catenary, while two options are available to carry the pantograph along the contact wire without loss of current collection; either an arrangement of skids is set below rod insulators (section 12.18) to form a skidded SI, or the rod insulators themselves carry the pantograph through the SI - a skidless SI. The latter is capable of higher speeds, being lower in weight, but the insulators require regular cleaning.

SIs are a significant hard spot in OLE, and for this reason their use is generally restricted to crossovers, sidings and station areas where speeds are lower. They should be supported at a structure wherever possible – if not, the droppers must be shortened locally to counteract the dead weight of the assembly. SIs are also difficult to set up, and there are more restrictive rules on horizontal position, depending on the width of the SI.

Figure 167: (l-r) SI types; Arthur Flury skidded, Arthur Flury skidless. Swindon and King’s Cross, UK

12.6.2. Insulated Knuckles

Many historical systems have achieved electrical separation of adjacent wires in complex track layouts using an insulated knuckle. This takes the form of one or two insulators directly attached between two wire runs. Although electrically effective, the large and often unsupported mass means dynamic performance and contact wire wear is degraded. These assemblies are not used in modern systems.

Figure 168: Insulated knuckle. Southend, UK
12.6.3 Neutral Sections

An electrical break is required wherever different supply phases meet (section 10.1.3); or where there is a change of system voltage, as occurs at many European interfaces; or where an earthed section of operational OLE is to be provided at a location where sufficient electrical clearance (section 10.8) cannot be provided. At these locations a neutral section is used. This is a section of earthed OLE sandwiched between an insulator on either side. For AC systems fed from three phases with a phase angle of $120^\circ$, the total strength of the insulation between phases must be $\sqrt{3} \times \text{line voltage}^{165}$.

Neutral Sections are found at feeder stations and midpoint sectioning locations. The train must not draw power through the neutral section, since an arc would be drawn to earth. For this reason the train power is tripped off by a trackside APC magnet (section 11.9), which operates the train's circuit breaker via a reed switch.

![Figure 169: (l-r) Principle of a magnet-switched neutral section, arcing caused by missing APC magnet](image)

When the train has cleared the neutral section, the circuit breaker is closed by a second APC magnet. For this reason care must be taken to place signals so that there is no risk of a train becoming stranded at a neutral section.

![Figure 170: APC magnets; Vortok type and traditional type. Witham, UK](image)

It is possible to eliminate the electrical arcing risk and the short-duration loss of power by adopting a switched neutral section. In this configuration the APC magnets are eliminated in favour of automated HV switching which is controlled by the signalling system, and enables the neutral section to be fed from either of the two traction supplies. The direction that the train approaches the neutral section will determine which of the two supplies is connected; once all pantographs are within the neutral section, the first supply is disconnected and then the second supply connected before the train leaves the neutral section.

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$^{165}$ It is possible to reduce this potential difference somewhat by using specific patterns of three phase connections, as has been done on the Madrid-Seville line. "Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance", Kiessling, Puschmann, Schmieder; 3rd Edition, 2017; Publicis MCD Verlag; p42.
Figure 171: Principle of a signal-switched neutral section

This approach requires all pantographs to fit within the neutral section, and adds complexity in terms of HV switching and control. For these reasons it is not used in the UK.

In mechanical terms there are two types of neutral section; the **inline** type, and the **overlap or Carrier Wire Neutral Section (CWNS)** type.

The inline type consists either of glass bead insulators (over which a pantograph is able to run), or high speed section insulators, placed either side of the neutral point. Sacrificial **arching horns** are often provided in the event that a train draws power through the earthed section. Inline neutral sections have been used on mainlines at up to 200km/h; however the geometry can be difficult to maintain, and the glass bead insulators require regular cleaning. Reliability problems in the UK have led to inline types being banned above 160km/h for new installations.

Figure 172: Arthur Flury type inline neutral section; note the uninsulated cantilever at the neutral point. Drayton Park, UK
Figure 173: Transfer of a pantograph through a carrier wire neutral section
The carrier wire type consists of two or more overlaps in quick succession; the first transfers the pantograph from the first live wire run to an electrically floating wire run – the carrier wire; the second overlap transfers the pantograph back onto a second live wire run. Train power is switched off in the normal way. If the route carries trains with more than one pantograph, there are two ways of approaching the problem. If the multi-pantograph trains on the route have electrically common pans via an on-roof 25kV busbar, the CWNS must be made longer than the longest pantograph spacing. If the pans are not electrically common, then either the CWNS is made longer than the longest pantograph spacing, or is shorter than the shortest pantograph spacing.

Alternatively, the arrangement can be extended to three or four overlaps, as used in the UK. Either option must ensure that the incoming and outgoing wire runs are never connected through the carrier wire, pantographs and train busbar.

Carrier wire types can give better dynamic performance and reliability than the inline type, but require a more complex OLE arrangement and take up much more space. This can make it harder to find a location away from bridges, stations, junctions and signals, but still close to the switching site. Carrier wires were first used on European high speed lines and High Speed One, and are now being used in the UK on the GWML.

12.7. Isolators

OLE isolators provide a point of isolation in the traction circuit for the purposes of isolating sections or subsections of OLE (section 10.3) for planned or unplanned maintenance. They generally take the form of a horizontal or vertical throw knife switch, which when open provide a visible air gap between the supply and the OLE equivalent to at least Basic Insulation (section 10.8). In their simplest form they are not capable of making or breaking current, and so are only operated once the power supply has been disconnected at the circuit breaker (section 10.2.7). In this configuration the widely used term "switch" is not accurate, and they should correctly be referred to as isolators or disconnectors.

OLE isolators are typically mounted on the lineside, either on OLE masts also carrying support and registration equipment, or on standalone switching structures. Since the live elements are not insulated or screened, it is essential that the isolator is placed at sufficient height to minimise electric shock hazards.

Figure 174: (l-r) MLE two-position non-load-break isolator in open position, MLE three-position closed/open/earth non-load-break isolator in closed position. Swindon, UK
Isolators can be either two position or three position. Two position isolators are either open or closed, and provide a simple point of isolation. Three position isolators have a second set of contacts, which can be used to:

- Provide an alternate feed path (closed/open/alternate closed) to allow another means to energise a subsection;
- Provide an earth connection (closed/open/earthed) to protect staff working on the OLE from inadvertent re-energisation (section 10.12.1) by the ECO making a mistake or by an electric train accidentally entering the isolated section;
- Earth a feed cable to allow it to be safely worked on (when used in the opposite orientation).

The knife blades and contacts are typically copper or silver-plated copper.

![Isolator configurations](image)

**Figure 175: Isolator configurations (l-r) two-position closed/open, two-position open/earth OLE, three-position closed/open/earth incoming feed, three-position closed/open/earth OLE, three-position closed/open/alternate feed**

Most isolators normally operate in the closed position – they are Normally Closed (N/C) – but some switches, such as those providing alternative feeds or an earthing facility, may be Normally Open (N/O).

OLE isolators can be manually operated or motor actuated. Manual isolators have a simple switch handle at the base of the mast. A padlocking arrangement is provided so that the isolator can be secured in the required position, and each isolator has a unique key which is held inside a locked key box. The key box is then locked with a generic key, and an authorised person can then operate the isolator as follows:

- Unlock key box and remove unique isolator key;
- Operate the isolator to the desired position and lock isolator;
- Remove the unique key and keep it with them, preventing inadvertent re-energisation until all staff are finished work.

Modern installations increasingly use a SCADA (section 10.7.3) operated motor box to provide rapid isolation by the electrical control operator.
Regardless of manual or motor actuation, the connection between the actuator and the switch assembly is either a torsion tube (for horizontal throw isolators), a push rod (for vertical throw isolators) or a flexball drive. Torsion tubes are the simplest to configure but can be prone to twist failures when actuated after a long unused period, during which the switch blade and jaws can become locked together through oxidisation. The flexball drive comprises a flexible hose filled with ball bearings; a piston at the drive end pushes the bearings further into the hose, and a piston at the isolator end translates that pressure into movement. This provides an easier installation set-up than the push-rod design.

Modern motorised isolators often have a method of remotely detecting that the isolator blade is secured in the correct position, since the security of the isolation depends on it, and the integrity of the rod mechanism cannot be taken for granted. These isolators have a reliable indication microswitch fitted to the base of the isolator pivoting insulator itself, which detects the switch position and reports it back via the SCADA system.
Some isolators are required to break load current (section 10.1.2) so that they can safely be operated without first disconnecting the power supply – these can be properly described as load break switches. In this case there must be a means of extinguishing the electrical arc that will otherwise form as the isolator contacts move apart.

This is achieved by attaching a vacuum interrupter to the isolator. As the isolator path is broken, the traction current instead follows the path of least resistance through a vacuum bottle, which contains a pair of contacts. After the isolator contacts are safely open, the interrupter contacts are then opened by the actuator, and no arc is able to be struck in the vacuum.
12.7.1. Circuit Main Earths

OLE systems in the UK are now applying the concept taken from the Electricity Supply Industry - that of the Circuit Main Earth (CME). This is an arrangement which will discharge electrical energy to earth in the event of an inadvertent re-energisation (section 10.12.1) of equipment which has been disconnected from its power supply in order to carry out maintenance or repair work.
The CME may be provided either by use of portable earths at a DEP location (section 10.12.1), or increasingly by using a device – typically a motorised two-position (open/earth) isolator with load-break capability. In either case the location must be coincident with a high-integrity cross-bond location (section 10.10.1) to ensure that energy is properly discharged to earth, and within a short distance\textsuperscript{166} of the location at which the re-energisation could occur.

12.7.2. Feeding Arrangements

The options available for connecting an isolator to the OLE depend on the track configuration. Where the OLE is immediately adjacent to the isolator, a feed wire is run direct to the catenary and contact wire. However, this is not an option where the feed needs to cross other wire runs to reach its connection point.

In this situation three options are available. The first is to use a candlestick feed arrangement, where a bare feed is run above a suitable portal or TTC boom (section 12.10) using a series of insulators on stovepipes. This

\textsuperscript{166}In the UK, CMEs must be within 90m of the point of inadvertent re-energisation.
arrangement has one significant disadvantage; when the wire runs below it are isolated, the live equipment above staff forms a residual hazard (section 18.12). This is often mitigated by lengthening the stovepipes to move the hazard further from the wire runs.

An alternative is to use a spanwire feed structure. This arrangement uses freely suspended wires slung between tall lineside masts. Feed wires then run down to the connected wire run. These allow the live parts to be placed higher up, thus reducing the residual hazard. It is also increasingly common to use separate structures rather than the structures used for support and registration, moving the residual hazard away from the location most frequently visited by maintenance staff during an isolation.

![Figure 184: Spanwire feed structures. Bushey, UK](image)

The final option (which completely removes the residual hazard) can be applied only if the isolator is switching one track only across a section insulator (section 12.6.1) or insulated overlap (section 12.4.2). In this case the isolator can be placed directly over the related wire run(s), on a suitable portal or TTC boom. Actuation of the isolator is achieved by means of push-rods which run in rollers along the boom from the mast to the isolator, or a flexible ball drive.

![Figure 185: (l-r) Push-rod switch actuation, MLE 2-position push-rod actuated switch. Euston and Birmingham, UK](image)
A single push-pull rod (known as a *pear drive*) is now favoured over twin rods in the UK, as this arrangement is easier to set up and does not unevenly load the rods.

### 12.8. Mechanical Clearances

It is essential to maintain mechanical clearances between static live parts of the system, and those parts which move. Key mechanical clearances are:

- Pantograph (section 12.1) to registration arm (section 12.13.2);
- Pantograph to drop bracket;
- Registration arm to supporting assembly;
- Insulated pantograph horn to bridge arch.

Typical mechanical clearances are 15mm for pantograph to registration arm, and 80mm for live pantograph to all other live parts.

### 12.9. OLE Structure Loadings

All OLE structures must be capable of withstanding a number of loads:

- *Permanent actions* (also known as *dead loads*) in the system caused by equipment weight and tension;
- *Variable actions* (also known as *live loads*).

Variable actions may be further subdivided into:

- *Environmental loads*, created by the action of wind and weight of ice and snow;
- *Accidental loads* caused by a dewirement or other temporary situation;
- *Construction loads*, caused by the extra weight of staff working on the structure, or unbalanced loads caused by partial installation of equipment.

![Figure 186: Mechanical loads in the cross-track direction on a typical cantilever structure](image)
These load cases must be calculated, partial factors (factors of safety) applied to each, and then combined into a set of load case combinations which describe the loads experienced under different conditions. For instance, in the UK maximum wind is unlikely to be experienced at the same time as maximum ice, so the low temperature load case combination applies a reduced wind load. Windspeeds are calculated based on a regional statistically-determined windspeed, modified by the shielding or exposure of the local terrain.

The load case combinations are compared with the Ultimate Limit State (ULS) of the structure – that is, the point of mechanical failure. Each load case combination must be less than the ULS – if it is not, then either the design is changed to reduce the loads, or the steelwork size increased. Structure loads that are checked include normal force (compression/tension), biaxial shear, biaxial moment and torsion. Shear loads and torsion are generally much lower than their ULS capacities, and so structural checks are usually undertaken for the interaction between axial load and biaxial moments for each individual load combination.

ULS checks ensure that the structure will not fail, but more stringent limits are needed to ensure that the OLE performance is not compromised by less onerous environmental conditions. This is done by calculating the Serviceability Limit State (SLS), which is the level of loading needed to deflect the structure to the point that OLE geometry is compromised. Most OLE systems have across-track and vertical deflection limits. SLS tests use lower factors of safety, to reflect the lower risks involved.

The most common form of OLE structural failure is long-term foundation (section 12.11) movement, driven by the overturning moment at the base of the mast; this is easy to detect and can be controlled by height and stagger adjustment and/or structure support measures.

Main steelwork generally only fails due to accidental impact; the failure mode will depend on the steel

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167 Dead loads are green, live loads are red.
168 Dead loads are green, live loads are red, relieving loads are purple.
section used. For instance, the key failure mode for an I-beam structure is known as lateral torsional buckling. This is induced by a moment acting in the direction of the stronger axis, and occurs in structures where the major axis stiffness is far higher than that of the minor axis.

The permanent loads on a cantilever structure will lead to a certain amount of elastic deflection of the mast. Depending on the loads and mast capacity, this may be large enough to be visible to train drivers. While not unsafe, this can be unsettling for drivers, and so in the UK it is normal to apply mast rake using the foundation holding down bolts (section 12.11.2) to lean the mast between $\frac{1}{2}^\circ$ and $1^\circ$ away from the track in the unloaded condition.

12.9.1. Wind Loadings

ULS wind loads are typically calculated based on a 1 in 50 year return period; that is, the maximum 10 minute mean windspeed which statistics show will not be exceeded over a 50 year period. For SLS checks a 3 year return period is generally used, to reflect the lower risk (and unlikelihood of running trains during a 1-in-50 year storm).

This base windspeed is modified by factors reflecting the local topography, to give the design windspeed or design wind pressure which is used in all wind loading calculations. Wind forces will bear on both the structure itself, and the wires which are attached to it.

![UK isocline map of base windspeeds for wind loading calculations](image)

12.9.2. Ice Loadings

The level of ice loading to be used is determined by the climate in which the system operates; in the UK, radial thicknesses between 3.5mm and 9.5mm are used, depending on location and risk factors.

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169 UKMS drawing MS/B98/K07/A3 "Rake Instructions for Masts"; Rev 00, 27 March 2017; Network Rail.

12.10. OLE Structures

OLE structures play an electrical as well as mechanical role. Mechanically, they must hold the wires at their design positions under a range of environmental conditions, and keep deflections under wind within specified limits. Electrically, they must be capable of withstanding the mechanical stress and thermal stress caused by voltage and current surges under fault conditions.

For AC systems, the structures and their foundations also form a distributed earth system (section 10.10.1), and they must be electrically continuous so that fault currents can pass freely to general mass of earth in the event of an insulator failure. This means that structures are generally formed from galvanised steel (or in some cases, weathering steel), although painted steel structures were widely used historically. Some administrations
outside the UK have made extensive use of concrete; although the weight of these can cause constructability issues, and their form of construction is problematic for earthing and bonding when used in AC systems.

For steel masts, the form that the mast takes is largely a matter of local preference and the relative cost of hot rolled steel sections versus welded fabrication of a lattice structure. Using rolled steel gives the advantage of a ready-made section that requires little fabrication other than the welding of a baseplate; whereas a lattice structure reduces the amount of steel used, but requires increased workshop time and the availability of a skilled welding workforce. For DC systems, stray currents (section 10.10.2) mean structures must be insulated from earth, and therefore non-conductive materials may be considered.

Historic and current standards in each administration give rise to a set of standard steel sections. Most systems use standard structure designs which are held in Basic Design Ranges (section 14.1). These designs are pre-approved for use in appropriate locations.

OLE geometry is controlled at structures in two ways; supporting the OLE means fixing the vertical position. This is usually done at the catenary, by means of a clamp, link or pulley (section 12.3); the contact wire vertical restraint is via the droppers suspended from the catenary. A structure may also be used to register the OLE; that is, to fix the horizontal position. This is done at the catenary, as above; and at the contact wire, by means of a registration arm (section 12.13.2). This is free to move vertically to take account of uplift. Structures for auto tensioned systems also have to allow for along-track movement (section 12.3).

It is sometimes necessary to use a structure for support only (for instance to support the mass of an SI), or to register only (to get a wire run around a heavy curve). These structures are designated as Not Registered (NR) or Not Supported (NS). Sometimes a wire run may not need any direct connection to a structure and will pass through – for instance a switching structure carrying a feed onto the OLE; these are designated as Not Supported or Registered (NSR).

There are many different types of OLE structure, each appropriate to a particular use.

12.10.1. Single Cantilever

The single cantilever is the basic building block of most OLE systems. It is designed to support one wire run over one track.

![Figure 192: (l-r) Traditional single cantilever, and Series 1 equivalent with live envelopes shown (insets)](image)

The single cantilever is cheap, easy to construct and adjust, and is the standard structure for use on a two track...
railway. Efficiently designed railways maximise the use of these structures.

The traditional cantilever shown above left has a large electrically live envelope, and is awkward to construct due to the use of sloping tubes. Recently in the UK cantilevers have been used which have a much smaller electrical envelope (above right) and a rapid adjustment mechanism, so that construction time is minimised and staff safety maximised.

12.10.2. Double Cantilever

It is often necessary, particularly at crossovers and overlaps, to support two wire runs over one track. The simplest way to do this is by means of a double cantilever.

The two cantilever arms are separated along track on horizontal spreader channels to allow for along-track movement (section 12.3) without the equipments clashing. Some high speed railways place an overlap on crossovers to avoid using an SI (section 12.6.1), and these systems use a triple cantilever (section 12.5.8) on the same principle as the double cantilever.

The double cantilever illustrates the important principle of Mechanically Independent Registration (MIR). This means that each wire run has a support and registration which is independent of any other. In the event of one wire run being damaged, the other should continue to operate within geometrical limits. This has important implications for OLE availability in the event of a dewirement.

12.10.3. Back to Back Cantilever

Where there is sufficient clearance between two tracks, a back to back cantilever may be used to support wire runs over two tracks.

This has the advantage of requiring less materials than a pair of single cantilevers.

However, maintenance access is more difficult if traditional cantilevers are used, since the live equipment on one track must be isolated in order to work on the second track, meaning the railway is closed to electric services. This arrangement can also cause problems with signal sighting (section 17.7.1) but is often used in tram systems to improve aesthetics and reduce land-take.

Figure 193: Typical double cantilever. Edgbaston, UK

The double cantilever illustrates the important principle of Mechanically Independent Registration (MIR). This means that each wire run has a support and registration which is independent of any other. In the event of one wire run being damaged, the other should continue to operate within geometrical limits. This has important implications for OLE availability in the event of a dewirement.

Figure 194: Typical back to back cantilever. Rugby
12.10.4. Two Track Cantilever

It is often the case that foundation space is only available on one side of a two track railway; either due to a physical obstruction such as signalling equipment, or because signal or level crossing sighting (section 17.11) requires a clear sight line on the other side. In this case, the Two Track Cantilever (TTC) is used to support several equipments over two tracks.

Pairs of TTCs can also be used to aid construction on a four track railway where all-lines closure for portal installation (section 20.6) is not practical.

The TTC will experience a higher overturning moment (section 12.9) at the base of the mast, and for this reason the foundation will be larger to resist the moment. TTCs are usually used only where single cantilevers or portals are not suitable.

TTCs can be provided with MIRs, with wire runs on separate cantilevers; or can be configured to use a cross span wire strung between the TTC mast and a nose assembly at the extremity of the TTC boom. In this configuration the TTC will not be mechanically independent.

12.10.5. Flying Tail Structures

On heavy curves and complex junctions it is sometimes necessary to register the OLE without supporting it, to maintain horizontal geometry. These Not Supported structures are known as flying tail structures.

Figure 195: Typical spanwire two track cantilever. Egbaston, UK

Figure 196: Flying tail structures registering tram OLE around a tight curve. Manchester, UK
For railways with more than two tracks, it is not generally possible to use single cantilevers as there is insufficient space between tracks. For this reason the standard structure for a multi-track railway is the portal.

The structure shown has MIRs, and in this configuration it is relatively easy to make adjustments on the structure; however construction or demolition requires a possession (closure) of the railway, and isolation and earthing of all OLE. The use of a crane, along with good access, is also necessary. For this reason, feasibility of construction must be considered when designing with portals. Portals can also be provided with spanwires.
A portal may be either a fixed or hinged type. The fixed type has rigid bolted moment connections at each foundation and at each corner; this means all structure loads are transferred to the foundation.

A hinged or pinned portal will have one or two hinge pin connections, either at the foundations or at the connections between the mast and boom.

With this arrangement, only the vertical and shear component of the across-track loads are transferred to the foundation – an arrangement which is especially useful on older viaducts, which may not be capable of withstanding overturning moments, or may have limitations on intrusive works due to their heritage status. Along-track loads are unaffected.

12.10.7. Headspans

An alternative to the portal in multi-track areas is the headspan structure. This structure comprises two extended masts, with two horizontal tensioned wires (the upper cross span and lower cross span wires) strung between them to locate the OLE. A third top wire is a profiled headspan wire, and this provides support to the overall arrangement.

The headspan has the advantage of being cheaper and easier to install than the equivalent portal. However the headspan is a load-balanced system, where the tensions in the wire runs themselves contribute to the geometric stability. If a wire run breaks, the design geometry will be lost since all other wire runs will be out of balance. This type of structure is therefore not mechanically independent, and a failure means all tracks are out of service. Headspans require regular maintenance to check the span wire tensions, and adjustment of the equipment tends to trigger design and replacement of assemblies. For high speed lines, the mechanical wave created by the passage of a train can also affect adjacent wire runs. Headspans also require larger foundations than portals, to resist the high overturning moments (section 12.9) caused by the headspan tension, and this can cause problems in areas of poor ground. Wire corrosion problems have also been experienced in the UK.

UK-pattern headspans use an inclined tube between the upper and lower span wires – unlike many European patterns. This provides resistance to the twist forces which the radial loads would otherwise impart onto the span wires, as well as a connection point for the registration arm (section 12.13.2). UK headspans have no temperature compensation on the span wires, but some overseas systems use a spring tensioner to maintain a quasi-constant tension.

Note that the pinned boom retains an element of moment transfer into the foundation.

Figure 199: (clockwise from top left) Portal configurations; fully fixed, single pin base, pinned boom, double pin base
Because of the reliability issues, headspans are best suited to lower speed applications or applications where low capital cost is more important than high availability or performance. In the UK headspans have historically been installed in large numbers; however their poor performance means they are not used for new designs on mainlines.

Headspans are however a good solution to the problem of visual intrusion at sensitive sites such as listed stations; with intelligent design and use of rod insulators, these structures can come close to invisibility.
12.10.8. Spanwire Portals

A compromise can be struck between the performance advantage of a portal and the cost advantage of a headspan, by using a spanwire portal. This uses a portal boom but with a spanwire to fix the registration equipment, thus avoiding expensive stovepipe arrangements. This is not an MIR arrangement, and is generally confined to sidings or complex areas.

Figure 202: Typical spanwire portal. Kentish Town, UK

12.10.9. Bridge Supports

Wherever possible, OLE passes through bridges without being connected to them. These bridges are free running. Where low headroom or long width makes it impossible to achieve this, it is necessary to attach one or more support and/or registration assemblies to the bridge. This type of OLE arrangement is known as a fitted bridge. Fitting can be done in a number of ways, depending on the type of bridge and the clearance restrictions.

Figure 203: Glass fibre claw-ended bridge arm (insulator in white). Whitecraigs, UK
Many bridges have flat decks constructed of iron, steel or concrete, and these can pose a problem if the bridge was not designed to take account of OLE clearances. In this case a glass fibre bridge arm can be used. The arm both supports and registers the OLE. The insulator material has some flexibility, and this provides for a reduced amount of uplift to assist with clearances. Thus the OLE is both supported, but also held down, by the arm. Various end fittings are available; a claw-ended arm provides support for a centenary (section 10.8) with a small system height and a live fitting, and a stress-graded arm for twin contact equipment (section 12.13.1) provides a specially shaped live fitting which minimises the electrical stress at the live point closest to the bridge, to help prevent flashover. More recently insulated head arms (see figure 73 for an example) have been used where the whole head is covered with an insulated coating, to further reduce flashover risk.

![Glass fibre stress-graded bridge arm](image)

**Figure 204:** Glass fibre stress-graded bridge arm; note the dome shape of the end fitting. Perry Barr, UK

### 12.10.10. Terminating Anchors

Anchors are required wherever a wire run is terminated. They must be capable of withstanding the overturning moment created by the tension in the contact wire and catenary, both under normal operation and in the event of a wire breakage.

Terminating Anchors take a variety of forms. A stand-alone anchor structure may be used, although wherever possible an existing cantilever, TTC, headspan or portal mast is used to keep steelwork costs down.

An anchor structure may be **self-supporting**; that is, the steel section and the foundation withstand the entire overturning moment; or it may use a **compression strut** on the same side of the anchor as the terminations; or it may be **back-tied**, where a tensioned tie wire or rod extends from the top of the structure down to a mass foundation at a short distance from the structure.

The back-tied type has the advantage that a significant portion of the tension load is transferred to the mass foundation, and so the steel section and main foundation size can be reduced. The self-supporting type is used where there is no space for a back-tie. Terminating anchors can carry balance weights, spring tensioners (section 12.3) or fixed anchors.

It is often necessary to terminate a series of wire runs at the end of a set of sidings; in this situation, using individual masts would be inefficient and provide a collision risk for any train which overruns the buffer stop. For this reason a **goalpost anchor** is generally used.
Figure 205: (l-r) UK1 Siemens back-tied anti-fall balance weight anchor, self-supporting fixed anchor. Rugby and Glasgow, UK

Figure 206: Tensorex spiral torsion spring tensioners. Lower Basildon, UK
12.10.11. Midpoint Anchors

Full auto tension lengths (section 12.3) require the use of a midpoint anchor to constrain the tension length and prevent along-track migration. The arrangement of a midpoint anchor depends on the type of structures in use. For cantilevers, the MPA is arranged by means of a tie wire which is clamped to the catenary. This wire is terminated at the structure either side to form the restraint.

For portals, a direct connection to the portal boom via insulators is generally used. The connection is jumpered to maintain electrical continuity, and a z-dropper may be provided to additionally restrain the contact wire.
For headspans, the MPA cannot be a single point restraint due to the flexible nature of the system. Therefore a distributed MPA is used; the catenary is clamped to the upper cross span wire over several structures to distribute the load.

12.11. OLE Foundations

OLE foundations play a similar dual electrical-mechanical role to OLE structures; the foundation must withstand the mechanical loads, but also facilitate the flow of fault current to general mass of earth for AC systems (section 10.10.1), or (ideally) assist in preventing it for DC systems (section 10.10.2).

The main component of mechanical load on an OLE foundation is the overturning moment at the base of the mast (section 12.9). This determines the configuration of the foundation, and there are a number of different types, each designed to resist this moment. The type of foundation chosen must be matched to the ground conditions, ground profile and construction methodology (section 20.4).
12.11.1. Planted Mast Foundations

Planted Mast Foundations are formed by setting a polystyrene former into a previously dug hole, pouring concrete around the former, and then inserting reinforcing steel into the wet concrete. The former is then burned away, and an extended mast placed into the foundation and grouted. Although extensively used in early OLE systems, they are no longer favoured when electrifying operational railways, due to the requirement to support the mast while the foundation is curing, the safety risks of excavating deep holes, and the use of chemicals in burning away the former. A modern form of planted mast is however used on greenfield railways, notably for high speed lines (section 9.5) where access is less restrictive.

Figure 210: Planted mast. Stevenage, UK

12.11.2. Side Bearing Concrete Foundations

A side bearing concrete foundation comprises a cuboid of reinforced concrete, with the long side arranged vertically. The overturning moment is resisted by this long side bearing on the surrounding ground.

Figure 211: (l-r) Bolted side bearing concrete foundation, clamped side bearing concrete foundation. Stratford, UK

A hole is dug, a reinforced steel cage placed in the hole, the foundation poured, and a dressed concrete cap incorporating holding down bolts poured on top of the main foundation. The holding down bolts protrude from the cap, and a bolted base mast is clamped between upper and lower nuts to allow for adjustment of mast verticality.

A variant of this design, used for more highly loaded masts, is to clamp the mast baseplate directly to the concrete cap. This has the advantage of removing the bending forces on the bolts, but means that no verticality adjustment is available. Accuracy of concrete levelling is essential for this type of foundation.
Side bearing foundations are favoured for level ground with a high bearing pressure and good access for appropriate plant.

12.11.3. Mass Concrete Foundations

These are used to attach back-ties for anchor structures. They comprise a cuboid of reinforced concrete dug into the ground; an attachment point is provided for terminating the back-tie.

![Figure 212: Mass concrete back-tie foundation. Peterborough, UK](image)

12.11.4. Piled Foundations

Modern piling techniques offer a number of solutions, which are generally used where either ground conditions are poor, or access time is limited.

Like the side bearing concrete foundation, the moment is resisted by the long side of the pile bearing against the surrounding ground. All the types of pile detailed below, with the exception of the driven steel type, have a dressed concrete cap added after piling, to give controlled water runoff and to take the holding down bolts for a bolted base mast.

![Figure 213: Augered pile foundation. Stoke Gifford, UK](image)

A bored pile foundation consists of a reinforced concrete cylinder similar to the side bearing type. A boring rig is used to dig the hole in stages, and concrete is poured onto a reinforced steel cage placed in the hole. This piling method is only suitable for good ground, since the hole has a tendency to collapse before the concrete can be poured.

An augered pile (or to give its full name, continuous flight augered pile) is similar to a bored pile, except that the hole is created in one operation; after having placed a short steel sleeve into the ground, a hole is augered down through the sleeve. As the auger is withdrawn, concrete is pumped down the hollow shaft of the auger and into the hole from the bottom upward. A reinforced steel cage is placed into the concrete before it cures. This avoids the problem of hole collapse.

A driven concrete pile consists of a precast reinforced concrete pile, which is driven into the ground by a series of blows from a piling rig. These are particularly suited to soft ground.
A driven steel tube pile uses the same installation technique as the driven concrete type, but the pile is a hollow steel cylinder. This makes it much easier to drive, and allows driving of long piles in sections, as each can be bolted on as the previous section reaches ground level. The holding down bolts are pre-welded into the top of the pile, making it an attractive proposition for rapid installation. The disadvantage is that the steel can corrode if placed in acidic ground conditions without suitable protection.

Unlike other foundation types, the steel tube has no bottom to bear on the ground below it, and so relies on skin friction to withstand vertical loads. This can make it less effective for heavily loaded anchor portals where the anchor forces bear down on the foundation.

The screw pile comprises a self-driving bore which forms the foundation itself; it is screwed into the ground, and the pile cap or steel grillage added.

12.11.5. Gravity Foundations

A gravity foundation (also known as a gravity pad) takes the form of a shallow cuboid of reinforced concrete, arranged to form a large footprint. The pad is dug a short way into the ground; the moment is resisted by the underside of the pad bearing against the ground below it on the compression side, and the mass of the foundation on the tension side.

Gravity foundations are used in locations where depth is not available, such as on viaducts, or where ground conditions below the surface are poor.

12.11.6. Rock Foundations

Rock foundations are used where the railway runs through an area where bedrock is on or near the surface. The rock is usually dressed with a flat concrete bearing face, and holding down bolts are drilled into the rock and bonded with a suitable adhesive. Fractured rock strata can be especially problematic, and grouting or even rock-breaking may be necessary in these cases.
12.11.7. Attachment to Other Infrastructure

In restricted clearance areas there is often not room for a dedicated OLE structure foundation. Typically, these areas are at:

- Stations;
- Overbridges;
- Underbridges;
- Cuttings with retaining walls.

In these areas it is necessary to attach OLE structures or assemblies to the existing infrastructure.

Figure 217: OLE supported from station roofwork. Manchester, UK

For these attachments, the OLE designer must take account of the following:

- Condition of the structure;
- Load capacity of the structure;
- Ownership of the structure (many bridge structures are owned by third parties, who may or may not consent to the fixing);
- Effect of fault current on structure and other systems and utilities attached to it;
- Electrical clearances;
- Fixing arrangements;
- Safety of the public.

It is often the case that other assets such as signal heads, CCTV or depot lighting can be attached to OLE structures. In this case it is necessary to consider management of earthing, and safe access for maintenance.

Figure 218: Portal mast pedestal on outside of viaduct. Manchester, UK

12.11.8. Foundation Basic Designs

The basic design range of each OLE system (section 18.9.2) generally contains a number of foundations, which are pre-approved for use at appropriate locations. Foundations are allocated (section 19.4.4) based on the constraints at the location, geotechnical conditions, embankment stability, any environmental constraints, and the construction methodology.

Where standard foundations cannot be allocated, specially designed foundations are used, and these are subject to a civil/structural approval procedure.
12.12. OLE Assemblies

A full description of the often-confusing and contradictory terminology used in OLE design and construction (in common with most engineering sectors) is beyond the scope of this book. The following diagrams give an overview of a few the terms used.

Below is a pull-off cantilever; so-called because the assembly staggers the wire toward the mast.

![Diagram of pull-off cantilever](image)

*Figure 219: Typical modern pull-off cantilever, with classic feeding, return conductor and structure bonding*

Overleaf is a push-off cantilever (sometimes known as a push-pull cantilever); so-called because the assembly staggers the wire away from the mast.
12.13. OLE Geometry

The requirement for continuous contact between the OLE and the pantograph means that the geometry of the system must be kept within strict limits. It is important to ensure that the OLE geometry complies with the rules set out below. Failure to do so will compromise the reliability – and potentially safety – of the system.

The contact wire geometry is defined in terms of height and stagger at each structure. The height is measured parallel to the track centreline; the stagger as the offset perpendicular to it.
12.13.1. Vertical Geometry

The vertical range is limited by the pantograph operating range (section 12.1.2). Therefore each system has both a minimum and maximum contact wire height. Above the upper limit, the pantograph will auto-drop leading to loss of power; below the minimum height electrical clearances to the train will be compromised. The requirement for height variation arises from the need to achieve minimum safe clearance for road and pedestrian traffic at level crossings (section 17.11), and to operate through low overbridges.

Modern high speed lines, however, are usually new construction, with no level crossings (due to the unacceptable safety risks), and overbridges built to give generous clearances. In these circumstances it is possible to maintain a constant contact wire height throughout the route. For instance in the UK, High Speed One has a contact wire height variation of only 0.01m.

For systems where there is a need for height variation, the pantograph has a maximum rate of rise and fall per second, above which it will not be able to follow the wire. Therefore the rate of rise and fall of the wire over the pantograph – the contact wire gradient – must be controlled if good current collection is to be achieved. The maximum gradient is generally proportional to the maximum linespeed – for instance European Standards\textsuperscript{172} specify maximum gradients ranging from 1 in 40 at 50km/h to 1 in 1000 at 250km/h. A useful rule of thumb for good current collection is:

\[ G_{\text{max}} \leq \frac{1}{5v} \]

where \( v \) is measured in mph.

Additionally, areas of gradient change are subject to profile rules as below. Failure to control gradient, and change of gradient, can lead to long term current collection problems and locally increased contact wire wear.

\textsuperscript{172} BS EN 50119:2020 “Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; April 2020; BSI; section 5.10.3.
At low overbridge locations, the system height (the distance between the contact wire and catenary) is reduced and catenary (section 10.8) used. For very low bridges the system height is eliminated by using a twin contact arrangement, where catenary is spliced into the catenary and then brought down until it is side by side with the contact wire.

The design of OLE through the overbridge itself must be carefully managed. It is essential to maintain sufficient clearance from all live parts – including the pantograph – to both the bridge structure above and to the side, and to the train below. This must include allowances for track maintenance, OLE maintenance, train sway, OLE uplift and the depth of the live equipment itself.

Although the diagram overleaf shows the vertical build-up of clearances under a bridge, this approach is too simplistic to be used on its own. It is essential that lateral clearances are also considered, and as a general rule, the more complex the bridge shape, the more the design has to be considered as a three-dimensional problem. At arched bridges, the pantograph is often the constraining clearance.
If adequate clearances cannot be provided through an existing overbridge, then the air gap must be increased; either by jacking or reconstruction of the bridge, or by lowering the track. Neither of these options is straightforward or cheap.

The free uplift (section 12.1.2) is the uplift the system must be capable of catering for without failure. For bridge arrangements where clearances are restricted, support and registration assemblies which restrict the uplift are available (section 12.10.9).

Figure 224: Build-up of clearances at an electrified overbridge

Figure 225: Mechanical and electrical clearances at a bridge
An additional consideration is the \textit{span differential} for each OLE structure. This is the difference between the span lengths either side of the structure. A large span differential corresponds to a large elasticity differential between the two spans of OLE, and this can affect current collection. Objective evidence of this effect is hard to come by, but nevertheless most UK systems have a maximum permitted span differential.

Conversely, having a large number of equal spans can produce a mechanical resonance effect known as \textit{galloping} where wind gusts and/or passage of trains at a specific speed can produce a standing wave in the wire which can lead to dewirement. For this reason many administrations have a limit on the number of equal spans, and require the introduction of a longer or shorter span to break up the resonance.

