Background

This paper is addressed to the regular members of the Permanent Way Institute, who may consider that the design, construction, operations and maintenance of the Track asset is purely a civil/structural engineering concern. The paper aims to describe the other aspects of Track as a rail system that is an integral part of the electrical and signalling systems of a modern railway. It covers the history of electrified railways, and the technical, reliability and safety aspects of the rail systems associated with Track and demonstrates that, while the Track is occasionally required to support rolling stock, it is also required, 100 percent of the time, to carry electrical current and to provide communications between a range of signalling systems.

History

Electric traction

The first electric passenger train was built by Siemens and was demonstrated at Berlin, Germany in 1879. The electricity was supplied through a third, insulated rail situated between the tracks. A contact roller was used to collect the electricity from the third rail. The world’s first electric tram line, also built by Siemens, opened in Lichterfelde near Berlin in 1881. Electric railways and tramways were opened in 1883 in the United Kingdom and in 1888 in the United States.

Much of the early development of electric traction was driven by the increasing use of tunnels. The City and South London Railway underground line opened in the United Kingdom in 1890, and electricity quickly became the power supply of choice for subways.

The first use of electrification on a mainline was on a section of the Baltimore Belt Line of the Baltimore and Ohio Railroad in the US in 1895. The Chicago, Milwaukee, St. Paul and Pacific Railroad electrified its lines across the Rocky Mountains and to the Pacific Ocean starting in 1915. During the 1930s, the Pennsylvania Railroad electrified its entire territory east of Harrisburg.

The early electrified railways employed direct current (DC). The first practical alternating current (AC) traction system was installed on the Lugano Tramway (Switzerland) in 1896. By 1904, the Seebach-Wettingen line of the Swiss Federal Railways was completed using a 15 kV AC traction power supply system.

The 1960s saw the electrification of many European main lines. In the 1980s, development of very high-speed service brought a revival of electrification, typically employing 25 kV AC power supply systems.

Electric signalling

The ‘fail-safe’ signalling track circuit was invented in 1872 by William Robinson, an American engineer. His introduction of block occupancy detection was the key to the development of railway signalling systems. The first practical automatic railway signalling system was subsequently installed on the Philadelphia and Erie Railroad in Pennsylvania.

Today, a wide range of train detection technologies are employed. The predominant mainline system is the audio frequency track circuit which uses ‘tuned loops’ that do not require conventional insulated rail joints to subdivide the track into blocks, and this technology enables long lengths of fully welded ‘joint-less’ track sections to be constructed.

Electric rail systems in Australia

Melbourne ran its first electric trains in 1919. The first electric train ran in Sydney in 1926 and, by 1932, the system had replaced steam-hauled trains on the major suburban lines, including a city railway with a circle line, a link across the Sydney Harbour Bridge and, at the time, the largest complex of grade-separated flying junctions in the world.
Track – The Electrical Asset

In an electric traction system, one or both of the track running rails are used to provide a return path for traction current, from the locomotive back to the substation, and also to provide electrical connections in the signalling track circuits that detect the presence of trains.

Figure 1 is a simplified sketch of a typical ballasted plain track, showing the rails and sleepers only, overlaid with an equivalent circuit diagram showing the key electrical parameters.

Viewed with an electrical engineer’s eye, the track is an electrical circuit. Based on standard gauge track with 60kg/m rail, the electrical parameters are approximately:

- $R_R$, Rail Resistance: $\approx 0.03 \text{ ohm/km}$
- $L_R$, Rail Inductance: $\approx 2 \text{ mH/km}$
  
  \[1 \text{ mH} = 1 \times 10^{-3} \text{ Henry}\]
- $R_E$, Rail to Earth Resistance: $\approx 100 \text{ ohm.km}$
- $R_T$, Track Resistance, rail to rail: $\approx 200 \text{ ohm.km}$
- $C_T$, Track Capacitance, rail to rail: $\approx 1,000 \text{ pF/km}$
  
  \[1 \text{ pF} = 1 \times 10^{-12} \text{ Farad}\]

