APPLICATION NOTE

Railway Bonding

Railway electrical systems

In the UK, we have two common power systems supplying locomotives. A 25 kV overhead line system and a 750 V third rail system. Both systems use the track as a return path for current flow (see figures 1 and 2).

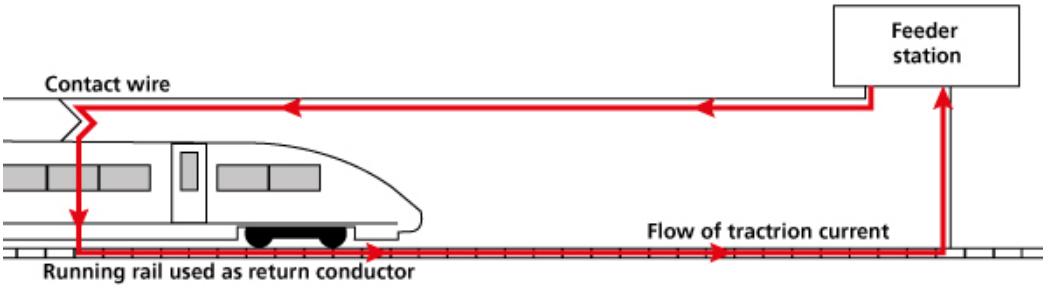

Fig1: Overhead line power supply to a train

Fig2: Third rail supply to trains (broken at crossing point to prevent electrocution)

The traction return can be implemented in multiple ways. However, it is worth noting that you can expect at least one rail to act as a return path (see figure 3). This will be earthed to prevent the rail voltage rising to a dangerous level (see figure 4). Sometimes the second rail will act as a parallel return path. In other areas, it will not form part of the power system at all. Instead being used as a signalling conductor.

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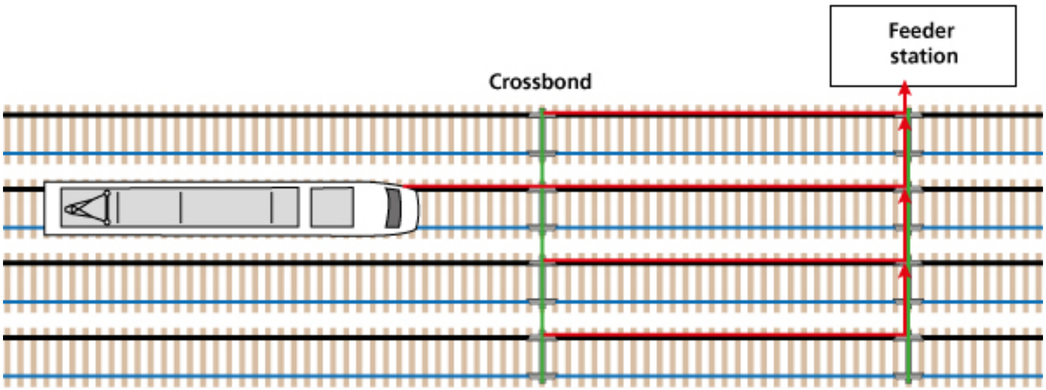

Fig3: Crossbonded traction return rails

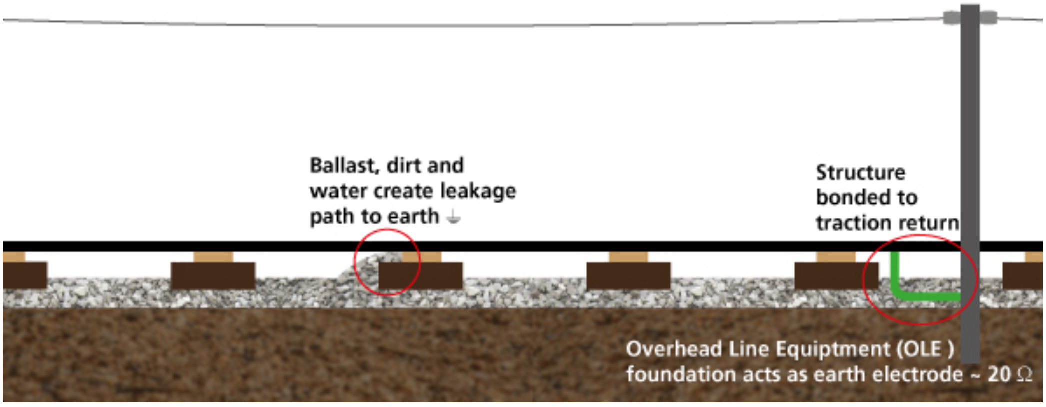

Fig4: Deliberate connection from rail to earth. Without it, the voltage between the rails and earth would rise to significant potentials.

