An introduction to the overhead electric traction system

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INTRODUCTION

In the last few years, the PWI has moved to strongly encourage those of the electrification discipline to become members of the Institution. As the PWI welcomes increasingly more members from that community, it is the intention that articles presented in this Journal will in future explore technical and specialist detail of the electrical and mechanical engineering of the traction system.

There are many forms of overhead electric traction. The development and evolution of the technology has been ongoing since the later years of the 19th century. Today variations of the basic system can be seen around the world powering trams, urban metro systems, high speed railways and heavy haul freight across continents. Electrical systems vary, there are examples of direct and alternating current systems with many different voltages. In the 1950s/60s British Rail adopted the 25kV OLE system as the standard for UK main lines.

Network Rail has published plans to meet the challenges of decarbonisation towards the net zero target of 2050 and that proposes a near doubling of the electrified network. The plan also heralds a modal shift of freight traffic from road to rail. Over the next 30 years it is therefore all but inevitable that many more in the industry engaged in maintaining and renewing the railway, especially those from the PWI's more track and civils biased member base, will want to understand how the electric traction system is configured and how it works. This article has two purposes; first to offer some explanation of the building blocks of an electric traction system, second is to provoke interest in seeking more detail which future papers and articles will present.

THE ELECTRIFICATION SYSTEM

The electrification system consists of many constituent elements to enable electrical power to be transferred from where it is generated to the trains. Much of the electrical system adopts standard industrial practices but there are some features of railways that require special attention.

For main line railways in the UK a 25kV single phase 50 Hz alternating current (AC) overhead line system has been the preferred system for more than 60 years. Adopting 50 Hz AC enables connections to be made directly to public supplies without the need to change frequency (16.7Hz is a common system in some countries) or rectify to a direct current (DC - as required for lower voltage third rail and tram systems). The electricity supply industry (National Grid and Distribution Network Operators) use three phase systems from the highest 400kV transmission networks to 400V local substations and industrial premises (most domestic properties then have a single phase 230V supply). Although there have been attempts to use three phases on railways, it is impractical to have three conductors above every track, hence the railway adopting a single phase for power distribution between the supply network and trains.

Simple electrical theory dictates that the higher the voltage, the lower the losses due to the resistance in the wires. Hence the relatively high voltage of 25kV was adopted as standard for many railways worldwide, including in the UK.

The simplest connections between the railway and the supply are made by connecting the primary side of a supply transformer between two of the three phase conductors at 132kV, 275kV or 400kV and the secondary side to the railway feeder station at 25kV (see Figure 1). The traction system is not therefore balanced from a three-phase distribution perspective.

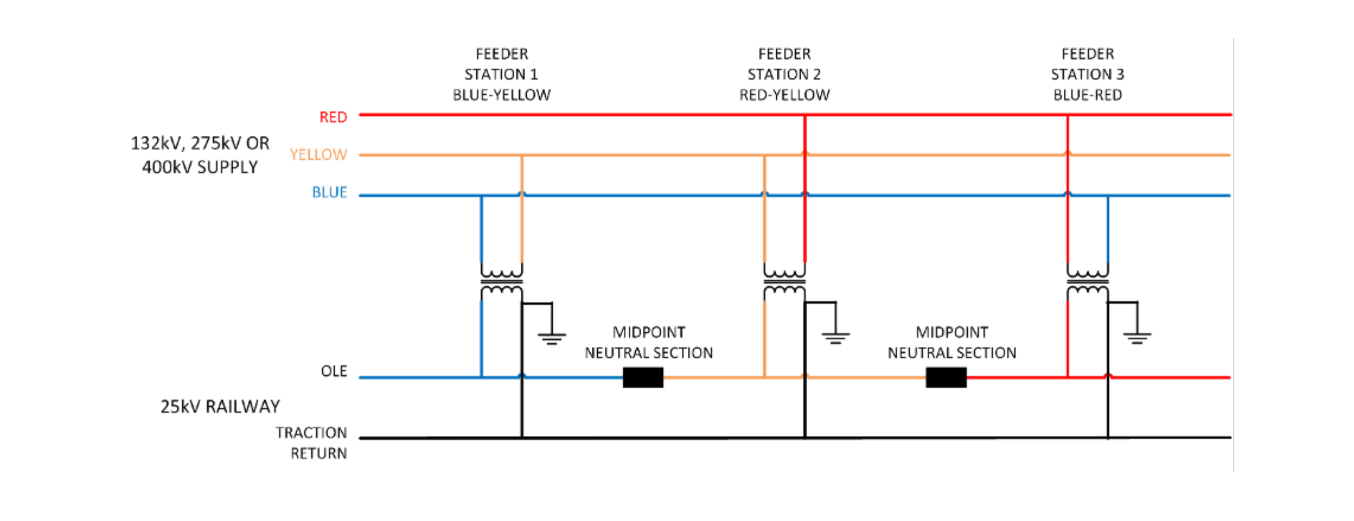

Figure 1: Simple representation of three phase supply providing single phase railway