\subsection*{12.13.2. Horizontal Geometry}

The pantograph also has a horizontal operating range (section 12.1), and contact wire deviation outside this limit runs the risk of the pantograph coming off the wire. The pantograph will then rise without restraint, and as it interferes with the wire, dewirement is a certainty.

The horizontal displacement of the contact wire from the pantograph centre line at registration points (stagger) is required to ensure even pantograph carbon wear and carry overhead line around a curve.

This leads to the concept of \textit{maximum stagger}. The maximum stagger is not usually a constant value; as contact wire height increases, the \textit{sway} of the pantograph created by train roll increases. This reduces the effective operating range of the pantograph, and so the maximum stagger is linearly reduced to compensate.

The stagger is achieved by restraining the contact wire with a registration arm. This assembly is attached to the structure by means of a \textit{drop bracket}. The registration arm length is matched to the stagger – a \textit{minimum stagger} is set – so that the pantograph does not come into contact with the drop bracket when the registration arm is raised to the design uplift. In particular, some arms are designed to reach over the pantograph centre line; others are not.

Staggers on a multi-track railway are usually all set in the same direction - opposing staggers should be avoided where possible as this brings cantilevers (section 12.10.1) on adjacent tracks into close proximity, with attendant electrical hazards when one track is isolated for maintenance (section 10.12) and the other remains live.

An associated parameter is that of the \textit{heel setting}. This is the vertical distance from the contact wire to the attachment of the registration arm to the drop bracket. This, combined with the minimum registration arm stagger, ensures the pantograph does not hit the registration assemblies.
There are a number of different types of registration arm for use in different situations. Most arms on mainline systems are of the curved type to allow for uplift. The amount of curve is a function of the design uplift (section 12.13.1) – higher speed systems require deeper curved arms.

On slow speed systems where uplifts are smaller, straight arms are often used. These are sometimes also used on mainline systems with a large angle of inclination, to increase electrical clearances or clear a pantograph on an adjacent track.

By contrast, an overreach arm is used to reach over the first contact wire to reach the second at overlaps or turnout control structures.

A knuckle is a registration assembly designed to provide staggering at a distance from an OLE structure, or where it is not possible to fit a conventional registration arrangement in.

The point where the horizontal operating range is most at risk is at the midspan between the structures. This is because wind forces cause blowoff of the contact wire from its still air condition. This leads to the concept of Maximum Total Offset (MTO). This is the sum of Midspan Offset (MSO), blowoff, and stagger effect. The MTO for
each span must be less than the *Maximum Permissible Offset* (MPO). MPO is derived from the pantograph half width, sway and track tolerances, and includes a factor of safety to keep the contact wire away from the end of the operational width under all conditions\textsuperscript{173}.

**Figure 230: MSO, blowoff, stagger effect and MTO**

MSO is the distance from the contact wire to the track centre-line under still air conditions midway between registration points. MSO is a function of the stagger at either end of the span, and the track curvature, measured as *versine* (also known as *stringline*). It is important to control MSO by varying structure spacing and stagger, since the other factors in the MTO are less easy to control. Smaller structure spacings are needed on small radius curves to keep MSO within limits.

Versine is measured using a straight line drawn from the running rail at one structure to the same rail at the next structure; the distance between this line and the same rail at the midpoint is the versine. Versine is a function of span length and track radius. If versine is too high then MSO will be compromised, and structures spacings must be reduced.

Blowoff is the amount through which the contact wire is moved at the midspan as a result of maximum wind conditions. It is a function of the contact wire tension, the contact wire *drag factor* (which is a measure of the

\textsuperscript{173}“Overhead Line Equipment Design and Pantograph Interface”, K. Warburton; 2015; IET.
The design wind speed.

Stagger effect is the difference between the worst deviation in the span under wind, and the deviation at midspan – when the staggers at each end of the span are not the same in magnitude and direction, the MTO may not occur at midspan. The stagger effect figure is added to the midspan offset and blowoff to find the MTO.

Similarly to maximum stagger, MPO is not a constant, due to the increased sway of the pantograph with height. MPO is reduced linearly to compensate for this sway.

Sweep is the distance the contact wire moves across the pantograph in the course of travelling between two registration points, be it either from one side to the other, or from one side to the centre line and back again. Sweep ratio is the ratio of this distance to the span length; it is thus a measure of the speed of the contact wire movement over the pantograph.

It is important to keep the sweep ratio between minimum and maximum values across a whole OLE route, since if the contact wire moves too little, the carbons may wear unevenly. This can cause the pantograph to ‘snatch’ as the contact wire passes over the carbon discontinuity. Sweep ratio is less important on individual spans.


The OLE support and registration is subject to a number of mechanical loads. These are;

- Permanent vertical loads; the dead loads caused by self-weight of the equipment;
- Ice vertical loads; live loads created by the weight of ice on the wire under cold weather conditions;
- Permanent radial loads; dead loads caused by a component of the wire tension being transferred to a structure when the wire changes direction due to stagger;
- Wind radial loads; live radial loads created by the action of wind on the wire.

The support and registration components must be capable of withstanding all of these loads in combination. In particular, the permanent and wind loads affect the operation of the support and registration assemblies, since registration arms (section 12.13.2) behave poorly if not held in tension. If there is little or no tension, the registration arm will "chatter" at the drop bracket fitting, and electrical arcing may occur across the fitting, eventually causing failure through erosion. At the other extreme, too much radial load can lead to failure of the registration arm fittings.

If there is a compression load on the registration arm, the combination of self-weight load and radial load results in a downward force, creating a hard spot. In extreme cases the registration arm could flip around, with catastrophic results for the next train. Most systems have special registration arms designed specifically to take a compression load, since there are occasions where there is no other practical option.
For all these reasons it is important to keep the registration arm load within design limits, by adjusting stagger and versine. The effect of versine on radial load is approximately four times that of stagger, so structure spacing on curves is key.

The same limitations apply to a lesser extent on the catenary support; there is a maximum vertical and radial load. Most support arrangements are capable of taking compression loads; however care should be taken with cantilever arrangements which use a top tie wire rather than a top tube, as these can collapse if sufficient compressive radial load is applied.

A partial factor (section 12.9) is applied to all maximum loads. This factor of safety is generally lower for registration assemblies than for structures; for instance, UK heavy rail typically uses a factor of safety for assemblies of 1.3 to 1.4.

12.15. OLE Materials

The choice of materials for OLE fittings is critical – the components being subjected to a variety of electrical and mechanical stresses as well as environmental conditions, with very limited inspection and maintenance access.

Most fittings in modern OLE are galvanised malleable cast iron, aluminium or (increasingly) stainless steel and copper alloy. Historically, galvanised mild steel was more common. Moving connections are typically either ball and socket, or hook and eye, to provide the required degree of freedom.
The advantages and disadvantages of various materials are outlined below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Excellent electrical conductivity; resilience to fault current; excellent</td>
<td>Expensive; theft risk; less commonly available; relatively heavy for a given strength</td>
</tr>
<tr>
<td></td>
<td>corrosion resistance</td>
<td></td>
</tr>
<tr>
<td>Copper alloys (CuNi, CuSn, CuZn)</td>
<td>Stronger than copper; better durability</td>
<td>Lower conductivity than copper</td>
</tr>
<tr>
<td>Galvanised steel</td>
<td>Low cost; easy to manufacture; low theft risk; commonly available</td>
<td>Lower conductivity than copper, copper alloys or aluminium; corrosion issues if galvanising is damaged; medium/high weight for given strength</td>
</tr>
<tr>
<td>Galvanised malleable cast iron</td>
<td>Easy manufacturing for cast items such as clips and clamps; well understood material; complex shapes can be made</td>
<td>Not suitable for long items; relatively heavy; galvanising prone to damage during short circuits</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Excellent corrosion resistance; acceptable weight for a given strength; good</td>
<td>Higher coefficient of thermal expansion than galvanised steel; more complex to manufacture; lower conductivity than copper; can cause electrolytic corrosion when in contact with less noble metals</td>
</tr>
<tr>
<td></td>
<td>resilience to fault current/temperature</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>Generally lighter weight for a given strength; low price/weight ratio; good</td>
<td>More specialist manufacturing, cutting and welding needed; issues around bimetallic corrosion need careful management; prone to damage if handled or stored without care</td>
</tr>
<tr>
<td></td>
<td>conductivity; good atmospheric corrosion resistance in neutral pH atmospheres</td>
<td></td>
</tr>
<tr>
<td>Aluminium alloys</td>
<td>Stronger than aluminium</td>
<td>Lower conductivity than aluminium</td>
</tr>
<tr>
<td>Tinned copper</td>
<td>All the benefits of copper, plus: prevents bi-metallic interfaces with</td>
<td>Expensive; can corrode if coating is damaged</td>
</tr>
<tr>
<td></td>
<td>aluminium</td>
<td></td>
</tr>
<tr>
<td>Phosphor bronze</td>
<td>Ideal plain bearing material for used where lubrication is marginal or</td>
<td>Expensive; hard to form when hot; hard to machine; moderate conductivity</td>
</tr>
<tr>
<td></td>
<td>non-existent; high wear resistance; excellent corrosion resistance; low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>friction; high fatigue resistance for a non-ferrous metal</td>
<td></td>
</tr>
</tbody>
</table>

Fabricated or forged components are now favoured over castings, having the following advantages:

- Consistent quality is hard to achieve or detect with casting processes;
- Forged components are generally stronger than equivalent castings due to the smooth metal grain flow and elimination of voids;
- Forgings tend to have better dimensional accuracy than castings and so don’t always require machining.
Forging is however relatively expensive due to the need for machined forging dies, and so is more economical for large quantities. Casting is cheaper than forging, and remains the only choice for complex shapes that are impossible to forge.

The type and quality of welding for OLE components requires careful consideration and quality assurance, since these interfaces are often carrying the heaviest loads.

Catenary wire is usually a copper alloy, but historically cadmium copper and mixed steel/aluminium conductors were used. Other conductors are aluminium, copper alloy, or stainless steel. Non-ferrous materials are used for certain live fittings in contact with copper conductors.

12.16. Wire Types

The various wires used in the system are also chosen for their electrical and mechanical characteristics.

12.16.1. Contact Wire

The contact wire has five main requirements:

- To transmit electrical energy along its length;
- To transfer electrical energy to the pantograph (section 12.1);
- To withstand the mechanical stresses placed on it by the tension, environment and passage of trains;
- To withstand wear from the passage of trains;
- To facilitate connection for droppers (section 12.16.4), registration arms (section 12.13.2) and electrical connections.

![Figure 233: (l-r) 107mm\textsuperscript{2} CuSn and 120mm\textsuperscript{2} CuAg contact wire; note single and double identification grooves](image)

Contact wire cross sections conform to a worldwide standard shape, which is a circular section with two notches for connection and support purposes. EU standards\textsuperscript{175} are centred on 107, 120 and 150mm\textsuperscript{2} sections. Larger sections have a larger wear allowance, but there is a trade-off with the higher weight. Some administrations use

\textsuperscript{174}Cadmium copper is now prohibited in UK installation due to cadmium’s status as a carcinogen and toxin.

\textsuperscript{175}BS EN50149:2012 Incorporating corrigenda October 2015 “Railway Applications – Fixed Installations – Electric Traction – Copper and Copper Alloy Grooved Contact Wires”; 31 October 2015; BSI; section 4.5.4.
an oblate section rather than a circular one, to mitigate excessive wear on the pantograph in the initial period after construction, until a flat has worn on the wire.

Figure 234: Typical CuNiSi forged contact wire swivel clip. Iver, UK

Contact wire material selection is generally a balancing of the mechanical and electrical requirements. The cross section must be kept as small as possible (to keep weight down) while keeping the conductivity high; however materials with a higher conductivity usually have a lower tensile strength and exhibit long-term stretching under tension, a behaviour known as creep.

Copper and copper alloy comprise the de-facto standard for contact wires, due to copper’s excellent conductivity, tensile strength and hardness, as well as good performance under temperature change and corrosion resistance. Copper has the advantage of forming a hard but conductive oxidising layer when exposed to air.

Alloy additives are added to copper to improve the mechanical performance; however they reduce the conductivity to a greater or lesser extent. Therefore the material is chosen to balance these criteria for the particular system. For instance, hard drawn copper can be used up to a wire temperature of 80°C, beyond which the wire will begin to anneal and lose strength.

If higher operating temperatures are required, silver copper (CuAg) anneals at around 150°C and has otherwise identical electrical and mechanical properties.

European contact wires use a system of grooves along the top of the wire to identify the material type.

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176 1/014/401/A3 “MkIIID A.T. Equipment - Conductor Particulars - Simple Catenary”; P04, 23 August 2008; Network Rail.
<table>
<thead>
<tr>
<th>Number of Grooves</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Normal and High Strength copper</td>
</tr>
<tr>
<td>1 centred</td>
<td>Copper-cadmium alloy</td>
</tr>
<tr>
<td>1 offset</td>
<td>Copper-tin alloy</td>
</tr>
<tr>
<td>2</td>
<td>Copper-silver alloy</td>
</tr>
</tbody>
</table>

One of the key aims of the system design (section 18.9.1) is to deliver uniform low wear of the contact wire, since the life of a whole tension length (section 12.4) will be reduced should any sections experience excessive wear.

Figure 236: Contact wire strength against conductivity

12.16.2. Rigid Overhead Contact Line

It is sometimes not practical, for a variety of reasons, to provide conventional OLE using flexible wires. In these cases a Rigid Overhead Contact Line (ROCL) is used. This takes the form of a grooved bar designed to accept a conventional contact wire.

This system is only used in situations where conventional OLE is not feasible, since the bar requires frequent support, and so is more expensive than conventional OLE. However it has a number of advantages, including the lack of tension in the system and the ease of contact wire renewal compared with conventional systems.

ROCL has now been certified as safe and reliable at speeds up to 275kph.


180 Also known by the trademarked name Rigid Overhead Conductor System (ROCS) or rigid overhead conductor bar. ROCL is used here in accordance with the definition in European Standards. BS EN 50119:2020 "Railway Applications – Fixed Installations – Electric Traction Overhead Contact Lines”; 30 April 2020; BSI; section 3.1.1.6.
Typical uses include:

- Tunnels where clearances are too small for conventional OLE supports and conventional levels of uplift (section 17.5.6);
- Tunnels and stations where fire and public safety requirements are such that a vulnerable tensioned system is not acceptable;
- Locations where OLE design is driven by aesthetic and architectural considerations. The risk of dewirement is so low with this system that an OCLZ (section 10.10.1) is not required;
- Locations where retractable or moving OLE (section 16.5) is required.
The transition from conventional OLE to ROCL must be carefully managed since the elasticity of the conductor bar is much lower. This is usually done with a transition bar section which has graduated cut-outs to provide increasing stiffness.

Figure 239: Rigid overhead conductor line as architecture. Salzburg, Austria

12.16.3. Catenary Wire and Auxiliary Catenary

The *catenary wire*\(^{182}\) and auxiliary catenary (section 12.2), if there is one – has fewer requirements than the contact wire; it is required to transmit electrical energy along its length and to withstand the mechanical stresses placed on it, but not to withstand pantograph wear or transmit energy across a small interface area.

For this reason stranded wires are used for catenary wire. Pre- and post-war systems used hard drawn copper, but in the 1970s aluminium/steel *Alumo-Weld Aluminium Composite* (AWAC) catenary was widely used in the UK for reasons of economy. However this wire has given reliability issues, as the two steel wires – which give the conductor most of its strength – are prone to galvanic corrosion and failure if the aluminium coating is damaged by mishandling or flashover\(^{183}\).

\(^{181}\) OLEMI Drawing 1/148/075/A3 "Aluminium Covered Steel-Aluminium Conductors"; rev 3; BICC; 1979.

\(^{182}\) This conductor is known as a messenger wire in Europe and the US.

\(^{183}\) NR/L2/ELP/27009/MOD C64 "Overhead Line Campaign Changes – Renew AWAC Catenary prone to failure due to Corrosion of the Stainless Steel Inner Cores"; Issue 1, 2011; Network Rail.
Current best practice for catenary is to use copper alloys such as Bz II.

12.16.4. Droppers

All droppers have two main requirements:

- To hold the contact wire at the correct height relative to the catenary;
- To withstand the unloading/loading cycle created by the passage of trains.

Traditionally droppers have not had an electrical function, but modern systems increasingly use current carrying droppers with suitable electrical connections to improve resilience to potential differences between catenary and contact wire.

For locations with small system heights, a conventional dropper would be subject to excessive flexing due to pantograph passages, and so an uplift dropper, without a fixed catenary connection, is used instead.
Droppers (other than uplift types) have historically been made from solid copper wire or galvanised steel wire; however these are prone to long-term failure due to the cyclic loading / unloading created by the passage of trains. Modern droppers use a stranded copper alloy wire, which is more expensive but gives better load cycle performance.

12.16.5. Ancillary Conductors

Conductors which are not contact wire or catenary, but carry traction and/or fault current, are collectively known as ancillary conductors.

Return Conductors (section 10.4.1) have historically used 19/3.25 mild steel or 19/3.25 hard drawn copper, but modern systems in the UK use aluminium as a good balance of conductivity and corrosion resistance versus cost. Current standard wires are 19/3.25 Al (given the codename hornet in British standards\textsuperscript{184}) or 19/4.22 Al (cockroach), depending on electrical load. These are used as bare cables in open route, and with a PVC sheath in accessible areas such as stations.

Figure 244: 19/3.25 PVC sheathed Al cable, used in the UK as bonding cable; minus the PVC sheath it is also used as earth wire and return conductor

\textsuperscript{184} BS215-1:1970 “Aluminium Conductors and Aluminium Conductors, Steel-Reinforced – For Overhead Power Transmission – Part 1: Aluminium Stranded Conductors”, March 1970; BSI; appendix C.
19/3.25 Al is also used for aerial earth wire, although some systems use the All Aluminium Alloy Conductor (AAAC) equivalent 19/3.35 to eliminate creep. 19/4.22 Al (with a PVC sheath) is also used for MSCs and RSCs (section 10.4.5), which being ground-mounted and untensioned do not suffer from creep.

Cross track feeder wires (section 12.7.2) typically use the same aluminium conductors as return conductors, although more recently 37/2.27 hard drawn copper has been used when connecting to copper catenaries, so avoiding the need for bimetallic lugs (section 12.17.2) and associated complex wire connections, which are a known failure mode.

ATF conductors (section 10.4.3) typically use one or two 19/4.22 Al wires (depending on electrical load), but for heavily loaded areas a 37/3.78 Al wire (*centipede*) is used. Since ATFs are live they need greater sag control than EWs or RCs to prevent them coming too close to the ground. This means higher tension which exacerbates creep, and so recently a 19/4.2 AlMgSi AAAC wire has been used.

Tail wires (section 12.4.5) must withstand the combined tension of the contact wire and catenary and so are a proportionally larger section. Standard UK practise is to use 37/2.36 hard drawn copper wire.

Jumpers (section 12.4) typically use 40mm\(^2\) to 70mm\(^2\) flexible stranded hard drawn copper wire, depending on electrical load.

Bonding cables (section 10.10.1) typically use 19/3.25 or 19/4.22 PVC sheathed Al cable depending on electrical load.

### 12.16.6 Other Wires

Headspan structures (section 12.10.7) comprise three horizontal wires; from top to bottom, these are the headspan wire, the upper cross span wire and the lower cross span wire. These are not current-carrying in normal operation and so are arguably not conductors. The upper and lower span wires are nominally taut and in the UK these use 19/2.1 hard drawn copper, although historically 19/1.85 copper covered steel wire (known as copper ply) was used for reasons of economy. The copper ply is prone to damage if rough handling is experienced during construction. This led to instances of water ingress and subsequent corrosion, and so as with AWAC (section 12.16.3) a programme is under way to replace them with Bz II\(^{185}\).

The headspan wire provides the mechanical support for the whole configuration, and for this function a 19/1.63 stainless steel wire is the norm in the UK. For large headspans these are doubled up to provide sufficient support.

\(^{185}\) NR/L2/ELP/27009/MOD C17 “Overhead Line Campaign Changes – Replace Copper Ply Span and Tail Wire”; Issue 1, 2011; Network Rail.
mechanical strength. The vertical headspan droppers which support the OLE registrations typically use solid 8mm galvanised steel wire.

MPA tie wires (section 12.10.11) generally use the same wire as the catenary wire for the system. MPA tie wires are usually tensioned at between 3 and 5kN at the setup temperature for the system.

All of the wires discussed so far are designed to be broadly static, and subject to movement only from wind and passing trains (with the exception of tail wires). Some wires need to withstand frequent and significant flexing without fatigue – for instance the connection between a fixed post insulator and a moving blade insulator (section 12.7) of an isolator. For these connections a flexible braid is used.

These comprise a very large number of small diameter strands – usually copper – which are woven into ropes which are capable of carrying high currents, but remain extremely flexible.

12.17. Wire Connections

A variety of connections are required in and onto OLE conductors, and these can be divided into two groups – tensioned and untensioned. All such connectors are part of the electrical system, and must be able to withstand repeated thermal cycles and fault currents without degradation of the connection.

12.17.1. Tensioned Connectors

These connectors are placed directly into the conductor, either as part of the termination onto a mast or boom, to effect the transition from one wire to another, or to create an electrical break with a cut-in insulator (section 12.18). As such they experience the same tension as the wire and are safety-critical, since failure will inevitably result in a dewirement.

For many years the standard means of terminating a stranded wire was a dead end clamp, a cast iron fitting comprising an outer sleeve which carries a clevis, and an inner wedge. For stranded wires, the wire is bent around the wedge, and the tension in the wire pulls the wedge into the dead end sleeve and secures the wire.
For solid conductors such as contact wire, a variation on this design was used with the conductor bent through 90° rather than back on itself.

An alternative for terminating stranded wires was later adopted from the electricity supply industry – the **preformed dead-end** (also known as a PLP after the manufacturer). This uses a prefabricated set of three copper or aluminium covered steel wire strands (to match the conductor) which are spiral wound, formed into a U-shape and bonded together with a liberal coating of resin and grit. This is then threaded around a terminating casting and the strands spiral wound around the wire in the same direction as the wire layup. The action of the wire tension pulling on the PLP tightens it around the wire, and the friction of the resin coating ensures that the wire does not slip.
Preformed dead ends require a high level of care in installation\(^{186}\), and this led to the use of the cone end fitting; which uses a conical hollow brass wedge which sits around the central strands of the wire, with the outer strands arranged outside it. The wire tension pulls the conical wedge into a conical gunmetal sleeve which carries the clevis, and the outer strands provide the necessary friction to hold everything in place.

![Cone end clamp for catenary termination](image1.png)

Figure 249: Cone end clamp for catenary termination

Most of these traditional termination devices have now been replaced by the forked collar socket. These are a modern form of cone end fitting, but the whole of the wire sits inside a forked collar, which has grooves or collets machine into it. These allow the collar’s diameter to reduce as the outer sleeve compresses the collar under tension. The design removes the need for skilled setup and are less prone to failure, but they require a reliable minimum tension to operate correctly, and so low tension wires such as spanwires still use dead end clamps.

![Forked collar socket for 19/2.1 catenary termination](image2.png)

Figure 250: Forked collar socket for 19/2.1 catenary termination

\(^{186}\) An installation video is available online at [youtu.be/B7zXcSiIPc8](https://youtu.be/B7zXcSiIPc8).
It is often necessary to join two tensioned wires together – for instance when joining RCs, EWs or ATFs in long runs, splicing contenary into catenary (section 10.8), or as part of a repair after a dewirement. For many years the standard way to do this was via a compression splice. This comprises a double-ended copper or aluminium sleeve (to match the wire) which is internally coated with a conductive grease (to keep out water), into which the wire ends fit. A compression tool is then used to create a series of crimps to hold the wires\textsuperscript{187}.

This process is time-consuming and easy to get wrong, and so in recent years compression splices have been replaced by double-ended conical couplers. These comprise a CuNiSi barrel and AlBz collet with internal spring-loaded teeth which point away from the direction of tension. The wire simply push-fits into place, and as the wire is tensioned the teeth bite into the wire and secure it. These fittings are much easier and quicker to fit, and are more reliable in use.

None of the above solutions are suitable for joining two lengths of contact wire together – something which is done only as part of a repair, since it introduces a potential failure mode into the most sensitive part of the system; or for terminating an in-running contact wire at a section insulator (section 12.6.1) or in-line neutral section (section 12.6.3). Various designs are available, but all use the contact wire groove (section 12.16.1) to

\textsuperscript{187} An installation video is available online at youtu.be/K7A_awOIlYA.
make a connection.

The *battleship splice*, so-called because of its (alleged) resemblance to a warship, has been used since the 1960s. A set of inclined bolts bear down on the top of the contact wire, cutting into it to transfer the tension to the casting. The bolts are then wired together to prevent loosening.

![Battleship contact wire splice](image1)

Figure 253: Battleship contact wire splice

This was superseded by the *butt splice*, which uses two symmetrical CuNiSi castings clamped via a set of opposing screws. It relies on the friction between the clamp and the contact wire groove.

![Butt splice for contact wire](image2)

Figure 254: Butt splice for contact wire
Special arrangements are required when a wire run is converted to a tail wire arrangement (section 12.4.5) or tensioned via a single tensioner (section 12.3). The contact wire and catenary are terminated at each end of an equalising plate (also known as a balance plate) and the tail wire or tensioner connected at the centre.

The ratios of the lengths of the equalising plate arms determines how the tension provided by the tensioner is shared between the contact wire and catenary; equal lengths provide equal tensions, and unequal lengths are used to split the tension unequally between the wires.

### 12.17.2. Untensioned Connectors

It is often necessary to connect an untensioned wire to a tensioned one – for instance at jumpers (section 12.4), midpoint connections (section 10.4.2) and switching locations (section 12.7). There are a number of ways of achieving this.

Parallel Groove (PG) clamps use a similar arrangement to the butt splice overleaf. They come in two variants; one which connects two stranded wires together by clamping around both, and another which clamps a stranded wire to a contact wire (again using the groove).

An alternative method which has been used for connecting aluminium wires together is the Impact wedge connector. This uses an aluminium wedge which is driven between the two wires as they are held in an
aluminium C-sleeve. The required amount of compression is achieved by firing a small explosive charge from a specially-designed gun\textsuperscript{188}.

Figure 257: Ampact wedge clamp connection onto RC

In the UK these have been deprecated in favour of a version which uses shear bolts and so does not require specialist explosive charges.

Figure 258: Wedge connector – shear bolt type

Special measures are required when connecting wires of dissimilar metals together, to prevent cathodic corrosion. In this case a \textit{bimetallic lug} is inserted between the two wires. This is a specially fabricated assembly, which comes in various forms, each including two metals (typically aluminium and copper) friction welded together. These can be used in conjunction with PG clamps or wedge clamps to facilitate joining of copper jumpers to AWAC (section 12.16.3) or aluminium feeder wires to copper RC (section 10.4.1).

\textsuperscript{188} An installation video is available online at \url{youtu.be/6TmdxEwLWhL}. 
When arranging these types of connections, it is important to arrange the aluminium wires and fittings above the copper ones; otherwise any acidic rainfall (a feature of areas with high pollution) will wash copper sulphate (copper wash) onto the aluminium, causing corrosion.

12.18. Insulators

Insulators are required to separate live parts of the system from earthed parts, or to separate electrical sections. The insulators chosen for the system must meet the following requirements:

- Sufficient electrical strength (section 10.8) for electrical loads, faults, and lightning strikes, as determined by the insulation coordination process;
- Sufficient mechanical strength for the location and use – including tension, bending or torsional loads;
- Sufficient creepage path for the environmental contamination at the location;
- Sufficient durability to withstand vandalism;
- Wherever possible, be self-cleaning under the action of rain and wind.

The electrical strength is chosen to match the system voltage (section 10.1.1). The creepage path is the distance measured around the outside of the insulator, and the required distance may be achieved by means of ribbed sections (sheds – so called because they are designed to shed water), or they may simply be long rod insulators.

12.18.1. Materials

The material used for an insulator is dependent on placement, cost and environmental factors. Hard porcelain has historically been favoured in the UK due to its cost-effectiveness and ease of fabrication. However these are prone to vandalism (especially by air rifle) and to explosive failure if moisture ingress occurs. Some porcelain insulators have a hollow gas-filled core, but these are prone to leakage and subsequent failure by the same water ingress mechanism.
In recent years *shed protectors*, comprising a rubber sleeve which fits tightly around the shed, have been added to porcelain insulators. These help the sheds to withstand vandalism, and can hold together a damaged insulator.

Pre-stressed glass is used extensively in Europe, being more robust than porcelain, but also more expensive.

![Lightweight shedded polymeric 25kV insulator. Manchester, UK](image)

**Figure 260: Lightweight shedded polymeric 25kV insulator. Manchester, UK**

Plastic (or polymeric) insulators – comprising a Glass Fibre (GF) and epoxy resin core with silicone sheds - are now standard in the UK, as they are lighter and smaller than their porcelain or glass counterparts, and are naturally *anti-vandal*, since the sheds deform rather than break on impact. However polymeric insulators bring new problems – sheds can deform if not stored correctly prior to construction, and some birds will eat the polymers (section 12.19).

![Polymeric 25kV rod tension insulators, with anti-torsion bars. Edgbaston, UK](image)

**Figure 261: Polymeric 25kV rod tension insulators, with anti-torsion bars. Edgbaston, UK**

Plastic insulating materials may also be formed into rod insulators. These also use silicone over a GF/epoxy core, and are used at locations where clearances to the pantograph are small, and a shedded insulator would be too large. When placing rod insulators into stranded wires, it is important to control the natural torsion which a wound wire applies to the insulator, since rod insulators are very weak in torsion. This is usually managed by means of *anti-torsion bars* which are clamped to the catenary and contact wire either side of the insulators. *Glass Fibre* insulators can withstand small bending loads, although with a certain amount of flexure. This property is exploited when glass fibre insulators are used as *bridge arms* (section 12.10.9).

Plastic materials are also used extensively for *rope insulators* on tram systems.
12.18.2. Mechanical Requirements

The mechanical load requirements of the insulator depend on the use. Tension insulators are designed to take a purely tension load. They are used as cut-in insulation in conductors, and as vertical catenary supports.

Figure 262: (l-r) Insulator types; porcelain cap-and-pin type, porcelain post type

They may be formed as individual shed components, joined together by means of a cap and pin arrangement to form an insulator of the required electrical strength.

Post insulators are designed to take bending and compression loads, and are used to support feeder wires and support catenaries.

Some switching insulators are designed to take a torsional moment and are used in torsion-tube operated switches. Others are used in push-rod switches and do not need to withstand torsional moments.

Glass Bead Insulators are formed of glass beads threaded onto a rod, and they are used in circumstances where an insulator is required in the in-running contact wire; for instance, at inline neutral sections (section 12.6.3). This type of insulator needs regular cleaning to remove carbon deposited by the pantograph, and their use is therefore minimised.

Suspension insulators (colloquially known as danglers) are used to support auto-tensioned (section 12.3) wires which only require a small range of movement, typically near the midpoint anchor (section 12.10.11) or fixed anchor (section 12.10.10) locations. They are also used to support fixed termination ancillary conductors, especially ATFs (section 10.4.3), as they help to equalize the wire tension between spans without imposing high bending moments on individual insulators.

Figure 263: Suspension insulator for ATF. Cholsey, UK
12.19. Protection Against External Factors

A number of external factors can result in damage to OLE, and a range of measures are adopted to mitigate these.

12.19.1. Vehicle Damage

It is often necessary to place structure foundations (section 12.11) within areas accessible to road vehicles, such as a station car park, access road or RRAP approaches (section 20.2.1). This makes the critical interface between the foundation and the structure vulnerable to accidental damage. Crash barriers are often fitted at these locations.

![Figure 264: Armco vehicle protection barrier. Severn Tunnel Junction, UK](image)

12.19.2. Wildlife Deterrents

All OLE systems suffer to a greater or lesser extent from interactions with wildlife - especially, but not exclusively, with birds. These interactions often result in damage to the OLE and injury or death for the animal. Since many countries offer legal protections to wildlife, infrastructure managers are often obliged to take reasonable steps to prevent harm to animals, as well as protecting the system from damage. Many systems adopt deterrent measures to dissuade birds from flying into conductors or roosting in areas with small air gaps, and some systems attempt to dissuade climbing animals from approaching live parts.

The extent to which animals are a problem, and the type of problems they cause, are a function of the local environment; and in some countries, the problem is highly seasonal. The following are just some of the problems encountered around the world, and the mitigation measures in place:

- United Kingdom: low-flying water birds can fly into conductors, and so bird scarers are attached to the outermost conductors in areas with aquatic habitats;
- Australia: administrations have reverted to using glass insulators, since the local parrots were eating the polymeric insulators;
- India: eagles and other large birds cause significant problems by nesting within lattice structures and around lineside switching. Monkeys often climb from adjacent trees onto OLE and have been known to eat polymeric insulators.
12.19.3. Anti-Vandalism Measures

Vandalism and trespass is an unfortunate reality in many parts of the world, and railways take steps to guard against interference with the safe and reliable operation of OLE systems, as well as protecting people from the consequences of their own actions. Typical measures deployed include:

- Polymeric insulators (section 12.18);
- Anti-climbing guards (ACGs) or shrouds on vulnerable structure masts;
- Anti-walking guards on vulnerable portal and TTC booms.

12.19.4. Icing Mitigations

Railways in colder climates suffer from significant ice accretion; while the additional load on structures can be mitigated by appropriate loading allowances (section 12.9.2), accretion on the contact wire can cause loss of contact, damage or increased wear to the pantograph carbons (section 12.1), or in extreme circumstances, parting of the wire.
Some administrations deploy trains with special scraping pantographs to combat this; others rely on running ordinary electric trains at night in an effort to prevent ice forming on the wire. Still others utilise Joule-effect defrosting, where a resistance is switched into the OLE circuit, ensuring that some traction current flows even when no train is in section, so providing a degree of electrical heating; however this is an expensive solution to the problem.
13. **Signage**

OLE is typically provided with a number of signs to:

- Identify the names and locations of equipment;
- Provide a means of identifying location during safety-critical communication;
- Ensure that the right piece of equipment is being operated or worked on;
- Give the driver of a train critical information or instruction relating to the traction system;
- Warn of electrical dangers at locations accessible to staff and the public.

The following signage examples are all from the UK; other administration use different depictions and conventions to convey the same information.

13.1. **Asset Signage**

These signs are provided as a means to identify the names and locations of equipment.

13.1.1. **OLE Structure Signage**

OLE structures are generally given a unique identification number. In the UK the historical convention has been to use a combination of route code and along-track location. The structure number is in the form [Route code][Unit]/[Number]. The route code comprises one or more letters.\(^{189}\)

The unit is either the mile (historically) or kilometre (more recently) within which the structure is located, and the number is a simple increment within the unit. For instance, the first structure at the zero point at London Liverpool Street is B00/01; the route code is B, and the structure is the first in the ‘0’ mile. Subsequent structures are B00/02, B00/03... until the 1 mile mark is reached. The first structure past this mark is B01/01, then B01/02 and so on.

Where new structures are introduced on an existing electrified route, a letter suffix is used; so if a new structure is required between B01/04 and B01/05, it would be numbered B01/04A. A second new structure at this location would be numbered B01/04B, and so on.

More recently this system has been replaced by a system which uses the Engineer’s Line Reference – a more widely used route code in the UK – and the along-track kilometrage. For instance, an OLE structure at Didcot on the GWML is numbered MLN85.507 – MLN being the route code and the structure being 85.507km from Paddington.

\(^{189}\) A comprehensive list of UK route codes is available online at Phil Deaves’ railway codes website www.railwaycodes.org.uk/electrification/mast_prefix0.shtm.
13.1.2. **Wire Run and Section Insulator Signage**

UK installations are provided with section numbers at Section Insulators (section 12.6.1), and (more recently) with wire run marker plates at anchor locations (section 12.10.10).

![Section Insulator with number plate. Edinburgh, UK](image)

Figure 269: Section Insulator with number plate. Edinburgh, UK

13.1.3. **Switch Signage**

All OLE isolators (section 12.7) are provided with a unique number which is marked at the switch location and referenced on the isolation diagrams and instructions (section 19.4.13). Numbering for mid-section switches takes the form:

\[\text{subsection number}/\text{number of switch in subsection}\]

Switches bridging two sections take the form:

\[\text{subsection 1}/\text{subsection 2}\]

![Switch number plate for switching joining subsection 430D to 431F. Stratford, UK](image)

Figure 270: Switch number plate for switching joining subsection 430D to 431F. Stratford, UK
13.1.4. Designated Earth Positions

Marker plates are provided at DEP locations (section 10.12.1).

13.2. Operational Signage

A number of signs are provided to assist train drivers to carry out their duties.¹⁹⁰

13.2.1. Neutral Section Signage

A Neutral Section Warning Board is placed around 1.6km on approach to a neutral section location (section 12.6.3), to give to driver advance notice of the need to shut off power.

A Neutral Section Indication Board is provided immediately on approach to the neutral section to denote the location of the neutral section.

A Rear Clear of Neutral Section Board is provided at a position beyond the neutral section to indicate that all pantographs on the train are now clear of the neutral section.

13.2.2. Power Changeover Signage

These signs are provided wherever trains must change between different electric traction systems, or from electric to diesel traction.

¹⁹⁰ GIGN7634 “Index for Lineside Signs”; Issue 1.1, July 2019; RSSB; section G2.2.6. Signs themselves are found by searching Railway Group Standards Online using appropriate search terms.
The Warning of Traction System Changeover Board is placed on approach to an electrical changeover from one system to another. This applies equally to 750V DC third rail to 25kV AC OLE, or vice versa.

The Traction Changeover to 25kV AC Board is placed at an electrical changeover from any other system to 25kV AC OLE.

The Lower Pantograph Board is provided at all locations where a bi-mode electro-diesel train is required to switch from electric power to diesel, or a dual-voltage train is required to switch from overhead power to 3rd or 4th rail power.

The Traction Changeover to 750V DC Board is placed at an electrical changeover from any other system (typically 25kV AC in the UK) to 750V DC third rail.