When more than one rail is used as a return path for current flow, the rails are cross-bonded at regular intervals in order to prevent rises in ground potential (see figure 3). Crossbonds distribute the return current over the tracks, reducing the return impedance, and lowering rail voltage. They also reduce the impact of a missing bond or break in the traction rail. The rail voltage can also be reduced by adding more parallel conductors (such as an Aerial Earth Wire (AEW)).

Earthing and Bonding

These are the reasons that adequate earthing and bonding is required:

- Human protection
- Functional
- Lightning Protection
- EMC

The risks associated with poor earthing and bonding systems are as follows:

- Safety of the general public
- Employee H&S
- Employee engagement
- Customer experience
- Financial
- Environmental
- Reputation

The UK's Electricity at Work Regulations specify the following ABSOLUTE (meaning must be done) requirements with regard to earthing and bonding of an electrical system.

Integrity of referenced conductors:

"If a circuit conductor is connected to earth or to any other reference point, nothing which might reasonably be expected to give rise to danger by breaking the electrical continuity or introducing high impedance shall be placed in that conductor unless suitable precautions are taken to prevent that danger."

The suitable precautions mentioned in this absolute requirement may be met by undertaking a programme regularly testing.

Connections:

"Where necessary to prevent danger, every joint and connection in a system shall be mechanically and electrically suitable for use."

Testing the resistance of joints and connections in a system upon installation would help to prove compliance with the above requirement.

The railway electrical systems are a small proportion of the cost compared to a railway's civil infrastructure. Therefore, it will not significantly affect a projects budget by allowing the funding for testing. But, it will help to ensure compliance with the Electricity at Work Regulations and subsequently make sure that railway staff and the public are safeguarded against electric shock.

Railway Bonding

Why test?

Commuters expect a reliable service. As a result, there is constant pressure to reduce delays and cancelations. This is understandable, when considering that research found UK train delays to cost passengers 3.6 million hours in 2016 (Lancefield, 2017).

This has a significant impact on rail industry revenue. Rail line disruption can cost as much as £3 million per day, in some locations (BBC News, 2018).

Routine testing can reduce the risk of unexpected failures, and the high costs associated with them. As can thorough testing during installation.

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Key concerns

Lightning strikes

Lightning strikes have been found to damage rail infrastructure almost 200 times per year in the UK. Typically causing 6 hours of delays on each occasion. On average, 58 trains per year are cancelled in the UK because of damage caused by lightning.

Rails and overhead line equipment (OLE) structures are prone to lightning strikes. Figure 5 shows an example incident. The high voltage from a lighting strike hitting a rail can damage electronic signalling equipment. This will cause all nearby signals to turn red, as the system will fail-safe. Lineside LV equipment is also susceptible to lightning phenomena. A low resistance path to earth helps to protect signalling equipment and lineside LV equipment from damage. A high resistance path caused by a broken conductor could fail to protect sensitive equipment from failing.

Fig5: Lightning stiking overhead line equipment (OLE)

Ground Potential Rises (GPR)

GPR is not permitted to exceed 60 V under normal conditions and 645 V under fault conditions. But, the true values will vary throughout the system. Ideally, it is kept as low as possible.

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The grounded rail will vary in potential across the large distances that they stretch. Cross bonding rails helps to keep the rail voltage within limits. But, the rail voltage will still peak at the furthest points from each cross bond. In other words, halfway between a pair of cross bonds, the voltage will be at its highest. The effects of 800 m and 400 m cross bonds on rail voltage are shown in figure 6. The smaller the distance between cross bonds, the smaller the peak rail voltage. The larger the distance between cross bonds, the larger the peak rail voltage. So, what would be the effect of losing a single cross bond? A 400 m spacing would sudden change to an 800 m spacing. Or, an 800 m spacing changes to 1600 m. Increasing the rail voltage at that location. This could result in a dangerous situation for anyone who comes in contact with the rail. Routine inspection and testing of the cross bonds can reduce this risk. Original design to include multiple conductors with cross bonds also reduces risk by adding redundancy in to the system.