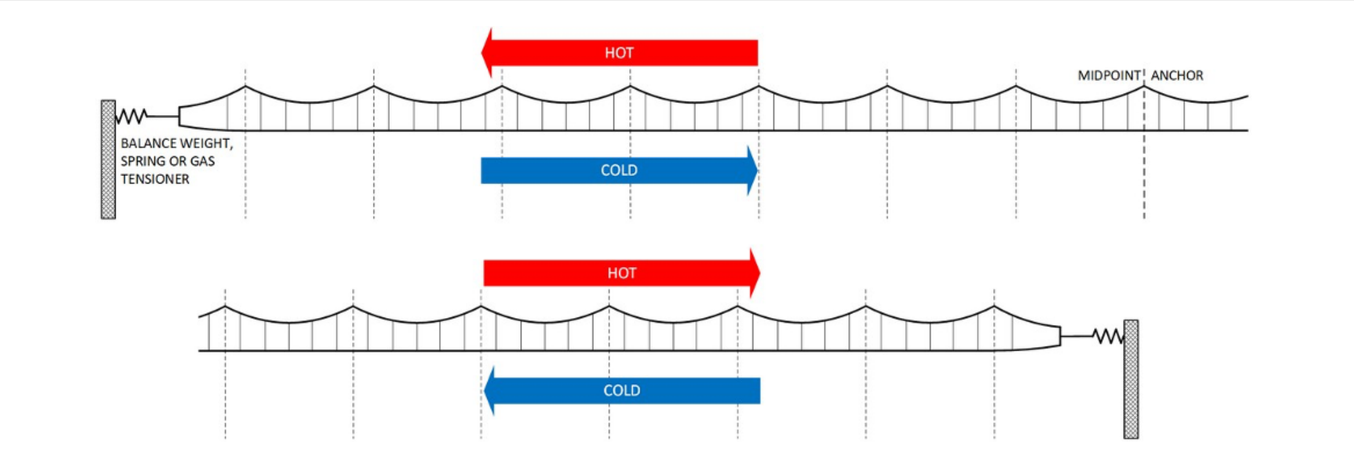

Figure 2: Auto tensioned OLE

As the railway can be a significant load on the high voltage electrical supply, additional equipment or special transformers are sometimes provided to reduce the imbalance which, if significant in magnitude, can cause disruption to other customers of the electricity supply companies. Supplies around the country are taken from different phase pairs to provide some balance. It is necessary to keep these supplies separate so insulated sections are provided in the overhead line between supplies, known as Neutral Sections.

Relatively recent developments in the UK have resulted in distribution of power on some main line routes at 50kV, known as autotransformer or AT systems, allowing higher loads over longer distances, with no effect on train systems as only 25kV is “seen” by the train. Semiconductor switchgear can also be used to take a balanced three phase supply and convert it to the required single phase for the railway (although in the UK they are 50Hz systems, they were developed for 16.7Hz so are called Static Frequency Converters (SFCs)). However, these are not currently widely used in the UK, with the first installation only recently commissioned at Potteric Carr near Doncaster.

Having transformed the supply voltage to the single-phase railway voltage it is now necessary to distribute it to the trains. At the supply point “feeder station” substations are provided. These contain electrical switchgear to enable each line to be separately supplied. For a “classic” 25kV system, one terminal of the secondary side of the supply transformer is connected through a “circuit breaker” to a busbar. This busbar is then connected to each track through individual circuit breakers and overhead line switches. In simple terms this is like the consumer unit in a domestic property with the main circuit breaker and then separate circuit breakers for each electrical circuit typically; upstairs and downstairs lights, upstairs and downstairs sockets and other equipment ie electric oven.

The line side overhead line switches could be compared to the socket or light switches. The second terminal of the supply transformer is connected to a “return current busbar”. This in turn is connected to the running rails and provides the return circuit from the trains to complete the electrical circuit. As this is connected to earth there is no additional switching provided in this part of the circuit.

Additional electrical substations are provided between feeder stations along the railway to provide additional switching and facilitate redistributing power when sections are isolated (“alternate feeding”). These substations are similar to feeder stations but without the incoming supply transformer. In addition to the circuit breakers in the substation, additional equipment is provided for protection and control purposes. This equipment enables the circuit breakers to be opened in the case of a fault or when required for an isolation of the overhead line and are remotely controlled from the Electrical Control Room (ECR). There are also sensors on the equipment to enable the Electrical Control Operator (ECO) to observe the status of the equipment. This is known as the SCADA system (Supervisory Control And Data Acquisition). Modern SCADA systems include complex telecommunications technology that enable significant automation of the traction infrastructure speeding up the isolation of faults, minimising the extent of disruption due to a fault, identifying accurately where a fault has occurred and potentially reducing the time for taking isolations.

OVERHEAD LINE EQUIPMENT

The primary purpose of the Overhead Line Equipment (OLE) is to conduct the electrical supply to the pantograph of the trains. In electrical engineering terms it is a power distribution system, but it is also an electrical commutator, allowing solid and continuous electrical supply between the fixed OLE and the moving pantograph. The mass and upward pressure of the pantograph and the reaction of the wire as the pantograph passes create a complex mechanical interface, so whilst the electrical functions of the OLE are relatively straightforward, the mechanical design is quite the opposite.

TENSIONING ARRANGEMENTS

Typically, the OLE consists of a contact wire suspended from a catenary wire, though some slow speed systems may consist of a contact wire alone. These wires are supported from lineside structures at regular intervals and tensioned to maintain the contact wire height along the span between supports to provide continuous current collection by the pantograph. Contact wire tensions run from 8kN for slow speed systems up to around 30kN for high-speed systems.