The signs above are shown in permanent locations; but temporary situations (such an obstruction on the overhead line) often require electric trains to coast through a section of railway, relying only on its inertia until operational OLE is reached at the other end. This means that all pantographs must be lowered for a short period, and for this purpose signs are temporarily placed sequentially along the railway as follows:

- Advance lower pantograph board;
- AJ03 board;
- obstruction;
- AJ05 board;

Figure 273: (l-r, top to bottom) Operational signage boards; AJ04 Warning of Traction System Changeover, AJ05 Traction Changeover to 25kV AC, End of Traction Changeover Zone, AJ03 Lower Pantograph (with train type label), AJ03 Lower Pantograph (with diverging route label)

The Traction Changeover to 750V DC Board is placed at an electrical changeover from any other system (typically 25kV AC in the UK) to 750V DC third rail.

The signs above are shown in permanent locations; but temporary situations (such an obstruction on the overhead line) often require electric trains to coast through a section of railway, relying only on its inertia until operational OLE is reached at the other end. This means that all pantographs must be lowered for a short period, and for this purpose signs are temporarily placed sequentially along the railway as follows:

- Advance lower pantograph board;
- AJ03 board;
- obstruction;
- AJ05 board;

191 GE-RT8000-AC "Rule Book: AC Electrified Lines"; Issue 6, September 2020; RSSB; section 15.5.
• End of traction changeover zone board.

This mode of working is limited to 20mph in the UK. For planned works, *High Speed Coasting* at linespeed may be authorised, allowing a longer section of OLE to be out of use, but requiring correspondingly higher starting speeds.

### 13.2.3. Limit of Electrification Signage

A *No Access to Electric Trains* sign is provided at all locations where an overhead electric train could be mistakenly signalled or shunted onto a line not provided with OLE. Complex locations with a mix of permissible and non-permissible routes for electric trains are provided with additional explanatory text.

![Figure 274: Limit of Electrification boards. Didcot, UK](image)

### 13.3. General Safety Signage

A number of different types of warning sign are provided at locations where railway workers or members of the public are in proximity to live parts.

![Figure 275: General electrical hazard sign on overbridge. Brinkworth, UK](image)
14. Types of UK Equipment

There are approximately 100 different types and subtypes of OLE present in the UK, including tram and light rail systems. The type refers to the generic system, such as Mark 1 or Mark 3b. The subtype refers to the suspension and tensioning system, and the tensions in each wire. A type may have many subtypes; for instance Mark 1 has simple and compound, auto-tensioned and fixed termination variants.

The complete list of OLE types in the UK can be found in Appendix D.

Care must be taken when modifying existing equipment, to determine the type in use and ensure that compatible parts are used.

14.1. Basic Design Ranges

A Basic Design Range is a set of drawings which define the components, materials, geometry and parameters of a given OLE system. Each range may contain one or more types of equipment. The allocation designer applies these to a given location in accordance with the requirements of that location.

![Figure 276: Typical basic design drawing](image)

The following sections give an overview of the various basic design ranges in use in the UK. Each country will have a set of basic designs in this manner; these are developed appropriate to the technology available at the time, and to the performance requirements of the system.

14.2. Historic Design Ranges

These ranges were developed in the UK during the period before standardisation and metrication was introduced, but they remain in use on legacy routes.
14.2.1. The MSJ&A Range

The Manchester South Junction and Altrincham (MSJ&A) railway is one of only two routes in the UK to have been energised at three different voltages; it was electrified at 1500V DC in 1931, then converted to 25kV AC in 1971, and then in 1991 to 750V DC to become part of the Manchester Metrolink tram system. Although the original OLE did not survive conversion to 25kV, many original structures remain and are the oldest in the UK. Much of the 750V DC system still uses the previous Mark 3 (section 14.3.1) 25kV support and registration arrangements and insulators.

Figure 277: 750V DC OLE for trams on original MSJ&A portals with 25kV insulators. Timperley, UK

14.2.2. The GE/MSW Range

The Great Eastern (GE) range was developed by London & North Eastern Railways (LNER) and subsequently BR, and was first installed in 1949 for the electrification of the lines out of Liverpool St at 1500V DC. It was then used on the Manchester to Wath and Sheffield (MSW) route in 1954. The range was updated to reflect the conversion of GE lines to 6.25kV, and the subsequent conversion of both GE and the remaining section of MSW to 25kV AC. GE/MSW equipment, where it remains, is the oldest working type in the UK. However the amount in service is rapidly decreasing as routes are upgraded to GEFF equipment (section 14.4.2).
The range is imperial and robustly engineered, using large quantities of copper, which was a cheap material at the time. The range uses painted steel fabricated portals and planted masts, with a large amount of fabrication carried out on site. Most structures are MIR type, with spanwire portals used in complex areas and sidings. The system had a large quantity of fixed termination equipment on running lines – most of which has now been upgraded to the GEFF auto-tensioned system – as well as auto tensioned equipment for higher speeds. The contact wire, auxiliary and catenary are of a very large cross section, reflecting the original requirement to carry DC currents; this, coupled with the low tension, means system heights are large and supports are substantial. The insulation has been upgraded to 25kV standards, but the configuration of the original DC catenary supports means that electrical clearances are small by modern standards.

The range is no longer available for design use.

14.2.3. The SCS Range

The Shenfield-Chelmsford-Southend (SCS) range was first installed in 1956 as an extension to lines electrified using the GE system. The range was also originally 1500V DC, and was updated to reflect the conversion of GE lines to 6.25kV and then 25kV AC. The range replicated most of the features of GE equipment, including heavy contact wire, fixed termination and compound suspension. As with GE equipment, the insulation has been upgraded to 25kV standards. The range is no longer available for design use.
14.2.4. The Mark 1 Range

The Mark 1 range was developed by BR and Balfour Beatty in the early 1960s for the first phases of WCML electrification. Like the GE range, the assemblies are imperial and use copper. The range also uses painted steel fabricated portals and planted masts. All structures are MIR type, with catenary pulleys. Again, system heights are large (nominal 1980mm). For the first time mainlines were equipped with auto-tensioned equipment, setting the standard for all later equipment types. Mark 1 equipment originally came in simple, compound and stitched variants, but the stitched version was soon abandoned. Simple and compound equipments remain in widespread use today. Network Rail has recently developed an upgrade range for Mark 1, UKMS R1 (section 14.4.5); and this will be used for midlife renewals (section 18.1) in the coming years.

The range is no longer available for design use.
14.2.5. The Brown Boveri Range

The Brown Boveri range was specified by Pirelli for the second stage of the Glasgow South Suburban electrification scheme, as an alternative to Mark 1 equipment. However this scheme was subsequently taken over by BICC who instead specified Mark 2 equipment (see below). As a result Brown Boveri equipment is confined to the Neilston branch of the Glasgow network. This equipment is unique in the UK in using a simple stitched (section 12.2) configuration.

![Figure 281: Brown Boveri Cantilevers with stitch wire (arrowed). Whitecraigs, UK](image)

14.2.6. The Mark 2 Range

The Mark 2 range was a short-lived development of the Mark 1 range, and was installed in the Glasgow suburbs in the 1960s. It pioneered the use of galvanised steel support and registration equipment. It remains in use on these lines but is not available for design use.

![Figure 282: Mark 2 portal. Bishopton, UK](image)
14.2.7. The Tyne & Wear Metro System

This system was developed in the late 1970s for the electrification of the Tyne and Wear Metro. The system is configured for use as a 1500V DC system, using simple auto-tensioned equipment with a mix of lightweight cantilever and headspan structures. Some heavily loaded sections use twin contact wire and/or twin catenary to minimise volt-drop.

14.3. The OLEMI System

The OLE Master Index (OLEMI) was initiated in the early 1970s in response to the requirement for cheaper OLE builds, and was still being added to until quite recently. It was developed by BR, is now owned by NR, and consists of approximately 13000 drawings. The OLEMI was developed as a modular system, where a single component can carry out several tasks. It is also a metric system, and was initially developed with mechanically dependent supports in the form of headspans. MIR assemblies were later added to the range. The range contains the Mark 3, Mark 3a, Mark 3b, Mark 3c, Mark 4, Mark 5 and UK1 ranges, and metric conversion assemblies for Mark 1. OLEMI schemes include the second phase of WCML electrification, the ECML and the southern section of MML. In an effort to reduce structural steelwork costs, the standard system height was reduced (as low as 900mm for Mark 3b).

The OLEMI is available for use in modifications and extensions to existing OLEMI routes, but is out of favour for new electrification due to its numerous failure modes; it is mature, and no longer subject to update.

14.3.1. The Mark 3 Range

The Mark 3 range was developed in the late 1960s, and introduced headspans in a bid to reduce both capital costs and the ongoing maintenance that painted portals need.

It also pioneered the use of pre-sagged simple equipment (section 12.2) in the UK. The range maximised the use of galvanised steel, in lieu of copper, since prices had risen steeply by this time. Copper clad steel wires were used for headspans, but these have since suffered corrosion issues and are now being replaced (section 12.16.6).

Figure 283: Mark 3 spanwire TTC and single cantilevers. Enfield, UK
14.3.2. The Mark 3a Range

The Mark 3a range was introduced in the early 1970s as an evolution of Mark 3. It also used headspans, but introduced bridles at the catenary support in order to reduce catenary wear at pulleys. In a further effort to reduce the amount of copper used, AWAC (section 12.16.3) was introduced. Midlife corrosion issues mean that this wire is now being replaced on Mark 3a and Mark 3b installations.

![Figure 284: Mark 3a headspan. Harringay, UK](image)

14.3.3. The Mark 3b/3c Range

The Mark 3b range continued the use of headspans and AWAC, but introduced bolted base masts to help speed up construction. Mark 3c was introduced to allow a copper catenary to be used instead of the now-problematic AWAC variant, but is otherwise identical. In the 1990s MIR portal assemblies were also added to the Mark 3b range.
14.3.4. The Mark 3d Range

The Mark 3d range was developed in the mid 2000s as an upgrade range for existing OLEMI equipments, particularly for use on the ECML. The range is designed to rectify specific failure modes in Mark 3a and 3b equipment, including problems with AWAC (section 12.16.3) and solid dropper failures (section 12.16.4).

14.3.5. The Mark 4 Range

The Mark 4 range was developed in the 1970s as a high speed compound system to support the introduction of the APT (section 8.5) on WCML. It was never implemented.

14.3.6. The Mark 5 Range

The Mark 5 range is a heavy current version of Mark 3c, using 150mm² copper contact wire. It was used only at Dollands Moor freight yard as part of the Channel Tunnel construction.

14.3.7. The UK1 Range

The UK1 range was developed in the late 1990s in response to the requirement under West Coast Route Modernisation (WCRM) to raise WCML linespeeds. The existing Mark 1 and Mark 3a equipments on the route were not adequate for these speeds, and so an upgrade range was required. The range covers the upgrade of Mark 1 and Mark 3a equipment to either 200 or 225km/h, although only the 200km/h upgrade was used.

The range was developed by Balfour Beatty and Atkins, is modular and uses aluminium MIR assemblies derived from continental best practise. It is used at existing Mk1/Mk3a locations and for new schemes. The range is now mature, and is not subject to updates.
14.3.8. The ATF Range

The ATF range was introduced around 2000 for the upgrade of the WCML to Auto Transformer feeding. It contains a range of AT feeder support assemblies and bridge route solutions. It is mature, and is being used on the Crossrail project and Paddington to Stockley auto transformer upgrade.

14.3.9. Other Assemblies

A number of other arrangements exist in the UK, which have not been included in an approved design range, and are therefore not officially available for new use. For instance, under the Euston Remodelling contract on WCRM, new Mk1 FT assemblies were introduced. These are not part of OLEMI or UK1.
14.4. Modern Mainline Systems

14.4.1. The SICAT Range

The SICAT (Siemens Catenary) range was introduced to the UK in 2005 for the Larkhall–Milngavie project, and was subsequently used on the Shields–Gourock project. It uses Siemens SICAT SA medium speed equipment, with aluminium alloy cantilevers and extensive use of side-bolted connections rather than clevises.

Unlike other UK systems, heel settings are variable depending on radial load, and so setup requires more care.

Figure 288: SICAT portal cantilevers. Paisley, UK

14.4.2. The GEFF Range

The GEFF (Great Eastern Furrer+Frey) range was developed by Network Rail and Furrer+Frey for the Great Eastern route upgrade. The range was a response to the poor performance of the ex-1500V DC Fixed Termination equipment (section 14.2.2) on the route from Liverpool St to Shenfield, and provides a lightweight modern sagged simple AT equipment for the existing GE structures. Only the structural elements of the original GE equipment are retained.

The range was based on Swiss practice, and contained a number of first-of-type arrangements for the UK, including double boom anchor portals and Single Insulator Cantilevers (SICs) which give a reduced component count and smaller live envelope, and are easier to install and adjust than conventional cantilevers.

Figure 289: Single insulator MIRs on GEFF equipment. Bethnal Green, UK
14.4.3. The Series 2 Range

The Series 2 range was introduced as part of the National Electrification Programme in the late 2000s to provide a reliable medium speed sagged simple OLE system which comprehensively addressed the shortcomings of OLEMI systems.

Initially developed for 160km/h, it is a development of Mark 3c, with modern support arrangements including both Bonomi and Furrer+Frey cantilevers.

Series 2 has now been extended to cover speeds up to 200km/h and provide NTSN-compliance for multiple pantographs, as part of the UKMS catalogue (section 14.4.5).

14.4.4. The Series 1 Range

The Series 1 range was introduced as part of the National Electrification Programme in the early 2010s as a 2x25kV auto transformer configuration, providing reliable NTSN-compliant, multiple pantograph 225km/h-rated sagged simple system which comprehensively addressed the shortcomings of OLEMI systems. The system has been installed on the Great Western Mainline and includes a number of innovations designed to improve electrical safety, increase ALO working (section 20.12.3) for construction and maintenance staff, and improve installation productivity during short possession windows.
The system was developed by Network Rail and Furrer+Frey, and develops some of the arrangements used in the GEFF range (section 14.4.2). The system pioneered the use of single span overlaps without anchor spans (section 12.4.3) and was the first to extensively use *land-and-leave* structures which have rapid installation connections between masts and booms.

Series 1 has now been incorporated in the UKMS catalogue (section 14.4.5).

### 14.4.5. **UK Master Series**

UK Master Series (UKMS) was developed in the mid 2010s as a single OLE design catalogue for Network Rail, and incorporates Series 2 (renamed as UKMS100 and UKMS125), Series 1 (renamed as UKMS140), and UKMS R1, an upgrade range for Mark 1 equipment (section 14.2.4).

### 14.5. **Other Systems**

All of the aforementioned systems operate on UK mainline infrastructure and are owned and administered by Network Rail. The following systems are owned by private operators.

#### 14.5.1. **The Alstom Cariboni Range**

The *Alstom Cariboni* range was introduced in 2018 for those surface sections of the Crossrail project in London which are not owned by Network Rail. The range adopts typical French componentry with conventional cantilevers and portals, and support and registration arrangements have much in common with the High Speed One range (section 14.5.3); but also adopts elements of UK best practice such as spring tensioners (section 12.3).
14.5.2. The Channel Tunnel Range

The Channel Tunnel range was installed inside the Channel Tunnel between the UK and France in 1994. Although nominally a Balfour Beatty design, it was influenced by French high speed practice, despite the tunnel being limited to 160km/h. It uses sagged simple equipment with conventional galvanised steel cantilevers and portals, and glass insulators.
14.5.3. The High Speed One Range

High Speed One uses the only true high speed OLE system in the UK. It was designed by Amec Spie and installed in the early 2000s. It comprises pre-sagged simple equipment (section 12.2) configured for auto transformer feeding (section 10.4.3).

The configuration is typical of French high speed systems, with galvanized steel structures carrying inclined cantilevers, deep curve registration arms (section 12.13.2) and opposing cantilevered ATF hangers. It operates at speeds of up to 300km/h.

Figure 295: High Speed One cantilever. Stratford, UK
15. Tram and Trolley Systems

Trolleybus systems (section 9.2), as well as a few older tram systems\(^{192}\) take a different approach to current collection, using guided trolley pole collectors rather than pantographs. For trolleybus systems the double pole nature of the system means that using trolley pole collectors is the only practical option, since the vehicle must be able to change lanes and pull over to the kerb to transfer passengers. Trolley OLE allows the vehicle to occupy up to three lanes using a single set of wires.

![Articulated trolley bus. Vancouver, Canada](image)

**Figure 296: Articulated trolley bus. Vancouver, Canada**

A full description of the design and operation of trolley systems is beyond the scope of this book, but this section summarises those features of trolley systems which are significantly different to those of conventional OLE\(^{193}\).

The key advantage of using a guided pole rather than a pantograph is that contact wire position no longer needs to be strictly controlled relative to the vehicle. This has obvious advantages for unguided trolleybuses, but was also useful for early tram networks, which used a dense network of tracks. Removing the strict geometrical relationship between track and OLE means that more flexible tram wiring arrangements can be adopted, with groups of wire runs clustered in the centre of multiple tracks. For early tram systems, the pole arrangement placed the contact point well to the rear of passengers on an open-top tram – an important consideration given that debris could fall from the wire under the action of the head. Finally, the flexibility of wire position was useful for routes with open deck trams and low bridges – allowing the wire and pole to be slewed to the side of the tram as wire height reduced, to maintain safe separation of live parts from passengers.

\(^{192}\)Many of these tram systems have since been converted to use pantographs, and only a few remain in use.

\(^{193}\)en.wikipedia.org/wiki/Trolley_pole.
15.1. Trolley Collector Poles

The trolley collector pole takes the form of a long, flexible pole mounted on a spring- or pneumatically-actuated carrier or a mast on the roof of the vehicle. Modern poles are typically made of aluminium.

A collector head is mounted at the top of the pole; the carrier exerts an upward force on the pole, and the collector head rests on the underside of the contact wire. The pole deflects elastically, and this ensures a continuous contact force is maintained on the wire. Modern trolley poles are provided with a traction cable running down the centre of the pole, whereas older metal poles were often live and insulated from the tram roof or deck.

The pole carrier is free to pivot in the horizontal plane, and the collector head is pivoted in the same plane. The collector head has a groove which sits around the contact wire. This means that the collector will follow the wire as the vehicle moves along the track, with the trolley pole slewing right or left as necessary.

Modern trolley poles are double insulated (section 10.10.2) with one insulating layer below the collector head, and the second at the pole base.

Trolley poles on trolley buses are usually longer than those on trams, to provide the driver with more freedom to deviate away from the OLE, allowing them to pick up and drop off passengers at the kerbside.

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195 Historically, wood and steel were also used.

196 Videos taken from pole-mounted cameras on trolleybus systems provide an excellent overview of the system at work; see videos at [youtu.be/QHsMKWCm1dM](youtu.be/QHsMKWCm1dM) and [youtu.be/MhCrE08pP4](youtu.be/MhCrE08pP4) for examples.
The collector head originally came in two distinct forms. The *wheel collector* used a freely rotating wheel that pressed on the contact wire. This had the advantage that no carbon needed replacing, but the small metal-to-metal contact patch between the wire and wheel led to increased arcing and wear. This system is seldom used now and is only found on heritage and museum trams.

Instead the *slipper collector* is now standard; this uses a carbon block that sits within a grooved carrier which can pivot in the vertical plane (*a fixed slipper collector*). More recent designs also swivel in the horizontal plane (*a swivel slipper collector*); this double articulation minimises the chance of dewirement. The carbon block is replaced when worn, in the same way as the carbon strip on a pantograph. The slipper collector provides quieter operation and less sparking than the wheel type\(^{197}\), but both types were popular in pre-war tram systems.

Crucially, the trolley pole system only works when the collector head is behind the vehicle in the direction of travel, as it relies on the restoring force of the vehicle’s motion, which is always trying to return the trolley pole to its neutral axis. Attempts to drive the vehicle in the opposite direction (at anything other than very low speeds) will result in the pole leaving the wire.

Vehicles using this system therefore cannot reverse direction until the trolley pole has been rotated.

\(^{197}\) *Electric Traction*, A.T. Dover; Third Edition, 1929; Pitman; p211.
through 180°. This was originally undertaken manually by a person using an insulated pole\textsuperscript{198}, but this time-consuming process does not lend itself to short turnback times, and requires the driver to place themselves at risk in busy traffic. In the UK the \textit{reversing triangle} became popular in the OLE design; this uses the natural resistance of the trolley pole to being pushed rather than pulled, to effect an automatic reversal using spring-back frogs (section 15.4)\textsuperscript{199}. To avoid the need for this operation, many trams were fitted with a trolley pole at each end of the vehicle, with a manual changeover process at each end of a route. Modern trolleybus systems utilise a simple turning circle at each end of the route, so that vehicles do not need to reverse direction.

The propensity of trolley poles to accidentally leave the wire means that a system of restraint is needed to prevent damage to the OLE. An insulated rope is often provided between the vehicle roof and the top of the pole, and fitted with a manual raise/lower mechanism to assist the operator. The function of this mechanism is often extended to become a \textit{trolley retriever}; this prevents the pole rising rapidly in the event of coming off the wire.

![Figure 301: Trolley Retriever. Ottawa, Canada]

Many modern trolley poles use a pneumatic actuator, and this offers an ADD functionality similar to those in pantographs (section 12.1) by detecting a dewirement event, and rapidly dropping the trolley pole by exhausting the air circuit. Systems using pneumatic trolley poles can also be fitted with \textit{threading horns} mounted on the OLE at specific locations, allowing the raising of the pole and locating of the collector head to be carried out without the driver leaving the cab.

15.2. Trolley Support Systems

Early trolley systems used a contact wire (section 12.16.1) of circular section without notches, with fittings clamping around the top half of the section\textsuperscript{200}, but this form of clamp was necessarily wider and necessitated the use of wheel collectors to maintain adequate current collection. As the advantages of slipper collectors became clear, a means of narrowing the profile of the contact wire support fixing was needed, since a conventional contact wire swivel clip (section 12.16.1) would be too wide and foul the slipper as it passed through. Trolley

\textsuperscript{198} A video of manual reversal can be seen at yououtu.be/yfKCsQQ-SZA.
\textsuperscript{199} A video of a reversing triangle in operation can be seen at yououtu.be/1maKZSOb1HU.
\textsuperscript{200} "Current Collection for Tramway & Trolleybus Systems", Baddeley, Oakley; 1975; p9.
systems therefore use a slimmer, longer assembly, to achieve the same clamping force without fouling the collector. This clamp is known as an ear.

On many systems ears are attached to a hanger which provides the same horizontal pivot function as swivel clips on conventional OLE. An insulator connects the hanger to the ear, providing a single level of insulation, and is typically supplemented by insulators in the span wire to form double insulation (section 10.10.2) and to maintain electrical separation between tracks.

In the UK the twin line hanger was the standard fixing for trolleybus systems, consisting of two ears separated by a rigid insulator; whereas North American systems favoured separate ears.

![Figure 302: Straight hanger and ear. Beamish, UK](image)

Hangers are adequate for slow speeds, but as speed increases – as with modern trolleybus systems – the hard spot (section 12.1.2) formed by the traditional hanger increases arcing and wear. They are also incompatible with pantograph working. Modern systems often use either conventional bridle tramway OLE (section 12.2) or a pendular support system, which uses a pair of flexible wire hangers and parallelogram fittings to maintain the verticality of the wire, regardless of radial load.

![Figure 303: Pendular trolley supports. Vancouver, Canada](image)

Tram systems typically have more curves of smaller radii than conventional railways as they negotiate narrow city streets, and so frequent use is made of flying tails (section 12.10.5), either to buildings or poles via span wires. Also known as pull-offs, these would twist the contact wire if directly connected, and so hangers are divided into the straight type, only for use on tangent track, and the pull-off type for use on curves. Pull-off hangers are arranged such that the radial load from the pull-off intersects the centre of the contact wire, keeping it level. Ears on these hangers are also curved, to avoid the high stresses that would otherwise occur in the contact wire at the point of radial load.
On tangent sections of track, support may either be by span wires, or if road width and aesthetic restrictions permit, by using cantilevers (which on tram and trolley systems are referred to as bracket arms). Where these are used, they are typically designed to be aesthetically sympathetic to their surroundings. Early tram systems were driven by the need to reduce steelwork costs\(^{201}\), so back to back bracket arms or twin track poles were favoured.

\(^{201}\) An additional factor was that local authorities would often charge the tram company a levy for each pole installed. Ibid.; p12.
Figure 307: Twin track pole. Ottawa, Canada

Tram and trolley systems at curves and junctions employ much more sophisticated span wire connections than conventional OLE to achieve the required contact wire position; multiple span wires may be anchored at a single point, and wire runs may have pull-offs connecting them together, providing the same function as knuckles (section 12.13.2) in conventional OLE. Tensions are lower than for mainline systems and this helps to reduce radial loads (section 12.14). The wiring arrangement for a complex junction can however weigh more than one tonne.

It is not necessary to adopt staggering rules as with conventional OLE (section 12.13.2), but that does not mean there are no limitations on the lateral position of the wire. The natural path of the trolley pole must be considered, and this forms the basis for the design of the wiring geometry, particularly on curves.

Trolley masts are often circular hollow section, providing the necessary strength as well as a degree of aesthetic harmony with a high street environment; this also provides a convenient protected conduit for feeder cables. However these have the disadvantage that their inner surface is hidden and so corrosion is much harder to detect. It is therefore essential that hollow masts are capped at the top to prevent rainwater incursion.

15.3. Insulators for Trolley Systems

A variety of different insulator types may be found in trolley systems. Loop insulators are popular for insulation within spanwires, as are globe-and-link insulators.

Figure 308: Trolley wire geometry on curves
Trolley systems require section insulators (section 12.6.1) for the same reasons as conventional OLE systems. However the need to guide the collector head means that the contact wire insulator must present a shape that matches the contact wire.

This led to the development of a standard SI for trolley systems which comprises a running insulator made of a hard-wearing plastic (which is reversible to double its life span) clamped between cast contact wire termination fittings. Two rod insulators sit above the runner and provide the assembly with the necessary stiffness, as well as a useful clamping location for support assemblies. This SI forms the core of a modular fittings system for junctions, with feeder and jumper terminations built in, and direct connections to frog and crossing units (section 15.4).

### 15.4. Arrangements at Turnouts

Special arrangements are needed where wire runs diverge and converge, since unlike pantograph operation, the collector head must be actively or passively guided onto the correct wire. Unlike conventional OLE, the low tensions and speeds mean that it is practical to split one wire run into two; this is done using an assembly known as a turnout frog, mirroring the terminology used in the track discipline.

Three distinct types of frog are available, and the selection of the right type depends on the track turnout type and mode of operation.

The simplest type is the fixed frog, which comprises a grooved casting offering a path for the collector head in both directions. These can use used in both trailing and facing turnout configurations. When used in a trailing arrangement, the collector head will naturally take the correct path through the frog. However when used in the facing configuration, the orientation of the collector head will determine the path it takes, and this means that it can only be used with fixed collector heads (section 15.1).

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202 Early insulators were made of hardwood and then Bakelite. Ibid.; p18.
The second type is the spring-back frog. Here the fixed casting provides the path into the frog, but the central section contains a pivoted tongue. This tongue is spring-loaded to normally lie in one direction. This is then installed over a track turnout which is also spring-loaded to lie in the same direction.

Collector heads approaching in the trailing direction will naturally take the right path, those coming from the non-favoured direction pushing the tongue into the correct orientation; the tongue will return to its default path as the collector head clears the tongue. This is mirrored in the behaviour of the vehicle, the wheels providing the force to move the switch rails. Collector heads approaching in the facing direction will always take the default path, as will the vehicle itself.

For turnouts where trams can take either route in the facing direction, active measures must be taken to switch the tongue to the correct route before a trolley pole passes, and so a switched frog will be used. This has the same components as the spring-back frog, but a lever actuator is provided so that the tongue can be switched to either orientation.

The means of providing this actuation varies depending on the age and sophistication of the system. The earliest and simplest arrangement was to provide a manual operating handle at ground level, which would be switched by a member of staff before each tram passed. A spring-back frog was generally used, allowing a simple cable actuator to be used rather than a push-pull linkage. In some cases the switching of the track and OLE was effected by means of one operation. This time-consuming process is not suitable for the modern era, so automatic switching of the OLE frog is provided, using the orientation of the vehicle. There are a number of ways to achieve this.

Early systems used the vehicle orientation; in this arrangement a switched frog is located beyond the turnout, so that by the time the collector head reaches the frog, the vehicle is beyond the track turnout and already well along its chosen route. The tongue is actuated by a long lever at the frog, that hangs well below contact wire level in such a way that when the lever is vertical, the tongue is set for straight on.

When the track turnout is set to route the vehicle in the straight direction, the trolley pole will pass the lever without engaging it and the frog remains set for straight on. When the track turnout is set in the diverging direction, the vehicle passes through and the pole naturally moves away from the track centreline. As the head approaches the frog the pole engages and lifts the lever, temporarily moving the tongue to the diverging route.
The lever length is set so that the head is safely through the frog before the lever is released, the tongue returning to the straight through orientation\(^\text{203}\).

Modern systems provide full automatic operation of both track and OLE turnouts, with the driver selecting the appropriate route. This is used in both tram and trolleybus systems, and can be achieved in a number of ways\(^\text{204}\).

The power-coast system uses the traction current flow itself to actuate the OLE frog (and for trams, also the track turnout) through a relay system. If the driver is not taking power, the switch will not actuate and the collector head will continue straight on. If the driver is taking power, the OLE and track turnouts are actuated and the vehicle will take the diverging route. This system relies on the appropriate use of the driver’s power handle, which can be a challenge at some locations where either coasting or drawing power is not operationally appropriate.

The Selectric system works in a similar way to the mechanical lever system, but uses the orientation of the collector head as it approaches the frog to determine which route is being taken. A head taking a straight-through route will bypass the electrical contacts, whereas one taking the diverging route closes the contacts and actuates the frog. Selectric can be used in trolleybus systems, where contacts in the positive and negative wire are positioned so that only poles taking the diverging route will simultaneously make contact and switch the frog.

The Fahslabend system achieves full automation by linking a radio system in each vehicle to the driver’s turn indicator. Thus the whole route can be set by the driver’s explicit intention, without the need to take power or coast.

For all these systems, a mechanical switch can be placed on the wire beyond the frog, triggered by the collector head to reset the switch; whereas other systems use a simple time-delay reset to achieve the same functionality.

15.5. Arrangements at Crossings

Where two wires cross and are of the same electrical section on a tram system, a simple grooved diamond is provided which mirrors the function of a track diamond.

Trolleybus systems bring additional challenges when wires cross, since the positive conductor must cross the negative one while remaining electrically separate, and vice versa. Therefore the crossing must incorporate insulation, using two section insulators (section 12.6.1) either side of the crossing in one of the wire runs; and a jumper across the diamond to maintain electrical continuity.

Figure 313: Diamond crossing. Beamish, UK

\(^{203}\) A video of this operation can be found at `youtu.be/2hJQEewcbhQ`.

\(^{204}\) `en.wikipedia.org/wiki/Trolleybus#Wire_switches`. 
15.6. Disadvantages of the Trolley System for Trams

As can be seen, the trolley system, being a guided collector, requires all of the switch and crossing features that guided railway track systems do. The complexity of providing all of these in an aerially suspended system adds construction and maintenance cost, and means that it is not uncommon for trolley poles to lose contact with the wire when travelling on these systems\textsuperscript{205}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure314.png}
\caption{Wire crossing section insulators and jumper. Beamish, UK}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure315.png}
\caption{Skid assembly at frog for trolley-pantograph mixed working}
\end{figure}

\textsuperscript{205} A video of a trolley pole dewirement can be seen at youtu.be/OfSDu-Vbh4E.
For this reason modern tram systems are specified with conventional OLE and unguided pantographs, and many older systems have been converted to pantograph operation. This creates a dilemma for existing trolley system owners, since it is very disruptive and expensive to convert a whole system and fleet at once. Arrangements have therefore been developed to allow mixed working of collector heads and pantographs, typically using a skid at switch and crossing points to depress the pantograph a little as it passes through the junction. However some systems, such as Lisbon, choose mixed working on a single vehicle as a permanent arrangement, taking advantage of the narrow swept envelope of the trolley pole in areas of narrow winding streets, and using the more reliable pantograph working elsewhere.
16. Special Arrangements

The arrangements described so far in this book are for conventional overhead contact systems. However a number of non-standard configurations can be found at locations around the world; these came into being either through historical quirks, technological dead-ends, or as a response to the special conditions within which the system must operate.

16.1. 50kV Supply Voltage

A handful of mining railways have operated with a supply voltage (section 10.1) of 50kV. The higher voltage provides the ability to power heavy mining trains for long distances with fewer feeder stations. Of these, only the Sishen–Saldanha railway in South Africa remains operational.

![50kV OLE on a mining railway - note the unusually long insulators. Sishen–Saldanha, South Africa](image)

16.2. Three Phase OLE

The supply of a single phase OLE system from a three phase grid causes additional complexity (section 10.1.3). A handful of railways have tried to implement three phase AC overhead line – some successfully, others less so. A three phase OLE system allows for easy regeneration of kinetic energy under braking back into the three phase grid, and this made it an attractive option for mountain railways. However any such advantages are more than offset by the complexity of providing two electrically separate contact wires – the traction return rail providing the third phase – and the use of squirrel cage AC motors, which only operate at a single rotor speed. There are now only four such railways operating in the world\(^{206}\).

16.3. Dual Voltage Crossings

There are occasionally locations where two railways of differing voltages cross at grade. The most well-known of these is in Melbourne, Australia\textsuperscript{207}, where the 600V DC tram system crosses the 1500V DC mainline system. At these locations a special OLE subsection is created, which is isolated from high and low voltage sections on either side, but capable of being fed at either voltage. The supply switching is interlocked with the signalling system, meaning the correct voltage is supplied for the tram or train due to cross.

\textsuperscript{207} More information is available online at en.wikipedia.org/wiki/Trams_in_Melbourne#Tram.E2.80.93train_level_crossings.
Inclined OLE

The main constraint on span length between structures – and therefore OLE cost – is the deviation of the straight contact wire from the track centreline at midspan (section 12.13.2). The purpose of inclined OLE is to force the contact wire to more closely follow the curve of the track. By doing this span lengths can be increased, with a corresponding decrease in support steelwork costs.

The horizontal curvature of the contact wire is produced by offsetting the catenary wire (section 12.16.3) to a significant degree towards the outside of the curve. This forces each dropper (section 12.16.4) to become inclined, imparting a radial load on the contact wire which pulls it outwards and reduces the midspan offset. Each dropper effectively becomes a registration point, with the contact wire striking a series of chords between droppers rather than between structures. Depending on the extent of the inclination, this configuration can also remove the need for registration arms (section 12.13.2) altogether.
Inclined OLE is especially useful on routes with many small radius curves, such as those in the Swiss mountains. The system requires careful design, construction and maintenance to ensure that the vertical and horizontal force components are balanced; and also requires inclined dropper clips (section 12.5.7) to prevent the radial loads from twisting the dropper clips over into the path of the pantograph carbons (section 12.1).

16.5. Moving OLE

There are a number of scenarios where it is necessary to provide OLE that is capable of being moved. This requires special arrangements, both mechanically and electrically.

A common scenario is in maintenance depots, where for shunting convenience OLE is generally provided into the inspection and maintenance sheds, but where this OLE then poses a safety hazard and prevents access to the roof on the train. Modern rolling stock often maximises passenger capacity by moving air conditioning and other equipment into the roof space, meaning maintenance access is necessary.

The standard solution is therefore to provide a ROCL system (section 12.16.2) on supports which can swing horizontally through 90°, or lift vertically, retracting the OLE away from the train and allowing access. This system is electrically interlocked with the depot power supply and staff warning systems, so that the OLE cannot be retracted until it is isolated and earthed, and staff will not receive permission to access the roof until that process is complete.208

Figure 320: Retractable rigid overhead contact line. Temple Mills, UK

208 Video of a retractable depot conductor bar in operation is available online at youtu.be/lM5hYT-Xs3s.
A much more technically demanding problem exists where a railway crosses a navigation channel by means of a lifting (or Bascule) bridge or a swing bridge. It is usually not practical to raise the level of the bridge to make it fixed, since shipping has guaranteed access upriver. In this case it is necessary to build an OLE arrangement which can swing or raise/lower with the bridge. As with depot systems, ROCL is an ideal solution.

Unlike depot OLE, these systems often need to operate at significant speed, and the transfer mechanism from fixed OLE to moving must be carefully designed to ensure that alignment and elasticity change is carefully managed. Additional complications arise from the way the bridges move; for bascule bridges, the counterweight swings downward to occupy the space immediately above track level. This means that a section of the rigid bar must be retracted out of the way prior to the bridge lifting to make way for the counterweight. Sophisticated designs have been developed to achieve this, using winch-actuated portal structures running on rails to pull the ROCL away from the bridge, with special sliding electrical connectors to ensure electrical continuity onto the bridge. The portion of ROCL on the bridge is within touching distance of track level when the bridge is raised, so motorised isolators (section 12.7) are provided to connect the ROCL to earth. All of these arrangements must be mechanically interlocked with both the bridge actuation and the railway signalling system. Traction power continuity must be provided across the bridge even when it is raised, so submarine traction feed cables are provided across the navigation channel.

Swing bridges have similar movement challenges and solutions; a rotary rigid bar overlap section is provided at each end of the bridge, which rotates in the vertical plane to provide a clear space for the bridge ends to move through.

Some electric freight railways have a requirement to load hopper wagons from above, and so it is necessary to have a break in the OLE. This can be achieved by having anchor portals either side of the hopper feed, with skid arrangements in the contact wire to manage the pantograph as it leaves and re-joins the OLE at slow speed.

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209 "Electrification of Swing and Bascule Bridges with Overhead Conductor Rails", Cox, Nünlist, Marti; September 2000; Furrer+Frey.
16.6. Roundhouse OLE

Historically many railways used the *roundhouse* concept - a circular or semi-circular locomotive maintenance shed surrounding a turntable. As electric traction was introduced, some of these were electrified, and a few still survive today. The OLE configuration comprises a central ring positioned over the turntable centre, which acts as the termination for a series of radially-arranged contact wires; each contact wire services one shed road, and the balance of tensions holds the ring in place.