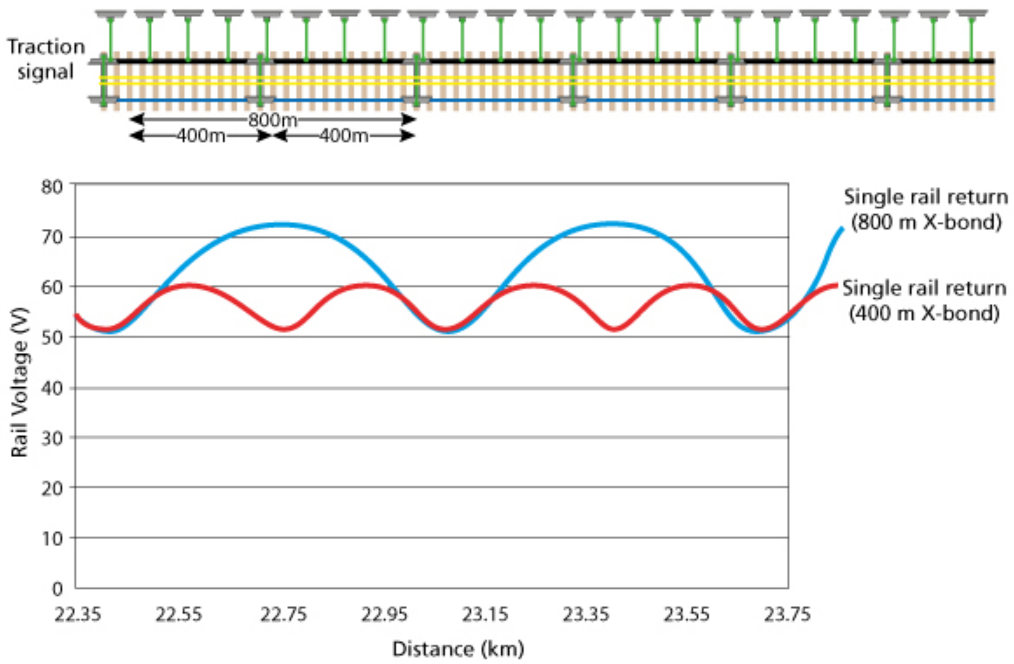

Fig6: Spacing between track to track cross bonds

If it is necessary to reduce the rail voltage at the cross bond itself. Parallel conductors are required. Such as an Aerial Earth Wire (AEW) connected to OLE structures. Where these are employed, they are usually bonded to the traction rail every 400m. Like with cross bonds, there is potential for the rail voltage to rise if the bond resistance increases to an unsatisfactory level. This can occur due to a number of reasons. Here is a list of potential causes:

- Poor / rough mating surfaces

- Dirty mating surfaces
- Damage
  - Frayed wires / broken strands etc.
- Corrosion due to damp
- Chemical attack
- Environmental and chemical attack
  - Even air will oxidize
  - Moisture ingress
  - Oil and salt will degrade connections even more rapidly.
  - Chemical corrosion can attack the mating surfaces
- Electrical stresses
  - Over voltages or impulses
- Mechanical stress
  - Vibration, impact, start / stop
  - Metal fatigue
- Equipment heat up and cool down cycles

In-service failure of bonds

In addition to the concern of cross bonds failing. Which can lead to a rise in rail voltage. There are also concerns of the failure of joints in locations inaccessible to maintenance (such as earth mats) and of failed bonds in high-risk areas (such as bridges).

Earth mat bonds

Earth mat joints must be capable of holding for a significant period of time. This is particularly so in public locations such as railway stations. If enough joints fail in a buried earth mat. It could cause the earth resistance to rise to an unacceptable level. It would then cause significant disruption to dig up and rectify the issue. In one case study for the Crossrail project (shown in figures 7, 8 and 9). It was necessary to measure the resistance of each of the individual joints prior to pouring the concrete. The bonds were formed by copper tape connections to the rebar buried in concrete (see figure 10) Testing with a micro-ohmmeter, this process indicates whether any of the many joints have slight weaknesses. Minor weaknesses, that may not be apparent from visual inspection, could deteriorate further over time. Reducing the longevity of the earth mat. In the case of Crossrail, it was a requirement that the earth system last for at least 120 years. Given its importance, it was deemed worth the time taken to measure the resistance of every joint during installation and again prior to pouring the concrete.