The tensioning arrangements must take account of the expansion and contraction of the wires with varying temperature. A complete length of OLE (with a wire run typically 1500m to 1700m long) will expand and contract as much as 1.5 metres over a typical range. This has a significant effect on tensioning arrangements.

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 (see Figure 2). Constant tension is provided by a tensioning device – traditionally by a set of balance weights attached to the catenary and contact wire.

A mechanical advantage of 3:1 or 5:1 is provided via pulleys or drum-wheels. 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 highspeed systems typically have independent tensioning of the two wires.

Balance weights are simple and robust, but for mainline railways they suffer from a number of disadvantages. A recent development is the use of spring tensioners instead of balance weights (see Figure 3). These maintain a constant tension by using a spiral torsion spring. The tensioners are often placed over the track for ease of maintenance access using rail-mounted plant.
Whatever tensioning device is used, along track movement is provided for at intermediate structures by pulleys, flexible links or pivoted cantilevers.

TENSION LENGTHS AND OVERLAPS

The length of a wire run is limited due to frictional drag (at all the moving components and hinges at the registration supports) and stagger change (due to the angular movement of the registration assemblies, the arc described by that movement resulting in the contact wire moving further from the track centre line), as well as practical considerations of maximum wire length on a drum. OLE is therefore split into tension lengths. Turnouts and crossovers are provided with their own wiring, and due to the shorter length of OLE needed are often provided with a half tension length comprising a tensioner at one end, a fixed anchor at the other, and no midpoint anchor.

At the end of each 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 (see Figure 4). At its simplest, an overlap is a purely mechanical arrangement. However, it can also be a convenient place to create an electrical break in the OLE for sectioning purposes.

The standard arrangement is a single span overlap, so-called because it 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 (see Figure 5).

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 is matched to the pantograph head width and operational performance of the train suspension. 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 of the contact wire at each structure. The height is measured parallel to the track centreline, perpendicular to the plane of the rails; the stagger as the offset perpendicular to the track centreline (see Figure 6).

The vertical range is limited by the pantograph operating range. Therefore, each system has both a minimum and maximum contact wire height. The requirement for height variation arises from the need to achieve minimum safe clearance for road and pedestrian traffic at level crossings, and to operate through low overbridges. The pantograph has a maximum rate of rise and fall per second, above which it will not be able to follow the wire (see Figure 7).

Therefore, the maximum permissible contact wire gradient is generally set to be in proportion to the line-speed – a useful rule of thumb for good current collection is:

$G_{max} \leq 1$ in $(5v)$ where v is measured in mph.

The contact wire is installed so that its position does not dwell in one place on the carbon collector strips of the pantograph. This is known in the UK as stagger (perhaps more descriptively in Europe it is

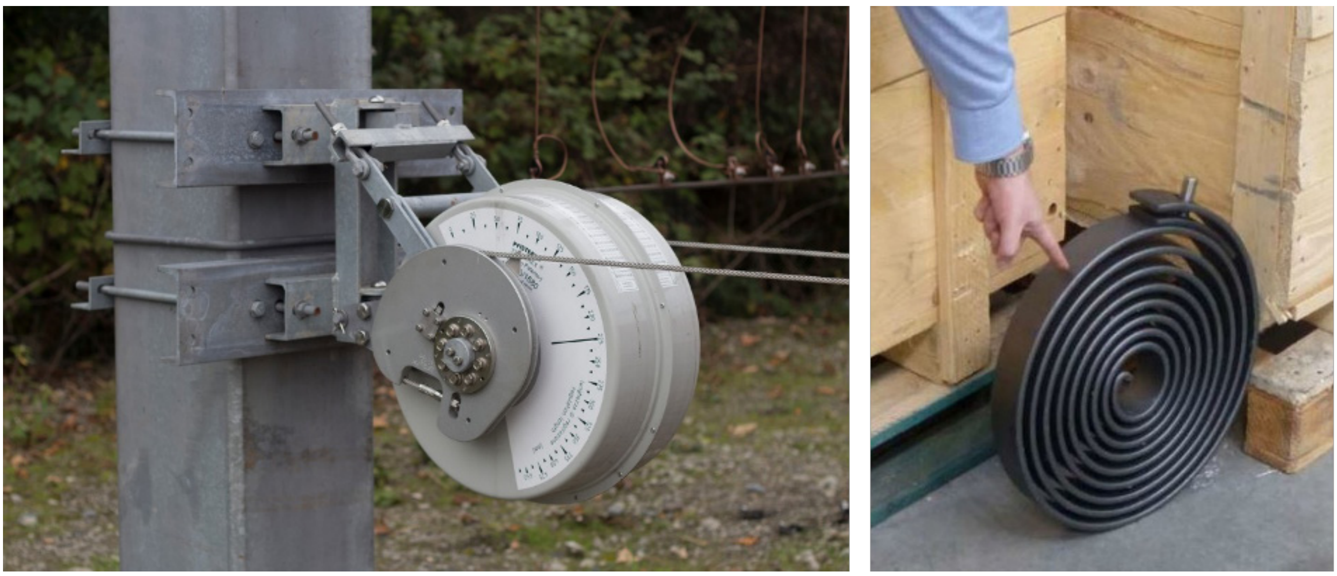

Figure 3: Pfisterer Tensorex C+ spiral torsion spring tensioner, and Tensorex spring

