Estimation of electrical losses in Network Rail Electrification Systems
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1. BACKGROUND

Rail is responsible for less than 1% of UK carbon emissions. Electric traction powers around 60% of rail journeys but accounts for around 43% of rail carbon emissions.

The Climate Change Act 2008 creates a legally binding target to reduce the UK’s emissions of greenhouse gasses to at least 80% below 1990 levels by 2050.

To enable the industry to account for energy usage with more accuracy, the ORR periodic review 2008 contained the provision for on train metering, and the track access arrangement to allow for EC4T settlement via meter readings.

The ORR provision includes the acknowledgement that metered consumption would need to be uplifted to ensure that infrastructure transmission losses are accounted.

2. PURPOSE

The purpose of this report is to provide a guide to the magnitude of loss occurring in the electrification systems operating modern trainsets.

3. SCOPE

Electrical losses incurred in the electricity supply industry or on board trains are excluded from this report. This report only considers losses incurring on railway infrastructure.
### 4. DEFINITIONS & ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Ac</td>
<td>alternating current</td>
</tr>
<tr>
<td>AT</td>
<td>Autotransformer</td>
</tr>
<tr>
<td>BT</td>
<td>Booster Transformer</td>
</tr>
<tr>
<td>CP4</td>
<td>Control Period 4</td>
</tr>
<tr>
<td>dc</td>
<td>direct current</td>
</tr>
<tr>
<td>EC4T</td>
<td>Electric Current for Traction</td>
</tr>
<tr>
<td>ESI</td>
<td>Electricity Supply Industry</td>
</tr>
<tr>
<td>ESTA</td>
<td>Electricity Supply Tariff Area</td>
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<tr>
<td>NR</td>
<td>Network Rail</td>
</tr>
<tr>
<td>OLE</td>
<td>Overhead Line Equipment</td>
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<tr>
<td>ORR</td>
<td>The Office of Rail Regulator</td>
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<tr>
<td>RR</td>
<td>Rail Return</td>
</tr>
<tr>
<td>TPH</td>
<td>Traction Paralleling Hut (DC)</td>
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<tr>
<td>TSC</td>
<td>Traction Section Cabin (AC)</td>
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</tbody>
</table>
5. NETWORK RAIL INFRASTRUCTURE BACKGROUND

Network Rail has around 8000km of ac OLE electrified routes and 4800km of dc electrified tracks. Last year, a higher proportion of energy per route km was consumed on the dc than ac systems.

![Figure 1 - NR Electrified Track and Power Consumptions in (Apr 08 – Mar 09)]

5.1. ac Electrification

The NR ac traction system is based on 25kV OLE and is installed on WCML, ECML and the suburban areas of Glasgow, Leeds, Birmingham & Anglia. The system consists of

- HV Transformer substation (nominal 132/25kV or 400/25.0.25kV)
- Feeder station and along track distribution buildings
- Mid Point distribution buildings with neutral sections
- OLE contact wire and catenary
- OLE structures, associated track bonds
- The ECR and SCADA system which control the status of ac and dc circuit breakers, and other remote operated devices.

Originally, the railway was electrified using the rail return system. However as the load increased, so did the voltage induced into telecoms circuits. Booster transformers were installed to boost the return current into the return conductor which due to its closer proximity to the OLE provides an electric field cancellation effect. Booster transformers are installed in over 85% of the ac network.

Unfortunately, booster transformers add impedance to the electrical system, which limits system capacity. Network Rail has developed autotransformer technology to retro fit on existing infrastructure. This successfully lowers the system impedance. The addition of an anti phase conductor, also doubles the transmission voltage, further improving the efficiency.
The OLE is sectioned so only one supply transformer can feed an electrical section. Neutral sections provide electrical insulation between two sections.

Figure 2 – Rail Return system

Figure 3 – Booster Transformer system

Figure 4 – Autotransformer system
5.2. dc Electrification

The Network Rail dc traction system is based on a nominal 750 V, top contact, third rail system. This system is installed on over 4800 km of railway tracks south of London, plus North London Line, Northern City Lines, Euston to Watford and Merseyrail.

The third rail system consists of the following major components:

- The 3-phase high voltage ac Grid supply points
- The 3-phase high voltage ac distribution cables and switching stations
- The dc distribution track paralleling huts and substations including the transformer rectifiers
- The ETE and associated return current equipment, ie impedance bonds.
- The ECR and SCADA system which control the status of ac and dc circuit breakers, and other remote operated devices.

Substations / track paralleling huts are provided every 2 – 5 km along the electrified route. Originally these alternated (Figure 8). However, as the power requirements have increased a significant number of TPHs have been converted to SS resulting in double end fed sections (Figure 7). Some simple, stub end feed electrical sections also exist, though these tend to be located at terminal stations and depots.

There are about 370 DC SS and more than 260 TPH which are used to section and protect the ETE by means of circuit breakers. These allow most roads to be independently controlled.

The significant factor in the overall system capability is the loop impedance of the electrical sections. Initially, 100 lb/yd and 106 lb/yd steel conductor rail was used. However, since the 1960’s, it has been railway policy to install 150 lb/yd steel rail. Low impedance aluminium conductor rail has been trialled in some locations, but it lacked durability. This has limited its suitability. Likewise, the running rails have also increased in size from 95 lb/yd and 109 lb/yd, to 113 lb/yd and now UIC 60.

