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23. 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.

23.1. 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. 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.

![Figure 381: Tractive effort/speed curve for electric traction](image)

The other factor that determines the tractive effort 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/s² for a traction unit with 20% adhesion would require 50% motored axles, and 1.5m/s² would require 75% motored axles. 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

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233 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.
234 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 \( v=V_1 \) 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 \( V_1 \) to \( V_2 \) 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 \( V_2 \) 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 \( (V_B) \), 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.

23.2. 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.

23.2.1. 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, and the loss of energy in the associated resistance control mechanism (section 23.2.2); although this was later solved by using solid-state control (section 23.3).

### 23.2.2. 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.

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235This 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.

23.2.3. 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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236 “Electric Trains in Britain”, B.K. Cooper; 1979; Ian Allan Ltd; p18.
237 Ibid.; chapter 2.
238 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. This was the first time these devices had been used on a moving vehicle.

![Image](image1.png)

**Figure 387:** (l-r) Air-cooled steel tank mercury arc rectifier 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 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.

### 23.3. 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

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239 For more information see en.wikipedia.org/wiki/Mercury-arc_valve.

240 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.

241 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\(^{242}\) 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\(^{243}\)) 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\(^ {244}\), with British Rail preferring to wait until the technology had matured and EMC issues were understood.

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\(^{242}\) 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.

\(^{243}\) 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.

\(^{244}\) 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 23.4.1) 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 23.6.

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 tractions 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.

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.

![Figure 390: 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 23.5).

GTOs have now been superseded by the IGBT, which is described in section 23.5.

### 23.4. 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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245 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.

246 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.
23.4.1. 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\(^{247}\). 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\(^{248}\), 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.

![Figure 391: 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

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\(^{247}\) The DC motor remains in use in some diesel locomotives such as the UK class 66, due to its inherent simplicity and reliability.

\(^{248}\) A small skew is usually introduced to reduce magnetic hum and avoid the motor stalling.
Voltage Variable Frequency (VVF) inverter (section 23.5) 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 392: 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\(^{249}\) and is effectively maintenance free\(^{250}\), 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 23.2.2).

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\(^{251}\) 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.

### 23.4.2. 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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\(^{249}\) 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.

\(^{250}\) Bearing replacement after 5 to 10 years of service is broadly the only maintenance required for an AC motor.

\(^{251}\) 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.

### 23.4.3. 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 23.1) 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.

![Nose-suspended AC traction motor on a UK class 455/8 EMU bogie - nose suspension on right, suspension tube on left](image)

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\(^\text{252}\). This completely removes the unsprung mass, but at the cost of some additional complexity in the coupling.

\(^{252}\)Examples in the UK include the class 91 locomotive and class 390 high-speed EMU.
23.4.4. 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 23.5) 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.

23.5. 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 23.4.1); 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\(^\text{253}\) and inverts it to a three-phase AC output.

The GTO (section 23.3) 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\(^\text{254}\) than a thyristor, and does not require

\(^{253}\) 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.

\(^{254}\) 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\textsuperscript{255}. 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 \textit{Pulse Width Modulation} (PWM), itself a development of the basic thyristor method (section 23.3). 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 395: Pulse Width Modulation - switching a DC input to form an AC output](image)

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\textsuperscript{256} by shortening or lengthening the time between the \textit{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.

\textsuperscript{255}IGBTs are at least 5-6% more efficient than GTOs.

\textsuperscript{256}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 23.4.1). 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 23.8) is used for this purpose.

23.6. 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 398: Typical traction architecture for an AC OLE traction unit fed from AC OLE](image)

Traction current from the pantograph (section 11.1) passes through a roof-mounted VCB and other roof-mounted equipment (section 23.8) 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 23.4.4), 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\(^{257}\) 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>

\(^{257}\)Traction ratings are nominal, and may include additional peak ratings, particularly for DC motors.
### Class 390

**Traction Characteristics**
- IGBT-based controlled rectifier, inverter; 12x 425kW AC asynchronous motors; 33% of axles motored

**Electric Braking Characteristics**
- Rheostatic, regenerative

**Auxiliaries**
- Heating via tertiary winding on main transformer; AC auxiliaries via inverter

#### 23.7. 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) 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.

#### 23.8. 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 23.6) 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.

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258 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 23.5) rather than relying on a voltage measurement at the traction transformer (section 23.6), 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\textsuperscript{259}. 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 11.1.2), while still providing all of the benefits of distributed traction, and the flexibility to switch

\textsuperscript{259}This cable, while having an insulating sheath, is not insulated to HV standards and so must be treated as a live part.
to the second pantograph when needed. Distribution purely using LV is impractical since it would require a large transformer and heavy cables.

23.9. Automatic Power Control

AC tractions units usually operate on routes with neutral sections (section 11.6.3) 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 23.6). 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 12.2.1) 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 401: (l-r) APC magnet receivers on UK EMUs; old pattern, and new pattern](image)

23.10. 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 traction earth through the wheels. It is important to ensure that no traction current passes across the wheel bearing races, since micro-arching 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.

### 23.10.1. 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 23.6), 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.

### 23.11. Pantograph Configuration

The pantograph (section 11.1) 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 11.13.2) 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 402: Tilting Brecknell Willis HS-A pantograph on UK class 390