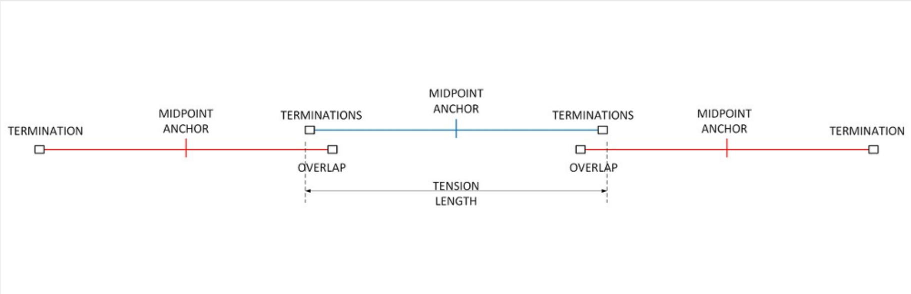

Figure 4: Tension lengths, overlaps and midpoint anchors

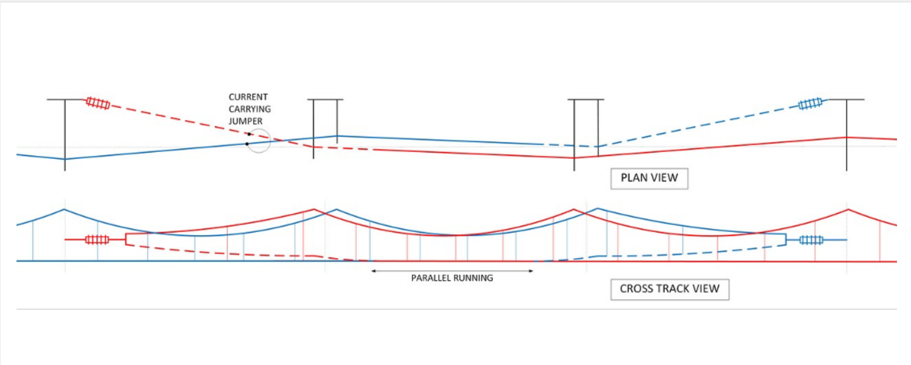

Figure 5: Uninsulated single span overlap

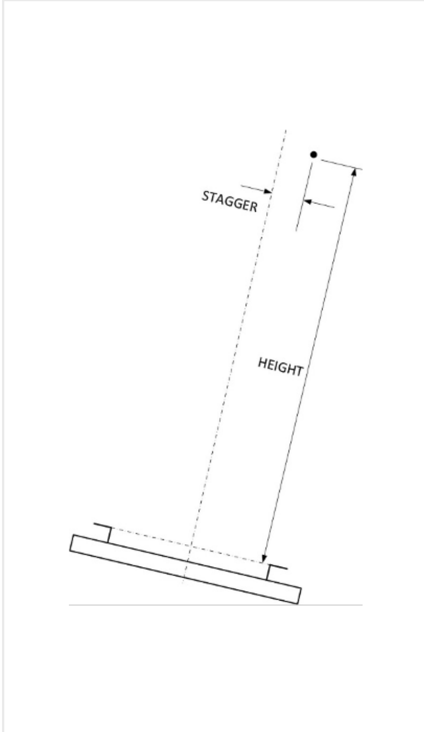

Figure 6: Height and stagger

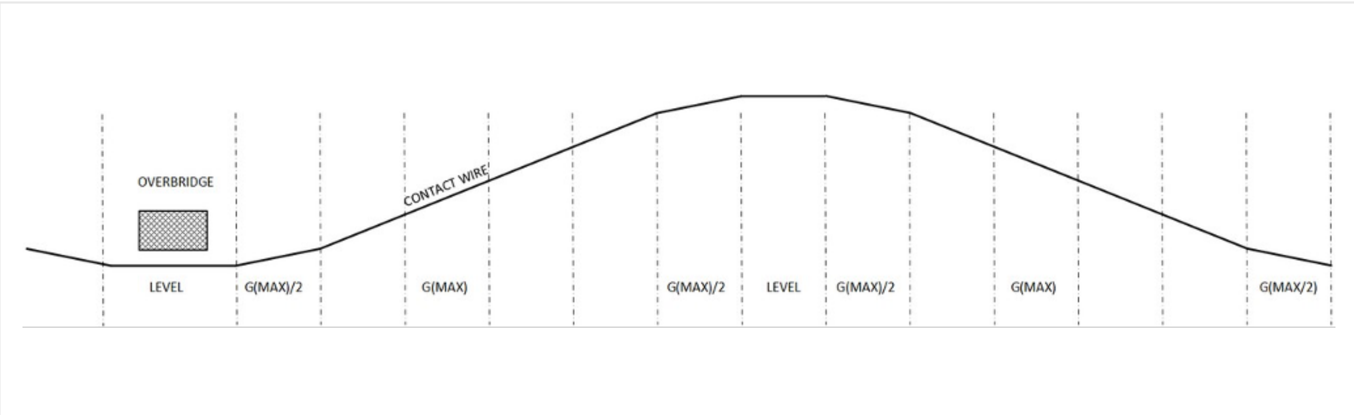

Figure 7: Typical contact wire profile (y axis exaggerated)