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Fig7: Crossrail station earth mat under construction (Jonathan King FIET, 2018)

Fig8: Crossrail station earth mat – tested joint resistance before concrete pour (Jonathan King FIET, 2018)

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Fig9: Crossrail – concrete poured over earth mat. Has to last at least 120 years (Jonathan King FIET)

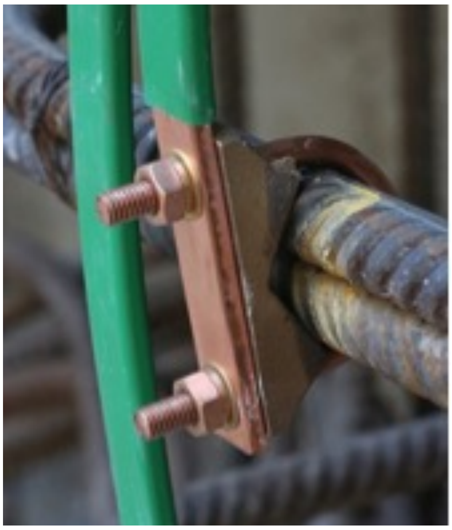

Fig10: Copper Tape Connection to rebar (Jonathan King FIET)

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Bonds in high risk areas

OLE equipment running beneath bridges is often supported by securing to the underside of the bridge itself (see figure 11). This presents a risk in that a high voltage conductor is supported from a structure that may carry a significant amount of vehicular and pedestrian traffic. Any rise in potential on the bridge will be dangerous to unsuspecting passers-by. Bonds will also be subject to additional vibration from vehicles travelling across the bridge.

Fig11: OLE running underneath a bridge

In the event of insulation failure, protection is provided by bonding any extraneous or exposed conductive parts to earth (see figure 12). Given that there is a high risk to the public in the event of a fault, the condition of these bonds should be checked regularly.

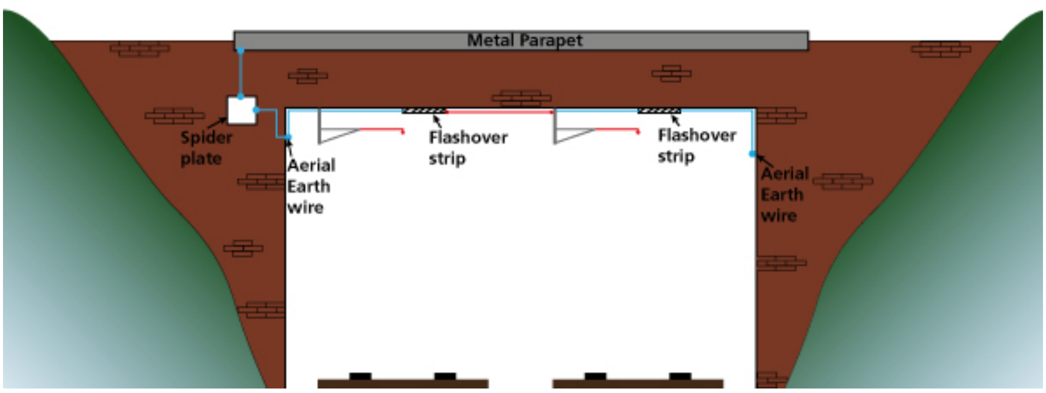

Fig12: Bridge bonding for OLE

Live conductor joints

So far, the focus has mostly been on the bonding of protective conductors. However, failure of live conductor joints can be equally problematic. In addition to the inconvenience of resolving unexpected failures. High resistance faults can also become dangerous due to overheating. Particularly in high current system, such as the supply of trains.

As previously mentioned, various causes can lead to an increase in resistance at a joint. These can result in excessive heating at that location when carrying the rated current, based on the formula $P=I^2R$. For example:

6000 A across a 1 μΩ bus = 36 W.

6000 A across a 100 mΩ bus = 3,600 kW, which will result in excessive heating.

Figure 13 shows an example of excessive heating at a joint in a live conductor. The thermal image shows the fault clearly. However, it is important to note that thermal imaging can only identify overheating while large currents are flowing. As soon as the trains cease to run, the joint will cool down. The fault becoming invisible to thermal imagers. This is also the reason that thermal imaging are not suitable for identify protective conductor faults. Whereas, a low resistance measurement will identify the fault every time.

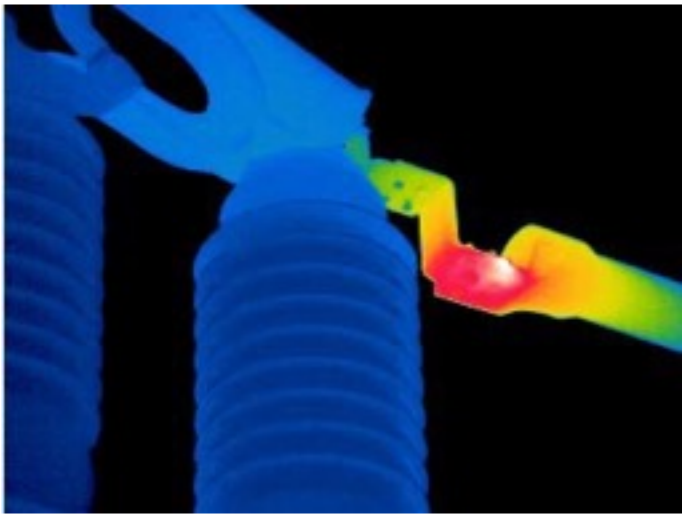

Fig13: High resistance joint heating up while high current flows

In this type of situation, the system may continue to function normally. But eventually, the heating is likely to cause either a sudden failure of the joint or, even worse, the start of a fire.