The Rail Resistance, $R_R$, is a function of the resistivity of the rail material and is inversely proportional to the weight of the rail – larger rail sections have a lower value of resistance. Rail Inductance $L_R$ and Track Capacitance $C_T$ are determined by the physical dimensions of the track system, particularly the size of the rail and the spacing between the rails. Rail to Earth Resistance $R_E$ and Track Resistance $R_T$ are determined by the type of rail fastenings, sleeper material and the condition of the ballast. Rail Resistance $R_R$ and Rail to Earth Resistance $R_E$ are the key parameters that determine the performance of the track system for traction return and for stray current effects.
When both the signalling and traction systems are considered together, they require the track to carry a range of different currents and voltages at different frequencies, and therefore the electrical characteristics of the track need to be well known. As an electrical system, the track is required to:

- carry large traction return currents (i.e. 1,000s of amps, at DC or mains frequency AC (50Hz in Australia))
- provide a return path for traction fault currents, under short circuit conditions (i.e. 5,000 to 10,000 amps)
- conduct signalling track circuit currents, that may be DC, mains frequency AC (50Hz), audio frequency AC (~1,000 to 3,000Hz) or impulses (up to ~100V)
- block signalling currents to prevent interference between adjacent track circuits
- insulate the signals carried by the rail from earth.

**Rail Systems**

**DC traction**

In DC traction systems, the track is usually negative and the overhead wiring is positive, and the track is not usually earthed. As the track in an unearthed system is electrically ‘floating’, there will be a voltage difference between the track and earth. The magnitude of the voltage will vary depending on the train load, the electrical resistance of the rails, the condition of the track support system and the distance from adjacent substations.

On the Sydney suburban network, the traction power supply is 1,500V DC and the substations are arranged with pairs of rectifiers that are rated up to 5MW each. Traction return currents are typically around 2,000A.

The track, therefore, a significant electrical conduction system, in which the rails are the conductors and the track support system is the insulation. The rails and the associated electrical connections must be designed to carry very large DC return currents, and the track support system – sleepers, fastenings, ballast and the track formation – needs to provide electrical insulation from the general mass of earth.
Due to the magnitude of the traction return current, the rails in multiple track areas are ‘cross-bonded’ to each other so that current is conducted back to the substation by all of the available rails and not just by the track that is carrying the train. The cross-bonding has the effect of increasing the current carrying capacity of the traction return system, and the sharing of return current reduces the voltage rise on the track and also reduces the levels of stray current in the earth adjacent to the track. The sharing of return current across multiple tracks is illustrated in Figure 2.

**Stray current effects in a DC traction system**

In DC traction systems with poor track insulation, the return current can leave the track in areas that are remote from the rectifier substations where the rail is positive with respect to the general mass of earth and the current can pass back to the track in areas close the substations where the rail is negative with respect to earth.

This ‘stray’ current will use the path of least resistance where it passes through the earth, generally via any buried metallic structures that are close to the track. At the point where the stray current leaves the metal structure and enters the earth, electrolytic corrosion of the metal will occur. The rate of corrosion can be significant as, in the case of steel, this corrosion rate is approximately 9kg of metal lost, per amp of current, per year. In track systems with good resistance to earth and with appropriate stray current mitigation measures in place, such as structural insulation and equipotential bonding, the rate of corrosion is negligible. However, when the track insulation is compromised (e.g. by a direct metallic connection between rail and earth), stray currents of a few hundred amps can flow and the rate of corrosion of adjacent metallic structures increases dramatically.