![Electrified Roundhouse. Landquart, Graubünden, Switzerland](image)

The roundhouse shown above is arranged with two through-running contact wires, which cross at 90° to each other, so that pantographs are able to pass through the very centre of the turntable without snagging.

16.7. Offset OLE

Some railways use an OLE system which is offset from the track centreline, in order to deal with a specific constraint on the route. For instance, in Zurich the *Sihltalbahn* railway is electrified with 15kV AC OLE, while the *Uetlibergbahn* railway uses 1200V DC OLE. The two systems share a single set of tracks for part of the route; on this section the DC OLE is offset to the side, and DC trains have their pantograph offset to the same extent. AC trains are provided with a pantograph on the train centreline as normal.
16.8. Electric-Steam Traction

Shortage of coal during World War 2 drove Swiss Federal Railways to fit two coal-fired steam locomotives with pantographs, hydro-electric power being plentiful in the region.

The locos used traction current from the 15kV 16.6Hz OLE to boil water using an electric heating element, creating steam pressure to move the locomotive. Pressure was sufficient to run off the wires for around 20 minutes before returning to recharge.
17. Interfaces with Other Systems

OLE interfaces with almost every other railway system, and several non-railway systems. It is often at the interfaces that unexpected failures can occur; for this reason it is vital that these are fully considered in the design process (section 19). The key interface issues to be considered during OLE design are discussed below.

17.1. Permanent Way

This is the one of the most important interfaces, since the OLE must follow the track geometry. Particular items to understand are:

- Track position;
- Track tolerances (which must be allowed for when designing OLE, particularly through overbridges) and any managed track position strategy (section 18.8);
- Track lift, slew and change of cant (for projects with an element of track modification);
- Available extent of track lowers (for bridges with insufficient clearances);
- Position of toes of points;
- Areas of reduced track stability (when constructing adjacent foundations, particularly in hot weather when rails may be beyond their stressing temperature and prone to buckling).

17.2. Geotechnical

This is also a key interface, since it determines the long-term stability of the OLE. Particular items to understand are:

- Natural ground types (in cuttings and flat ground);
- Made ground types (on embankments);
- Slope stability;
- Mining areas and subsidence risk;
- Grouting, toe loading and other slope remediations.

This is discussed further in section 19.1.3.

17.3. Civil & Structural

Key civil and structural issues to be considered are:

- Electrical clearances to overline structures;
- Attachment to structures.

17.3.1. Bridge Fixings

Fixings to overbridges include supports for bridge arms (section 12.10.9), conductive assemblies (section 10.10.1) and earth wires. The type of fixing used depends on the form of construction of the bridge, the location of the fixing on the bridge, and the loads imposed on it.

Access to these locations is often highly constrained, and so preference is given to fixings which can be rapidly installed without drilling. Where the bridge is of metallic construction, fixing designs based on Lindapter clamps are frequently used to clamp to an L-, H- or C-section bridge member. These clamps come in a range of different types, to suit different clamping requirements. A key advantage of these clamps is that they provide positional flexibility; for instance, when combined with a new C-channel beam they can provide cross-track
adjustment for bridge arms.

Figure 325: Different styles Lindapter clamps (arrowed) used for bridge arm support and bonding cable support to steel bridge girder. Glasgow, UK

Lindapter clamping is not suitable for concrete bridges, which pose additional challenges since they are often pre- or post-stressed, containing reinforcing bar (or rebar) which cannot be drilled into without compromising the structural integrity of the bridge. Some concrete bridges are constructed with I-section parallel prestressed decks beams with narrow gaps between them; these offer the opportunity to use a steel T-bolt which comprises a thread bar welded to a T-shaped paddle to match the slope of the beams. The bolt is inserted into the gap between the beams and rotated through 90°. The assembly to be supported is then clamped to the bolt, which exerts force on the back of the beams.

Figure 326: T-bolt design for prestressed concrete beam fixings

(21) M10 washers
(2) M10 nuts
Threaded M10 x100 long with slot to assist orientation
50 x 10 flat x100 long
For concrete and brick structures where drilling cannot be avoided, *chemical resin anchors* are used. These take the form of a threaded bar (usually of stainless steel) which is secured in a pre-drilled hole in the masonry using a rapid-curing resin injection mortar. The anchor product to be used must be carefully selected to meet the loading, performance and environmental criteria, as well as the brickwork type and condition.

Figure 327: (l-r) Resin anchor bolt designs for earth strip support on a concrete bridge abutment, earth wire support from infilled concrete beam bridge deck

### 17.4. Modern Tunnels

Tunnels present unique spatial and environmental constraints for OLE, and the design, construction and maintenance of OLE in tunnels must take account of these. The nature of these constraints varies widely depending on the age of the tunnel, its form of construction and the geology through which it travels.

Modern tunnels are usually constructed using *Tunnel Boring Machines* (TBMs), which cut a circular bore or bores (two track railways often being formed of two single bores). Each bore is then lined with concrete segments to form a watertight cylindrical bore. Constructing tunnels in this way is a costly, complex and time-consuming process, and the diameter is usually minimised to avoid further expense. This means that the space available for OLE between the train and the tunnel is often both small and unusually shaped, and this often precludes the use of conventional OLE, which requires space-consuming cantilevers to provide the necessary along-track movement (section 12.3). The shape of the tunnel often means that lateral space is as much of a constraint as vertical space.

Conventional OLE with bridge arms (section 12.10.9) is not generally used in long tunnels, due to the potential for mechanical resonance (section 12.13.1) as the pantograph passes through the regularly-spaced short spans, causing excessive wear and loosening of fittings. Bridge arms can be used for shorter tunnels, but care is needed in design and construction, since the short spans require tighter tolerances to avoid uneven contact wire gradients.

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210 OLEMI Drawing 1/076/852/A3 “Assembly of 10φ Fixing Bolt Used with Cable Cleat on Pre-stressed Concrete Beam Decks”; revision 0; British Railways Board; 1984.

211 Some leakage can be expected over the life of the tunnel, and so drainage measures are also included in the tunnel design.
Figure 328: Conventional 300mm system height 1500V DC OLE in a Victorian tunnel (right) in the process of being converted to sliding ROCL (left) as part of a gauge increase project; the space advantage of ROCL can clearly be seen. Sicily, Italy

For this reason, electrification of small-diameter modern tunnels is often undertaken using ROCL (section 12.16.2); while this does not have any construction depth advantage over twin contact OLE\(^\text{212}\), it occupies significantly less space - both vertically and horizontally - than conventional small system height OLE. This is possible because ROCL overlaps are very simple compared to those in conventional OLE (section 12.4.2), and so can be frequently installed, reducing along track movement. The remaining movement can be accommodated using either a short pivoting support, or a sliding ROCL support, removing the need for pivoting cantilevers altogether and reducing the size of the supports even further.

ROCL has another major advantage over conventional OLE in a tunnel – it is much more resistant to fire or

\(^{212}\)Twin contact conventional OLE has a live construction depth of around 120mm plus 70mm allowance for uplift, whereas ROCL construction depth is typically around 200mm (110mm for the bar, and the remainder for the live support bracket), but does not experience any significant uplift.
electrical flashover damage, and in dewirement scenarios will not release mechanical energy in the way that a
tensioned system would. This is essential given the stringent safety requirements in modern tunnels.

Some modern tunnels have a larger diameter, and these use conventional OLE, which is significantly cheaper
than ROCL.\textsuperscript{213} Regardless of age, tunnels have a much narrower operating temperature range than an outdoors
environment, and so it is possible to use a longer tension length matched to those conditions. However
if the tunnel is longer than the resulting maximum tension length (section 12.3) then tensioners must be
provided within the tunnel, and this is typically achieved using specially-configured weight stacks (section 12.10.10)
designed to sit on the flank of the tunnel wall, or if space is particularly constrained, in pockets set into the tunnel
wall. The short span lengths typical of tunnels, combined with the lack of cross-track wind, means that blowoff
(section 12.13.2) can safely be ignored. Along-track windspeeds are high, as a result of the piston effect of
passing trains.\textsuperscript{214}

Regardless of the type of OLE used, the supports are usually fixed into the cast concrete segments using resin
anchors (section 17.3.1), although mechanical rawlbolts are sometimes used, or recesses can be precast into the
segments to receive T-bolts.

\textbf{17.5. Historic Tunnels}

Older tunnels present a number of different challenges. Unlike modern tunnels, the shape, construction and
condition of older tunnels varies widely depending on a variety of factors. It is essential to understand the
history of the tunnel before design work can begin.

\textit{17.5.1. Tunnel Configuration}

The basic configurations of historic tunnels in the UK are as follows:

\begin{itemize}
  \item Tunnels in stable rock conditions are usually unlined; there are currently around 30 unlined tunnels in
  the UK - an example can be seen at Ffestiniog;
  \item Tunnels in rock of a less competent nature typically have a relatively thin cosmetic lining to prevent rock
  falls onto the track; this often takes the form of vertical side walls of stone masonry, a brick semi-circular
  arch around 450mm thick, and no invert. An example can be seen at Clifton Down Tunnel;
  \item Tunnels in even softer rock, or softer ground such as clay, typically have a horseshoe profile made up of
  five circular curves, and no invert. Somewhere around 600 of the 750 currently operational UK tunnels
  are of this type - an example can be seen at Standedge Tunnel;
\end{itemize}

\textsuperscript{213} Video of conventional OLE installation in a modern tunnel is available online at\url{youtu.be/BGbOH7T7MUg}.

\textsuperscript{214} A windspeed equal to twice the linespeed is sometimes used in structural calculations.
• Tunnels in even softer ground such as clay, sands or gravel typically have a horseshoe profile made up of five circular curves, with a structural invert\(^{215}\) - examples can be seen at Bletchingley and Saltwood Tunnels;

• A few tunnels in over-consolidated clay (such as London Clay) experience very high horizontal forces, and these have a circular or near-circular profile to resist the ground load - an example can be seen at Hadley Wood;

• A few tunnels have an elliptical profile with a horizontal major axis to resist large horizontal forces - an example can be seen at Toadmoor Tunnel, which was built through a landslip area.

Figure 331: (clockwise from top left) Clifton Down Tunnel, Standedge Tunnel, Hadley Wood North West Tunnel, Toadmoor Tunnel

\(^{215}\) An upside-down arch under the track which resists horizontal forces from the surrounding ground.
17.5.2. Construction Techniques

Short tunnels (up to about 300m long) were usually built inward from the two ends, after driving a small heading from one end of the tunnel to the other to establish the alignment. Longer tunnels were more commonly driven outwards as well as inwards, using one or more vertical shafts driven down from above, permitting multiple working faces to be established to speed up construction\textsuperscript{216}. While some construction shafts remain open today for ventilation, some had no use beyond the construction stage and so were bricked over at the bottom end and infilled from above, resulting in blind or hidden shafts. Where the tunnel lining meets these shafts there can be some misalignment due to original survey errors, but this is relatively rare. Many twin track historic tunnels in the UK are around 7.5m wide and 6.1m high, but dimensions vary considerably due to the requirements of the multitude of original railway companies. It is also relatively common for the tunnel profile to change within the length of the tunnel - for example, having a horseshoe profile for part of its length and semi-circular arch on vertical side walls for another.

Longer tunnels were provided with permanent vent shafts at fairly regular intervals to permit steam to escape, and these offer further routes for water ingress during rainy conditions. These are sometimes fitted with a

\textsuperscript{216}For more information on the construction techniques used in historic tunnels, see Graeme Bickerdike’s “Tunnel Vision” video at youtu.be/_c8jvixQGpQ.
witch’s hat, an inverted cone that deflects water coming down the shaft into a garland gutter around the shaft perimeter, while permitting air to flow up or down the shaft in response to pressure from passing trains.

17.5.3. Water Ingress

Some tunnels pass through impermeable geology, and will remain dry; whereas tunnels through permeable rock will experience frequent groundwater ingress at multiple points, typically forcing its way through gaps in the mortar. Some may even have underground springs emptying into them. The Severn and Abbotscliffe Tunnels are examples of this.

Figure 334: Examples of water ingress in a wet tunnel. Severn Tunnel, UK

Wet tunnels are often provided with a system of weep holes and drains, to allow water to enter the tunnel without damaging brickwork, and to manage flow out of the tunnel. In some cases water ingress is captured by drainage pans fixed to the lining, drip shield sheeting or decking (Balcombe Tunnel is an example with drainage decking) and these can be significant challenges for electrification. In extreme cases mineral-rich groundwater can form stalactites, which can build up on OLE components, fouling mechanisms and reducing air gap clearances (section 10.8).
17.5.4. Tunnel Masonry

The quality of brickwork in a tunnel crown and haunches varies considerably, even between tunnels built by the same contractor on the same route. The compressive strength of the bricks increased from the 1830s to the 1860s, as they were often made in the adjoining cuttings using portable kilns, the effectiveness of which improved over time; resulting brick strengths can be as low as 13N/mm² and as high as 50N/mm². The mortar was commonly a sand and lime mortar mix, with a typical strength of 1-2N/mm², but occasionally the mortar is described as cement mortar and this can be stronger - perhaps 2-4N/mm². Occasionally drawings will refer to roman cement, a rapid hardening waterproof material developed in the early 1800s and used when conditions were very wet, such as in the Brunel’s Thames Tunnel. With a reddish brown colour similar to roman terracotta materials, this can have a strength of 3-10N/mm².

Most early tunnels were built with the haunches and crown in a series of separate unbonded rings of bricks each about 110mm thick; these only align intermittently due to the increasing number of bricks in each successive ring. Later in the 19th century some tunnels were built with two 225mm bonded brick rings. Regardless of the construction detail, the brick rings were formed over temporary timber formwork, and this often led to the outermost rings (which are hidden from view) being of poor quality, having little or no mortar. An example of this is Bradway Tunnel near Sheffield.

17.5.5. Tunnel Surveys

The complex nature of these tunnels means that both non-intrusive and intrusive surveys are an essential prerequisite to electrification.

It is important to understand the shape of the section at all points within the tunnel by undertaking a point cloud survey (section 19.1.2) throughout the whole tunnel length. Coring of the brickwork will determine the overall thickness of the masonry, and if large diameter cores (typically 100 to 150mm) are taken they can be subjected to compression testing to determine strength. Mortar samples can be chemically tested to determine the ratio of sand, lime and cement; these can also be subjected to X-Ray Diffusion (XRD) tests, which although expensive give much more reliable results for mortar composition.

The eventual OLE fixing design can only be proven by undertaking a pull-out test, where a trial fixing is installed in the tunnel, left to cure, and then tested to destruction by applying an increasing axial load to the fixing.

17.5.6. OLE Design

The design of OLE in historic tunnels requires particularly careful thought, especially where masonry is in poor condition and/or suffering from water ingress. Significant remedial works may be required prior to electrification, including brickwork and mortar repairs, and diversion of frequent water flows using drip trays and pipework. Old brickwork may require significant intervention before it can accommodate the weight of the OLE supports. The nature of the water chemistry must also be understood; acid or alkaline soils will form acid or salt solutions which can attack OLE components, and tunnels running though marine environments
present even bigger challenges, with aggressive saline solutions and even marine microbial fauna\textsuperscript{217} which will eat through metalwork.

For all of the reasons detailed above, each older tunnel requires an OLE configuration tailored to its shape and length. Where possible, tunnels use a conventional OLE system, with a small system height and more frequent support. Two track tunnels often use short cantilevers supported from the crown of the arch, with the drop tubes staggered along-track and across-track to provide sufficient room for each cantilever.

![Diagram of OLE systems in older tunnels](image)

**Figure 336:** (clockwise from top left) OLE systems in older tunnels; two track bore with small system height conventional OLE, two track bore with ROCL, single track bore with tunnel arm, single track bore with ROCL

This is not possible in small single bore tunnels, which use either an elastic *tunnel arm* - which operates in much the same way as a bridge arm (section 12.10.9), but with a shape matched to follow the tunnel lining - or a ROCL configuration.

\textsuperscript{217}The Severn Tunnel is a rare example of a tunnel under a saltwater estuary, and the mudflats of the estuary are home to *Sulphate Reducing Bacteria* (SRBs). These have been shown to make their way into the tunnel through water ingress points and then digest metal components. For more information see [en.wikipedia.org/wiki/Sulfate-reducing_microorganism](en.wikipedia.org/wiki/Sulfate-reducing_microorganism).
Longer tunnels are unlikely to have sufficient room for the necessary tensioners (section 12.3), and unlike modern tunnels it is not possible to design a pocket for balance weights.

The smallest historical tunnels face the same problem as that of their modern equivalent – that there is insufficient room above the train to accommodate a conventional cantilever. In this case, ROCL will be used.

17.6. Additional Tunnel Challenges

All tunnels face the problem of preventing insulators (section 12.18) electrically tracking by keeping them clean, since the normal self-cleaning action under rainfall is not available. This problem is worse in tunnels with a significant amount of diesel traffic, dust from mineral traffic or an aggressive atmospheric environment.

For tunnels using Auto Transformer Feeding (section 10.4.3) there is usually insufficient room to achieve ATF to earth and ATF to OLE air gap clearances (section 10.8), so an insulated ATF cable (section 10.2.9) is often
used, supported from the tunnel wall.

Earthing and bonding (section 10.10.1) in long tunnels often requires special measures, since the lack of OLE foundations means that a good connection to earth is not guaranteed.

17.7. Signalling

Key signalling interfaces are;

- Electrical clearances to signalling structures (from RCs, ATFs, OLE, and pantograph);
- Signal positions with respect to overlaps and neutral sections;
- Conflicts with signal sighting requirements due to OLE ‘clutter’;
- Earthing & bonding.

17.7.1. Signal Sighting

Most railways worldwide still keep trains apart by means of line of sight signalling, meaning that the driver must be able to clearly see signal indications in good time to act on their instructions. OLE equipment can interfere with the sight lines, meaning that the driver has less time to read and understand the signal. In the past poor signal sighting has caused accidents, and in the case of Ladbroke Grove (1999) 218 31 people died in a head-on collision after a new OLE installation obscured a critical signal aspect. For this reason signal sighting is a critical element of the OLE layout design process (section 19.4.1).

Figure 339: (l-r) Traditional and virtual signal sighting methods

17.8. Telecoms

Overhead line electrification has impacts on two existing groups of communication systems - those which are copper-based, and those which are radio-based.

218 Accident report is available online at www.railwaysarchive.co.uk/eventsummary.php?eventID=142.
17.8.1. Electromagnetic Interference

In the UK the primary telecommunication network providing voice and data communications for the railway is the Fixed Telecoms Network (FTN). This copper system runs along most routes and links into a number of signalling assets such as location cases, Principle Supply Points (PSPs) and Relocatable Equipment Buildings (REBs).

The primary method of immunising these and any other copper telecoms cables from electromagnetic interference via OLE-generated inductive coupling (section 10.4) is to reduce the length of the circuits, terminating each in an FTN node before continuing with a new circuit.

UK routes are progressively replacing the copper FTN with the fibre optic-based Fixed Telecoms Network - Next Generation (FTNx), replacing the main backbone to provide higher bandwidth and the ability to use IP-based communications protocols. This also has the advantage of being completely immune to EMI. Copper is often retained at the interfaces with legacy communication systems.

A number of local telecoms systems at stations and level crossings can also be adversely affected by EMI, including:

- CCTV cameras;
- Public Address systems;
- Passenger Help Points;
- Customer Information Screens.

These may require additional shielding to prevent degradation or interruption of communications.

17.8.2. Radio Interference

Complementing the FTN system in the UK is the Global System for Mobile Communications - Railway (GSM-R) system. This is based on the GSM standard, and is used for voice and data communication between trains and railway control centres. GSM-R radio masts are placed at regular intervals along the railway and are linked to the FTN system.

GSM-R reception can be adversely affected by installation of OLE structures and reconstruction of adjacent overbridges, which can create radio shadows. Remedial measures are sometimes required, including installation of a higher gain antenna, increasing its height, adding repeaters or even an additional mast.

17.8.3. SCADA Interface

The introduction of new SCADA (section 10.7) for monitoring and control of OLE brings with it the need for additional telecoms capacity and infrastructure to provide communications between the ECR and the substation locations. Implementation of FTNx is advantageous, providing immunisation and also simpler communication, if an IP-based control and monitoring (10.7.4) system is being used.

17.9. Electrical & Mechanical Services

Electrical & Mechanical (E&M) Services include all non-electrification power supplies, as well as water courses, drainage, water and gas services. The key interfaces are:

- Signalling Supply Points;
- Earthing & bonding of LV systems and exposed metalwork;
- Overhead power wires;
• Gas & water pipes;
• Buried power cables;
• Telecommunication cables.

17.9.1. Signalling Supply Points

Signalling Supply Points (SSPs) are locations where a feed is taken from the OLE and used as a backup supply, usually for signalling power. This is done by means of a mast-mounted auxiliary transformer (10.2.5), with the primary winding connected between the OLE and traction earth, and the secondary winding providing an LV feed to a signalling power changeover panel. A removable 25kV fuse is provided on the primary side to protect the transformer from damage in the event of a flashover on that side.

Figure 340: (l-r) Signalling supply point with 25kV to 400V transformer, detail of 25kV fuse in drop-out link. Winkwell, UK

17.10. Stations

Special arrangements are needed at stations, due to the interface with a diverse (and sometimes unpredictable) general public. Typical restrictions at stations include:

• No live equipment over platforms;
• All live parts including the pantograph to be at least 3.5m stringline from platform surface (section 10.9)\textsuperscript{219};
• ATF routing away from platforms or in protected ducting;
• Earth wire protection from vandalism;

\textsuperscript{219} GLRT1210 “AC Energy Subsystem and Interfaces to Rolling Stock”; Issue 2, December 2019; RSSB; section 2.2.2.1. This standard permits live parts of the pantograph to infringe this clearance, subject to a site-specific risk assessment being completed.
• Anti-climbing measures (section 12.19.3);
• Integration of traction bonding with station LV bonding.

Figure 341: Earthed cantilever with no live parts over platform. Finsbury Park, UK

It may be necessary to apply special arrangements in order to meet standing surface requirements - this can include special earthed cantilevers or opposing staggers to keep live equipment sufficiently far away from the public.

Figure 342: Opposing stagger arrangements for stations

17.11. Highways

The key interface with highways for mainline railways is at level crossings. Special safety arrangements are needed wherever OLE crosses a public right of way. National standards will typically specify minimum wire heights to be observed under all environmental conditions, based on national road vehicle height standards and typical crossing usage. For instance, UK standards\(^{220}\) specify 5.8m as the minimum wire height for all road

\(^{220}\)Ibid., section 3.1.5.
crossings, and 5.2m wire height for foot and bridle crossings.

Figure 343: Typical hazards at an electrified level crossing. Enfield, UK

It should be noted that many vehicle crossings in the UK are for private access to farmland, and as such the user may be regularly crossing with over-height vehicles. It is therefore important to risk-assess each crossing prior to undertaking the OLE design, to ascertain what control measures are needed to protect both crossing users and the railway. Additional mitigations may be imposed, such as height barriers on the road approach to the crossing.

A further consideration for the many user-worked crossings in the UK is that they rely on the pedestrian crossing user to visually check for trains before crossing. OLE masts can reduce the user’s sighting distance, and so a sighting assessment must be undertaken similar to that for signal sighting (section 17.7.1). This may recommend the relocation of OLE masts to improve sight lines, but ultimately the best mitigation is crossing closure in conjunction with an alternate means of safely crossing the railway. This is often not possible due to legal restrictions, in which case Miniature Stop Lights (MSLs) may be fitted to give crossing users a warning of approaching trains.

For tram and trolley systems, highways interfaces are multiple and complex.

17.12. Overhead Power Lines

Overhead power transmission lines frequently run alongside and across electrified railways. Most electricity supply administrations impose clearance requirements at all such crossing points. These typically take the form of minimum air gap clearances between all conductors in the transmission line and all OLE parts - live or dead - under all conditions for both systems.

221 The worst case condition for fixed termination power lines is generally the high ambient temperature/maximum power demand scenario.
In the UK these requirements are encoded in a national agreement between the supply industry and the railway as follows:

<table>
<thead>
<tr>
<th>Transmission Line System Voltage (kV)</th>
<th>Minimum Clearance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 33</td>
<td>3.0</td>
</tr>
<tr>
<td>66</td>
<td>3.0</td>
</tr>
<tr>
<td>132</td>
<td>3.7</td>
</tr>
<tr>
<td>275</td>
<td>4.6</td>
</tr>
<tr>
<td>400</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The process of raising an overhead power line becomes more costly as voltage rises, and the opportunities for switching off the electricity network to do so become more limited. Sometimes the necessary clearance can be achieved by increasing the tension in the power line conductors; if this is not possible then it is usually necessary to erect a new pylon to increase the height.

For higher voltages it can often be more cost-effective to treat the power line in the same way as an overbridge, and grade the OLE down (section 12.13.1) to meet the clearance requirement. For lower voltages (such as the 11kV, 22kV and 33kV wooden

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pole routes common in the UK) the low height of the poles will usually mean that the overhead crossing must be replaced with an under-track crossing before the route can be electrified.

The potential exists for induced voltages wherever power transmission lines either cross OLE at an oblique angle or run parallel in close proximity for a significant distance. This can lead to unsafe voltages being present in the OLE during an isolation. It may be necessary to provide additional DEP facilities (section 10.12.1) either side of the crossing point, or for the length of the parallel section.

17.13. Environment

Environmental interfaces include:

- Visual impact;
- Ecology and flora impacts;
- Vibration and noise impacts on local people.

This is discussed further in section 18.11.
18. The Planning Phase

When carrying out an electrification project of any kind, it is essential that the works are carefully planned and executed. Section 17 shows that OLE has significant interfaces with almost all other railway subsystems; failure to carefully plan OLE works will inevitably result in cost and time overruns, as well as potential for unmitigated safety hazards and incidents. The process of planning an electrification project involves multiple disciplines, since the whole railway is affected by the introduction of OLE.

An electrification project should be seen as a production line, one which starts in the planning office and finishes with Entry Into Service (section 21.8). Delays at any stage of the process will affect completion dates and costs, and each step of the process requires careful management.

In this section and section 19 the drawings and documents described form a hierarchy; each overlaps with the one above and below in terms of information. This hierarchy is described in descending order.

18.1. Types of Electrification Projects

Overhead electrification projects can broadly be split into three categories:

• New electrification - implementation of OLE along a previously non-electrified route;
• Renewal of electrification - mid-life refurbishment of an OLE system to improve reliability, extend lifespan and eliminate known failure modes;
• Modification of an existing electrified location or route to support a wider railway project, such as capacity increase, junction remodelling, platform extensions and other infrastructure modifications.

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

Planning of new electrification is critical to the success of the design and construction phases, which should not start until the planning is complete. A project may spend a significant amount of time in this phase, and this can often allow the subsequent phases to proceed more quickly and result in a quicker entry into service.

18.2. Project Goals and Requirements

The first step in any electrification project is to clearly articulate its aims. This is typically codified as a series of requirements in a Project Requirements Specification. Requirements for a new electrification or electrification renewals project should include:

• Operational factors, including the number of and type of electric trains to be supported, their routes, speeds and stopping patterns;
• Future capacity allowances;
• Electrified depot and stabling facilities;
• Traction power demand, including how and where it will be supplied;
• Route reliability, broken down to system level;
• Maintenance access;
• Interoperability;
• Pantograph interface (section 12.1.2) requirements;
• Standards to be applied to the project;
• Interfaces with adjoining projects and routes;
• Any interim stage electrification limits;
Reliability, Availability, Maintainability and Safety (RAMS) targets.

Requirements should be high level and output-based - that is, specifying what outputs are required rather than how those outputs are to be achieved. Each requirement should be clearly articulated, deal with a single aim, and be measurable. Supporting this document is the Lines To Be Wired Diagram, which provides a schematic overview of the end state of the project. This should include any diversionary routes which require electrification to retain resilience during planned or unplanned disruption.

The traction power engineer should be consulted during the development of the project requirements to ensure that they are sufficiently detailed for the traction power modelling to begin. The planning process should not proceed beyond this point until the requirements and wiring extents have been formally authorised.

As well as defining the core lines to be electrified, consideration must be given to non-electrified lines which diverge from, and converge with, the electrified lines. Depending on the signalling and traffic management system to be used, there may be a small but significant risk that an electric train is accidentally misrouted onto a non-electrified line. In this case overrun protection will be provided in the form of a short section of live operational OLE on the non-electrified line, to provide protection against dewirement as the pantograph leaves the electrified line. This protects both OLE and pantograph from damage, and facilitates recovery of the electric train. This provision is generally only provided for tracks with a permissible signalled move from the electrified to non-electrified line.

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At key junctions it may be necessary to go further and provide full passive provision for future electrification.

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223 In the UK the standard provision is 7.5m of OLE per km/h of diverging linespeed. NR/L2/ELP/27715/02 “Overhead Contact System Design Specification: Allocation Design Principles”; Issue 1, March 2018; Network Rail; section 13.
18.3. Operations and Timetable

It is essential to assess the expected power demand both in the short term, and several years into the future, allowing headroom for future growth and recognising that electrified railways often attract new customers due to the sparks effect (section 7.3.3). This process is known as power modelling.

Traditional power modelling has focused on development of a notional timetable, which must incorporate potential electric freight as well as passenger services - since freight is particularly demanding on the traction power system (section 10). The development of this timetable is itself a complex process, and unlikely to reflect the actual timetable many years into the future. A better approach is therefore to base the modelling on generalised traffic patterns, train types and frequencies rather than specific trains and timetables. Any future aspirations to extend electrification should also be allowed for as far as possible.

18.4. Power Planning

The completion of the wiring extents and expected electric train services allows the development of the power system to begin. This can start prior to completion of the project requirements, and may indeed influence them. It is important to understand the demarcation between the three elements of the electrification system:

- The traction power system - all of the elements owned by the DNO or NGC (section 10.1.3) up to and including the supply transformers (section 10.2.2);
- The Power and Distribution (P&D) system - all of the elements owned by the railway infrastructure manager between the output of the supply transformer and the lineside sealing ends (section 10.2.9);
- The OLE system from the sealing ends to the train.

This differentiation is crucial because the contracting strategy is different for each of them. The traction power system is funded and procured by the railway infrastructure manager, but designed, built and managed by the DNO or NGC (depending on voltage); whereas the power and distribution system is generally designed and built by a specialist HV power equipment supplier, but operated and maintained by the railway. The OLE is generally designed and built by a specialist contact systems installer, but operated and maintained by the railway.
18.4.1. Grid Supplies

The process starts with the identification of potential grid feeding locations, taking into account the ESI networks (section 10.1.3). Any such locations must be confirmed as having the required supply capacity, unless a local grid upgrade project can be developed in tandem with the railway electrification project. This is necessarily an iterative process, since the definitive capacity requirements will not be known until the power simulation (section 18.5.1) is complete. Grid locations are often some distance from the railway that is to be electrified, in which case an appropriate aerial or buried cabling route should be identified. Regardless of the location of the grid site, a suitable and available piece of land must also be identified alongside the railway to accommodate the railway feeder station. Depending on the specifics of the site, the ESI compound containing the supply transformers (section 10.2.2) may be co-located alongside the railway substation or sited remote from it. The ESI has specific legal powers that make it easier to gain land-take and wayleaves, so they will often lead the selection process, proposing the best connection points and consulting with the infrastructure manager to develop the optimum supply arrangements.

18.5. Equipment Philosophy

As part of the power planning process it is necessary to begin to make choices about the equipment types that will be used, in terms of:

- Brick-built, modular or containerised building (section 10.2.1);
- Indoor or outdoor switchgear (section 10.2.7);
- Air-insulated or gas-insulated switchgear.

These choices significantly affect the size of the substation and therefore the feasibility of the proposed locations.

18.5.1. Initial Feeding Configuration and Power Modelling

The identification of feeding locations allows the development of an initial feeding configuration. This includes the identification of notional FS, TSC and MPTSC sites for a classic system (section 10.4.4), or ATFS, ATS and MPATS sites for an AT system (section 10.4.3). At this stage the choice of classic or AT feeding may not be defined, and options can be developed for both systems to determine whether a classic system can support the planned timetable. It is important at this stage to focus on the feeding requirements in terms of voltage regulation, and to exclude sectioning requirements (section 18.6). This approach maximises the efficiency of the initial feeding design.

At this point it is essential that the theoretical locations of FS, MPTSC, ATFS and MPATS sites and their associated neutral sections (section 12.6.3) are tested against the physical realities of the railway. It is often the case that the locations which provide the ideal electrical outcome do not have space or land provision available for a substation. Buried or aerial feeds between the grid site and the railway, which can require land-take or wayleaves, also need to be considered. Neutral sections have their own constraints, and matching a feeder station site to a suitable neutral section site can often be challenging. These constraints must be fed back into further modelling iterations until a compliant, practical and cost-effective outcome is achieved.

It is also necessary to consider how any electric depot will be fed; although simply using the OLE into the depot as the feed may be acceptable, this can mean loss of power to the depot when the adjacent mainline OLE is isolated. Some depots are provided with their own dedicated circuit breaker or feeder station to permit depot operations to continue independent of the mainline.

The resulting substation locations, together with the track layouts, are used to build a power model using specialist modelling software. This software allows the railway to be modelled as a complete traction power system, and crucially includes the ability to simulate the running of the timetable, including the...
minute-to-minute movements of the electrical loads along the railway, as well as their changing power demand as trains accelerate and brake.

The power modelling assesses both normal and N-1 (section 10.1.3) feeding requirements; it is normally the N-1 feeding arrangements that identifies any voltage regulation problems. Low voltages can occur due to the extended feeding length, or currents in a track feed or OLE conductor can be higher than the system rating. The modelling also takes into account isolations for maintenance access to equipment, including any bypass feeding which is necessary to maintain supplies elsewhere.

These simulations are designed to expose weaknesses in the initial feeding configuration, and usually result in modifications being needed to it. The modified configuration is then modelled to confirm that it meets the requirements. Care should be taken to avoid too many iterations, in case the system becomes locked to a specific timetable, with insufficient capacity for unforeseen future demand.

![Figure 349: Power modelling with different train positions (shown in red)](image)

The power modelling also defines the rating of the various AC supply equipment components (section 10.2); the electrical and physical parameters must be agreed by the OLE and P&D designer to ensure that the same electrical and environmental assumptions are used in both the P&D design (section 19.2) and OLE system specification (section 18.9.1).

As the feeding configuration develops, it will begin to be documented in the Major Feeding Diagram (MFD). This diagram shows the interface between the electricity supply authority and the railway; feeder stations, TSCs, AT sites and neutral sections are included.
The MFD will typically pass through a number of iterations as the project develops, reflecting changes driven by the design of the feeding and switching sites, and the availability of additional detail as subsequent design development is completed.

### 18.6. Sectioning Arrangements

Once the MFD has reached a stable feeding configuration, the development of the sectioning arrangements should be undertaken. This process defines all of the required sectioning locations, including those at TSCs or AT sites, as well as TSS sites (section 10.3).

It is necessary at this point to select a general sectioning philosophy. Sectioning in the UK has traditionally been based on major sectioning carried out at TSCs, with these located at regular intervals; and a TSC located at every significant junction where two electrified routes diverge, or indeed a non-electrified route diverges which may be electrified in future. Additional sub-sectioning locations were provided between TSCs using non-load-break isolators (section 12.7).

The advent of IP-Based Control and Monitoring (section 10.7.4) has challenged this philosophy, with the ability to automate the fault-finding and clearing process meaning that the same level of electrical protection can be provided with fewer busbars and circuit breakers. Some new electrification projects are now being planned with fewer TSCs or SATS - instead TSSs are provided with load-break isolators and these are used to clear faults in conjunction with circuit breakers at the FS, MPTSC, ATFS and MPATS sites.

The sectioning requirements of an electric railway are heavily influenced by train service patterns, stabling requirements and other requirements of the trains operators, as well as those of the infrastructure maintainers when taking isolations. Sectioning points should be aligned with signals controlling possession limits to prevent inadvertent re-energisation (section 10.12.1), and decisions are required on which isolators (section 12.7) should be motorised. As with neutral section locations (section 18.5.1), all proposed sectioning locations must also be checked for OLE feasibility before they can become part of the section diagram. Any normally open section breaks (whether insulated overlap or section insulator) must additionally be checked against the location of controlled signals so that the pantograph of any stopped train will not bridge the sectioning point;
this can result in arcing and potentially cause a wire burnout.

For these reasons the development of the sectioning arrangements requires a collaborative approach, including representatives from the operation and maintenance organisations as well as P&D and OLE and signalling engineers.

It should be noted that any changes to TSC, MPTSC, ATS or MPATS locations during this process do not invalidate the traction power design (section 18.5.1), and it is generally not necessary to renegotiate with the DNO or ESI as long as overall power demand has not changed.

18.6.1. Electrical Section Diagram

The resulting electrical section diagram - often shortened to section diagram - is based on the Lines to be Wired Diagram (section 18.2) and MFD (section 18.5.1) and shows the detailed electrical feeding & sectioning. It details switch numbers and locations, booster transformers, section numbers, and protecting signals. The drawing will be in a preliminary state at the start of the project, and structure numbers and other details will be added as the detailed design progresses.

18.7. Enabling Works Planning

At the planning stage of the project, it is essential to identify all of the Enabling Works interventions that are required to railway and non-railway assets to permit electrification to proceed. These include assessment of:

- All overbridges and tunnels to determine any reconstructions, track lowers or track slews that are required to provide electrification clearances;
- Suitability of all bridge parapets to protect against electrical safety hazards (section 10.9);
- Immunisation readiness of signalling and telecoms assets;
- Clearances and separations to existing signal posts and gantries (sections 10.8 and 10.9);
- Initial signal sight lines (section 17.7.1) to determine any major conflicts;
- Clearances to overhead ESI transmission lines (section 17.12);
- Any electrical clearance or electrical safety issues at stations that need resolution - for instance cutting back of canopies;
- All vehicle and foot level crossings to determine safe clearances and any required sighting lines (section 17.11);
- The relationship between overbridges, level crossings and stations to ensure that compliant contact wire gradients (section 12.13.1) are achievable;
- All buried or overhead services (gas, water, electricity and telecoms - see section 17) that need avoidance or diversion during the works;
- Any areas of geotechnical instability due to poor earthworks (section 19.1.3);
- Any mine workings which could affect geotechnical stability;
- Any civils structures - such as viaducts and cutting walls - needed for support of OLE structures;
- Integrity and suitability of all existing fencing;
- Vegetation management (section 20.8).