Figure 8: Contact wire stagger (zigzag) on tangent track; East Boldon, UK

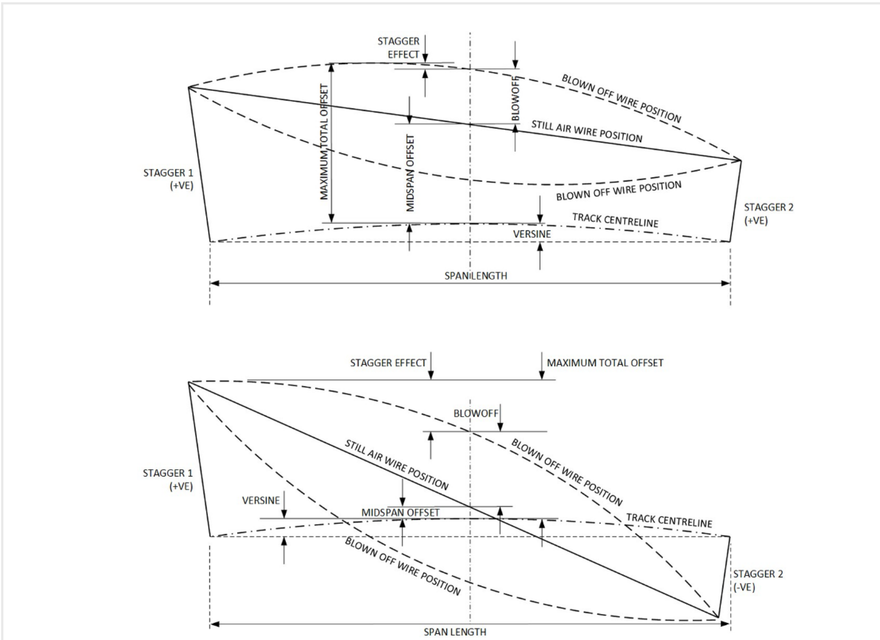

Figure 9: Midspan offset and blowoff illustrating in case two how a midspan offset can allow wire to be biased into the prevailing wind to improve reliability

more commonly known as zigzag – see Figure 8) and the horizontal stagger range is limited by the width of the pantograph. In operation, the horizontal operating range is most at risk at the midspan between the structures. This is because wind forces cause blowoff of the contact wire from its still air position. Designers must focus on minimising midspan contact wire offset, bringing the still-air position of the wire as close to zero as possible by adjusting stagger at the ends of the span accordingly. Midspan offset is a function of the stagger at either end of the span and the track versine (see Figure 9). Smaller structure spacings are needed on small radius curves to keep midspan offset within limits.

TURNOUT AND CROSSOVER WIRING

Special arrangements are required where tracks diverge, converge or cross, to ensure continuity of current collection and to 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, and then gets underneath the pantograph head with catastrophic results (see Figure 10).

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 (see Figure 11). The control structure is carefully positioned to hold the wire at a fixed stagger relative to the switch toe opening. UK OLE systems have evolved over time; there are a variety of rules applicable to individual OLE types, but all sit within a range of toe opening positions between 200mm and 350mm.

One method used to minimise the hook-over 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 (see Figure 12), which is set inboard of the control structure by careful staggering. The cross contact bar ties the two wires together while allowing for along-track movement.

The cross contact system has been used extensively in UK heavy rail - although the cross contact bar can cause high dynamic forces between the wire and pantograph 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.

TANGENTIAL METHOD

The latest UK designs instead favour a tangential arrangement with the crossover wire running parallel with the main line wire in the span before the control structure, and a different form of droppering around the turnout (see Figure 13).