The current return system utilises all available running rails, which are cross-bonded around every 800m, to allow for current sharing and reduce the impedance of the system. Impedance bonds are used to provide continuity of the dc traction return current whilst maintaining segregation of the ac track circuits. Therefore, with varying lengths, and varying conductors / running rails, plus the number of running rails, the loop impedances of electrical sections vary significantly as Figure 5 shows.
Figure 5 – Southern Circuit Breaker Impedance Settings

Figure 6 – Simple Stub End fed section

Figure 7 – Double end fed section (SS-SS)
Figure 8 – Conventional fed section (SS-TPH-SS)
6. FUNDAMENTALS OF ENERGY LOSS

Power losses will occur during the cycle of generating electricity, transmission, distribution and use of appliances, machines or other consumers of electricity. In terms of elementary physics, the energy loss in real power of an electric circuit is determined by the current and resistances of the circuit. This is expressed in the following equation:

\[ P = I^2 \cdot R \]  

(1)

An illustrative diagram of the electric traction system is shown in Figure 3.

![Electric traction system circuit](image)

**Figure 9 - Electric traction system circuit**

In the diagram, the power source is represented by an ideal voltage source \((V_{ss})\) with inner impedance \((R_{ss})\), the train is represented by an ideal current \((I_{train})\) taking power from the system, the voltage drop of the train is represented by \((V_t)\) and the impedance from the train to the power source is represented by loop resistance \((R_{loop})\). The train’s inner impedance is not considered in this example.

From the electric circuit in Figure 3, the power supplied by the power source is:

\[ P_{source} = V_{ss} \cdot I_{train} \]  

(2)

The power demand of the train is,

\[ P_{train} = I_{train} \cdot V_t \]  

(3)

The power loss is:

\[ P_{loss} = I_{train}^2 \cdot (R_{ss} + R_{loop}) = I_{train}^2 \cdot R_L \]  

(4)

The energy loss in percentage terms is thus expressed as:

\[ Loss(\%) = \frac{P_{loss}}{P_{source}} \]  

(5)
Two key factors are therefore the impedance (or resistance) of the transmission system and the current drawn by the train. The calculation results are shown visually in Figure 10. The impedance from the train to the power source is represented by loop the impedance. The energy losses of the DC system are shown in the 3D diagram on the right hand side of Figure 10.

![3D diagram showing energy loss](image)

Figure 10 - 3 dimension chart showing the resultant energy loss

6.1. Train Current (Load)

The maximum current drawn by a trainset is well understood as this is used to dimension the capacity of electrical circuits.

The average current a trainset draws during an average day is less well understood. There will be significant periods of time when the train will draw minimal current. However, minimal current attracts minimal losses and the majority of losses will occur when the train is accelerating and drawing heavy current.

For the purpose of this report the train current is assumed to be around 80% of the maximum current.
6.2. Loop Impedance

The loop impedance is dominated by the distance between the train and the substation. For the purpose of calculation the cumulative losses will be calculated to simulate a moving train along a typical electric section.

Various other factors influence the infrastructure impedance. These include:

- Feeding Section length
- Number of tracks
- Single or Double traction return
- Configuration of electrical network
- Length of cables
- Wear on contact system and running rail
7. AC 25 KV ELECTRIFICATION

A 250 amp train load was simulated along the entire section length for the three ac configurations for typical feeding lengths and the cumulative energy loss calculated.

Due to the length of the ac feeding sections it is likely that more than one train will be present. Two or more trains present in the same electrical section will result in additional resultant losses.

To illustrate this effect, three simulations were run to demonstrate the effect of train density and load assumed.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Headway [mins]</th>
<th>Speed [mph]</th>
<th>Distance between trains [km]</th>
<th>Load [Amps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>125</td>
<td>36</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>125</td>
<td>18</td>
<td>125</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>125</td>
<td>18</td>
<td>250</td>
</tr>
</tbody>
</table>
Figure 12 – Multiple train load, cumulative energy loss comparison for 25 kV ac system under different density of trains and single train load conditions

Scenario 3 uses the same train load as with the single train simulation (results shown by horizontal line on Figure 12). This illustrates that the energy losses rise when more than one train is present. For example, BT 20km results, previous calculated as 2.3%, now increased to 3.2%.
8. DC 750V ELECTRIFICATION

Trainsets operating on the dc network have comparable power to the ac train fleets. To provide this power at much lower voltages, the current in the system is far higher.

dc trainsets configurations vary, but the maximum current is around 1500 Amps per 4 car EMU.

These currents dominate the magnitude of energy losses. Incremental train loads were simulated to determine the electrical loss in the dc distribution and contact system. To take account of the variation in system loop impedance two values were chosen:-

- 40 mohm representing SS-SS configuration
- 80 mohm representing SS-TPH-SS configuration

![Figure 13 – Single train load, cumulative energy loss for 750V dc system](image)

The effect of multiple trains will theoretically occur again with the dc system. However, the electrical sections are far shorter, so the likelihood of more than one train present is reduced.

The dc system is fed from a HV (majority 33 kV) cable network. This takes electricity from around 40 ESI connections and distributes to the 370 substations. The losses associated with this are believed to be similar to 25 kV OLE system, and are additional to the losses incurred by the dc energy.
9. REGENERATION

Regenerative braking reduces energy consumption by 15%-20%
This saving only occurs on the dc system if a receptive load is also present. If no load is present then the opportunity to regenerate is missed.
On the ac system, if no receptive load is present then the energy is transmitted back to the ESI via the supply transformers. This will incur similar losses as load conditions.

10. CONCLUSION

Losses on 25 kV OLE system are expected to be below 5%
Losses on the 750 V system could be up to 35% and vary greatly with respect to train current which in turn, is strongly correlated to train length.