The goal of the project team during this stage must be to identify and then minimise the extent of these route clearance and signalling immunisation works, since they can account for anywhere between 25% and 50% of the total cost of electrifying a route, and implementation of these works must take place well in advance of OLE construction (section 20). Local authority permission is often needed for bridge works, so time for planning application and consultation must also be factored in to the programme (section 18.13). The output of the
planning process will typically be a set of feasibility and option selection assessments, to determine the most cost-effective ways of preparing the route for electrification.

18.7.1. Telecoms Immunisation, Earthing and Bonding and EMC Strategies

It is essential that the telecoms immunisation and bonding designs (section 19.4.7) are treated as part of a single integrated cross-discipline process, since many non-electrification assets need to be bonded, and there is usually a complex interplay with third party (DNO) earthing systems. The development of an Earthing and Bonding (E&B) strategy takes place in the planning phase, and this sets out the principles and general arrangements that are then followed in the bonding design. EMC sources and victims (section 10.4) are also identified at this stage, and the mitigation principles set out in the EMC strategy for the project.

The output of the power modelling (section 18.4) is used to assess the unmitigated impact of EMI on the various lineside assets along the route. This is typically undertaken by feeding the data from the power model into a more detailed multi-conductor simulation which calculates the current flows in each of the OLE conductors over time as electric trains move along the route. This simulation then calculates the electromagnetic fields, induced voltages and touch potentials (section 10.10.1) generated by the OLE in the rails, telecoms cables and other conductive lineside assets. The E&B strategy is developing based on this information.

The simulation outputs are also used to develop the telecoms immunisation strategy and define the work that must take place prior to energisation of the OLE. The full definition of this work is outside the scope of this book, but the work typically begins with a detailed survey of the telecoms assets, whether copper-, fibre optic- or radio-based.

18.8. Track Position Strategy

A key dilemma for the OLE designer is that the contact wire position is measured relative to track, which can and does move over time, but mast positions are fixed in space. It is common for track to move tens of millimetres between the walkout survey (section 19.4.2) and installation of the wire runs (section 20.12), due to the track forces imparted by trains or maintenance interventions such as tamping. This movement renders the designed support and registration geometry invalid, and the necessary rework can seriously undermine construction efficiency.

For this reason it is essential that each project develops a track position strategy, aimed at minimising this rework. This can be based on a managed track position, where the track is maintained within an agreed distance of an approved design alignment. Regardless of the strategy selected, it is essential to agree it with the track maintainer at an early stage of the project, to avoid complications during construction.

18.9. The OLE Design Catalogue

There are three stages of OLE mechanical design which must be undertaken before construction can be started. The first two stages should be completed during the planning phase, and together provide a design catalogue that can be used during the design phase (section 19). This ensures that the design phase can be executed in an efficient manner, without the risk of rework due to changes in the OLE catalogue.

- **System design** is the matching of mechanical and electrical parameters to a railway performance specification, to produce basic wire run parameters (wire sizes and tensions) - with a typical output being a system description manual;
- **Basic design** is the creation of components and assemblies for a system, together with detailed geometry and load rules - typical outputs being basic design drawings (section 18.9.2).
18.9.1. OLE System Specification

The correct selection of an OLE system is an essential prerequisite to a successful new electrification project. The chosen system must provide safe, reliable performance and be compatible with both the infrastructure and the rolling stock for the route. Specific compatibilities to check when selecting a system include:

- Rolling stock formations and pantograph spacings;
- Train speeds;
- Pantograph types (section 12.1.1);
- Electrical loads and their impact on conductor sizes;
- Environmental conditions, including ambient temperature range (section 12.3), wind (section 12.9.1) and ice conditions (section 12.9.2) and their impact on system geometry and loadings;
- Track configuration and geometry;
- Route topography;
- Requirements to meet TSIs or NSTNs (section 12.1.2);

Most administrations have one or more existing system designs (such as those in section 14) for use on new electrification - for mainline railways, these are typically categorised into low, medium and high speed variants. If no OLE system design exists which meets the requirements of the project, it is necessary to develop a new one - or preferably, modify an existing one, since this reduces the amount of time that the development will take.

18.9.2. OLE Basic Design

The assemblies and components to be used on the project must support the aims of the system design (section 18.9.1), while being reliable, affordable, and so far as is practicable, maintenance free. Again, most infrastructure managers will have basic design ranges in place for use on electrification projects, but it is common for each new project to add specific assemblies to solve problems specific to the topography or environment of that route. Basic design ranges can either be proprietary - that is, licensed from a specific OLE manufacturer - or designed and owned by the infrastructure manager. The advantage of a proprietary system is that the designs are proven and available, with existing supply chains in place. The disadvantage is that a licensing fee is typically levied, and the administration is locked into using that manufacturer for spares and modifications. With a wholly owned basic design, there is no licensing or lock-in, but the administration is required to develop its own designs and supply chain, with the risk that the resulting assemblies are not reliable. Most modern systems are a hybrid of the two, comprising proprietary items where mechanical reliability and/or complexity is high\textsuperscript{224}, and self-designed components for lower risk items.

18.10. OLE Wiring Planning

With the power planning (section 18.4) complete and an OLE catalogue selected, the planning of the OLE wiring in accordance with the Lines to be Wired Diagram (section 18.2) can begin. This process pinpoints the insulated overlaps (section 12.4.2) necessary for the sectioning points detailed in the Section Diagram (section 18.6.1), as well as all intermediate construction overlaps according to the maximum tension length (section 12.4) specified in the OLE System Design (section 18.9.1).

\textsuperscript{224} Common proprietary items include cantilevers, insulators, registration arms, section insulators, neutral sections, isolators, bridge arms, droppers and tensioning devices.


### 18.10.1. Wire Run Diagram

The resulting Wire Run Diagram is a schematic showing the wire run numbers and their indicative anchor locations for a given route. The diagram also identifies the Construction Units (CUs) - running from overlap start to subsequent overlap start - which are used to plan the OLE design and construction phases.

![Wire Run Diagram](image)

**Figure 351: Typical wire run diagram detail**

### 18.11. Environmental and Consents Constraints

Electrification projects have multiple impacts on the environment through which they pass, and these must be managed and mitigated. Environmental legislation varies from country to country, but most jurisdictions will impose constraints on what the project is permitted to do, and the times of day or year when it is permitted to do them. It is essential to have a full understanding of these during the planning stage, as there are likely to be legal consents required before certain activities can take place, and obtaining these consents can be a lengthy process. The constraints will also have impacts on construction sequencing and task durations.

In the UK the environmental planning process begins with an Environmental and Social Appraisal. This captures all of the potential areas that must be assessed during the planning process. Potential impacts fall into a number of categories listed below. Once all of the potential impacts are identified, an Environmental Management Plan is created to capture all of the required mitigation processes.

#### 18.11.1. General Environmental Impacts

General environmental impacts of electrification construction activities include:

- Construction dust;
- Use of oil and fuel, with attendant risk of spillage and contamination of land or water courses;
- Use of hazardous substances;
- Disturbance of contaminated land;
- Existing flood risk (such as at substation sites) or increased flood risk (for instance as a result of a track lower);
- Generation of waste such as arisings from piling (section 20.4).

#### 18.11.2. Ecology

Ecological impacts of electrification can include:

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225 Sometimes known as Track Units.
• Impact of vegetation management (section 20.8) on wildlife and nesting birds;
• Changes to water courses as a result of drainage diversions;
• Impacts on protected species\textsuperscript{226} due to foundation, overbridge fixing or viaduct fixing installation;
• Disturbance of invasive species\textsuperscript{227} or species harmful to health\textsuperscript{228} during construction.

Protected species may need to be relocated before intrusive construction activities such as piling can start, and this process can only take place when the animals are not hibernating or breeding. Some trees have Tree Preservation Orders (TPOs) placed on them, restricting what is permissible in terms vegetation management on them.

18.11.3. Conservation

Many natural and manmade features in the landscape enjoy legislative protections, and these must be identified and any impacts from electrification eliminated or mitigated. UK locations include:

• Sites of Special Scientific Interest (SSSIs);
• Special Areas of Conservation (SACs);
• Special Protection Areas (SPAs);
• Wetland sites protected under the Ramsar Convention;
• Areas of Outstanding Natural Beauty (AONBs);
• National Parks;
• National Nature Reserves;
• Local Nature Reserves;
• Ancient Woodland Sites;
• Listed buildings;
• Scheduled ancient monuments;
• Conservation areas;
• World heritage sites.

18.11.4. Local Neighbours

Electrification construction inevitably impacts on people living in the vicinity of the affected route, and care must be taken to minimise those impacts, while communicating and consulting with neighbours before, during and after the work.

Typical impacts of electrification construction include:

• Noise and vibration from piling (section 20.4.2), excavation, drilling (section 20.5.1) and depot activities (section 20.2.1);
• Night time disturbance from construction activities, including noise and temporary lighting;
• Additional lorry movements to depots and access points (section 20.2.1);
• Temporary or permanent use of third party land;

\textsuperscript{226} Protected species in the UK include bats, badgers, dormice, breeding birds, reptiles, great crested newts, fish, otters, water voles and crayfish among others.

\textsuperscript{227} Invasive non-native species cause problems by crowding out other native species. The most common UK example that affects electrification construction is Japanese Knotweed, but there are several others.

\textsuperscript{228} Giant Hogweed is the most common harmful species in the UK; contact with the plant causes phytophotodermatitis, a chronic illness resulting in blisters and scars.
Temporary or permanent diversion of roads or footpaths (section 17.11), and curtailment of access for members of the public and business.

18.11.5. Consents Options

Depending on the national and local laws in place, a number of legal avenues can exist for obtaining the required consents for the works. In the UK there are national consents mechanisms such as a Transport and Works Act Order (TWAO), which require planning proposals to be lodged with national government, which then undertakes a formal consultation process on the proposals, accepting objections from interested parties. Often these objections will result in changes to the proposal to mitigate the impact.

A second national option is the hybrid bill. This is typically used for construction of new electrified railways, and follows a process where proposals are lodged before both houses of parliament, which will review and either pass or reject the proposal.

The third option is to go without a national consent, and instead seek planning permission from individual local authorities. This approach has been used on all recent UK electrification schemes, but has the significant disadvantage of requiring multiple separate consents processes with multiple statutory bodies. The multitude of separate processes introduces programme risk (section 18.13.3), and can have a negative impact on project efficiency.

18.11.6. Embodied Carbon

The embodied carbon (section 7.3.3) generated by electrification construction should be considered, and where possible, minimised. However it should be noted that the magnitude of these emissions is heavily outweighed by the carbon savings generated by running electric trains in place of diesel trains. The necessity of keeping electrification cost-effective (section 7.5) must always be borne in mind, since replacement of conventional steel and concrete with more expensive low-carbon alternatives can shift the cost-benefit ratio of electrification to the point where schemes will not be authorised and the net carbon savings not realised.

18.12. Hazard and Risk Assessments

During all of the planning activities detailed above, multiple new hazards will be identified due to the introduction of electrification, and the asset interventions required to enable the works. These hazards can manifest at any stage of the electrification lifecycle; during construction, operation, maintenance or demolition. All of these should be captured in a series of hazard assessments, which will proactively identify all hazards. A project may conduct formal HAZard IDentification (hazID) workshops, bringing stakeholders together to systematically consider aspects such as equipment functions, risk to exposed populations, and interfaces - both in normal operation and in the event of failures.

\[\text{Figure 352: Hierarchy of hazard controls}\]

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\[229\] “Why Rail Electrification?”, Shirres, Keenor, Dolphin, Hooper; March 2021; Rail Industry Association; section 3.3
The results of this process will feed into a risk assessment process aimed at eliminating hazards wherever reasonably practicable, and mitigating those which cannot be eliminated. The hazard and risk assessments will be reviewed and updated at key points during the planning, design and construction phases. Any residual hazards that cannot be eliminated in the design phase should be clearly recorded on the drawings, and any that remain at project completion should be recorded in the Health and Safety File.

Figure 353: Warning triangles denoting hazards on a layout plan

18.13. Programme

A robust project programme is an essential precursor to beginning the design phase. This should be developed only once the project scope has been defined, to avoid rework and abortive costs. The programme should be agreed with all stakeholders, and progress of design and construction should then be tracked against the programme. Contractual arrangements should be taken into account when writing the programme, since these can influence the time taken to complete elements of the work.

It is essential that the programme is driven by a realistic expectation of the rate of design and construction outputs. Entry Into Service (section 21.8) dates should be driven by available output, and not the other way around.

18.13.1. Work Breakdown Structure

A Work Breakdown Structure (WBS) should be established and agreed, organising all of the activities that make up the programme. Organisational and personal accountability for each element of the WBS must be clearly defined; this allows the project planner to build a clear framework for agreeing and maintaining the programme. WBS elements are often embedded in design and construction contracts.

WBS activities are then be added to the programme to define the elements of work to be completed. It is important to consider and document realistic project working times; the availability of resources - people, plant and materials - is a key constraint on the programme, and these must be taken into account. Procurement
durations (section 20.2.4) for items with long lead times\(^{230}\) should be obtained from suppliers. Construction durations (section 20) will be dependent on track access arrangements, labour resources and plant.

### 18.13.2. Programme Logic

The programme logic - that is, the dependencies between the start and end of individual activities - is equally important to get right, since slippage of one activity will have consequences for multiple later steps. Electrification projects are multidisciplinary, and logic between disciplines must be included in the programme.

Depending on the contracting strategy there may be a requirement for programme integration between multiple parties (client and contractors), which should be considered when producing the baseline programme. Interfaces between parties should be defined and managed as part of the programme.

It is important to include gaps between the completion of one construction activity and the beginning of the next; this time is used for completion of quality assurance checks, and failure to allow time will lead to quality problems that will eventually delay entry into service.

### 18.13.3. Assumptions and Risks

All key assumptions and risks should be recorded in an assumptions document, sometimes referred to as a basis of schedule or programme narrative. This document is updated throughout the project life cycle. Each assumption and risk should be assigned an owner, who will manage that risk to conclusion. While often not a contractual requirement, it is an essential tool for managing change during the programme.

All activities, durations, programme logic, interfaces, assumptions and risks should be agreed with the project engineers, taking into account previous experience of electrification projects. All parties should formally accept the programme before work starts.

### 18.13.4. Measuring Progress

As well as programme updates, design and construction metrics can be a helpful way to communicate progress against the baseline programme. However it is important to remember that individual installed items are components of an overall railway system, and so metrics work only if chosen wisely as meaningful steps along the way to entry into service. Metrics drive designer and installer behaviour that can be hard to change, especially if embedded in contracts. For instance, measuring foundation installation (section 20.4) across a project is counter-productive, since it is possible to achieve 95% completion and still have a pile missing in every construction unit, thus preventing any wiring (section 20.12) taking place. A more meaningful metric is to treat completion of all foundations in a construction unit as a single target.

It is equally important to measure metrics accurately; for instance a foundation is not complete until the holding down bolts (section 12.11) have been installed and the as-fitted location confirmed as within tolerance.

Carefully-chosen and measured metrics are however an essential project tool, allowing progress to be compared to the plan, giving the team confidence that works are on target and highlighting where early intervention and mitigation is required. Metrics should be clearly documented and communicated, and the project should clearly define how the individual targets come together to allow testing and commissioning (section 21) and entry into service to be completed.

\(^{230}\)Typical long lead items include cantilevers, insulators, registration arms, section insulators, neutral sections, isolators, bridge arms and tensioning devices.
A reporting cycle - usually monthly or four-weekly - should be agreed and implemented before work commences.

### 18.13.5. Change Management

Once an agreed set of requirements (section 18.2) and programme is in place, a process for change management should be implemented on the project. Change is inevitable on any large programme of work, but must be undertaken in a structured and informed way, since poor change management is implicated in most project failures. Determining which changes are acceptable and which are not is a matter for the individual project, but each change must be rapidly identified and scoped, and an impact attached to it in terms of:

- Cost;
- Programme time;
- Safety;
- Quality of output.

The change should then be reviewed by the project team, and budgets and programme adjusted to take account of the new reality. As a general rule, changes should be avoided to a section of OLE which has entered the construction phase as this is extremely disruptive to the process set out in section 20. Instead the change should be undertaken in a separate sequence once construction activities are complete.
19. The Design Phase

The design of OLE is subject to a strict process designed to ensure that designs are safe, robust and meet the performance criteria. This section focuses on the general principles, with examples of UK practise used to demonstrate the process.

As with the planning phase (section 18), the design phase involves all railway disciplines and cannot simply be viewed as delivery of OLE design. A typical electrification scheme will involve civil engineers (bridge attachments, canopy cutbacks, substation compounds), geotechnical engineers (foundation designs), signalling engineers (signal sighting, head changes, structure modifications, immunisation), track engineers (track lowers at bridges), telecoms engineers (immunisation) and electrical engineers (earthing and bonding) as well as OLE and P&D engineers.

The general sequence for design is as follows:

1. Gather existing asset data;
2. Undertake surveys;
3. Complete outline design;
4. Undertake Interdisciplinary Design Check (IDC);
5. Repeat steps 1 to 4 for detailed design;
6. Produce Approved For Construction (AFC) drawings.

The reality is far more complex than this simplistic list would suggest; there are multiple dependencies between different elements of the design - for instance, between the OLE design at a location and the design of a reconstructed bridge carrying OLE attachments; and between design, procurement and construction. It is therefore essential that the design is carried out against a robust project programme (section 18.13).

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

19.1. Surveying

It is essential that all new electrification or modification to existing electrification is based on an accurate and recent survey. It is not sufficient to rely on existing record drawings, as these are not always kept up to date. The range and extent of the surveys required depends on the nature and extent of the work to take place. The expense and time needed for surveys means it is essential to coordinate the requirements of the electrification surveys with those of other disciplines to ensure an integrated survey strategy, and to reuse existing recent surveys where available.

Figure 354: Height and stagger survey with non-contact gauge
19.1.1. Height and Stagger Survey

For modifications to existing OLE, it is essential to understand the current geometry and configuration of the existing OLE. This is traditionally captured during a height and stagger survey, where a small survey team use a height and stagger gauge to capture basic OLE geometry at each support and/or registration point, and often at midspan locations as well.

The gauge typically comprises a laser distometer held in a transverse sliding mount with a horizontal ruled scale, which in turn sits on the running rails of the track to be measured. The laser dot is placed on the point of interest; the height is measured using the distometer, and stagger is measured using the ruled scale. Track cant, mast offset from track\(^{231}\) and span lengths are often measured at the same time.

The height and stagger survey should also capture high quality photo images of the support and registration arrangements, to allow the designer to determine the available adjustment in the equipment. Any other relevant information which could affect the design, such as splice locations (section 12.17.1), damaged equipment or fixing details should also be recorded during the survey.

Traditional height and stagger surveys are time-consuming and require safe track access, and so they are increasingly being deprecated in favour of point cloud surveys (section 19.1.2), which can safely gather much more information in a shorter period of time. An alternative to this for simple locations is to use the output from train-mounted OLE monitoring (section 23.2) to provide recent OLE geometry data.

19.1.2. Geospatial Surveys

Geospatial surveys provide a much more complete survey of a section of railway than the height and stagger survey can, providing vital context and spatial relationships with other infrastructure, as well as a 3D output that can form the basis of a multi-disciplinary design model.

The traditional technique for these surveys is to use a tripod-mounted total station theodolite to gather angle and distance measurements to key points. These are then geo-referenced to the required geographic grid for the project using the Global Navigation Satellite System (GNSS) receiver on the total station.

This approach provides high accuracy, and is often necessary to collect specific track data such as toes of points; but it is still a relatively time-consuming way to collect the many points needed for a complete OLE system and the surrounding infrastructure.

For this reason projects are increasingly using 3D point cloud scanning techniques to gather survey data for railway projects. The configuration of the surveying equipment varies, but all work on the same basis; a Light Detection And Ranging (LiDAR) scanner uses a rapidly-sweeping laser to gather angle, distance and colour data across the entire field of view. The data is then georeferenced in the same way as traditional topographical surveys.

The advantage of a 3D point cloud scan is its ability to gather detailed information on a whole section of railway in a very short period of time, often without the need to place people or equipment on the live railway. LiDAR scanners can be used in a number of different ways, including:

- Lineside scanning using a tripod-mounted 360° scanner;
- Drone-mounted scanning;

\(^{231}\) In the UK this dimension is measured as Running Edge to Face Of Steel (REFOS).
- Train-mounted scanning;
- Aircraft-mounted scanning.

Each technique offers different advantages, disadvantages and accuracy. The accuracies quoted below are based on best-in-class methods, and highly dependent on the detail of the survey equipment and methodology.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Accuracy</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lineside tripod</td>
<td>Cost-effective for small sections; easy to eliminate shadows</td>
<td>Inefficient for longer sections</td>
<td>High</td>
<td>All design stages</td>
</tr>
<tr>
<td>Drone mounted</td>
<td>Cost-effective; can survey longer sections quickly</td>
<td>Cannot eliminate shadows under structures; vegetation can mask ground levels unless clearance takes place; legal limitations on overflying a live railway</td>
<td>Medium to High</td>
<td>Outline design only</td>
</tr>
<tr>
<td>Aircraft mounted</td>
<td>Fastest way to capture long lengths of railway; can capture surrounding terrain and buildings</td>
<td>Expensive; cannot eliminate shadows under structures; vegetation can mask ground levels; minimum height restrictions on overflying a live railway</td>
<td>Low</td>
<td>Feasibility design only</td>
</tr>
<tr>
<td>Train mounted</td>
<td>Can capture long lengths of railway quickly</td>
<td>Requires planning and coordination of train availability and paths; not cost-effective for smaller projects; vegetation can mask ground levels</td>
<td>High (with sufficient passes)</td>
<td>All design stages</td>
</tr>
</tbody>
</table>

Figure 355: (l-r) Lineside LiDAR scanner, in use scanning an OLE structure
19.1.3. Geotechnical Surveys

The geotechnical ground characteristics play a large part in determining the correct OLE foundation to use (section 12.11), and failure to correctly understand the ground conditions will have adverse impacts on the rate of installation (section 20.4), as well as the foundation’s ability to withstand the loads imposed on it (section 12.9). The ground conditions are a direct input to the foundation design (section 19.4.4).

Figure 356: Point cloud scan output from a 1½ hour lineside LiDAR scan of the structure in figure 355

Figure 357: Bedrock and surface geology for a region of the UK

The geotechnical investigation starts with a desktop study which reviews existing information. Geological survey maps are typically reviewed to determine the superficial and bedrock geology across the site. Information on mining risks, any historical boreholes, hydrogeology, and the potential presence of contaminated land is also reviewed.

These maps are not sufficiently granular to determine the ground conditions at a specific OLE structure location, and they can only provide information on natural ground conditions - whereas railways are constructed on a mix of natural ground (for flat and cutting sections) and made ground (for embankments).

For this reason, the desktop study is followed by a geotechnical Ground Investigation (GI). Exploratory hole locations are planned along the route, using information from the desktop study helping to identify appropriate hole locations. Borehole spacings depend on a number of factors, including ground conditions, the availability of historical borehole information, and the presence of historical mining. Typical borehole spacings are between 150m and 500m. It is essential to carry out appropriate GI along a route to be electrified, to derisk the construction phase (section 20.4) as much as possible.

A range of different ground investigation methods are available, depending on the information needed. A selection of which are summarised in the table below.

<table>
<thead>
<tr>
<th>Ground Investigation Method</th>
<th>Description</th>
<th>Information Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windowless Sampling</td>
<td>Used to bore through soft, shallow soils. In-situ testing such as a Standard Penetration Test (SPT), Cone Penetration Test (CPT) or dynamic probe testing can also be undertaken. Borehole installations such as water or gas monitoring wells and piezometers can also be included.</td>
<td>Suited to exploratory holes 5-8m deep. Resulting borehole log shows ground characteristics (superficial and/or bedrock geology, thickness of different units, water level).</td>
</tr>
<tr>
<td>Cable percussion (shell and auger) drilling</td>
<td>Used to bore through harder strata. Boreholes can be drilled at a variety of diameters (such as 150mm, 200mm, 300mm). As above, in-situ testing can also be undertaken.</td>
<td>Suited to deeper exploratory holes, up to 50m; depths of 10-12m are usually sufficient for OLE foundations. Borehole logs can also be produced.</td>
</tr>
<tr>
<td>Standard Penetration Testing (SPT)</td>
<td>An in-situ test giving information on soil strength. Uses a standard tube size which is driven 150 mm into the ground; the number of blows required for the tube to penetrate each 150 mm (up to a depth of 450 mm)</td>
<td>The blow count can be correlated to different sediment types and indicates the hardness or otherwise of the sediment.</td>
</tr>
<tr>
<td>Dynamic Probing</td>
<td>A fixed cone is driven into the ground using a high frequency hammer, and blows per 100mm are recorded.</td>
<td>Gives information on the strength of the ground material, in a similar way to SPT testing.</td>
</tr>
</tbody>
</table>

19.1.4. Buried Services

Wherever new OLE structures are to be installed, it is essential to the safety and continued performance of the railway that the location of all buried services is accurately known. This can be very challenging on older railways, where historical records may be poor, and cables may have subsequently moved under the action of
track maintenance. Railway corridors often carry a wide variety of services, crossing over, under or running alongside the track including:

- Railway signalling and telecoms cables;
- Third party telecoms cables;
- HV and LV power cables;
- Water and gas;
- Culverts and drains.

The process usually starts with the construction of a burden services model based on a comprehensive search of the services records for the route. This will generally be a low-accuracy CAD model, since the underlying records will have some uncertainty.

The model is then used to avoid services during the design process. Where an OLE structure must be placed in close proximity to the service, additional surveys should be undertaken to confirm an accurate position.

In recent years it has become common practice in the UK to dig a one metre deep trial hole at every proposed foundation location to confirm the absence of services. This practice was introduced by the Great Western Electrification Programme (section 8.6) to mitigate the local practice of burying signalling cables directly into the lineside ballast. However the practice has two major shortcomings:

- It removes up to 1m of effective depth (section 19.4.4) from every foundation location, necessitating a deeper foundation to compensate;
- It introduces an additional time-consuming step in the design process, as trial holes must be dug in between layout plan design (section 19.4.1) and cross section design (section 19.4.3).

Taken across a whole route this is an expensive process. It has also been used as a way of checking local ground conditions, but a well-specified borehole strategy (section 19.1.3) is sufficient to derisk ground conditions without the need for trial holes.

A number of more effective alternatives to trial holes exist, such as more effective use of local maintainer knowledge and record drawings, slit trenching, tag and trace identification of cables, or scanning with a Cable Avoidance Tool (CAT).

19.1.5. Environmental Survey

Environmental surveys are necessary to determine what environmental constraints (section 18.11) exist within the boundaries of the project; in particular, the ecology of the location (section 18.11.2) must be understood, and this usually necessitates an ecology survey to confirm the presence of protected species and habitats.

19.1.6. Windspeed Survey

An accurate assessment of the maximum winds speeds likely to be experienced by the OLE is essential to correctly determine the wind loads on the structures (section 12.9.1) and the blowoff experienced by the contact wire (section 12.13.2).

Windspeed assessments in the UK were traditionally undertaken using a simple on-site assessment of topographical and height factors, and applying these factors as modifiers to a base windspeed derived from a

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Use of a CAT is not sufficient in itself, as the tool is not capable of detecting all services, but it can be used as part of a wider cable detection strategy.
map similar to that in section 12.9.1. This process was subsequently replaced with one derived from the Eurocodes. This approach is much more complex to apply, and more suited to building design, involving as it does the assessment of Orography Factors, distance to coastline and other parameters. While this approach does have the advantage of not requiring a site survey, many designers are adopting a simplified version of the process more appropriate to small-scale structures such as OLE masts.

Regardless of the process, the output is a set of design windspeeds and/or wind pressures, which vary along the route as the topography changes. These are used in subsequent design calculations to ensure that the resulting system is reliable and safe.

19.2. Power and Distribution Design

The P&D design forms the interface between the traction power system and the OLE system (section 18.4), and details the location and electrical functionality of the railway power system, as well as its monitoring, control and operation. The design is developed from the MFD (section 18.4) and section diagram (section 18.6.1), and interfaces with the OLE layout plans (section 19.4.1 and switching cross sections (section 19.4.3)).

19.2.1. Substation Single Line Diagram

The substation Single Line Diagram (SLD) details the electrical relationships, layout and connections between the primary electrical plant at each substation, including connections to both the traction power system and the OLE. It also specifies the unique naming of each item of equipment, an essential safety prerequisite for use in safety-critical communication.

![Substation Single Line Diagram](image)

Figure 358: Substation Single Line Diagram for a TSC with facility for future conversion to SATS

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236 Orography is the study of the speeding up of wind as it flows up slopes.
19.2.2. Substation Protection Block Diagram

The protection block diagram develops the SLD by adding detail that defines the interaction between the electrical protection (section 10.7.1), circuit breakers (section 10.2.7), current transformers and voltage transformers. This is especially important for feeding sites which have a critical electrical protection interface with the NGC/DNO. The rating and class of CTs and VTs at these sites must be agreed between the railway infrastructure manager and the NGC/DNO.

![Substation Protection Block Diagram](image)

19.2.3. Substation Schematic

The substation schematic is an electrical schematic of a substation site, showing the power and distribution circuit from the incoming grid transformer (section 10.2.2) (if provided) through to the outgoing connections to the OLE. Historically both AC and DC circuitry were shown, but switchgear suppliers now produce schematics split by function. The schematic shows the control and protection functionality of the protection relays (section 10.7.1), circuit breakers (section 10.2.7), disconnectors, VTs and CTs (section 10.7.2).
19.2.4. Substation Layout Design

The substation layout design shows the detail of the physical equipment at a substation, based on the SLD and the agreed technical solutions such as AIS or GIS (section 18.5). It shows equipment bases, trough routes, access roads, fencing and building layouts, and includes interface routes and connections to the NGC/DNO and the OLE as appropriate. The output of this process is a series of site layout drawings for each substation site, which in turn enables the civils drawings for the site to be developed.
Figure 361: Substation Layout for a TSC with facility for future conversion to SATS

19.2.5. Substation Ancillary Design

A number of supplementary equipment designs are required at each substation location. These include:

- Battery charger (section 10.2.8);
- SCADA RTU (section 10.7);
- Telecoms design;
- LV supply from local DNO (section 10.2.5), including isolation transformer (section 10.2.4) if required.

Each of these will be provided with its own electrical schematics and equipment layout drawings as necessary.

19.2.6. SCADA Design

The SCADA (section 10.7) design is based on the section diagram (section 18.6.1) and substation SLD (section 19.2.1), and depicts the SCADA or control system operated by the ECO. It shows all of the controllable devices within the electrification system, and sometimes the manually controlled devices under the control of the ECO. The resulting drawing can be challenging to develop - especially for auto transformer (section 10.4.3) systems - since it must show all devices within the geographical scope, while remaining easy to read and understand.
19.3. Enabling Designs

*Enabling design* describes any design which modifies a non-electrification asset to permit electrification of a route to proceed, and section 18.7 details the assets that typically need modification. It is beyond the scope of this book to detail the design processes for these asset modifications, but it is essential that these designs are planned in good time, since the completion of enabling works construction is a precursor to many of the OLE construction activities (section 20).

19.4. OLE Allocation Design

OLE *Allocation Design* - also known as *Application Design* - is the process of applying the design rules, components and assemblies set out in the System Design (section 18.9.1) and Basic Design (section 18.9.2) to a location or route, and this process is at the core of any new electrification design. The process will drive, define and interface with all the modifications to existing railway assets (section 18.7) which are necessary to permit the electrification construction phase (section 20) to proceed. For this reason it is essential to carefully plan the sequencing of the Allocation Design process and the related infrastructure designs; as a broad principle, the OLE design should be sufficiently advanced to fully define the requirements of the enabling designs, before those enabling designs are completed. Failure to do so will inevitably result in rework of the supporting design - or worse, rework to the construction - once the OLE design is fully understood.

OLE designs for specific locations are presented in a standardised manner by a series of drawings, schedules and documents. This is to ensure that the details are easily understood by any competent person, and that no ambiguity can be present in the design. It should be noted that any proposed alteration to OLE will affect some or all of these drawings. Additionally, changes to other railway systems will often have an impact on the OLE drawings.

In the UK no written standard for drawing formats exists; however there are several examples of industry best practice in circulation. Detail of drawing formats tend to be agreed on a project by project basis, with specific details depending on client, contractor and designer preferences.
19.4.1. **OLE Layout Design**

*Layout Design* takes place against an agreed Section Diagram (section 18.6.1), Wire Run Diagram (section 18.10.1), and track geometry (section 18.8), and is the process of setting out:

- OLE structure locations and types (section 12.10);
- Wire run positions and anchoring (section 12.4);
- Overlap positions and configurations;
- Junction wiring configurations (section 12.5);
- OLE geometry (sections 12.13.1 and 12.13.2);
- Overbridge, level crossing (section 17.11) and station (section 17.10) wiring configurations;
- Ancillary wiring (section 12.16.5) configurations and geometry;
- Switching locations and configurations (section 12.7);
- Location of DEPs (section 10.12.1);
- Any alterations to existing OLE, track and/or signals;
- Along-track positions of existing OLE, track features (such as turnouts) and signals.

The process includes a full assessment of signal sight lines (section 17.7.1) to ensure that the new or modified OLE will not infringe on minimum sighting distances to any signal.

The output of this process is one or more *OLE layout plans* - this is the first drawing in the electrification hierarchy to show any geometric detail of the OLE. It is typically drawn at 1:500 for complex areas, and smaller scales for plain line areas, and shows OLE structures, wire runs, RCs, ATF, earth wires, overlaps, SIs, track curvature, span lengths, height and stagger, jumpers and other plan information.

![Figure 363: Typical layout plan detail](image)

19.4.2. **Site Walkout**

It is essential to subject the initial layout plan to a *site walkout* carried out jointly between the OLE, geotechnical and civil designers, and the installer. This allows the layout design to be checked for construction practicality. The location of each structure will be checked, coordinates confirmed and the position of any local cable routes or other obstacles recorded. Where a problem is found, an alternative structure location will be identified by the group.
The layout plan can only be finalised once this process is completed, and the cross section design and foundation design should not proceed without a completed site walkout.

### 19.4.3. Cross Section Design

**OLE Cross Section Design** builds on the layout plan and involves detailing of the individual OLE structures, providing the structure geometry and components necessary for construction. The resulting **OLE cross section** drawing shows detail of a specific cross section across the railway, including one or more OLE structures.

![OLE Cross Section Design](image)

**Figure 364: Typical cross section detail - sheet 1**

These drawings are typically 1:100 scale and include all the arrangements, dimensions, and assembly part numbers required to build the structure(s). The assembly part numbers are drawn from the basic design range (section 14.1) for the system. The drawing may have more than one sheet - for instance it may be split into support and switching sheets for complex arrangements. The cross section will include appropriate pantograph gauges (section 12.1.2) to confirm that minimum electrical clearances (section 10.8) have been met.
Cross sections should only be produced once the layout plan has been finalised.

19.4.4. Structure Loads and Foundation Design

It is essential to the long-term safety and reliability of an electrified railway that the OLE foundations are capable of withstanding the loads that are applied to it, without risk of significant short- or long-term movement.

Completion of the cross section design (section 19.4.3) enables the actual live and dead loads for the structure to be calculated and combined into a set of load case combinations (section 12.9). An allowance of 10% is typically added to these combinations to negate the need for redesign should the OLE design be adjusted at a later stage. These are fed into the foundation design, along with the grid coordinates, geotechnical findings (section 19.1.3), and the required walkout (section 19.4.1) and Finish Foundation Level (FFL) based on the ground profile. FFL is typically set at 300mm above the highest point of the surrounding ground.

The selection of foundation types (section 12.11) is a complex topic, driven by a number of construction factors, including:

- Type and condition of natural ground (on level ground and in cuttings) and of earthworks (on embankments);
- Geotechnical considerations such as the presence of a high water table, bedrock, poor embankment stability or soil types that make augering difficult such as gravel or sand;
- Proximity to mining areas;
- Availability of access to the railway;
- Availability of appropriate plant (section 20.4);
- Storage and handling processes (section 20.2.1);

237 Portal structure foundation locations must be coordinated with the various structure connection tolerances in all three planes.

238 FFL is the distance in the vertical plane between the top of foundation and the nearest rail.
Environmental considerations (section 19.1.5);
Presence of any drainage or buried services (section 19.1.4);
Local materials availability and cost (section 20.2.4);
Required production rates;
National and local preferences.

Foundation selection must take full account of the construction constraints as well as the engineering requirements, and for electrification of operational railways, speed of installation should be prioritised. For instance the maximum length of a single section pile should be treated as a constraint, since jointing of multi-segment piles on site is detrimental to productivity. For these reasons the selection of the appropriate foundation type(s) cannot be made solely by the designer, or indeed the installer; instead the selection should be made with involvement from both parties.

In the UK the output of this process is typically contained in project-wide civils Form 001 and 002 documents. This approach provides a strategy for the detailed design of foundations, and removes the need for basic principles to be re-addressed for every construction unit. The document should include a hierarchy of foundation preference that will be used throughout the project to maximise standardisation of the construction process.

The process of designing OLE foundations also depends on the type of ground at the location and the loads experienced by the structure. In the UK there are three processes available, in ascending order of complexity:

1. Standard design with empirical depth setting process;
2. Standard design with Eurocode depth setting process;
3. Bespoke foundation design.

The first option is used wherever ground conditions are expected to be good, and there is no evidence of mining or other earthworks defects. It provides a more efficient design process, and use of the empirical method should be maximised. A standard pile or side-bearing foundation design is selected from the basic design range (section 18.9.2), and the design depth is set using standard tables and formulae based on an empirical assessment of the topography of the site and the load bearing capacity of the soil.

In the UK this process is also known as the ORE method, and uses formulae derived from physical tests carried out in 1957 and updated in 2015. An additional non-effective depth is added to the design depth to give the overall foundation length, to account for the loose top section of soil which does not contribute to the load bearing capacity of the ground.