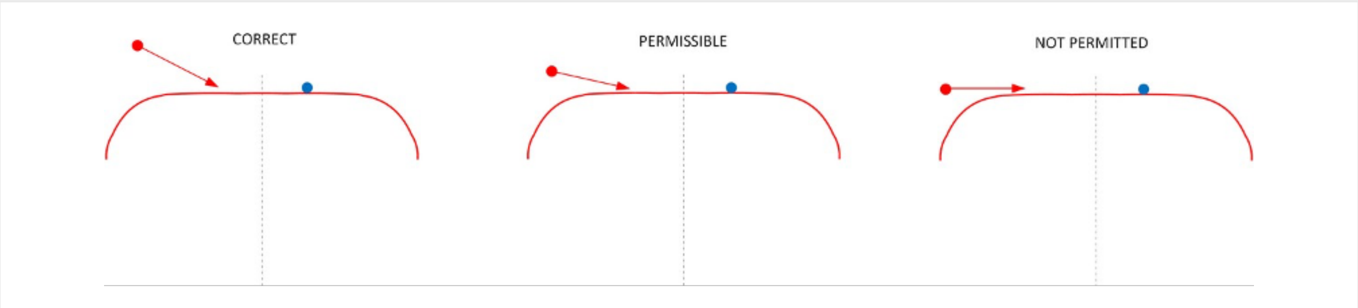

Figure 10: Hook-over risk for different wire/pantograph interactions

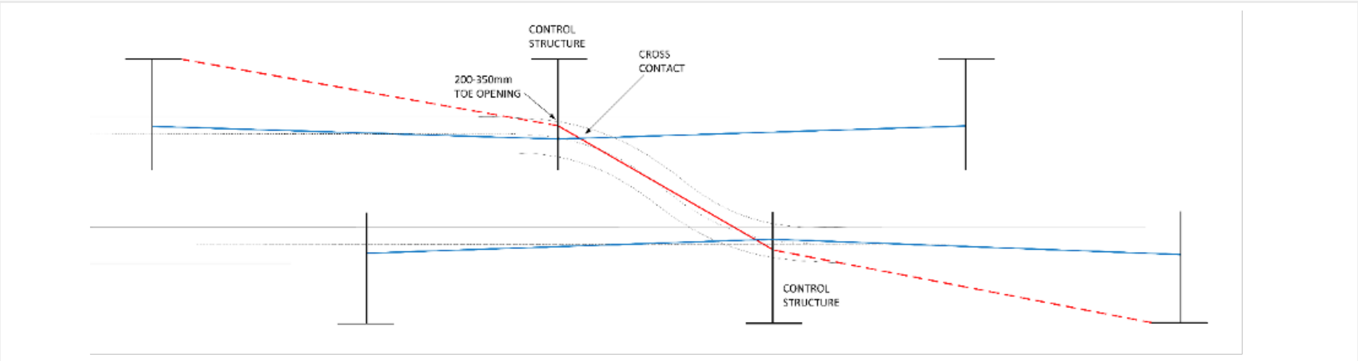

Figure 11: Traditional cross contact crossover wiring with mast anchors

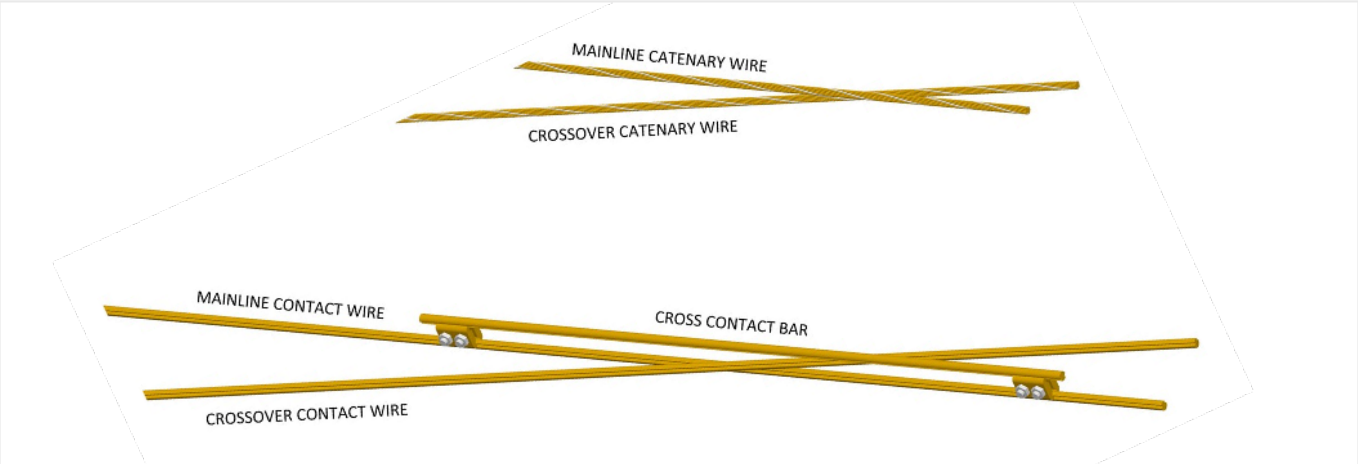

Figure 12: Traditional cross contact bar general arrangement

SECTION INSULATORS

Although overlaps are used wherever possible to create electrical section breaks, there are times when additional breaks are required. At these locations, a Section Insulator (SI) is used. This is a set of insulators spliced into the contact wire and catenary, while allowing the pantograph to pass directly in contact with the SI assembly. A standard insulator is used in the catenary, and an arrangement of insulators and skids are placed in the contact wire (see Figure 14); this allows the pantograph to pass over it without loss of current collection.

SIs introduce significant mass into the OLE which can result in high dynamic forces on the fragile pantograph carbon strip head assembly. Their use is generally restricted to crossovers, sidings and station areas where speeds are lower. SI installation design and set up are critical to achieve reliable performance.

NEUTRAL SECTIONS

An electrical section break is required wherever different supply phases meet at feeder stations and midpoint sectioning locations, or where there is a change of system voltage, as occurs at many European national borders; or where an earthed section of operational OLE is to be provided at a location where sufficient electrical clearance cannot be provided. At these locations a neutral section is used. This is a section of earthed OLE placed between the two electrical supplies (see Figure 15). This gives a high level of security against a short circuit between the two supplies.

The train must not draw power through the neutral section. The train power is automatically disconnected by a trackside Automatic Power Control (APC) magnet (see Figure 16), which signals the on-train APC equipment to open the circuit breaker on the train.

When the train has cleared the neutral section, the circuit breaker is closed by a second APC magnet. Care must be taken to place signals and neutral sections relative to each other to avoid the risk of a train becoming stranded in the neutral section.

There are two types of neutral section; the inline type, and the overlap or carrier wire (CWNS) type. The inline type consists of insulator rods cut into the contact wire and over the surface of which the pantograph runs. Sacrificial arcing horns are often provided to protect the delicate insulating rods in the event that a train draws an arc as it moves across the neutral section (see Figure 17).