Testing must take place overnight

A final key concern for railway earthing and bonding is that, where possible, all maintenance is performed overnight (figure 14). Always on site, it will be outdoors and could occur during poor weather conditions. This is vital to minimise disruption to commuters. However, it puts maintenance staff on a strict schedule. Any work they do must be made good for trains to run the following morning. As such, any test equipment must be quick and simple to use, even in poor lighting/weather.

Fig14: Railway maintenance team working overnight to keep the trains running

What needs testing?

Ideally, all bonds should be tested periodically to predict failures before they occur. In practise this is a large undertaking. So there should be an emphasis on thorough testing of bonds upon commissioning. Recording results for future comparison. During service, areas of high risk should be considered as candidates for periodic testing. This will allow for monitoring the trend in resistance measurements. As a result, future failures can be identified and repaired before they pose a danger or disruption.

These are some of the particular areas that periodic testing should focus on:

- Resistance of cross bonds
- Resistance of bridge bonds
- Resistance of live conductor joints
- Resistance of earth mat bonds

Figure 15 shows some of the failures that can be avoided by routine testing.

Fig15: Overheated connections due to high resistance

Cross bonds are often inspected visually. Unfortunately, testing is often neglected. Visual inspection is important. But, it will typically only identify faults that are already quite severe. A quick resistance measurement can indicate an increasing resistance before it becomes noticeable to the eye. Enabling a minor repair to be carried out at the maintenance team's convenience. Rather than rectifying a major failure at short notice.

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There is often a focus on the losing of a bond. Rather than being concerned about an increase in resistance across the bond. The former may be more noticeable and appear a more immediate concern. But the latter can be equally dangerous as it poses a fire risk. In the event of a fault causing current to flow through the bond to earth. The amount of current will be limited by the resistance of the bond. If high resistance, a situation could occur in which the fault current is not high enough to instantaneously activate a circuit breaker. However, the current could still be significantly higher than the rating of the earth path. Enough to cause a fire. Therefore, it is important that the effect of increasing resistance in a bond be considered. Not just the concern of losing the bond completely.

Here are some typical tests to be performed on railway earthing and bonding systems:

- Soil/electrode resistance
- Step and touch potential
- Earth fault loop impedance (EFLI) or prospective fault current (PFC) at feeder stations
- Bond resistance

Selecting an instrument

Care should be taken when selecting a test instrument to ensure the measurements will be adequate for the application. Possible sources of error include:

- Lead resistance
- Contact resistance
- External influences, such as:
    - Temperature
    - Noise ratio and induced currents
    - Thermal EMF / Seebeck voltage
    - Surface leakage due to contamination
    - Hotspot effects

True low resistance testers will overcome lead and contact resistance with a four terminal measurement. Most of the external influences can be overcome by selecting an instrument with a higher test current (as high as is practical for the situation) and a bi-directional test mode. The test current used should not exceed the rated current of the equipment under test. Up to this point, higher test currents gives better possibilities to obtain reliable test results.

In addition, the instrument should be suitable for use in the environments it will be used in. Such as, having a sufficient Ingress Protection (IP) rating and being sufficiently rugged for use on site.

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Summary

Failed bonds can have a significant impact on rail industry revenue. Rail line disruption can be very costly. Both financially and to the service providers reputation with commuters. Not to mention the safety concerns associated with bond failures. Testing during commissioning and routine testing can reduce the risk of unexpected failures and detect missing or high resistance bonds.

Megger offer a range of low resistance ohmmeters to measure bond resistance to a high degree of accuracy in harsh environment (such as the DLRO10HD in figure 15). In addition, Megger manufacture a wide range of earth resistivity and Earth Fault Loop Impedance (EFLI) test equipment.

Fig16: The heavy duty DLRO10HD taking a measurement

Remember that the railway electrical systems are a small proportion of the cost compared to a railway's civil infrastructure. Why take risks when the cost of testing will add little to a project's cost?

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