241 “Assessment of design methods for railway OLE Foundations”, W. Powrie, D.J. Richards; 2015; ORE/Network Rail, University of Southampton.
Ground conditions that prevent the use of this method include:

- Rock (except chalk);
- Peat (unless GI shows there to be sufficient strength);
- Areas where the earthwork condition is rated as poor, including those where earthworks are undermined by burrowing animals;
- Very hard ground (such as surface bedrock);
- Areas where the water table is high;
- Ground which can be affected by dissolution, such as limestone, gypsum and rock salt;
- Areas affected by historical mining;
- Areas of contaminated land.

For these locations, the designer will still use a standard foundation design wherever possible, but the depth will be set using a method derived from the Eurocodes (also known as EC7), using geotechnical techniques such as the Brinch-Hansen method to determine the likely bearing capacity of the ground, and so determine the design depth.

Most projects also have a small percentage of structures which are not suited to the standard foundation designs. These are typically at locations where unavoidable obstructions exist close to the surface (such as on viaducts), in areas with shallow bedrock, at locations with mine workings close to the surface, or in areas of marshland where no coherent soil exists. These will be the subject of a site-specific foundation design, specific

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242 MS/B98/K05 “Foundation Allocation Schedule - Grabbed and Hand Excavated Side-Bearing Foundations”; R00, 27 March 2017; Network Rail and MS/B80/L00 “Strength Depth Table for Different OLE Foundation Types - Based on ORE-UIC Method”; R00, 27 March 2017; Network Rail.

243 In the UK, this is defined as Earthwork Hazard Category (EHC) D or E, as derived from the Soil Embankment Hazard Index (SEHI). EHC indicates the statistical likelihood of an earthwork failing, and is determined from visual inspections and desk studies. NR/L3/CIV/065 Mod 04 “Definition of Soil Embankment Hazard Index”; Issue 1, September 2017; Network Rail.


245 More information is available online at bit.ly/3uynQps.
to the location and often taking the form of a gravity pad foundation (section 12.11.5) to resist the overturning moment horizontally rather than vertically.

The resulting **OLE foundation schedule** is a list of foundations, including everything needed for construction. The schedule will typically detail grid coordinates, FFL and walkout, foundation type, orientation and depth, and all other information necessary for construction to begin.

In the UK the foundation schedule is typically delivered as a civils design submission at the same time as the OLE allocation design is submitted for each construction unit.

### Figure 367: Typical OLE foundation schedule

#### 19.4.5. OLE Bridge Design

**OLE Bridge Design** is the design of OLE geometry (section 12.13.1) and attachments (section 17.3.1) through an overbridge. This process must be carefully coordinated with the civil engineer, since bridge ownership, form of construction, condition, existing loadings and shape will all influence the final OLE configuration.

The resulting **OLE bridge drawing** is a set of drawing sheets showing the detail of an overbridge with OLE attachments. These are typically comprised of a layout plan (section 19.4.1) extract at a larger scale, and a set of cross sections (section 19.4.3) showing the bridge attachments, and a bonding plan (section 19.4.7) extract. The cross section will also include appropriate pantograph gauges (section 12.1.2).
Figure 368: (top to bottom) Typical bridge drawings; cross section, plan and bonding detail
19.4.6. Conductor Schedule

The conductor schedule lists all of the contact wire, catenary, earth wire, RC and ATF wire types (section 12.16) and lengths to be used on a particular section of electrified railway. It is derived from information contained on the layout plan (section 19.4.1).

19.4.7. Bonding Design

Bonding Design is the design of all earthing and bonding arrangements (section 10.10) necessary to facilitate the safe and reliable operation of the electrified railway, in accordance with the earthing and bonding strategy (section 18.7.1). This includes the design of the traction bonding, and also the various ancillary bonding arrangements needed at stations, level crossings and other electrical and mechanical installations.

The resulting bonding plan shows the detailed arrangements for the traction earthing and bonding. For the reasons given in section 10.10 they often show signalling bonding as well. These composite bonding plans are generally owned by the signalling discipline, with input from signalling, OLE, civil and M&E Engineers.

Composite bonding plans are safety critical and are strictly controlled by the infrastructure manager.

Figure 369: Typical composite bonding plan detail

19.4.8. Dropper Tables

The dropper tables detail the lengths and positions of droppers (section 12.16.4) in each span, to give the correct profile for the particular equipment type. They use the wire height information on the layout plan (section 19.4.1), and are derived either from standard dropper tables in the Basic Design (section 18.9.2), or calculated from first principles for non-standard spans. Dropper length calculations should include compensation for any point loads in span such as section insulators (section 12.6.1), and dropper positions must take account of any cut-in insulation (section 12.18).
19.4.9. Bills of Quantities

The Bills of Quantities (BoQ) are a breakdown of the assemblies shown on the cross sections (section 19.4.3) into components, for use in the procurement of materials. These can be presented by assembly, by component, by wire run or by construction unit; the format should be matched to the requirements of the procurement strategy (section 20.2.4).

19.4.10. Supporting Documents

An OLE design typically includes a number of other supporting documents. These include hazard logs, design decision logs and supporting narratives explaining the basis and rationale for the design.

19.4.11. Testing & Commissioning Strategy and Plan

Where changes are proposed to the feeding, switching and sectioning of OLE, or new electrification is to be constructed, a Testing & Commissioning (T&C) strategy is required for the work. This sets out the overall approach to testing and commissioning. This is followed by a more detailed plan, which specifies the steps to be taken to ensure that the system has been installed as per the design; particularly in terms of feeding, switching, sectioning and insulation strength.

The T&C plan will detail the tests to be carried out prior to re-energisation, and between energisation and the operation of trains on the new equipment (section 21). The plan should be created in conjunction with the OLE T&C engineer so that the logistical requirements are taken into consideration.

19.4.12. Operation & Maintenance Manuals

Where new equipment is introduced to the system as part of a construction activity, a set of Operation and Maintenance (O&M) manuals are required. These give details of the O&M requirements of the new equipment, so that operations and maintenance staff can conduct familiarisation training to maintain the equipment in line with standards and manufacturers recommendations.

In the UK, the O&M requirements for standard types of OLE are detailed in a set of standards documents. Therefore O&M manuals are only required if novel or proprietary items are introduced in the design.

19.4.13. Isolation Diagram and Isolation Instructions

At the completion of a project and prior to energisation, the section diagram (section 18.6.1) is converted to one or more isolation diagrams. These documents are used for taking isolations and are therefore safety critical; for this reason they are strictly controlled by the infrastructure manager.
Alongside the isolation diagrams sit the *isolation instructions* - also known as *switching instructions*. These are a set of procedures detailing the steps to be taken to isolate and earth a particular section. These are also strictly controlled. Accompanying these are the *signalling isolation instructions*, which provide instructions to the signaller on the blocking signals and routes necessary to protect the isolation.

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Figure 370: (top to bottom) Typical isolation diagram and associated switching instructions

<table>
<thead>
<tr>
<th>Electrical Section or Sub-section</th>
<th>Lines Isolated</th>
<th>Limits of Isolation</th>
<th>Circuit Breaker / Switch</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS-11C</td>
<td>Up Gloucester</td>
<td>DB21/26</td>
<td>DB23/07</td>
<td>KSW5-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To</td>
<td>From</td>
<td>NSW5-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open Remotely</td>
<td>Open Manually</td>
<td>WS-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>WS-11D</td>
<td>Up Gloucester</td>
<td>DB23/11</td>
<td>BB80/87</td>
<td>KSW5-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>To</td>
<td>From</td>
<td>NSW5-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open Remotely</td>
<td>Open Manually</td>
<td>WS-11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

For this isolation, switch No. 3WS-56 WS-11D MUST NOT be in its alternate dead position.

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\(^{246}\) Health warning added by author.
20. The Construction Phase

It is essential to fully consider the construction of OLE at the planning (section 18) and design (section 19) stages, since construction is by far the most costly part of the whole process. Given the difficulties in gaining approval for electrification schemes (section 7.4), efficient construction must be the constant goal, in terms of:

- Installation to design at the first attempt;
- Completion of as much work off-site as possible;
- As little unfinished work as possible;
- As little need for rework as possible;
- The minimum use of materials and plant;
- The fewest possible people involved.

More than any other factor, the productive use of time during track access periods will determine the efficiency and cost of an electrification scheme. Poor use of time on site will delay completion, increase cost and ultimately degrade the cost-benefit ratio to the point where further scheme approval can be jeopardised. Efficient working is only possible if the design is matched to the site and access constraints, and to the labour, materials and plant to be used.

The following sections focus on new electrification at 25kV AC on an existing mainline railway, but many of the activities described are also needed for the other types of project.

The overall construction sequence is as follows. Each installed asset should be formally assured against the design, before the location is cleared for the next step in the installation process:

1. Off-site works including fabrication;
2. Foundation installation;
3. Pile cap and transfer plate installation (if required);
4. Mast erection;
5. Boom erection;
6. Dressing of steelwork (adding support fittings);
7. Installation of support and registration (also known as Small Part Steelwork or SPS) assemblies;
8. Installation of switching and feeding connections;
9. Bonding installation;
10. Wiring installation;
11. Registration of wiring (which may be combined with wiring installation in a high output system - see section 20.12);
12. Cutting in of section insulators and other tensioned inline assemblies;
13. Final wiring adjustment;

Traction power and P&D works (section 20.16) are usually carried out ahead of, or in parallel with, the OLE works with connections made near the end of the process.

20.1. Early Contractor Involvement

Early Contractor Involvement (ECI) during the design phase can dramatically improve the efficiency of the construction phase, by ensuring that the design is fully aligned with the procurement and construction approach, and the plant to be used. For instance, there are several ways to support OLE on a four track railway, and the choice of portals (section 12.10.6) or TTCs (section 12.10.4) is dependent on construction access.
It is important to strike the right balance between the requirements of reliability and safety, as expressed in the electrical and mechanical designs, and construction efficiency. Without any input from the installer, the resulting design is likely to be misaligned with the construction process. Conversely, if the installation contractor is given complete freedom to define the design, there is a risk that short-term targets will be met at the expense of long-term reliability of the system. ECI can also improve procurement outcomes by giving greater visibility of global materials costs so that, for instance, the lowest cost steelwork can be prioritised in the design. ECI also tends to improve collaboration, allowing for risk-sharing and a common goal of reducing overall costs.

Equally, it is important that the designer is involved with the construction phase of the work. It is rare that an OLE design is installed without any changes being required; for instance as a result of unrecorded buried services, entailing the moving of a structure from its design position. It is essential that this design change is undertaken using a controlled process known as Construction Design so that critical design choices are not unknowingly reversed by a construction change.

### 20.2. Construction Planning

Particular construction factors that should be considered during design are:

- Foundation installation methodology;
- Plant availability and preferences;
- Details of site stores for materials and off-site assembly;
- Materials lead times and procurement logistics;
- Concrete availability and curing time;
- Site access for labour, plant and materials;
- Crane access and ground stability;
- Possession availability, including both routine possessions and longer blockades;
- OLE isolation & earthing requirements;
- Environmental receptors and constraints, including adjacent residents and wildlife;
- Integration with other activities, such as permanent way, civil, and signalling works.

Construction often takes place on an operational railway; in this case, closure and isolation opportunities may be infrequent and short in duration. The design must be staged to maximise these opportunities, with as much preparation work as possible carried out off-site, or on-site with trains running. Off-site activities can include cantilever fabrication, building pile caps (section 20.4.2) and pre-dressing of SPS (section 20.7). Droppers should also be pre-fabricated to the lengths specified in the dropper tables (section 19.4.8); on-site dropper fabrication should be avoided at all costs, since correct dropper length and spacing is critical to correct dynamic performance.

Any longer possessions or blockade opportunities must be planned and used with extreme care, as these will typically be booked several years in advance. The programme development (section 18.13) must ensure that sufficient designs and detailed access planning are in place to maximise the utilisation of these scarce opportunities.

The installer must also consider the loads imposed on OLE assemblies during construction - these can differ significantly from those in the final configuration (section 12.9), and the designer will not generally assess these temporary loads during the design phase. For example, temporary anchoring of an earth wire (section 10.10.1) prior to splicing and onward extension can impose significant and unusual loads on a mast.
20.2.1. Depot and Compound Locations

Choices about the number and location of OLE installation depots are based on a range of factors, including:

- The geographical scale of the work;
- The type of plant to be used - *Road Rail Vehicles* (RRVs) or foundation, steelwork and wiring trains (section 20.12);
- The availability of land.

For projects using trains for installation, a traditional railhead depot is needed, ideally close to the centre of the route to be electrified to reduce travel time. The depot should be dedicated to, and fully under the control of, the electrification project. Facilities needed at this depot include:

- Sidings for stabling;
- Loading sidings with a concrete apron (with no overhead obstruction such as OLE);
- A maintenance shed with basic repair facilities such as lifting jacks;
- Train refuelling facilities;
- A large storage area for piles, masts, booms and SPS;
- A covered area with security for small materials, tools and high value items such as conductors (section 12.16);
- Racking for storage of small parts;
- A one-way system for delivery lorries, or a large turning circle;
- A large open area for fork-lift unloading of lorries;
- Office facilities for staff;
- Good local access roads for vehicles;
- A sheltered and heated fabrication area with IT for reviewing designs and drawings;
- Sufficient parking for staff.

Locations away from residential areas are preferred, since the depot is likely to be noisy at night. The depot should be staffed at all times, to allow any missing, damaged or lost items to quickly be replaced and so keep installation teams working. Consideration should be given to placing DEPs (section 10.12.1) close to RRAPs in electrified areas to speed up on-tracking of RRVs.

If space at the depot is at a premium, it is also possible to move the storage and/or fabrication function to a separate off-site facility, taking advantage of the good availability of industrial warehouse space for fabrication of OLE assemblies.

For projects using RRVs for installation, most of the depot facilities above are still required, but the sidings, maintenance shed and refuelling facilities are not needed. However the inability of RRVs to move long distances by rail (section 20.12.1) means that RRV compounds are required at frequent intervals along the route; each compound requires sufficient space to house plant, materials, welfare and parking, plus have an accessible road route without restrictions on lorry movements and access to the track via a *Road Rail Access Point* (RRAP). Each compound can typically cover around 5 route kilometres of railway.
Figure 371: Aerial view of High Output Operating Base (HOOB) for OLE construction trains. Swindon, UK.
20.2.2. Training Facilities

Construction and maintenance of OLE requires that sufficient competent people are available to carry out these activities. Each OLE system will have different setup requirements and specific training needs, and it is not practical to access operational equipment for training purposes.

For this reason most electrified railways will have a training facility, known in the UK as a training span. This typically consists of one or more spans of OLE erected in a convenient location away from the live railway. The OLE is permanently earthed (section 10.12.2) so that it is safe to work on at all times, and may consist of tension lengths installed at ground level, at full height, or ideally both. Track may be provided to permit RRVs to be on-tracked and simulate real-world construction and maintenance activities.

20.2.3. Construction Predecessors

A number of planning elements are required prior to beginning construction, including:

- Details of route access availability, including standard possession details and any required or available non-standard blockades;
- Safe system of work planning documents;
- Commercial agreements with strategic suppliers, including steelwork, conductors and cantilevers;
- Confirmation of materials delivery strategy - for instance elements may be delivered just in time, reducing store sizes but potentially increasing stockpile risk;
- Confirmation of logistics and materials handling availability (section 20.2.1);
- Permission for access to third party land, and attachment to third party structures;
- Any required legal consents to undertake the work (section 18.11);
- Communication plan for local residents (section 18.11.4);
- Earthing and bonding strategy (section 18.7.1 - for progressive bonding as construction progresses);
- Development of lean techniques to improve and refine the carrying out of individual tasks;
- Inspection and test plans.
The following design outputs must be available and fixed prior to beginning construction:

- Layout plans (section 19.4.1);
- Cross sections (section 19.4.3);
- Materials allocations (section 19.4.9);
- Foundation schedules (section 19.4.4);
- OLE bridge drawings (section 19.4.5);
- Dropper tables (section 19.4.8);
- Any additional documentation which is required by the infrastructure manager

The rate at which design is produced must be matched to the rate at which construction is to proceed, and vice versa. If insufficient design is available, then the project will inevitably begin planning works and ordering materials at risk, and this leads to rework and increased costs.

20.2.4. Procurement and Materials Handling

Efficient procurement and materials handling processes are critical to the success of an electrification project; failure to take advantage of economies of scale when ordering, or to accurately match supply to demand, will increase costs significantly.

Ideally all materials should be ordered based on Approved For Construction designs (section 19), as this virtually eliminates wastage. However this approach increases overall programme durations (section 18.13) due to ordering lead times (section 20.2.4), and reduces economies of scale since items are not ordered in bulk.

An alternative approach is to pre-order items in bulk - but this must be done with care, so as to avoid excess wastage. Pre-ordering should only be carried out after an analysis exercise aimed at identifying likely quantities of each item, based on the design catalogue (section 18.9) and the characteristics of the route. The designer should be involved in this process, since they have the greatest understanding of how the design catalogue will be used on the project. This collaborative approach will influence the choice of materials storage, handling and stillage design. Even with such an approach, some wastage is inevitable; but this is less of an issue if the excess materials can be used on another route as part of a rolling programme of electrification (section 7.5). Pipe for OLE piles (section 12.11.4) can be bought in bulk and then called off to length and bossed once the design is finalised.

Regardless of which approach is adopted, long lead items should be identified and tracked throughout the project. Conductor lengths will be taken from the conductor schedule (section 19.4.6), and appropriate allowances should be made for wastage based on the wiring methodology (section 20.12) to be adopted. Conductor drums can be ordered to specific lengths to suit the particular wire run to reduce wastage.

All materials delivered to a depot or stores should undergo quality assurance checks on receipt, in case of poor fabrication, damage or incorrect ordering. This is a good time to label materials and divide them into storage bays. A robust warehouse labelling and racking system is essential to manage and maintain a stockpile sufficient to feed construction activities. Some projects use a tracking system based on QR codes securely attached to each component, thus providing full traceability of every item from its place of origin to its installed location. This approach requires rigid depot and site discipline, but is particularly useful if a batch of components later develops a mechanical or electrical defect requiring a recall, or if an installation quality issue emerges requiring all such components to be checked.

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247 NR/L2/ELP/27314 "Construction Assurance for Overhead Contact Systems"; Issue 2, September 2019; Network Rail
The installation planning teams should be given the ability to interrogate the stocklist to check materials availability and delivery times for any given construction task, and to then reserve items, preventing two teams booking the same materials. A pre-fabrication team will then assemble components into the required assemblies, based on the AFC drawings and geometry information from previous site activities, and load the materials onto stillages in the correct order for unloading on site. These will either be loaded onto the train when needed (for train installation) or delivered to a secure compound at the nearest access point to the work (for RRV installation). The requisition system also needs the ability to revise the order when a design change occurs.

Components that are damaged or part of a defective batch must be suitably logged, labelled and quarantined in a separate area from the main materials storage, pending testing or return to the manufacturer.

20.3. General Construction Techniques

Construction techniques vary around the world, and depend on a number of factors. It is beyond the scope of this book to fully describe the construction process, but what follows is typical current UK construction practice. The descriptions in this book are necessarily simplified, and should not under any circumstances be used to undertake actual construction.

Particular care must be taken at each stage of the construction to ensure that partially-installed OLE is left in a safe state where it cannot interfere with the running railway. This is particularly important for items installed at height, such as cantilevers being restrained from swinging freely until conductors are installed, registration arms being secured to cantilevers prior to contact wire installation, and coils of feeder cable being secured prior to final connection. The relevant handback forms will be completed at the end of each installation shift - in the early construction stages this is to assure safe operation of non-electric traffic with partially completed OLE, whilst post-energisation, it performs the same assurance for all types of traffic.

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248 This can typically be done for SPS, cantilevers, switching base plates, false booms, stove pipes with cantilever brackets and similar assemblies.
20.4. Foundation Installation

The installation of foundations for OLE structures is one of the most challenging aspects of OLE construction. This is because - even with the most thorough planning and investigation - the nature of the ground in which the foundation sits (section 19.1.3) cannot be fully known prior to the time of installation. This means that the risks to construction timescales are high; just as with the rest of the construction sector, the challenges of getting out the ground should not be under-estimated. Foundation installation can account for 40% of total OLE system installation costs.

For portal structures (section 12.10.6) it is important to coordinate the installed positions of the foundations with the permissible across-track and along-track tolerances within the structure, to avoid a situation where the structure connections are over-stressed or installation cannot be completed.

A wide range of techniques are available around the world for foundation installation, and it is beyond the scope of this book to describe them all. The following sections describe typical current UK practice for installing various types of foundations.

The choice of RRVs or piling train for foundation installation is driven by many of the same access constraints that drive the choice of wiring plant, and this is discussed further in section 20.12.

20.4.1. Refusal Risk

One of the biggest challenges related to piled foundation is that of refusal risk - the likelihood that the pile will encounter solid rock or boulders during installation, preventing the installers from achieving the design depth (section 19.4.4) of the pile.

Unless steps are taken to mitigate this scenario, it can lead to abandonment of a pile, necessitating a costly and time-consuming redesign of the structure to an adjacent unobstructed location.

The risk of refusal must be assessed and mitigated as much as possible by assessment of GI data (section 19.1.3), but this is rarely sufficient on its own, since the data is never comprehensive. Careful planning of the works can further reduce the impact of the risk; for instance where a piling shift includes five piles in a low refusal-risk area and one with a known high risk of refusal, the high-risk pile can be pre-empted in the work planning. This could mean scheduling a pre-auger or - if the risk is low enough - installing the pile close to design depth. Techniques for further mitigating refusal risk are discussed in section 20.4.2.

Some piling techniques (section 20.4.2) result in a foundation deliberately being left partially out of ground between shifts. Any such plan must take into account the signal sighting requirements (17.7.1) of the route, since some piles could otherwise temporarily obstruct signal sighting. This is also the case for refusal risk near signals.

Whatever foundation type is being used, it is essential to mitigate the hazards of ground or track movement.
during installation - particularly when it is occurring alongside an existing operational railway. Areas of poor stability which were identified in the design phase (section 19.1.3) may need to be monitored, both during installation and for a period after. Actual ground conditions encountered during installation should be used to inform monitoring decisions.

20.4.2. Piled Foundations

Driven steel tube piles (section 12.11.4) are the default choice for OLE foundations into good ground in the UK. Where there is more than one diameter available within the basic design range (section 18.9.2), the installer will often seek standardisation on a single size (typically 610mm diameter) to simplify storage, handling and plant requirements. While it is never possible for all of the foundations on a project to be of a single type, the designer and installer should make every effort to maximise the percentage of standard designs - some projects have achieved 95% use of driven steel tube piles, so keeping installation costs low.

Piles are typically stored and transported in a steel stillage, providing a safe and standardised means of containment. A piling schedule will be created using the foundation design schedule (section 19.4.4), with each pile allocated a specific place in the stillage matching its installed location on site. Checks will be made at every stage of the preparation, transportation and installation of the pile, to ensure that the right pile comes off the stillage and into the right location on site.

Figure 375: (l-r) stillage for TTC masts and booms, wiring train stillage for 610 diameter steel tubular piles

Steel tube piles are driven into the ground using an Excavator-Mounted Vibrator (EMV) which can be mounted on an excavator RRV or piling train, and uses a combination of vibration and downforce to push the tube into the ground. This has the advantage of being much quieter than traditional drop-hammer piling techniques; this is an important consideration when working at night in populated areas, and is very efficient in granular soils. In cohesive soils and rock the EMV may not have sufficient capability to drive the pile to its design depth, in which case the EMV is replaced with a drop-hammer to drive the pile the rest of the way.

As piling progresses the blow count data will show the amount of embedment per blow, giving a good indication of actual ground conditions. This should be compared with the previous geotechnical data (section 19.1.3), to refine the project’s understanding of where different geologies lie, where rock is likely to be encountered, and to plan for potential refusals.

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249 This device is often referred to in the UK as a Movax head, after one of the companies that manufacture them.

250 Often referred to as a Fambo head, after one of the companies that manufacture them.
In areas of hard ground, driving the tube can be difficult. One option in these areas is to pre-auger using an auger bit diameter smaller than that of the tube\(^{251}\). The arisings from this operation are left in the hole to prevent collapse, and then the pile is driven in the normal way. OLE structures with higher vertical loads rely more on internal skin friction (section 12.11.4) and soil plugging effects to withstand loads, and this option should always be agreed with the designer prior to use. A rock-drill auger with bullet teeth provides an effective means of breaking through rock layers, and the flight angle and teeth setup can be varied to suit the geology\(^{252}\).

Another option is the Elemex system, where a cutting shoe is welded to the end of a steel tubular pile prior to installation. The cutting shoe engages with the drilling head and cuts into the rock using air flush and rotary percussive techniques, while simultaneously removing the arisings using the flush. This approach creates an annulus around the pile, and although the resulting side- and end-bearing load capacities are likely to be high, resistance to torsion will be low. For this reason the technique should be used with care, especially for TTCs (section 12.10.4) and other torsionally-loaded structures.

Alternatively, a rotary percussive drilling head mounted on an RRV can be used to drive through rock layers, followed by immediate filling of the hole with concrete and driving the tube pile while the concrete is still wet. This technique is simpler than Elemex as there is no pre-welding or reassessment of loading required, since

\(^{251}\)Typically 450mm.

\(^{252}\)“Great Western Railway Electrification, UK: Foundations for Overhead Line Equipment”, Esser, Lethbridge; 2020; Proceedings of the Institution of Civil Engineers - Civil Engineering.
the concrete is replacing the soil that would otherwise be in contact with the pile. A 750mm diameter drilling head is typically used to ensure that there is room in the annulus between the soil and the pile for the concrete to flow into when the pile is sunk.

Where a driven pile is close to its design depth but has suffered a refusal, the non-effective depth can be reduced by hand-excavating around the pile to 1m depth to remove any previously disturbed soil, and casting a concrete collar around the tube.

In some cases, the pile can reach solid rock a little short of design depth; in this case an assessment can be made that the pile has achieved the required capacity, if the rock has a higher capacity than the surrounding ground. The pile head can then be cut off, drilled on site and a steel pile cap installed. A purpose-made jig for cutting and a separate one for drilling is lifted into place using a crane RRV, simplifying the process and allowing several piles to be cut and drilled in a single shift. This technique is not a substitute for accurate assessment of ground conditions, and should be used only where necessary.

Figure 378: Cut-down steel tubular pile with drilling and pile cap. Moreton, UK

Concrete augered pile foundations (section 12.11.4) are usually used where the overturning moment exceeds the capacity of a steel tubular pile, where more end bearing capacity is required due to high vertical loads (for instance with large portals), or in areas where vibration is a concern. A steel casing (typically 1.8m long) is advanced into the ground prior to augering. This supports the soil around the top of the pile and prevents collapse, while providing a support for the rebar prior to the concrete pour.

A concrete auger causes less vibration than an impact hammer, but not necessarily less than an EMV. With good ground condition assessments as well as building and buried services sensitivity checks, conventional piling techniques can still be used if vibration monitoring is put in place.

20.4.3. Concrete Foundations

Concrete foundations have fallen out of favour in the UK in recent years. due to the logistics of bringing wet concrete to remote locations, the slow pouring and curing process, and the safety risks associated with open excavations. However concrete foundations are still widely used outside the UK, and are occasionally used in the UK where specific constraints prevent the use of piling techniques.

Installation of planted concrete masts (section 12.11.1) is undertaken by excavating a hole to the design depth with an RRV excavator, and then inserting the mast into the hole with an RRV crane. The mast is propped in the hole with wedges or a temporary grillage, and then concrete is poured into the hole. The risk of hole collapse must be mitigated, and this technique is only appropriate in the right ground conditions. The top of the hole
is shuttered with wooden planks to provide a rectangular former for the top of the foundation.

Installation of bolted base masts (section 12.11.2) follows a similar process, but rather than placing the mast into the hole, a cage of rebar is inserted in the hole, followed by the holding down bolts, which are temporarily held in the correct position using a template. Concrete is then poured and, once cured, the template is removed. Some designs require a two-stage pour, with the holding down bolts being secured in the second pour.

20.5. Structure Fixings

20.5.1. Overbridge Fixings

Fixings to overbridges (section 17.3.1) are typically installed using MEWPs or, if access is more generous, mobile scaffold towers. Pull-out tests should be undertaken to prove the strength of any resin anchor fixings.

20.5.2. Viaduct Fixings

Structures which are fixed to underbridges and viaducts (section 12.11.7) pose specific challenges related to the construction of the structure, its condition, and any heritage or aesthetic requirements.

Viaducts which require fixings on the outside of the structure create particular challenges for site access, due to the need for working at height and often over water. Depending on the height and location of the viaduct, access options include:

- Access from ground level using a tracked MEWP;
- Access from ground level using a scaffold tower;
- Access from track level using specialist rope operatives;
- Access from track level using bridge inspection cherry picker.
Depending on the information available on the structure, it may be necessary to undertake coring prior to installation to confirm the depth and condition of brickwork.
For portal structures, it is particularly important to position fixing brackets accurately; viaduct construction often includes skewed elements, and for brick viaducts the brickwork is often uneven. For this reason bracket designs must be bespoke to the location, incorporating packing pieces and/or and adjustment mechanisms as necessary to assist construction. Drilling templates are often used to assist in drilling accurate holes, which are then blown clean in preparation for resin anchor fixings (section 17.3.1). Concrete viaducts will also have reinforcing bar which, as with overbridges, must be avoided during drilling.

The type of resin used is dependent on the situation; viaduct fixings typically use long large diameter holes, which require a slower setting product injected from the back of the hole outwards. Overbridge fixings require a faster setting resin so that fixings can be installed in the same shift. Dependent on the design it is often necessary to grout the bracket after installation to reduce the stress in the fixings. As with overbridges, pull-out tests should be undertaken on the resulting fixings.

![Image](image.jpg)

**Figure 381:** Viaduct fixing template being prepared for drilling. Harpers Brook, UK
Tunnel fixings (section 17.5) also pose special challenges for installation. Factors which must be considered when planning the works include:

- Restricted access arrangements and volume of work to be undertaken;
- Working conditions in the tunnel and welfare arrangements;
- Restrictions on use of combustion engine plant;
- Ventilation requirements to replace air during works;
- Need for gas monitoring alarms.

Tunnel repair work may be required before fixing installation; this can involve removal, recasing, repointing, strapping, pinning or grouting of brickwork, to stabilise the tunnel ready for OLE support installation. As with viaducts, drilling templates and jigs are an essential aid to efficient installation of fixings in tunnels, and pull-out tests should be carried out on the installed bolts.

Figure 382: (l-r) Viaduct mast pedestals; side-bolted and through-bolted. Oakley Viaduct and Bromham Viaduct, UK

Figure 383: (l-r) Drilling drop bracket fixings in a tunnel with a bespoke drilling rig, fitting drop bracket
20.6. Steelwork Erection

The choice of RRVs or steelwork train for steelwork erection is driven by many of the same access constraints that drive the choice of wiring plant, and this is discussed further in section 20.12.

20.6.1. Masts

Mast installation is typically carried out using crane RRVs towing trailers which carry the masts, or a Multi Purpose Vehicle (MPV) consist including a crane vehicle and one or more mast carrying vehicles. Steel stillages allow multiple masts to be loaded onto the trailers.

Figure 384: (top to bottom) TTC booms on steelwork installation train, mast installation. Swindon and Didcot, UK
Masts can be lifted using slings or quick release hitches, and are placed on the lower holding down nuts (section 12.11.4). Any required rake (section 12.9) is applied, before the top holding down nuts are applied and tightened. If slings are used, a MEWP may be required for access to release the slings.

Masts can be installed pre-dressed with ancillary wire brackets and cantilever brackets set to the correct position based in the finish foundation level (section 19.4.4) and the cross section (section 19.4.3). This can speed up construction, but may reduce the number of masts that can be carried to site; and care must also be taken to transport the masts in a way that does not damage the brackets. Structure number plates (section 13.1.1) should also be installed at this time.

20.6.2. Booms

Smaller booms, such as those for TTCs (section 12.10.4), are installed using the same RRV or MPV plant as for the mast installation. MEWPs will also be used during the installation process to enable installation staff to guide the boom into place and to install mast/boom connections. TTC booms can usually be loaded into the same steel stillages as the masts. Larger booms for portals are installed using a larger rail-mounted crane or road crane, depending on the availability of access at the site. Wherever possible booms should be pre-dressed with any bracketry that assists later stages of installation.

If a sufficiently large lay-down area is available at the site, it is possible to fabricate and lift an entire portal or TTC - masts, boom and SPS together - using a road crane. The largest booms require a tandem lift using two road-rail cranes, a procedure requiring significant additional planning and coordination on site.

Figure 385: Lifting a pre-assembled multi-track 305DC portal. Stafford, UK

Portal and TTC masts are typically only partially torqued on installation, and full torque is applied only after the boom is installed (for portals) and the wiring installed (for TTCs).
20.7. Steelwork Dressing

This process installs all of the required support and registration equipment, and is an essential prerequisite for wiring. Efficient electrification demands that no wiring should take place until all SPS for that wire run is in place. It is important to place all equipment as close as possible to its design position, so that wiring can be installed to design height and stagger in one shift; this reduces the need for return visits for rework. Cantilevers will be pre-registered (allowing for any deviation once loaded with conductors) and secured using locking pins or cantilever clamps, so that they cannot move around under the action of wind, pending installation of wiring.

SPS installation is typically carried out with a combination of MEWPs (for installation staff access) and RRVs or MPVs (for lifting items into position). The RRV will tow trailers with stillages for cantilevers, stove pipes and tensioners, whereas the MPV will have stillages within its consist.

![Figure 386: SPS installation. Didcot, UK](image)

20.8. Vegetation Management

Vegetation growth poses a significant risk to OLE, with tree branches causing particular problems in terms of arcing and dewirement. It is essential that a vegetation management strategy is developed and implemented prior to erection of any wiring. This will typically involve cutting back of all vegetation to a fixed distance away from the railway. This process must be planned well in advance of construction, since it can involve cutting trees on third party land, as well as complying with legal prohibitions such as from TPOs (section 18.11.2) and restrictions during bird breeding season.

Once a vegetation management plan has been established, it must be maintained during the life of the system to prevent flashover problems building up over time.

20.9. Ancillary Wiring

Ancillary wiring (section 12.16.5) should ideally be installed before main wiring, as the lack of obstruction makes the process simpler, and provides early bonding continuity if an aerial earth wire is being used.

Unlike an auto-tensioned wire run, ancillary conductors are fixed termination (section 12.3), and so the installation process is slightly different to ensure that the tension in each span is equalised as far as possible.
The conductor is run out from a suitable anchor point at low tension using a wiring RRV and MEWPs, and is supported on temporary rollers at each structure. If the distance to be installed is more than a drum length (typically 500-1000m) then the new drum length is temporarily anchored at the mast adjacent to the splicing point, and spliced in (section 12.17.1) at the end of the installation.

The conductor is tied off at the second anchor location, and tension is applied with a pull-lift. The installer then works along the conductor, shaking the wire to remove any tension imbalance between spans or frictional drag. It is important to eliminate creep (section 12.16.1) in fixed termination wires, and to achieve this the tension is often set at 20% above the design value (taking into account ambient temperature) during this initial process, and then left for a period of 24 hours.

Once the wiring has settled, the installer returns and works back towards the pull-lift, again shaking each span to equalise tensions before moving the wire from the rollers to the conductor clamp while a MEWP applies the correct overall tension, adjusting for ambient temperature according to the design charts.

20.10. Bonding

Most line of route bonding is installed at ground level, using track trolleys to carry materials and the specialist drilling rig necessary for drilling rail connections (section 10.10). Bonding connections that are required to be installed on masts or booms - such as midpoint connections - are installed using MEWPs.

Bond connections must be made with particular care at locations with track circuits, since connection to the wrong rail can result in a wrong-side signal failure. Some bonding connections may be dependent on changes to the signalling system and/or bonding taking place first; in this case, one end of the bonding connection will be made, and the other left unconnected, but secured with an insulating boot until it is time for final installation.

Bonding cables should be routed so as not to create a tripping hazard, or leave the cable vulnerable to damage. Bonds should generally be routed under signalling cables so that maintenance access to these cables is not impeded.

Bonding connections at stations and other LV supply assets require coordination with the asset owner. The condition of existing electrical wiring can often require remediation as part of the works.

20.11. Switching and Feeding

Switching and feeding assemblies (section 12.7) are typically installed using long-reach MEWPs, supported by crane RRVs as necessary to lift larger switching bases into place. Isolator assemblies can be installed at any time after steelwork installation, but final connections can only be made after final registration (section 20.13) is complete. Hard standing and switching platforms will be installed using conventional civil engineering techniques.

Switching installation should be undertaken prior to wiring wherever possible, as the presence of wire runs makes access more complex.
Isolators are particularly sensitive to correct setup, to ensure that the isolator blade makes a good connection with the contacts, and that the actuation mechanism can move freely and without being overstressed; for this reason they should be assembled by the manufacturer in a factory environment wherever possible. Once assembled, transportation to site and installation requires particular care to avoid misalignment of the isolator blades. Correct operation of isolators should be checked on completion of the work. Motorised isolators should ideally be set up only once the LV power supply and SCADA (section 10.7.3) is connected, since adjusting the isolator in manual mode can result in misalignment once it is recommissioned in powered mode.

Cross-track feeds (section 12.7.2) can be partially assembled off-site, reducing work on site. Clearances between cross-track feeds and wire runs should be checked upon installation to ensure that minimum safety dimensions are met.

Particular care should be taken to ensure that switching and feeding connections are neither too slack, adding unnecessary weight to the wire run and running the risk that the conductor comes into contact with the pantograph; nor too tight, preventing free along-track movement of the wire run or unduly influencing height and stagger values.

Heights of all live parts should be checked to ensure that standing surface dimensions (section 10.9) are met.

### 20.12. Main Wiring

A number of options are available for installing the catenary and contact wire:

- RRV truck with *drum carrier* for each conductor, with friction or hydraulic brakes to install at low tension;
- Purpose-built RRV truck, installing at high or full design tension;
- MPV wiring train, installing at full design tension.