**AC traction**

AC traction systems differ from DC systems in that the traction power supply voltage is a lot higher – typically 15kV or 25kV AC compared to 1,500V DC – and the return currents are correspondingly smaller in an AC system. The track is usually solidly earthed and is bonded directly to the high-voltage power distribution earthing system.
An AC traction power supply system is normally arranged with power supply feeders along the length of the railway with transformers at regular intervals that provide ‘boost’ to the traction supply voltage. AC systems are arranged so that the majority of the traction return current flows through the power supply feeders instead of the running rails, which minimises electromagnetic induction and interference to other systems that may be in close proximity to the railway. The current flow in a typical AC traction system is shown in Figure 4.

Signalling track circuits

The running rails also provide the electrical connections in the signalling track circuits that detect the presence of trains in the railway sections. Track circuits are designed to be fail-safe and to provide:
- train occupancy detection
- broken rail detection
- default to ‘occupied’ indication for a range of failure conditions, including power supply failure, open circuit connection, broken rail, relay failure.

Various track circuit technologies are employed. On the NSW railway system track circuit types include:
- DC, in older non-electrified areas
- AC, in older DC electrified areas
- Audio frequency, on modern joint-less track main lines
- high-voltage impulse, on turnouts and sidings where rust may be present due to infrequent use.

The basic track circuit has a power supply connected across the rails at one end of a track section and a relay connected across the rails at the other end (see Figure 5). When the track circuit is clear, current flows from the power source, along the rails, to energise the relay.
When a train occupies the track circuit, the metal wheels connect the two rails together and the current from the power supply flows through the wheels. Negligible current flows through the relay, and so the relay is de-energised when there is a train in the track section (see Figure 6). This basic track circuit is fundamentally fail-safe. If the power fails or a connection (or rail) is broken, the relay will be de-energised, irrespective of the state of the track circuit. Under failure conditions, the track circuit will then appear to be occupied.

Where insulated joints are required, the preferred method is to use a glued joint rather than a bolted fishplate joint. Two short lengths of rail are fishplated and glued together under factory conditions and the joint is welded into the track as a complete unit, resulting in a highly reliable joint that requires minimal maintenance.

Areas with heavy traction loadings generally require double rail track circuits in which both rails are used for traction return and for signalling. Double rail track circuits may employ AC, audio frequency or high voltage impulse technology.

The preferred track circuit technology for mainline track is the audio frequency type, as it does not need physical insulated joints and enables the track to be continuously welded into long lengths. Insulated rail joints are only used at points and crossings or where there is a change to a different type of track circuit technology.

Audio frequency track circuits use a signal of a particular frequency, with different frequencies chosen so that adjacent tracks do not have the same audio frequency. The tracks are separated by electronic joints or ‘tuned loops’ that employ tuning units to connect the signalling transmitters (for power supplies) and receivers (for relays) to the track.

The tuning units make use of capacitors and inductors, and the electrical properties of the track, to produce an impedance characteristic that presents a high impedance to one track circuit frequency and a low impedance to the adjacent track circuit frequency. The key components of an audio frequency track circuit are shown in Figure 8 (on following page).
A typical tuned loop consists of two tuning units separated by a specific length of rail. Each unit is tuned to resonate with the frequency of its own track circuit, and the dimensions of the tuned loops and track connections are critical in achieving the correct resonant frequencies. The dimensions of a typical 20-metre tuned loop arrangement are shown in Figure 9:

Figure 9: Typical tuned loop

Figure 10: Tuned loop circuit diagram and impedance characteristics
With reference to the circuit diagram in Figure 10, the tuned loop operates as follows.

1. At the tuning unit end of track circuit A on the left, the rail to rail voltage encounters a high impedance to its own track circuit frequency (F1) and, at the same point, the tuning unit presents a low impedance to the frequency of the adjacent track circuit B on the right (F3).

2. At the right-hand end of the tuned loop, the rail to rail voltage of track circuit A is shunted by the low impedance presented at its frequency (F1) by the tuning unit of the adjacent track circuit B.

3. The action of the tuned loop, therefore, limits the propagation of track circuit voltage past the adjacent track circuit tuning unit in a similar manner to a conventional insulated rail joint.