The carrier wire type consists of two or more overlaps in quick succession; the first transfers the pantograph from the live wire at the entry to the neutral section where the pantograph transitions to an electrically floating wire run – the carrier wire; the second overlap transfers the pantograph back onto the live wire at the exit from the neutral section. As described previously APC systems automatically disconnect train power. In the UK, four overlaps are normally employed allowing an earthed section at the centre of the neutral section.

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.

TRACTION RETURN, EARTHING AND BONDING

These aspects of the electrification system are not the most exciting to look at visually, but they are a crucially important aspect of the system. The components, cables, connecting cable lugs, cable clips and fittings used for installation of the traction return system and for the earthing and bonding of the system seem to all look the same to the untrained eye and even to the trained eye, without careful reflection, the difference is not always obvious. Bonding cables can have a role both in traction return and in earthing. Any cable installed for these purposes is referred to generically as a “bond”.

TRACTION RETURN

As described elsewhere the train pantograph collects the 25kV supply current from the OLE. On the train, this is used to power the traction motors, run the air compressor for braking and provide lighting, heating and other domestic services. Also, on modern trains, it is used to power increasingly sophisticated control systems. Like all electrical power systems electric traction requires a circuit to function. Mains wiring in your home has a live and neutral conductor; the traction system equivalents are the OLE (live) and rail (neutral). In the simplest form an electrification system uses only the rails to complete the circuit back to the supply point. The rails must be electrically continuous, at places where that is not the case such as rail joints or around switches and crossings, then a bond, a bolted cable connection is placed across the electrical discontinuity. The cable must be sized to carry the current associated with the electrical load and the cross section of these bonds can be large. Steel conducts electricity, though it is a relatively poor conductor

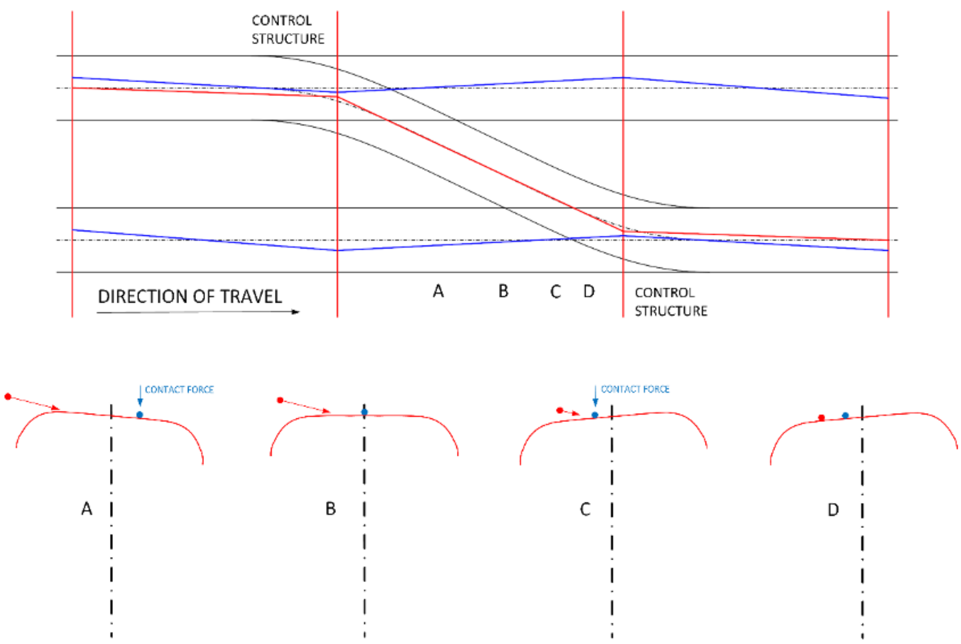

Figure 13: Pantograph approaching a turnout in the trailing direction, with hook-over risk controlled by careful staggering (head angle exaggerated)

having high unit resistance. A conductor made of steel presents just over 5 and a half times as much resistance as a copper conductor of the same physical dimensions. The resistance of the conductors in a distribution circuit limits the distance over which power can be distributed. That limitation is the result of the voltage lost in the conductors. Ohms law tells us that voltage loss is the numerical product of current (amps) times resistance (ohms). Rails have a large cross section compared to the OLE conductors, but the steel of the rails is part of the return circuit, so it follows that any steps to minimise the effect of the rail resistance will improve the overall efficiency of distribution. A significant contribution to securing best efficiency is by connecting all the rails on multi track railways together. At intervals of around 400m along the line “cross bonds” are installed which create a mesh connection of all the rails, placing them all in parallel electrically.

Alternating current (AC) for electric traction has the great advantage that higher voltage (25kV) can be used. The higher voltage means that lower currents are needed, making it possible to use lighter conductors. However, with that benefit comes an increased need to tackle electro-magnetic interference. OLE conductors produce a magnetic field and this will induce currents into any metal within the field; an effect called inductive coupling. Inductive coupling is most significant in its effect on cables running parallel with the OLE conductors. Induced currents can interfere with the function of signalling and telecommunications circuits on the railway, and non-railway electrical services beyond the railway boundary. Railway systems such as the signalling must be “immunised” on electrified routes. Immunisation measures for the railway systems entail some detail changes within the circuits and components of those systems. More conspicuous are the arrangements to supress the magnetic field at source. All magnets have a polar orientation. In radiated interference from conductors this orientation is linked to the direction of the current in the conductor. Placing the flow and return conductors in an electrical circuit in proximity has the consequence that the two magnetic fields, each equal to the other, but with opposite polar orientation, sum to zero, cancelling each other out. For an electric traction system this law of physics is exploited by the installation of an additional aerial return current conductor along the outside of the OLE structures above the cess. This is connected to the rails at the cross bonds described above. Some return traction current will therefore flow out of the rails and along the return current conductors, the proximity of which to the OLE will provide some significant suppression at source.