The choice of wiring method is project-specific; new electrification programmes may select a *high output* approach, using installation trains (section 20.12.3), whereas smaller projects are more likely to use RRV...
techniques (section 20.12.1). Projects involving modification of existing OLE will take a more traditional approach using RRVs, since it is necessary to thread the new wire between existing wires, a process known as flaking. Projects may also choose a mixed approach, with wiring trains used in open route areas, and RRVs used in complex junction areas.

The order of wiring is another consideration, regardless of the plant used; some projects will install wires in descending order of height, which (dependent on the system design) can mean:

1. Crossover catenaries;
2. Running lines catenaries;
3. Crossover contact wires;
4. Running lines contact wires.

However this is not compatible with wiring a complete wire run at full tensions in a single shift, in which case running lines wire runs will be installed first, followed by crossover wire run installation using RRVs. Wiring trains are however capable of wiring simple crossovers if a tangential arrangement (section 12.5.6) and boom anchors (section 12.10.10) are used, so that no flaking is necessary.

The following sections assume installation of new sagged simple auto-tensioned equipment (sections 12.2 and 12.3) on an existing mainline railway; however the process is broadly the same for all equipment types. There are multiple variations on the methodologies outlined below, which are provided for illustration purposes only.

20.12.1. RRV Installation at Low Tension

This methodology uses OLE wiring RRV trucks which carry contact wire and catenary drums, and pay the wire out under a tension which is significantly below that of the system design. The tension applied by this approach is not a fixed value; instead the operator will operate a brake on the drum carrier to maintain sufficient tension to keep the wire from sagging excessively. The wires are maintained at the correct height as they leave the RRV via hydraulic guide arms, and the process is supported by MEWPs.

The typical process for this approach is:

1. Catenary and contact wire are terminated at one terminating anchor location - temporarily securing to the mast or boom;
2. First team runs the catenary out, supporting on temporary catenary rollers at each structure, and continues to the MPA;
3. Second team begins running out the contact wire, staying a few spans behind the catenary team and supporting the contact wire on temporary droppers;
4. When the catenary team reaches the MPA location, the catenary is initially dropped into a temporary roller. A third team then cuts the catenary into the MPA terminations;
5. Catenary and contact wire teams continue through the second half tension length, supporting the catenary on rollers at each structure, then supporting the contact wire on temporary droppers. Teams continue until the terminating anchor is reached;
6. Third team moves back to the initial anchor and installs the catenary in the tensioner unit, adjusting to final tension. Then the same process is carried out for the contact wire;
7. Third team moves towards the MPA, installing permanent droppers and clipping the contact wire into the registration arms;
8. At the second anchor location, the catenary is installed in the tensioner unit, and adjusted to approximate tension. Then the same process is carried out for the contact wire;
9. Third team moves from the MPA towards the second anchor, installing permanent droppers and clipping the contact wire into the registration arms;
10. Team returns on a subsequent shift to adjust the tensioners to final tension.

The advantage of this approach is that it maximises flexibility and minimises plant costs, since RRV trucks are readily available and can easily be on-tracked at any RRAP. The low tension means that the wires can be installed on the wooden drums delivered by the supplier, rather than needing to be respoled onto stronger metal drums.

However this approach has some disadvantages; the RRV is not able to provide full tension to the wires, due to the vehicle’s lack of weight and adhesion. This means that a multiple-pass installation is needed, with initial tensioning and final tensioning carried in separate shifts, increasing overall time on site. RRV installation requires RRAPs to be available or created at regular intervals along the route (section 20.2.1). Each access point needs a secure compound big enough to store RRVs, fork-lifts and materials, as well as staff facilities and parking; and storage space for materials is likely to be more restricted that at a train depot. In the UK RRVs are only permitted to run within a possession, preventing early arrival on site. The lack of Adjacent Line Open (ALO) protection for staff means that adjacent lines must also be closed to traffic while work is taking place.

Tension distribution along the wire run is not achieved by the rollers alone, due to the weight distribution of differing span lengths; and it is not always possible to manually distribute the tension in the limited time available. Failure to equalise these tension differences leads to contact wire profile issues which will manifest as poor dynamic performance (section 12.1.2). On-site dropper length adjustment cannot then be avoided, but this can result in incorrect contact wire profiling or contact wire kinking which is difficult to remove. It can also be difficult to avoid twisting contact wires with smaller cross-sections, due to the low initial tension applied. Temporary droppers are often used in this scenario to reduce risk of contact wire twist.
This wiring approach will typically take several shifts, and so is not favoured on operational railways with short access opportunities. It is however suited to branch lines where access may be more generous, or to green field railway construction.
20.12.2. **RRV Installation at High or Full Tension**

This methodology uses a specialist wiring RRV, supported by MEWPs and a scissor lift RRV. Unlike the traditional wiring RRVs, this plant is able to install at much higher tension because it is significantly heavier and so has greater adhesion. The tension achieved in the initial running of wire depends on the plant used; some RRVs operate at tensions somewhat below the full design tension - often referred to as $\frac{3}{4}$ tension, although in practice this is only approximate. Other RRV types such as the Zeck unit are capable of installing at full design tension.

The typical process for this approach is:

1. Terminate the catenary and contact wire at one terminating anchor location - temporarily securing to the mast or boom;
2. First team runs the catenary out, installing the catenary into support clamps at each structure. They continue to the MPA;
3. Second team begins running out the contact wire, staying a few spans behind the catenary team and supporting the contact wire on temporary droppers;
4. Third team begins installing the permanent droppers and clipping the contact wire into the registration arms, staying a few spans behind the contact wire team;
5. When the catenary team reach the MPA location, the catenary is initially dropped into a temporary roller. A follow-up MEWP then cuts the catenary into the MPA terminations;
6. Catenary, contact wire and dropper teams continue to proceed through the second half tension length, installing the catenary into support clamps at each structure, then supporting the contact wire on temporary droppers, then installing permanent droppers and registration arms. They continue until the terminating anchor is reached;
7. At the second anchor location, the catenary is installed in the tensioner unit, and adjusted to the final tension. Then the same process is carried out for the contact wire.

If a high tension wiring RRV is used rather than a full tension one, the final tensioning process will introduce changes in cantilever positions that will require further adjustment prior to completion.

![High tension wiring with RRV and MEWPs. Bedford, UK](image-url)
This approach brings obvious benefits over the low tension approach in terms of a reduced number of wiring steps and less time on site. A wire run can be fully installed in its final profile in a single shift, with only registration, cut-in activities and final measurements needed before testing and commissioning (section 21) can begin. Unlike with a wiring train (section 20.12.3), many of the flexibility advantages of RRV installation are also retained, as it still uses road-rail plant. This plant also allows for wiring using wooden drums, without the need for respooling; the unit feeds wire off the drums at low tension, and then pays the wire out while applying tension via a bull wheel mechanism. It is also easier to avoid wire twisting using this plant.

Figure 391: SRS/Zeck full tension wiring RRV

The main disadvantage of this approach is the limited availability of the plant, and the ongoing requirement for frequent RRAPs, support compounds and travel only within possessions.

20.12.3. Wiring Train Installation at Full Tension

This methodology uses a purpose-designed wiring train, typically comprising multiple MPVs including drum carriers, tensioning units, and scissor lift platforms for staff. The weight and adhesion of the vehicles makes installation at full tension possible. This train may be part of a High Output Plant System (HOPS), or may be a standalone train.

The typical process for this approach is the same as for section 20.12.2, except that items 2 and 3 are merged, since the contact wire and catenary is run out and temporarily droppered by a single team, and the final dropping team (item 4) follow immediately behind.

254 A HOPS typically comprises several separate consists - such as a foundation consist, a steelwork consist, a wiring consist and a final registration consist - each formed of one or more Multi Purpose Vehicles (MPVs).
The advantage of this approach is a reduction of time on site, as with section 20.12.2. Time on site is further reduced since a wiring train is also permitted to run in normal traffic, allowing it to be driven to site and then the possession taken around the train. A train can also carry all materials and staff on board, so that logistics are dealt with in a controlled stores and depot environment. This method encourages supply chain efficiency, since materials do not get delivered to lineside and then overlooked. Wiring trains with ALO safety barriers are also able to install OLE alongside operational lines, giving them greater flexibility than RRVs which require adjacent lines to be closed to traffic.

However the plant is much more expensive to buy than RRVs, and requires its own stabling, maintenance and loading facility; the high capital cost means that it typically pays for itself over more than one project, and is best used as part of a rolling programme (section 7.5). Flexibility is much lower since the train must travel from its depot to wherever it is required, and train paths must be booked well in advance of the work. The conductors must be respooled from the wooden drums they are supplied on, to stronger metal ones capable of withstanding the compressive forces created by wiring under full tension. This type of plant is also not suited to wiring complex track layouts with multiple turnouts.
This option is the most suitable for plain line areas where access is highly constrained, and productivity within a shift is the highest priority.

20.13. Registration

Once wiring is complete, it is necessary to revisit each structure to ensure that the final geometry is aligned with the design, since tensioning and dropper changes this geometry.

Registration is typically carried out on MEWPs, with geometry being checked from track level using a height and stagger gauge (section 19.1.1). Adjustments are made to the support and registration assemblies to ensure that the acceptance criteria for the location are met. Typical acceptance criteria include:

- Contact wire and catenary heights at the structures and at midspans (to confirm presag - section 12.2);
- Contact wire and catenary staggers (section 12.13.2);
- Contact wire gradients (section 12.13.1);
- Heel settings;
- Electrical clearances (section 10.8);
- Correct settings for along-track movement (section 12.3).

Registration should take place before cut-in activities, to ensure that assemblies such as section insulators are registered in their correct design position.

20.14. Cut-In Activities

Cut-in activities are those that are needed to install assemblies with tensioned connectors (section 12.17.1) into the wires. This should be carried out after wiring, since it is not practical or safe to do this when running the wires out. Assemblies with untensioned connectors will also be installed during this process. Installation is carried out using MEWPs or a wiring train scissor lift platform.

Assemblies installed include:

- Section insulators (section 12.6.1);
- Neutral sections (section 12.6.3);
- Cut-in insulators (section 12.18) - this activity also allows tensioners to be reset in the likely event that conductors have experienced creep (section 12.16.1) since installation;
- Equipotential and current-carrying jumpers (section 12.4).

Installation is achieved by clamping a pull-lift to the wire either side of the cut-in point, taking the tension on the pull-lift, and then cutting the wire and installing the assembly. Once the assembly is secured, the tension can then be released and the assembly geometry adjusted and finalised.
20.15. Panning, Snagging and Works Completion

The panning stage involves a moving inspection of the completed installation from an elevated working platform on a vehicle that also has a pantograph fitted. This provides an initial basic check on OLE geometry and take-up of incoming and outgoing contact wires at overlaps (section 12.4) and crossovers (section 12.5).

Other items checked during panning inspections include:

- Electrical clearances between live and earthed parts (section 10.8) such as overbridges and signal structures;
- Tightness of all bolt fittings;
- Heel settings (section 12.13.1);
- Dropper loadings;
- Pantograph travel through high-risk cut-in locations such as neutral sections (section 12.6.3) and section insulators (section 12.6.1);
- Correct hanging of jumpers (section 12.4) and feeders (section 12.7.2);
- Elimination of contact wire twists or kinks;
- Smooth transitions at any contact wire splices (for alterations to existing OLE).

It is inevitable that an installation team will encounter problems during the process of OLE installation; this could stem from a material supply issue, failure of a piece of plant, adverse weather conditions, third parties such as track renewals affecting track geometry, or a multitude of other factors. The end result of these issues is that OLE is rarely, if ever, installed 100% correctly at first pass. Problems can include missing items or incorrect geometry. These items must be identified as early as possible, but no later than panning inspection, and categorised as follows:

- Defects: items which affect the integrity, functionality or maintainability of the asset, or poses a risk to safety;
- Snags: all other construction quality issues.

As construction is completed, attention must be given to progressively identifying all defects and snags, rectifying defects first. This provides flexibility in terms of permitting commissioning activities to proceed while minor non-service-affecting snags are cleared later on.

### 20.16. Substations

Substations are generally easier to construct than OLE, since their off-track location means they can constructed without disruption to railway operation, there is far less working at height involved, and there are no tensioning processes. For these reasons substation construction is much closer to a conventional construction site, apart from the electrical works and the steps necessary to connect the substation to the OLE.

#### 20.16.1. Civil Works

The initial stage of work creates the access road, fenced compound, earth mat and earth rods, then above that the concrete hard standing for transformers and buildings, any foundations necessary for switchgear masts, and cable trough routes for all of the cable runs. Trough routes between the substation and the lineside sealing end (section 10.2.9) locations are also installed at this stage. These will be built using conventional construction sector plant and processes, and the design must provide sufficient space for cranes and low loaders to move equipment around. Design of rural sites should pay special attention to local road access for heavy goods vehicles.

#### 20.16.2. Mast Erection

Outdoor switchgear (section 10.2.7) is carried on a series of short masts. These will be installed either as part of the civil works, or shortly after they are complete, using a conventional lorry-mounted crane.

#### 20.16.3. Containerised Building

The containerised building (section 10.2.1) will be constructed and fitted out with all switchgear, control and protection equipment at the supplier factory; this highly-controlled environment is designed to maximise the quality of the installation. The project team will visit the factory at key points in the fit-out to witness Factory Acceptance Testing (FAT). These tests are designed to demonstrate correct operation of circuit breakers, transformers and control equipment, and to progressively build validation assurance ready for entry into service.
20.16.4. Equipment Delivery

With the civil works complete, delivery of electrical equipment can take place. Depending on the type of substation, this can include:

- Transformers (section 10.2.3);
- Containerised building (section 10.2.1);
- Structure Mounted Outdoor Switchgear (section 10.2.7).

These will be delivered and installed using lorry-mounted cranes wherever possible, although larger buildings will need a full crane lift.

![Figure 395: Containerised ATFS building being installed from low loader. Borehamwood, UK](image)

20.16.5. Electrical Works

The substation now passes from being a civil construction site to an electrical fit-out site. All HV and LV cable connections, for both the live and neutral sides of the circuits, are laid in and connections made at each end. Outdoor switchgear is connected together using aerial busbars.

20.16.6. Grid Connections

Arrangements must be made for the connection of HV feeders at feeder stations (section 10.1.3), and LV power is required at all substations to provide power for SCADA (section 10.7), lighting and heating. These connections can be time-critical, with DNOs and NGCs having their own minimum timescales which must be factored into the programme (section 18.13).

20.16.7. Substation Bonding

The bonding of the substation site will now be carried out, connecting the substation equipment to the earth farm and to the adjacent railway through the neutral busbar.

20.16.8. OLE Connections

The final connection of the substation to the OLE (section 20.11) must be carefully coordinated with the OLE construction works to ensure that the lineside switching is complete and that the equipment is safe to connect to. Connections will be made using long-reach MEWPs or scaffold towers.

Once this work is complete, the site is handed over to the testing and commissioning team (section 21).
21. Testing, Commissioning and Entry Into Service

New OLE installations must undergo a number of electrical and mechanical tests prior to Entry Into Service (EIS). Depending on the extent of the changes and the level of novel design, any or all of the following tests may be needed. This process must be carefully planned, since it involves a complex sequence of tests conducted within restricted access to an operational railway. The tests themselves involve use of complex and sensitive specialists instrumentation, some of which must be installed on a test train. The complexity of planning and executing test trains on an operational railway should also not be underestimated, and the Testing & Commissioning (T&C) process is usually overseen by a separate specialist T&C team with experience of the activities within it.

21.1. Type Testing

*Type Tests* are carried out on components and assemblies of a new type, prior to their first use in a system, or use in a different system which will subject the item to new electrical or mechanical loads.

The nature of the type test will depend on the component, but will typically comprise one or more electrical and/or mechanical tests using loads significantly above the expected maximum loads in service. These tests may be to destruction, and are designed to establish the operational envelope of the component so that the maximum *working load* can be established and factors of safety confirmed.

The component may also be subjected to accelerated operating cycle tests, designed to simulate a working life in a much shorter space of time.

21.2. Snagging Walkout, Acceptance Tests and Completion Documents

It is an essential precursor for all of the subsequent tests that the construction is completed in accordance with the system and allocation designs (sections 18.9.1 and 19.4). This is usually confirmed by means of a walkout on site by senior representatives from design, construction, asset owner and maintainer. The walkout will identify any *snags* or corrections that need to be made prior to testing and entry into service. The walkout should be supported by completion documentation from the installer, recording the installed geometry, concrete *cube tests* and other important compliance evidence. These records will be checked against the acceptance criteria for the system, such as maximum stagger, gradient and other system parameters (section 20.13).

The later tests in this section should not be started until all elements of OLE construction are complete and all defects (section 20.15) have been cleared. Snags which do not affect the mechanical and electrical performance of the system can be cleared while testing continues.

21.3. Pressure Testing

Insulated cable elements of the OLE system, such as feeder cables at switching sites and ground level ATF routes, require electrical *pressure testing* to ensure that the insulation has not been compromised during installation. This test involves a voltage significantly above the operational level to be applied to the cores; for instance, UK standards255 specify a test at either 75kV DC for 15 minutes, or 44kV AC for 5 minutes.

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255 NR-PS-ELP-00008 “Product Specification for High Voltage Cables and Accessories for Traction Supplies”; Issue 3, December 2005; Network Rail; appendix B.
21.4. Section Proving

Section proving is a series of tests to confirm that the electrical sectioning (section 10.3) is as designed. Each electrical subsection is switched in turn - starting from the feeder station and working outwards - and each OLE subsection is then proved dead and live. This is done using a live line tester, an insulated pole connected between the OLE and the traction return rail. The pole allows a small leakage current to flow, which shows live via an indicator LED. These tests also act to test the electrical integrity of the isolators (section 12.7) when open and closed; they take place during a complete railway shutdown with all non-essential staff removed from site; and due to the safety critical nature of the test it is essential that both the ECO (section 10.7) and the site testers follow a strict test plan, and that the live line tester is always connected to traction earth before any test - live or dead - takes place.

21.5. Short Circuit Testing

Short circuit testing is designed to prove that the electrical protection (section 10.7.1) works as designed, and that all lineside equipment is fully immunised (section 10.4) under the most onerous conditions.

One or more electrical faults are deliberately introduced to live OLE - usually using a portable isolator test rig.
to connect the OLE to traction earth - and the performance of the electrical protection and the circuit breaker monitored during the subsequent electrical trip. Short circuit tests are carried out under the strictest of test conditions.

**Figure 398: Voltage and current traces from short circuit test at a feeder station**

Measurements taken during these tests include rise in earth potential, feeder current, fault clearance times and return current paths during the fault and data packet monitoring for the signalling system.

### 21.5.1. Tether Testing

Prior to any dynamic test, it is important to calibrate the aerodynamic behaviour of the pantograph. This is achieved by means of a **tether test**, where the pantograph is temporarily restrained by means of tether ropes attached between the pantograph carbon carrier (section 12.1) and the train roof. The ropes are set so that the pantograph will always be below contact wire height, and strain gauges are inserted into the ropes to measure the aerodynamic component of contact force. The train is then driven to full speed to measure this force. Once tether testing is complete the tethers are removed for the remainder of the dynamic testing.

**Figure 399: (l-r) Pantograph tethers (red) being fitted, tethered pantograph ready for testing**
21.6. Unpowered Mechanical Testing

This test is designed to validate the dynamic performance of the mechanical system\textsuperscript{256}, without introducing the additional risk of powering an electric train from the new OLE. A special test vehicle is used which carries an instrumented pantograph, and is pulled by a diesel locomotive. The test train will generally run at increasing speeds as the test proceeds, recording contact force and height and stagger data, as well as video of the pantograph. Any such train is treated as though it was electric for operational purposes, since it is in contact with the OLE.

21.7. Full Dynamic Testing

This test may also cover the areas described in the previous section, but will also confirm the expected electrical behaviour by using an electric train of the type planned for use on the electrified route. This is often combined with contemporaneous testing of lineside equipment to confirm immunisation levels (section 10.4) are as planned.

21.8. Entry Into Service

Entry Into Service (EIS) is the process of demonstrating that new electrification is safe to enter service and will perform as set out in the project requirements specification (section 18.2). The project will be required to produce evidence of the system readiness in accordance with applicable standards, safety and performance requirements. Evidence provided will include a range of risk assessments, safety justifications, construction completion evidence and test data.

In the UK and Europe the evidence is presented to one or more independent bodies, who will assess conformance with the relevant regulations and standards. In the EU a Notified Body (NoBo) is a country-appointed independent third party organisation which assesses the conformity of a railway system before it is entered into service. They do this by undertaking conformity assessments as set out in the applicable TSIs (section 12.1). In the UK an Approved Body (ApBo) carries out the same function against the applicable NTSNs. A Designated Body (DeBo) is a similar body, but which has competence to assess a railway system against the national rules (such as Railway Group Standards in the UK).

\textsuperscript{256}In the EU these tests are carried out against BS EN50317:2012 "Railway Applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line"; 29 February 2012; BSI.

\textsuperscript{257}Trace lines are stagger (red), height (green) and contact force (dark blue).
When the DeBo, NoBo and ApBo (as applicable to the project) are satisfied with the evidence presented by the project, they will make recommendations to the national regulator\(^{258}\) for the system to be placed into service. The regulator has the final decisions as to whether this takes place.

The authorisation process should be seen as a gradual building of evidence towards EIS throughout the design, construction and testing processes. As with the rest of the process, early EIS planning is essential to a successful completion of the project.

21.9. **As Built Documentation**

An essential final step in the project is to update all of the AFC drawings with any changes made to the design during the construction process. These updates are included in the *As Built* (or *As Fitted*) drawings, which should accurately represent the final installed equipment. These drawings are transferred to the maintenance organisation to provide a baseline configuration for future works. Any future change to the system should then use the As Built drawings as the starting point, updating them in accordance with section 19 before producing a new set of As Built records.

\(^{258}\) In the UK this is the Office of Rail and Road.
22. OLE Maintenance & Renewals

It is important to consider the maintainability of OLE at the planning and design stages, and OLE is relatively maintenance-free compared with other railway systems if designed correctly. It is usually inspected periodically, and any maintenance is carried out by small teams working from rail-mounted scissor lift or MEWP (section 20).

Depending on the age and type of the equipment, regular maintenance items can include:

- Checking component condition, corrosion and position;
- Checking and cleaning insulators;
- Checking and adjusting height and stagger;
- Adjusting and cleaning neutral sections and section insulators;
- Checking mechanical and electrical clearances;
- Checking continuity of electrical connections;
- Checking wire tensions;
- Checking mechanical wear (for instance on hinge pins - typically checking a percentage of fittings);
- Security of nut and bolt fixings;
- Greasing connections\(^{259}\);
- Structure painting (for older non-galvanised structures);
- Checking contact wire wear;
- Campaign change replacements of known problem components;
- Vegetation management (section 20.8).

Maintenance periodicity depends on age of equipment, traffic levels, criticality of the route, the matching (or otherwise) of pantographs and OLE, and the availability of access.

Contact wire will need replacing as part of a midlife renewal at around 25% to 33% wear, which is generally 20 to 30 years after installation. Leaving contact wire in situ significantly beyond this wear level creates a risk that dropper clips and other contact wire connections are impacted by the pantograph, and erodes the ability of the wire to withstand tension, leading to parting and dewirement. Midlife renewal will usually also address other issues which have come to light since installation.

More onerous rectification work is required after a dewirement. The team will be required to bring the OLE back into service as quickly as possible, and new wiring and support assemblies may be required. Each area has a store of materials for use in such incidents.

\(^{259}\)Modern systems are usually grease-free.
23. Remote Condition Monitoring

The lack of redundancy in the OLE system makes it very important to understand and control the condition of both the infrastructure and the train-mounted equipment. In recent years an increased emphasis has been placed on the use of automated monitoring systems to augment the normal visual inspection processes.

23.1. Lineside Pantograph Monitoring

Monitoring of pantograph condition may be undertaken from a fixed lineside location using various techniques. *Panchex* is a system which has been used at critical locations on the UK electrified network since the 1980s, and is designed to detect faulty pantographs. The system comprises a linear sensor attached to the contact wire, which measures uplift (section 12.13.1) as each train passes. The system is synchronised with the *train describer* system which the signaller uses to identify each train. In this way a train with a faulty pantograph can be quickly taken out of service before the fault causes a dewirement.

The Panchex system has the disadvantage of requiring equipment to be placed in the OLE system itself, and requires ongoing maintenance. It is now being replaced with the *PanMon* and *Pantobot* systems, which use 3D photogrammetry techniques to detect faults in passing pantographs, and thus do not need any connection to the OLE.

23.2. Train-Mounted OLE Monitoring

Many administrations now use a dedicated OLE monitoring train, which passes over the electrified network at standard intervals and provides dynamic monitoring (section 21.6) through an instrumented pantograph. This is often tied into a Global Positioning System and allows faults to be accurately located for rectification. Some train operators are now applying these systems to a small number of service trains, which travel key routes at much higher frequencies and so can spot trends earlier than a dedicated train.

Figure 401: Ricardo Rail PanMon pantograph monitoring equipment. Glasgow, UK

Figure 402: High speed Shinkansen class 923 OLE monitoring train, a.k.a. "Dr Yellow"
Appendix A

UK Electrification Build History

This list provides scheme extents and build dates for all known OLE installations in the UK.

Scheme extents are based on:

- Contemporary sources for recent schemes (2000 onwards);
- Various document sources for intermediate schemes (1985-2000);
- "The Age of the Electric Train" by J.C. Gillham (prior to 1985).

Completion dates are based on:

- Contemporary sources for recent schemes;
- "The Age of the Electric Train" by J.C. Gillham for historical schemes;
- "Electrifying the East Coast Route" by Peter Semmens for NER, GN and ECML schemes;

If no accurate date available from any source, 1st January on the year of opening is assumed. Opening date and status is based on first revenue-earning public electric service.

Categories are based on the following:

- **Tram** includes all UK schemes with a street-running element, or extensions of a scheme with a street-running element;
- **Metro** includes all self-contained non-tram systems, including DLR and Tyne & Wear;
- **Mainline** comprises all Network Rail-owned systems (including sections shared with LUL, Tyne & Wear Metro, Sheffield Supertram);
- **High speed** includes HS1, HS2 and the Channel Tunnel;
- **Heritage** includes all systems operating on heritage/tourist lines.

Status Codes are as follows:

- **Open** = currently in service;
- **Closed** = line closed;
- **Removed** = electrification removed;
- **Converted** = converted from one voltage and/or system to another;
- **WIP** = electrification under construction.