Bonding

In order for the track to satisfactorily conduct the various currents and voltages that are imposed by a modern electric railway system, cable connections are made directly to the running rail. These connections are collectively known as rail 'bonding' and are the sole responsibility of the signalling engineer.

Types of bonding include:

- fishplate bonding to provide a low resistance path around mechanical rail joints for electrical continuity along the track
- jumper bonding to provide the correct electrical connections for traction return and signalling currents in point and crossing areas
- traction return, at each substation, to provide a path for return current
- cross bonding, at regular intervals between substations, to share the return current path across all available rails in a multiple track area
- spark gaps, on DC traction systems, to provide a return path for fault currents directly to rail
- signal bonds for the connection of trackside signalling equipment to rail
- equipotential bonds for the connection of the track to adjacent metallic services and structures in order to minimise stray current effects.

The photo below shows a typical set of signalling bonding cables, rail connections and mechanical protection on a ballasted track with timber sleepers.

Safety Hazards and Safety Awareness

When work is carried out on or adjacent to the track, the work safety hazard assessment needs to include controls for the electrical hazards that are likely to be encountered. The track on an electrified railway presents similar hazards to those encountered on electrical power distribution systems. These hazards include electric shock, fire and corrosion damage due to stray current.

Rail removal

Rail removal and replacement in track circuited or electrified areas require special precautions to ensure that the risks associated with the work are controlled. These precautions include the protection of trains, alternative arrangements for traction return current and the testing and certification of affected track circuits upon the completion of the work.
In electrified areas, before there is any interference with the rails forming part of the traction return, adequate provision must be made for a return path for the traction current to the adjacent substation or section hut. It is important to recognise that, as noted in the section on ‘DC traction’ above, all of the rails in a multiple track area may carry traction return current, not just the track that is carrying the train. The signalling equipment must also be protected against damage due to the possibility of a rise in rail voltage as rails are disconnected and removed. Unsafe voltages can develop across rail breaks and cable disconnections, particularly if the last remaining traction return path is inadvertently broken.

In some circumstances, temporary rail bonds may be used around a rail break to maintain traction return currents or to keep signalling track circuits working in conjunction with welding of joints, renewing defective fishplates, and replacing short lengths of rail.

Bonding damage

Particular care must be taken to protect rail bonds during trackwork and all bonding must be thoroughly inspected before a section of track is returned to service. The following photos are two examples of signalling bonds that were damaged by track tamping machinery.

Rail to earth short circuit

Another hazard is the short circuiting (inadvertent connection) of the rail to earth by construction equipment. In such circumstances, rail voltages of up to 100 volts may be transferred into working areas that are remote from the track leading to the hazard of electric shock, and many hundreds of amps of traction return current might be caused to flow through the equipment and adjacent metallic structures, especially if such structures are effectively earthed.

While the voltage is not high and the risk of fatal electrocution is small, the relatively large currents that flow can become a fire hazard due to the possible arcing and sparking of overheated metal, and significant electrolytic corrosion damage can occur to structures due to stray currents as noted in the section on ‘Stray current effects’ above. The photo below is an example of metallic scaffolding on a rail construction site that was tied directly to the track.

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Conclusion

While Track is undoubtedly the Permanent Way of the railway and is mainly a civil/structural engineering discipline, it is hoped that this paper has made the reader more aware of the ‘other’ aspects of Track (i.e. as a rail system that is an integral part of the electrical and signalling systems of a modern railway).

Even when the Permanent Way is taken away in extreme situations such as flood, the track would still be capable of performing its electrical functionality (see photos below)!
The key message is that the Track should also be recognised as an electrical system that carries with it the same sorts of hazards that are found on power distribution systems and safety critical signalling systems. These electrical hazards, therefore, need to be respected and managed accordingly during the design, construction, operations and maintenance phases.

References