EARTHING

The electric traction system brings the risk of electrical injury to public, passengers and people. The exposed high voltage OLE conductors and assemblies are installed with clearances and associated guidance and rules to bring an acceptable balance of those risks. However, at ground level and in accessible areas the installation must always remain safe to touch.

Other electrical systems such as installations at stations and at the line side will bring electrical enclosures, lighting columns etc. into the same accessible zone. Furthermore, planet Earth itself is conductive, but the connection to that planetary conductor is variable due to topsoil qualities and water content. Without some attention, the OLE structures, the rails, lighting columns, metal bridges and structures and the planetary conductor would all settle at their independent voltage levels. Instantaneous changes in the relative levels of those voltages would result from the electrical load on the systems and from electrical storms. Electric shocks would be common, injury frequent and death a regular result. Thankfully, the elimination of that risk is simple.

The way in which connections to the planetary conductor (which we all refer to as “earthing”) is a matter of providing an electrical connection deeper into the ground. In most electrical installations copper covered steel earth rods are driven through the soils. For a railway traction system, the OLE foundations do the job. Each foundation on its own would not provide a good enough connection, but all the foundations are connected together, bonds connect the foundations to the rails and through the steel OLE structures to the return current conductors. All those connected parts form a bonding “mesh” which can be regarded as the traction earthing system. Bonds are added to connect the traction earth to the exposed parts of any other electrical system at stations and at the lineside, and to major metallic structures such as bridges, utility pipe crossings and station buildings.

RED BONDS

The interconnected traction return and earthing and bonding mesh includes one specific class of bond, the red bond. All bonds have the potential if they are disconnected to cause arcing and under short circuit to give rise to electric shock. Some equipment installed as part of and fed from the traction system such as protection

Figure 14: Arthur Flury section insulator; Rugby, UK

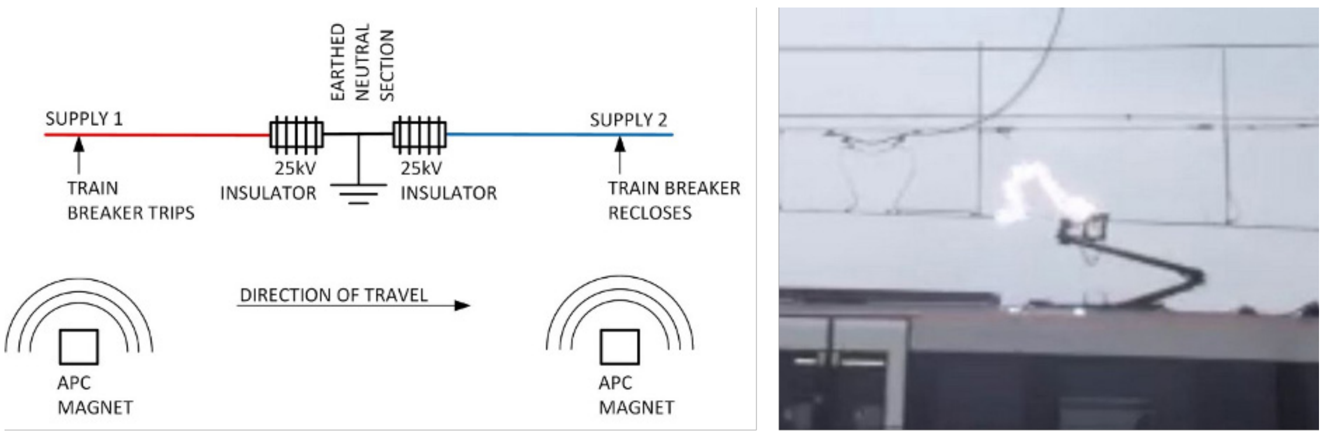

Figure 15: Hook-over risk for different wire/pantograph interactions

measurement and ancillary supply transformers make their return current connections through bonds that are sleeved or painted red. If, for any reason, these become disconnected under normal operation, dangerous voltages are exposed. Any red bond found cut, broken or not connected should never be approached or handled. It should be reported immediately to the Electrical Control Operator.

SUMMARY

This article describes the main electrical and mechanical system components of OLE electrification. The authors have tried to present wide coverage of a big subject area, necessarily avoiding the temptation to dive too deeply into technical detail to provide interest for those unfamiliar with or new to electrification.

We hope this will feed an appetite for more in-depth articles and technical papers which we intend will follow. Also, the PWI will, over the next few months, conclude the preparation of modules for a new training course as part of an electrification diploma, giving further opportunity to learn more.

This article and others which follow should prove essential reading for all, whether that is out of general interest, or to aid understanding towards formal qualification.

Figure 16: APC magnets

Figure 17: Arthur Flury type inline neutral section; Drayton Park, UK. Note the uninsulated cantilever at the neutral point

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