All items in red are to be confirmed.
<table>
<thead>
<tr>
<th>Build</th>
<th>Voltage From</th>
<th>Voltage To</th>
<th>Route</th>
<th>Scheme</th>
<th>Stage</th>
<th>Category</th>
<th>Type</th>
<th>OLE Type</th>
<th>Date</th>
<th>Status</th>
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<td>25kV 50Hz AC</td>
<td>Stafford - Crewe</td>
<td>West Coast Mainline South</td>
<td>Stage 3a</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>07/01/1963</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Chelsford - Colchester</td>
<td>Great Eastern</td>
<td>Stage 3</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>01/03/1963</td>
<td>Open</td>
</tr>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Lichfield - Stafford</td>
<td>West Coast Mainline South</td>
<td>Stage 3b</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>22/10/1963</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>600V DC</td>
<td>Town End - Glory Mine</td>
<td>Crich Tramway Village</td>
<td>Heritage</td>
<td>Trolley</td>
<td>-</td>
<td>01/01/1964</td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Nuneaton - Lichfield</td>
<td>West Coast Mainline South</td>
<td>Stage 3c</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>02/03/1964</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Rugby - Nuneaton</td>
<td>West Coast Mainline South</td>
<td>Stage 3d</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>16/11/1964</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>1.5kV DC</td>
<td>Darnall - Tinsley Yard</td>
<td>Woodhead Route</td>
<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>30/05/1965</td>
<td>Closed</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Cheadle Huime - Macclesfield</td>
<td>West Coast Mainline South</td>
<td>Stage 4</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>14/06/1965</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>London Euston - Rugby inc Northampton Loop</td>
<td>West Coast Mainline South</td>
<td>Stage 5</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>06/12/1965</td>
<td>Open</td>
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<td>De-electrification</td>
<td>6.7kV 50Hz AC</td>
<td>-</td>
<td>Lancaster - Morecambe - Heysham</td>
<td>-</td>
<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1966</td>
<td>Removed</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Wolverhampton - Stafford &amp; Bescot; Portobello Jct - Bushbury Jct</td>
<td>West Coast Mainline South</td>
<td>Stage 6</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>18/06/1966</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Colwich - Macclesfield via Stone</td>
<td>West Coast Mainline South</td>
<td>Stage 7a</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>05/12/1966</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Stone - Norton Bridge</td>
<td>West Coast Mainline South</td>
<td>Stage 7b</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>05/12/1966</td>
<td>Open</td>
</tr>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Rugby - Wolverhampton via Birmingham</td>
<td>West Coast Mainline South</td>
<td>Stage 7c</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>06/12/1966</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Birmingham - Walsall</td>
<td>West Coast Mainline South</td>
<td>Stage 7d</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>06/12/1966</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Aston - Stechford</td>
<td>West Coast Mainline South</td>
<td>Stage 7e</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 1</td>
<td>13/12/1966</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Glasgow - Gourock &amp; Wemyss Bay</td>
<td>Glasgow suburban lines</td>
<td>Stage 2</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 2</td>
<td>05/06/1967</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Clayhill Jct - Cheshunt Jct</td>
<td>Lea Valley</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3</td>
<td>05/05/1969</td>
<td>Open</td>
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<td>Conversion</td>
<td>1.5kV DC</td>
<td>25kV 50Hz AC</td>
<td>Manchester Oxford Rd - Altrincham</td>
<td>MS&amp;LA Line</td>
<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>03/05/1971</td>
<td>Removed</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Wolverhampton North Jct - Oxley</td>
<td>West Coast Mainline South</td>
<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1972</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>500V DC</td>
<td>Beamish Loop</td>
<td>Beamish Open Air Museum</td>
<td>Heritage</td>
<td>Trolley</td>
<td>-</td>
<td>01/01/1973</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>120V DC</td>
<td>Seaton - Colyton</td>
<td>Seaton Tramway</td>
<td>Heritage</td>
<td>Trolley</td>
<td>-</td>
<td>01/01/1973</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Bamfurlong Jct - Preston (Freight Only)</td>
<td>West Coast Mainline North</td>
<td>Stage 2</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>23/07/1973</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Weaver Jet - Bamfurlong Jct (Freight Only)</td>
<td>West Coast Mainline North</td>
<td>Stage 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>23/07/1973</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Weaver Jet - Preston (Passenger)</td>
<td>West Coast Mainline North</td>
<td>Stage 3</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>23/07/1973</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Preston - Motherwell; Hamilton Circle; Uddingston - Wishaw via Bolbollan - Motherwell - Whifflet</td>
<td>West Coast Mainline North</td>
<td>Stage 4</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>22/04/1974</td>
<td>Open</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Lanark Jct - Lanark</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>06/05/1974</td>
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<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Glasgow West St - Muihhouse Jct</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>01/01/1975</td>
<td>Open</td>
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<tr>
<td>Conversion</td>
<td>6.25kV 50Hz AC</td>
<td>25kV 50Hz AC</td>
<td>Gidea Park - Shenfield</td>
<td>Great Eastern</td>
<td>Mainline</td>
<td>OLE</td>
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<td>01/01/1976</td>
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<td>New Build</td>
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<td>25kV 50Hz AC</td>
<td>Drayton Park - Welwyn Garden City &amp; Hertford North</td>
<td>Great Northern Suburban</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>08/11/1976</td>
<td>Open</td>
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<td>25kV 50Hz AC</td>
<td>Wilham - Rainworth</td>
<td>Mainline</td>
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<td>Mark 3a</td>
<td>31/10/1977</td>
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<td>New Build</td>
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<td>25kV 50Hz AC</td>
<td>Melton Jct - Edwalton</td>
<td>RIDC Melton (Old Dalby Test Track)</td>
<td>Private</td>
<td>OLE</td>
<td>Mix</td>
<td>01/01/1978</td>
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<td>Build</td>
<td>Voltage From</td>
<td>Voltage To</td>
<td>Route</td>
<td>Scheme</td>
<td>Stage</td>
<td>Category</td>
<td>Type</td>
<td>OLE Type</td>
<td>Date</td>
<td>Status</td>
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<td>New Build</td>
<td>-</td>
<td>unknown</td>
<td>Dudley</td>
<td>Black Country Living Museum</td>
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<td>Heritage</td>
<td>Trolley</td>
<td>Mark 3a</td>
<td>01/01/1978</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Welwyn Garden City - Royston</td>
<td>Glasgow suburban lines</td>
<td></td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>06/02/1978</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>London Kings Cross - Finsbury Park</td>
<td>Great Northern Suburban</td>
<td>Stage 2a</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>06/02/1978</td>
<td>Open</td>
</tr>
<tr>
<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Dalmon Park - Yoker</td>
<td>Glasgow suburban lines</td>
<td></td>
<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1979</td>
<td>Open</td>
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<tr>
<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Pollokshields East - Cathcart</td>
<td>Glasgow suburban lines</td>
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<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1979</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Hertford North - Stevenage</td>
<td>Great Northern Suburban</td>
<td>Stage 2c</td>
<td>Mainline</td>
<td>OLE Mark 3a</td>
<td>Mark 3a</td>
<td>01/01/1979</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Finnieston Jt - Glasgow Central Low Level - Ratherglen</td>
<td>Glasgow suburban lines</td>
<td></td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>05/12/1979</td>
<td>Open</td>
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<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Dalmon Park - Finnieston via Westerton; Yoker - Jordanhill; Westerton - Milngavie</td>
<td>Glasgow suburban lines</td>
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<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1979</td>
<td>Open</td>
</tr>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Heaton Park</td>
<td>Heaton Park Tramway</td>
<td></td>
<td>Heritage</td>
<td>Trolley</td>
<td>Mark 3a</td>
<td>01/01/1979</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Castlefield Jt - Trafford Park FLT</td>
<td>East Anglia Transport Museum</td>
<td></td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3a</td>
<td>12/05/1980</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Haymarket - St James, Bank Foot, Howorth &amp; South Shields</td>
<td>East Anglia Transport Museum</td>
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<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>11/08/1980</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>London Liverpool St - Gidea Park, Shenfield - Southend</td>
<td>Great Eastern</td>
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<td>OLE Mark 3c</td>
<td>Mark 3c</td>
<td>01/01/1981</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Carlton Colville</td>
<td>East Anglia Transport Museum</td>
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<td>Mainline</td>
<td>OLE</td>
<td>-</td>
<td>01/01/1981</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Edgeley - Hazel Grove</td>
<td>Woodhead Route</td>
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<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>17/08/1981</td>
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<td>25kV 50Hz AC</td>
<td>-</td>
<td>Basildon - Canbridge FLT</td>
<td>Woodhead Route</td>
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<td>OLE Mark 3c</td>
<td>Mark 3c</td>
<td>11/08/1981</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>London St Pancras &amp; Moorgate – Bedford</td>
<td>Midland Mainline</td>
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<td>OLE Mark 3c</td>
<td>Mark 3c</td>
<td>28/03/1983</td>
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<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Hackney - Chingford</td>
<td>Woodhead Route (truncated)</td>
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<td>Mark 3c</td>
<td>10/12/1984</td>
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<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Manchester - Hadfield</td>
<td>Woodhead Route</td>
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<td>Mainline</td>
<td>OLE -</td>
<td>Mark 3c</td>
<td>12/05/1986</td>
<td>Open</td>
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<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Bury Street - Enfield Town</td>
<td>Woodhead Route</td>
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<td>Mainline</td>
<td>OLE Mark 3c</td>
<td>Mark 3c</td>
<td>12/05/1986</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Navarino Road Jt - Reading Lane Jct</td>
<td>Great Eastern</td>
<td>Stage 4</td>
<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>13/05/1985</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Freight Terminal Jt - Camden Road East Jct</td>
<td>Great Eastern</td>
<td>Stage 5</td>
<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>22/07/1985</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Colchester - Ipswich</td>
<td>Great Eastern</td>
<td>Stage 6</td>
<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>12/05/1986</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Ipswich - Stowmarket</td>
<td>Great Eastern</td>
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<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>12/05/1986</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Wickford - Southminster</td>
<td>Great Eastern</td>
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<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>12/05/1986</td>
<td>Open</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Manningtree - Harwich</td>
<td>Great Eastern</td>
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<td>Mainline</td>
<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>12/05/1986</td>
<td>Open</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Romford - Uptonmeer</td>
<td>Great Eastern</td>
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<td>OLE Mark 3b</td>
<td>Mark 3b</td>
<td>12/05/1986</td>
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<td>25kV 50Hz AC</td>
<td>-</td>
<td>Paisy - Ay</td>
<td>Great Eastern</td>
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<td>Mark 3b</td>
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<td>25kV 50Hz AC</td>
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<td>Hitchin - Huntingdon</td>
<td>Great Eastern</td>
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<td>OLE Mark 3b</td>
<td>Mark 3b</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>-</td>
<td>Kilsinnig - Ardrossan South Beach; Dubbs Jt - Byrehill Jt</td>
<td>Ardrossan South Beach - Large &amp; Ardrossan Harbour</td>
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<td>25kV 50Hz AC</td>
<td>-</td>
<td>Stratford FLT</td>
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<td>Mark 3b</td>
<td>01/01/1987</td>
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<td>-</td>
<td>Temple Mills Yard</td>
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<td>Mark 3b</td>
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<td>Canbury Jt - Finsbury Park</td>
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<td>Dalton Kingsland - Camden Road West Jct</td>
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<td>Mark 3b</td>
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<td>Dalton Kingsland</td>
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<td>Mark 3b</td>
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<td>Bishop's Storfford - Cambridge</td>
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<td>Mark 3b</td>
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<td>-</td>
<td>Ardrossan South Beach - Large &amp; Ardrossan Harbour</td>
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<td>Mark 3b</td>
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<td>Mark 3b</td>
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<td>Mark 3b</td>
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<td>Stage 3</td>
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<td>Mark 3b</td>
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<td>Route</td>
<td>Scheme</td>
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<td>Seven Sisters - Tottenham South</td>
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<td>25kV 50Hz AC</td>
<td>Doncaster - York</td>
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<td>York - Newcastle</td>
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<td>Stage 5</td>
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<td>Stratford - Copper Mill Junction</td>
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<td>Mark 3b</td>
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<td>Private</td>
<td>OLE</td>
<td>Siemens</td>
<td>Mark 3b</td>
<td>01/01/1990</td>
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<td>25kV 50Hz AC</td>
<td>Lilburn Lane Works, Derby</td>
<td>Tram</td>
<td>Siemens</td>
<td>Heritage</td>
<td>Mark 3b</td>
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<td>25kV 50Hz AC</td>
<td>Newcastle – Edinburgh</td>
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<td>Mainline</td>
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<td>Carstairs – Edinburgh</td>
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<td>Stage 7</td>
<td>Mainline</td>
<td>OLE</td>
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<td>25kV 50Hz AC</td>
<td>Dirn Jct - North Berwick</td>
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<td>Mark 3b</td>
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<td>Conversion</td>
<td>1.2kV DC</td>
<td>750V DC</td>
<td>Manchester Piccadilly - Manchester Victoria - Bury</td>
<td>Manchester Metrolink</td>
<td>Phase 1</td>
<td>Tram</td>
<td>OLE</td>
<td>06/04/1992</td>
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<td>750V DC</td>
<td>Manchester - Altrincham</td>
<td>Manchester Metrolink</td>
<td>Phase 1 (previously MJS&amp;A)</td>
<td>Tram</td>
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<td>15/06/1992</td>
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<td>Cambridge - King’s Lynn</td>
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<td>25kV 50Hz AC</td>
<td>Dollands Moor Freight Terminal</td>
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<td>OLE</td>
<td>Mark 5</td>
<td>01/01/1993</td>
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<td>North Pole Jct - West London Jct</td>
<td>Channel Tunnel enabling works</td>
<td>West London Line</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>01/01/1993</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Manchester Airport North Spur</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
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<td>Lichfield - Birmingam New St; Aston - Redditch</td>
<td>Cross City Line</td>
<td>Mainline</td>
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<td>Mark 3b</td>
<td>06/06/1993</td>
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<td>New Build</td>
<td>750V DC</td>
<td>Sheffield - Meadowhall, Halliway, Hirdings Park, Malin Bridge &amp; Sheffield Supertram</td>
<td>Tram</td>
<td>OLE</td>
<td>01/01/1994</td>
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<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>North Pole Depot</td>
<td>Channel Tunnel enabling works</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>01/01/1994</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Cherton - Freeth</td>
<td>Channel Tunnel</td>
<td>High Speed</td>
<td>OLE</td>
<td>Channel Tunnel</td>
<td>19/05/1994</td>
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<td>New Build</td>
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<td>Woodside - Taylor Street</td>
<td>Wirral Tramway</td>
<td>Heritage</td>
<td>Trolley</td>
<td>01/01/1995</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Leeds - Bradford, Skipton &amp; Ilkey</td>
<td>Leeds North West</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>20/09/1995</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Manchester Airport South Spur</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3c</td>
<td>01/01/1996</td>
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<td>Conversion</td>
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<td>25kV 50Hz AC</td>
<td>Camden Road West Jct - Acton Central</td>
<td>North London Line</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>01/01/1998</td>
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<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>London Paddington - Stockley Airport Junction - Heathrow Tunnel Jet</td>
<td>Heathrow Express</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
<td>19/01/1998</td>
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<td>25kV 50Hz AC</td>
<td>Heathrow Tunnel Jct - Heathrow Airport</td>
<td>Heathrow Express</td>
<td>Mainline</td>
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<td>Mark 3b</td>
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<td>750V DC</td>
<td>Birmingham Snow Hill - Wolverhampton</td>
<td>Midland Metro</td>
<td>Phase 1</td>
<td>Tram</td>
<td>OLE</td>
<td>30/09/1999</td>
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<td>Kensal Green Jct - Willesden Jct</td>
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<td>Mark 3b</td>
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<td>750V DC</td>
<td>Croydon - New Addington, Wimbledome, Beckenham Jct &amp; Elmers End</td>
<td>Croydon Tramlink</td>
<td>Tram</td>
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<td>30/03/2000</td>
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<td>New Build</td>
<td>750V DC</td>
<td>Cumberbrough - Eccles</td>
<td>Manchester Metrolink</td>
<td>Phase 2</td>
<td>Tram</td>
<td>OLE</td>
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<td>Peel Jct - Sunderland - South Hylton</td>
<td>Tyne &amp; Wear Metro</td>
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<td>SICAT</td>
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<td>25kV 50Hz AC</td>
<td>Crewe - Kidsgrove</td>
<td>West Coast Route Modernisation</td>
<td>Mainline</td>
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<td>Fawdon Jct - Chelton</td>
<td>Channel Tunnel Rail Link</td>
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<td>High Speed</td>
<td>OLE</td>
<td>HS1</td>
<td>25/09/2003</td>
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<td>750V DC</td>
<td>Nottingham - Phoenix Park &amp; Hucknall</td>
<td>Nottingham Express Transit</td>
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<td>Tram</td>
<td>OLE</td>
<td>UK1</td>
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<td>Larkhall Branch Extension</td>
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<td>25kV 50Hz AC</td>
<td>Euston - Liverpool, Manchester</td>
<td>West Coast Route Modernisation</td>
<td>Mainline</td>
<td>OLE</td>
<td>UK1</td>
<td>01/01/2008</td>
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<td>25kV 50Hz AC</td>
<td>Tamworth - Armitage/Handsacre</td>
<td>Trent Valley Four Tracking</td>
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<td>Shields to Gourcou (S2G) Mark 2 to SICAT</td>
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<td>Voltage To</td>
<td>Route</td>
<td>Scheme</td>
<td>Stage</td>
<td>Category</td>
<td>Type</td>
<td>OLE Type</td>
<td>Date</td>
<td>Status</td>
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<td>Paisley Canal Electrification</td>
<td>25kV 50Hz AC</td>
<td>Mainline</td>
<td>OLE</td>
<td>Mark 3b</td>
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<td>New Build</td>
<td>750V DC</td>
<td>Manchester Victoria - Rochdale</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Phase 3a</td>
<td>Mainline</td>
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<td>750V DC</td>
<td>Manchester Piccadilly - Droylsden</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Phase 3a</td>
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<td>Trafford Bar - St Werburgh's Road</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Phase 3a</td>
<td>Mainline</td>
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<td>25kV 50Hz AC</td>
<td>Manchester Victoria - Newtong-le-Wilnors</td>
<td>25kV 50Hz AC</td>
<td>North West Electrification Programme</td>
<td>Phase 1</td>
<td>Mainline</td>
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<td>Series 2</td>
<td>01/12/2013</td>
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<td>Springburn - Cumbernauld</td>
<td>25kV 50Hz AC</td>
<td>EGI</td>
<td>Mainline</td>
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<td>750V DC</td>
<td>Edinburgh Airport - York Place</td>
<td>25kV 50Hz AC</td>
<td>Edinburgh Tram</td>
<td>Phase 1A</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>31/05/2014</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>St Werburgh's Road - Manchester Airport</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Phase 3b</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>01/11/2014</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Droylsden - Ashton-under-Lyne</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Phase 3b</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>01/11/2014</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Rutherglen - Coatbridge</td>
<td>25kV 50Hz AC</td>
<td>North West Electrification Programme</td>
<td>Phase 2c</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>01/01/2015</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Newtong-le-Wilnors - Edge Hill</td>
<td>25kV 50Hz AC</td>
<td>North West Electrification Programme</td>
<td>Phase 2a</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>01/03/2015</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Preston - Larkpool</td>
<td>25kV 50Hz AC</td>
<td>North West Electrification Programme</td>
<td>Phase 2b</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>17/05/2015</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Nottingham - Clifton</td>
<td>25kV 50Hz AC</td>
<td>Nottingham Express Transit</td>
<td>Phase 2</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>25/08/2015</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Nottingham - Toton Lane</td>
<td>25kV 50Hz AC</td>
<td>Nottingham Express Transit</td>
<td>Phase 2</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>25/08/2015</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Birmingham Snow Hill - Birmingham New St</td>
<td>25kV 50Hz AC</td>
<td>Midlands Metro</td>
<td>Phase 2</td>
<td>Mainline</td>
<td>OLE</td>
<td></td>
<td>30/05/2016</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>St Peters Square - Manchester Victoria</td>
<td>25kV 50Hz AC</td>
<td>Manchester Metrolink</td>
<td>Second City Crossing</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>01/02/2017</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Stockley - Maidenhead</td>
<td>±25kV 50Hz AC</td>
<td>Crossrail</td>
<td>Maidenhead</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>22/05/2017</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Scours Lane - Didcot</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 3</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>28/12/2017</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Kettering Bridge - Reading - Scours Lane</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 3a</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>28/12/2017</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Maidenhead - Kettering Bridge</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>28/12/2017</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Gospel Oak - Barking</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>15/01/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Preston - Larkpool</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>21/05/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Newbridge Junction - Glasgow Queen St via Falkirk High</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>24/07/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Barrow Green - Bromsgrove</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>29/07/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>750V DC</td>
<td>Meadowhall South - Rotherham Central</td>
<td>±25kV 50Hz AC</td>
<td>Sheffield Tram-Train</td>
<td>Meadowhall South - Rotherham Central</td>
<td>Tram</td>
<td>OLE</td>
<td>Series 2 DC</td>
<td>25/10/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Didcot - Swindon</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 5</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>29/10/2018</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Strirling - Alkma - Dunblane</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 5/6</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>02/01/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Reading - Newbury</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 2</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>02/01/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Manchester Deal St Jct - Preston via Bolton</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 4</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>11/02/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Woollton Basnett - Chippenham</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 7C</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>21/04/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Midcaldor Junction - Holytown Junction via Shotts</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 7C</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 2</td>
<td>25/04/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Walsall - Rugeley</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 8</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>15/12/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Patchway - Newport (excl. Severn Tunnel)</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 8</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>15/12/2019</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Bristol Parkway - Patchway</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 9</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>04/01/2020</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Newport - Cardiff</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 8</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>31/05/2020</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>±25kV 50Hz AC</td>
<td>Severn Tunnel</td>
<td>±25kV 50Hz AC</td>
<td>Great Western Electrification Programme</td>
<td>Route Section 8</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td>31/05/2020</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Bedford - Kettering - Corby</td>
<td>25kV 50Hz AC</td>
<td>Core Valley Lines Electrification</td>
<td>Key Output 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>UKMS125</td>
<td>16/05/2021</td>
<td>Open</td>
</tr>
<tr>
<td>New Build</td>
<td>25kV 50Hz AC</td>
<td>Cardiff Queen St - Rhymney (excl. Caerphilly - Lisvane &amp; Thornhill)</td>
<td>25kV 50Hz AC</td>
<td>Core Valley Lines Electrification</td>
<td>Key Output 1</td>
<td>Mainline</td>
<td>OLE</td>
<td>UKMS100</td>
<td>2022</td>
<td>WIP</td>
</tr>
<tr>
<td>Conversion</td>
<td>500V DC</td>
<td>Douglas - Ramsay</td>
<td>500V DC</td>
<td>Mews Electric Railway</td>
<td>Heritage</td>
<td>Trolley</td>
<td>unknown</td>
<td></td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>Conversion</td>
<td>500V DC</td>
<td>Gymn - Fleetwood</td>
<td>500V DC</td>
<td>Blackpool Tram</td>
<td>Mainline</td>
<td>OLE</td>
<td>Series 1</td>
<td></td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>Kewsl Green - Stockley</td>
<td>25kV 50Hz AC</td>
<td>Paddington to Reading (P2R)</td>
<td>Metro</td>
<td>OLE</td>
<td>Series 1</td>
<td></td>
<td>Open</td>
<td></td>
</tr>
<tr>
<td>Build</td>
<td>Voltage From</td>
<td>Voltage To</td>
<td>Route</td>
<td>Scheme</td>
<td>Stage</td>
<td>Category</td>
<td>Type</td>
<td>OLE Type</td>
<td>Date</td>
<td>Status</td>
</tr>
<tr>
<td>------------</td>
<td>--------------</td>
<td>-------------</td>
<td>----------------------------</td>
<td>------------</td>
<td>-------------</td>
<td>----------</td>
<td>------------</td>
<td>----------------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>Conversion</td>
<td>25kV 50Hz AC</td>
<td>±25kV 50Hz AC</td>
<td>Pudding Mill Lane - Shenfield</td>
<td>Crossrail</td>
<td>Mainline</td>
<td>OLE</td>
<td>OLE</td>
<td>Alstom Cariboni, F+F ROCS</td>
<td>TBC</td>
<td>WIP</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>±25kV 50Hz AC</td>
<td>Royal Oak - Liverpool St</td>
<td>Crossrail</td>
<td>Shenfield Section</td>
<td>Metro</td>
<td>OLE</td>
<td>Alstom Cariboni</td>
<td>TBC</td>
<td>WIP</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>±25kV 50Hz AC</td>
<td>Pudding Mill Lane - Plumstead</td>
<td>Crossrail</td>
<td>Plumstead Section</td>
<td>Metro</td>
<td>OLE</td>
<td>Alstom Cariboni</td>
<td>TBC</td>
<td>WIP</td>
</tr>
<tr>
<td>New Build</td>
<td>-</td>
<td>25kV 50Hz AC</td>
<td>Plumstead - Abbey Wood</td>
<td>Crossrail</td>
<td>Abbey Wood Section</td>
<td>Metro</td>
<td>OLE</td>
<td>Alstom Cariboni</td>
<td>TBC</td>
<td>WIP</td>
</tr>
</tbody>
</table>
Appendix B

UK Dual Voltage Areas

A number of UK locations have dual voltage electrification, and their stray current mitigation measures are summarised below\(^1\).

**AC Isolation Transformers**

AC isolation transformers (section 10.11.1) are fitted at:

- 25kV AC OLE on ECML to 750V DC 3rd rail on Moorgate Branch at Drayton Park;
- 2x25kV AC OLE on High Speed 1 to 750V DC 3rd rail on mainline at Dollands Moor freight yard, Ashford, Ebbsfleet and Fawkham Junction;
- 25kV AC OLE on WCML to 750V DC 3rd rail on North London Line (NLL) at Primrose Hill;
- 25kV AC OLE on NLL to 750V DC 3rd rail NLL at Acton Central;
- 25kV AC OLE on West London Line (WLL) and North Pole Depot to 750V DC 3rd rail WLL at Scrubs Lane;
- 25kV AC OLE on NLL to 660V DC 4th rail on London Underground at Willesden Junction.

**DC Contactors**

DC Contactors (section 10.11.2) are fitted at:

- 25kV AC OLE on Thameslink to 750V DC 3rd rail on Thameslink at Ludgate Cellars;
- Three Bridges depot (between earthed rails in depot and 25kV test facility).

**Non-linear Resistors**

Non-linear resistors (section 10.11.2) are fitted at:

- 25kV AC OLE on NLL to 750V DC 3rd rail on East London Line at Dalston to Highbury & Islington.

**DC Stray Current Collection Mat, AC Foundation Insulation**

DC Stray Current Collection Mats and AC Foundation Insulation (section 10.10.2) are fitted at:

- Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Victoria;
- Adjacent 25kV AC OLE on GEML and 750V DC 3rd rail on DLR between Bow Junction and Stratford. Stray current collection mats are not present on 100% of the route.

---

\(^1\) "Electrification Infrastructure – Reducing Whole Life Cost: DC Stray Currents", M. Sigrist; 2014; Network Rail.
No Specific Measures

No specific measures are believed to be taken at:

- Shared and adjacent 25kV AC OLE on WCML and 660V DC 3rd/4th rail on London Overground between Euston and Watford Junction;
- Adjacent 25kV AC OLE on London Tilbury & Southend (LT&S) and 660V DC 4th rail on London Underground between Bromley by Bow and Upminster;
- 25kV AC OLE on WCML to 750V DC 3rd rail on Merseyrail at Hunts Cross West Junction;
- Adjacent 25kV AC OLE on GWML to 660V DC 4th rail on London Underground between Paddington and Royal Oak and at Ealing Broadway;
- Adjacent 25kV AC OLE on GWML and 750V DC 3rd rail at Reading;
- Adjacent 25kV AC OLE on ECML and 750V DC 3rd rail on NLL at Canonbury West Junction;
- Adjacent 25kV AC OLE on LT&S and 750V DC 3rd rail on Docklands Light Railway (DLR) between Christian Street Junction and Limehouse;
- Adjacent 25kV AC OLE on mainline and 750V DC OLE on Midland Metro at Birmingham New Street/Stephenson Street;
- Adjacent 25kV AC OLE on ECML and 1500V DC OLE on Tyne & Wear Metro at Manors, Chillingham Road/Heaton and Benton;
- Adjacent 25kV AC OLE on GEML and 660V DC 4th rail on London Underground at Stratford. Systems are directly bonded together via red bonds.

To Be Confirmed

The following interfaces are to be confirmed:

- Adjacent 25kV AC OLE on Edinburgh & Glasgow (E&G) and 750V DC OLE on Edinburgh Tram between Haymarket and Edinburgh Park;
- Adjacent 25kV AC OLE and 750V DC OLE on Manchester Metrolink at Manchester Piccadilly, Deansgate, Manchester Airport;
- Adjacent 25kV AC OLE on Crossrail and 750V DC 3rd rail on mainline between Woolwich and Abbey Wood;
- Shared and adjacent 25kV AC OLE and 750V DC 4th rail at Melton Rail Innovation & Development Centre (RIDC) (also known as Old Dalby Test Track) between Old Dalby and Widmerpool;
- Shared and adjacent 25kV AC OLE and 750V DC 4th rail at Bombardier Derby Litchurch Lane Works;
- Adjacent 25kV AC OLE on GEML/Crossrail and 750V DC 3rd rail on DLR between Bow Junction and Stratford;
- Adjacent 25kV AC OLE on mainline and 750V DC 3rd rail on DLR between Stratford Carpenter’s Road North Junction and Stratford International.
Appendix C

UK Pantograph Types

This appendix describes the pantographs which are operational in the UK today, together with those which have been used on UK 25kV infrastructure in the past. Operational speeds quoted are maxima permitted in the UK – the pantograph may be used at higher speeds in other countries.

The details below are collated from a variety of sources. Individual train operators will often modify pantographs based on in-service experience, so these should be considered broad categories only.
### AEI Cross-arm Pantograph

**Figure C.1: AEI Cross-arm pantograph**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC</td>
</tr>
<tr>
<td>Use</td>
<td>Mainline</td>
</tr>
<tr>
<td>In UK Since</td>
<td>1960</td>
</tr>
<tr>
<td>Max Speed</td>
<td>177km/h</td>
</tr>
<tr>
<td>Arm</td>
<td>Two crossed diamond</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>Unknown</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>Provided by twin arms</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Twin plungers</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>None?</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>None</td>
</tr>
<tr>
<td>Strip Material</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Assume No</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>Assume No</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>Integral with carbons</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile$^1$</td>
<td>GB profile</td>
</tr>
<tr>
<td>NTSN Compliant</td>
<td>No</td>
</tr>
<tr>
<td>Fitted To</td>
<td>Originally fitted to class 86, 87. All now replaced.</td>
</tr>
<tr>
<td>Notes</td>
<td>No longer in use. All remaining pans are unserviceable on preserved rolling stock.</td>
</tr>
</tbody>
</table>

---

$^1$ “GB profile” denotes profile as per BS EN50367:2020 figure B.6; “Europan” denotes profile as per BS EN50367 Fig. A.6; “HS1 profile” denotes profile as per BS EN50367 Fig. B.3.
## Stone-Faiveley AM/BR Pantograph

![Image of Stone-Faiveley AM/BR pantograph with Brecknell Willis Head](image)

**Figure C.2: Stone-Faiveley AM/BR pantograph with Brecknell Willis Head**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>25kV AC</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Mainline</td>
</tr>
<tr>
<td><strong>In UK Since</strong></td>
<td>1959</td>
</tr>
<tr>
<td><strong>Max Speed</strong></td>
<td>140km/h</td>
</tr>
<tr>
<td><strong>Arm</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Strip Spacing</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Linkage Type</strong></td>
<td>External bar links</td>
</tr>
<tr>
<td><strong>Suspension</strong></td>
<td>Primary/secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Secondary Travel</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Aerofoils</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Strip Material</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Horn Mount</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Horn Type</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>Head Profile</strong></td>
<td>As per BW HS-P Mark 1</td>
</tr>
<tr>
<td><strong>NTSN Compliant</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Fitted To</strong></td>
<td>Class 81, 82, 83, 84, 85, 86, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 317/8, 318</td>
</tr>
</tbody>
</table>
Notes: The above data are based on the current configuration of the AM/BR pantograph, which has been retro-fitted with a Brecknell Willis HS-P Mark 1 head. This pantograph was originally fitted with a different head, which used a spring parallelogram as the secondary suspension\(^2\).

### Brecknell Willis HS-A Pantograph

**Figure C.3: Brecknell Willis HS-A pantograph**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC</td>
</tr>
<tr>
<td>Use</td>
<td>Mainline</td>
</tr>
<tr>
<td>In UK Since</td>
<td>1980</td>
</tr>
<tr>
<td>Max Speed</td>
<td>225km/h</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>300mm?</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td>Suspension Type</td>
<td>Primary/secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Torsion bar on trailing arm</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>65mm</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>On head</td>
</tr>
<tr>
<td>Strip Material</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Yes</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>Yes</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>Integral with carbons</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile</td>
<td>GB profile</td>
</tr>
<tr>
<td>NTSN Compliant</td>
<td>No</td>
</tr>
<tr>
<td>Fitted To</td>
<td>Class 87, 89, 90, 91, 92, 317/1, /5, /6, /7, 319, 320, 321, 322, 323, 325, 332, 333, 370, 390, 769, Eurotunnel class 9</td>
</tr>
<tr>
<td>Notes</td>
<td>Also known as BW high speed</td>
</tr>
</tbody>
</table>
### Brecknell Willis HS-P Mark 1 Pantograph

**Figure C.4: Brecknell Willis HS-P Mark 1 pantograph**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>25kV AC</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Mainline</td>
</tr>
<tr>
<td><strong>In UK Since</strong></td>
<td>1995</td>
</tr>
<tr>
<td><strong>Max Speed</strong></td>
<td>160km/h</td>
</tr>
<tr>
<td><strong>Arm</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Strip Spacing</strong></td>
<td>300mm</td>
</tr>
<tr>
<td><strong>Linkage Type</strong></td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td><strong>Suspension</strong></td>
<td>Primary/secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension Type</strong></td>
<td>Twin plungers</td>
</tr>
<tr>
<td><strong>Secondary Travel</strong></td>
<td>40mm</td>
</tr>
<tr>
<td><strong>Aerofoils</strong></td>
<td>On knuckle</td>
</tr>
<tr>
<td><strong>Strip Material</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Horn Mount</strong></td>
<td>Integral with carbons</td>
</tr>
<tr>
<td><strong>Horn Type</strong></td>
<td>Live</td>
</tr>
<tr>
<td><strong>Head Profile</strong></td>
<td>GB profile</td>
</tr>
<tr>
<td><strong>NTSN Compliant</strong></td>
<td>No</td>
</tr>
<tr>
<td><strong>Fitted To</strong></td>
<td>Class 334, 350/2, 357, 360 (some), 365, 375/6, 377, 378, 379, 380</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Also known as BW High Speed Plunger, Desiro Mk1</td>
</tr>
</tbody>
</table>
**Brecknell Willis HS-P Mark 2 Pantograph**

![Brecknell Willis HS-P Mark 2 pantograph](image)

**Figure C.5: Brecknell Willis HS-P Mark 2 pantograph**

<table>
<thead>
<tr>
<th><strong>Voltage</strong></th>
<th>25kV AC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use:</strong></td>
<td>Mainline</td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
<td>2005</td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
<td>175km/h</td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
<td>300mm</td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
<td>Primary/secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
<td>Twin plungers</td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
<td>40mm</td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
<td>On knuckle</td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
<td>Integral with head frame (carbons decoupled from horns)</td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
<td>Live</td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
<td>GB profile</td>
</tr>
<tr>
<td><strong>NTSN Compliant:</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Fitted To:</strong></td>
<td>Class 88, 331, 345, 350/1, 360 (some), 385, 387 (some), 700, 710, 717, 720, 730, 745, 755</td>
</tr>
<tr>
<td><strong>Notes:</strong></td>
<td>Also known as BW High Speed Plunger, Desiro Mk2</td>
</tr>
</tbody>
</table>

---

**OVERHEAD LINE ELECTRIFICATION FOR RAILWAYS | 6TH EDITION | 2021**

329
# Brecknell Willis HS-P Mark 2 "Donuts" Pantograph

![Image of Brecknell Willis HS-P Mark 2 "Donuts" Pantograph](image)

**Figure C.6: Brecknell Willis HS-P Mark 2 "Donuts" pantograph**

| **Voltage** | 25kV AC |
| **Use:** | Mainline |
| **In UK Since:** | 2005 |
| **Max Speed:** | 175km/h |
| **Arm:** | Single |
| **No. of Strips:** | 2 |
| **Strip Spacing:** | 300mm |
| **Linkage Type:** | Internal 4th bar attached to chain at knuckle, internal bar link to head |
| **Suspension:** | Primary/secondary |
| **Secondary Suspension Type:** | Twin plungers |
| **Secondary Travel:** | 40mm |
| **Aerofoils:** | On knuckle |
| **Strip Material:** | Unknown |
| **Auto-Drop Device?** | Yes |
| **Over Height Drop?** | Yes |
| **Horn Mount:** | Integral with head frame (carbons decoupled from horns) |
| **Horn Type:** | Live |
| **Head Profile:** | GB profile |
| **NTSN Compliant:** | Yes |
| **Fitted To:** | Class 387 (some) |

**Notes:** Donuts (toroids) are fitted to reduce electrical stress for arcing to the roof in low wire height areas.
Brecknell Willis HS-X Pantograph

Figure C.7: Brecknell Willis HS-X pantograph

<table>
<thead>
<tr>
<th>Voltage</th>
<th>25kV AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use:</td>
<td>Mainline</td>
</tr>
<tr>
<td>In UK Since:</td>
<td>2015</td>
</tr>
<tr>
<td>Max Speed:</td>
<td>225km/h</td>
</tr>
<tr>
<td>Arm:</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips:</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing:</td>
<td>450mm</td>
</tr>
<tr>
<td>Linkage Type:</td>
<td>Internal 4th bar attached to chain at knuckle, internal bar link to head</td>
</tr>
<tr>
<td>Suspension:</td>
<td>Primary/secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type:</td>
<td>Twin transverse springs</td>
</tr>
<tr>
<td>Secondary Travel:</td>
<td>~60mm</td>
</tr>
<tr>
<td>Aerofoils:</td>
<td>On knuckle</td>
</tr>
<tr>
<td>Strip Material:</td>
<td>Metallised carbon</td>
</tr>
<tr>
<td>Auto-Drop Device?:</td>
<td>Yes</td>
</tr>
<tr>
<td>Over Height Drop?:</td>
<td>Yes</td>
</tr>
<tr>
<td>Horn Mount:</td>
<td>Integral with head frame (carbons decoupled from horns)</td>
</tr>
<tr>
<td>Horn Type:</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile:</td>
<td>GB profile</td>
</tr>
<tr>
<td>NTSN Compliant:</td>
<td>Yes</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Class 397, 800, 801, 802, 803, 805, 807, 810 variants</td>
</tr>
<tr>
<td>Notes:</td>
<td></td>
</tr>
</tbody>
</table>
Faiveley GPU Pantograph

Figure C.8: Faiveley GPU\(^3\) pantograph

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>25kV AC, 1.5 kV DC</td>
</tr>
<tr>
<td>Use</td>
<td>High Speed</td>
</tr>
<tr>
<td>In UK Since</td>
<td>1993</td>
</tr>
<tr>
<td>Max Speed</td>
<td>300km/h (AC), 270km/h (DC)</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>Unknown</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>External bar links</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/secondary/tertiary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Single plunger (secondary), twin plungers (tertiary)</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>150</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>On head</td>
</tr>
<tr>
<td>Strip Material</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Yes</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>No – mechanical height limit device provided</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>To secondary-sprung head</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Insulated</td>
</tr>
<tr>
<td>Head Profile</td>
<td>HS1 profile</td>
</tr>
<tr>
<td>NTSN Compliant</td>
<td>Yes</td>
</tr>
<tr>
<td>Fitted To</td>
<td>Class 373 Eurostar</td>
</tr>
</tbody>
</table>

\(^3\) GPU stands for “Grand Plongeur Unique” (large, single plunger).
Notes: Captive to HS1 route only, now being withdrawn from service. During the period when Class 373s were running on domestic services North Of London, the NoL class 373 subvariant carried a variant of the GPU pantograph with a UK profile head, and wider suspension points, for compatibility with UK mainline OLE. It also carried modified aerofoils to improve uplift with Mark 3b OLE, and was limited to 110mph on the domestic network.
Faiveley CX PG Monoband Pantograph

Figure C.9: Faiveley CX PG monoband pantograph

<table>
<thead>
<tr>
<th><strong>Voltage</strong></th>
<th>25kV AC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use:</strong></td>
<td>High Speed</td>
</tr>
<tr>
<td><strong>In UK Since:</strong></td>
<td>2009</td>
</tr>
<tr>
<td><strong>Max Speed:</strong></td>
<td>225km/h</td>
</tr>
<tr>
<td><strong>Arm:</strong></td>
<td>Single</td>
</tr>
<tr>
<td><strong>No. of Strips:</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Strip Spacing:</strong></td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Linkage Type:</strong></td>
<td>External bar links</td>
</tr>
<tr>
<td><strong>Suspension:</strong></td>
<td>Primary/secondary</td>
</tr>
<tr>
<td><strong>Secondary Suspension Type:</strong></td>
<td>Twin plungers</td>
</tr>
<tr>
<td><strong>Secondary Travel:</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Aerofoils:</strong></td>
<td>On head</td>
</tr>
<tr>
<td><strong>Strip Material:</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Auto-Drop Device?</strong></td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Over Height Drop?</strong></td>
<td>No – mechanical height limit device provided</td>
</tr>
<tr>
<td><strong>Horn Mount:</strong></td>
<td>To fixed head</td>
</tr>
<tr>
<td><strong>Horn Type:</strong></td>
<td>Insulated</td>
</tr>
<tr>
<td><strong>Head Profile:</strong></td>
<td>HS1 profile</td>
</tr>
<tr>
<td><strong>NTSN Compliant:</strong></td>
<td>Yes (level contact wire only)</td>
</tr>
<tr>
<td><strong>Fitted To:</strong></td>
<td>Class 395 Javelin</td>
</tr>
<tr>
<td><strong>Notes:</strong></td>
<td>Captive to HS1 route only</td>
</tr>
</tbody>
</table>
**Faiveley CX NG Pantograph**

<table>
<thead>
<tr>
<th>Voltage</th>
<th>25kV AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use</td>
<td>High Speed</td>
</tr>
<tr>
<td>In UK Since</td>
<td>2016</td>
</tr>
<tr>
<td>Max Speed</td>
<td>360km/h</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>Unknown</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>External bar links</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/secondary</td>
</tr>
<tr>
<td>Secondary Suspension Type</td>
<td>Quad plungers</td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>Unknown</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>On head</td>
</tr>
<tr>
<td>Strip Material</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Unknown</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>No – mechanical height limit device provided</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>To fixed head</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Insulated</td>
</tr>
<tr>
<td>Head Profile</td>
<td>HS1 profile</td>
</tr>
<tr>
<td>NTSN Compliant</td>
<td>Yes</td>
</tr>
<tr>
<td>Fitted To</td>
<td>Class 374 (e320 Eurostar)</td>
</tr>
<tr>
<td>Notes</td>
<td>Captive to HS1 route only</td>
</tr>
</tbody>
</table>

*Figure C.10: Faiveley CX NG pantograph*
Brecknell Willis High Reach Pantograph

Figure C.11: Brecknell Willis High Reach pantograph

<table>
<thead>
<tr>
<th>Voltage</th>
<th>750V DC, 1500V DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use:</td>
<td>Tram, Metro</td>
</tr>
<tr>
<td>In UK Since:</td>
<td>1980</td>
</tr>
<tr>
<td>Max Speed:</td>
<td>80km/h</td>
</tr>
<tr>
<td>Arm:</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips:</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing:</td>
<td>Unknown</td>
</tr>
<tr>
<td>Linkage Type:</td>
<td>Internal chain (to upper arm), internal bar link (to head)</td>
</tr>
<tr>
<td>Suspension:</td>
<td>Primary only (although head mounting strips may provide some minor flex under load)</td>
</tr>
<tr>
<td>Secondary Suspension Type:</td>
<td>See above</td>
</tr>
<tr>
<td>Secondary Travel:</td>
<td>Negligible</td>
</tr>
<tr>
<td>Aerofoils:</td>
<td>None</td>
</tr>
<tr>
<td>Strip Material:</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?:</td>
<td>Unknown</td>
</tr>
<tr>
<td>Over Height Drop?:</td>
<td>Unknown</td>
</tr>
<tr>
<td>Horn Mount:</td>
<td>To fixed head</td>
</tr>
<tr>
<td>Horn Type:</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile:</td>
<td>1900mm width?</td>
</tr>
<tr>
<td>NTSN Compliant:</td>
<td>No</td>
</tr>
<tr>
<td>Fitted To:</td>
<td>Trams &amp; Metros: Birmingham Metro T-68 and T-69, Manchester Metrolink T-68A, Tyne &amp; Wear Metro Class 994</td>
</tr>
<tr>
<td>Notes:</td>
<td></td>
</tr>
</tbody>
</table>
### Schunk SB Pantograph

![Image](image_url)

**Figure C.12: Schunk SB pantograph**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>750V DC</td>
</tr>
<tr>
<td>Use</td>
<td>Tram</td>
</tr>
<tr>
<td>In UK Since</td>
<td>2000</td>
</tr>
<tr>
<td>Max Speed</td>
<td>80km/h</td>
</tr>
<tr>
<td>Arm</td>
<td>Single</td>
</tr>
<tr>
<td>No. of Strips</td>
<td>2</td>
</tr>
<tr>
<td>Strip Spacing</td>
<td>345mm</td>
</tr>
<tr>
<td>Linkage Type</td>
<td>External bar links</td>
</tr>
<tr>
<td>Suspension</td>
<td>Primary/secondary</td>
</tr>
<tr>
<td>Secondary Suspension</td>
<td>Flexible support (similar to leaf spring)</td>
</tr>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Secondary Travel</td>
<td>Very small</td>
</tr>
<tr>
<td>Aerofoils</td>
<td>None</td>
</tr>
<tr>
<td>Strip Material</td>
<td>Unknown</td>
</tr>
<tr>
<td>Auto-Drop Device?</td>
<td>Yes</td>
</tr>
<tr>
<td>Over Height Drop?</td>
<td>Unknown</td>
</tr>
<tr>
<td>Horn Mount</td>
<td>To fixed head</td>
</tr>
<tr>
<td>Horn Type</td>
<td>Live</td>
</tr>
<tr>
<td>Head Profile</td>
<td>1900mm width</td>
</tr>
<tr>
<td>NTSN Compliant</td>
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</tr>
<tr>
<td>Fitted To</td>
<td>ET-Urbos 3, Bham-Urbos 3, Manc-M5000, Croy-Flexity Swift CR4000, Croy-VarioBahn, Nott-Incentro AT6/5, Nott-Alstom Citadis 302, Shef-Siemens-Duewag, Blk-Flexity 2, Dub-Citadis 301, Dub-Citadis 401, Dub-Citadis 402</td>
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### Blackpool Transport Diamond Pantograph

**Figure C.13: Blackpool Transport diamond pantograph**

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<td>In UK Since:</td>
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<td>Max Speed:</td>
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Appendix D

UK Equipment Types
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<th>Tensioning</th>
<th>Contact Wire</th>
<th>Cross Section (mm²) &amp; Material</th>
<th>Tension @ setup temp (N)</th>
<th>Tension @ setup temp (lb)</th>
<th>Presag?</th>
<th>Catenary Layup &amp; Material</th>
<th>Tension @ setup temp (N)</th>
<th>Tension @ setup temp (lb)</th>
<th>Auxiliary Catenary or Stitch Wire Layup &amp; Material</th>
<th>Tension @ setup temp (N)</th>
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**Locations**

- London: Euston; Weaver Jt; Liverpool; Cribbs Causeway; Manchester; Rugby - Stafford via Birmingham; Reading - Rugby via Northampton; Glasgow suburban stage 1; Christian St - Shrewsbury; Barlins - Pkvia Grays; Chelmsford - Colchester; Colchester - Clacton & Walton; Belden Green - Bishop's Stortford; Fleet East; Erith & Changford;

- All installed equipment now removed.

- Network Rail 2019

- Mark 1 upgrade locations in East Anglia

- British Rail/BICC: 1966 - 25kV AC

- Network Rail 2019

- Whitelegg - Nelahton

- Weaver Jt - Glasgow; King's Cross - Royston & Hertford Loop; Waltham - Braintree

- Weaver Jt - Glasgow; King's Lynn sidings

- King's Lynn sidings
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<th>Designation</th>
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<th>Build Date</th>
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<th>Conversion Date</th>
<th>Conversion Voltage</th>
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<td>OLE damage causing major disruption. Bethnal Green, UK</td>
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<td>Electric freight with 1500V DC OLE. Penistone, UK</td>
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<td>1500V DC on the GE; this was converted, first to 6.25kV AC and then 25kV. Gidea Park, UK</td>
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<td>0 series Shinkansen in Japan</td>
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<td>TGV Sud-Est in France</td>
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<td>APT tilting on neutral section tests. Murthat, UK</td>
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<td>Class 374 Eurostar on High Speed One. Medway, UK</td>
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<td>A Hitachi IET forms the first electric train to run on the Reading-Didcot section of Great Western on 17 July 2016. Cholsey, UK</td>
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<td>Typical street-running tram with building-suspended OLE. Birmingham, UK</td>
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