RAIL POTENTIAL RISE DURING FAULTS IN 2x25 kV ELECTRIC TRACTION POWER SYSTEM: THEORY AND MEASUREMENTS

Umberto M Cella, Peter F Nussey, Igor Perin, Truc V Tran
Aurizon, 192 Ann St Brisbane QLD 4000, AUSTRALIA
Corresponding Author: Umberto.Cella@aurizon.com.au

SUMMARY

Aurizon’s Blackwater and Goonyella coal haulage rail systems use 2x25 kV electrification. The majority of the faults on the traction power system occur to the overhead line along the track. The fault current, in the order of 1 to 10 kA, causes a potential rise – with respect to remote earth – on the faulted item, on the rail and on bonded structures, and it induces a voltage along any conductor running in parallel to the overhead line and in proximity to the railway corridor.

The topic of this paper is how and where earth potential rise occurs along the rail corridor, and how to calculate its magnitude. A functional description of typical traction bonding and structure earthing is presented first, followed by an electrical model of the corridor which includes overhead line, tracks, earthing and bonding. Faults are simulated and EPR voltages calculated, and their values compared to field measurements.

1. INTRODUCTION

The topic of interference between the traction power system and the communication and signal lines and of dangerous EPR along the corridor is widely covered in literature. For example, [1] provides formulas for the calculation of the maximum length of a parallel run of signalling circuits that is acceptable in relation to a certain fault level (length of parallelism).

However, the modelling aspect of the issue is less covered, and a comprehensive approach that covers the issue from theory through to calculations and measurements is less frequent. This paper will focus primarily on disturbance and dangers posed by EPR following a fault.

The scope of this paper is to provide a case study where the problem is presented via a practical calculation and validation process, so that the reader can apply the same methodology to their own railway EPR issue.

This analysis regards the traction power fault or the traction current as the source of disturbance. An overhead fault is a breakdown of the insulation between the catenary-contact wire and the mast, caused for example by an animal crawling across an insulator, which allows a current of up to 10 kA (in Aurizon’s 2x25 kV system) to flow, albeit for a fraction of a second. The traction current, instead, flows from the catenary-contact into the rails via the locomotive traction system, but has similar effects as a fault, only one order of magnitude smaller. This current flow causes undesired voltages:

1. along other conductors within the corridor
2. between the components of the return path and the earth

The 2x25 kV AC electrification is considered (see [3, 7, 8] for more details). The return conductor for the fault or traction currents is composed of a combination of rails (RR), earth wires (EW) and feeder wire (FW). The FW is energised at 25 kV like the CC, but 180° out of phase, thus creating a 2-phase circuit, which is meant to carry the traction current over a long distance at a voltage of 50 kV. The 50 kV circuit connects to the RR and EW via autotransformers (AT), which are distributed along the track at about 10 km spacing, and at FS and TSC sites. The ATs extract the return current from RR and EW and direct it into the FW. Figure 1 offers a representation of the 2x25 kV system.

![Figure 1: 2x25 kV system](image)

Every effort is made to create a low impedance path for the traction current to reach the closest ATs, where it is redirected into the 50 kV circuit. This is achieved via interconnection of EW, RR and earthed structures such as overhead masts,
trackside equipment housings and signals. All these structures are within touch reach of the public, and as such must not bear a dangerous potential: hence the requirement for a low-impedance return path. The interconnection of the aforementioned structures is called “structure and traction earthing and bonding”.

In summary, to minimise the electrical impact of traction onto the surrounding environment, two engineering solutions are adopted:

- earthing and bonding (E&B), to contain potentials at ground level
- 50 kV power transmission (CC-FW circuit), to contain losses and interference

E&B, the main topic of the paper, is introduced in Section 2, and induction is mentioned in Section 3.

**ABBREVIATIONS**

RR Rails  
CC Catenary and Contact wires  
FW Feeder Wire  
EW Earth Wire  
GME General Mass of the Earth  
FS Feeder Station  
TSC Track Sectioning Cabin  
AT Autotransformer  
E&B Earthing and Bonding  
Z, Y impedance and admittance  
EPR Earth Potential Rise

**2. EARTHING AND BONDING**

The conductors that carry the traction current “back” to the FS are:

a) rails (RR)  
b) earth wire (EW)  
c) the mass of the earth itself (GME)

These conductors are interconnected as frequently as possible along the corridor. In particular, the following connections are made:

- RR to EW via overhead masts  
- EW to GME via mast foundations and mast-bonded structures  
- RR to RR via traction bonds and cross-track bonds in a multi-track corridor

Unintentionally, and in a variable measure, the following connection exists as well:

- RR to GME via ballast

The strength of this connection is proportional to age and fouling of the ballast [2].

**Figure 2a:** Bonding in an area without signalling track circuits

**Figure 2b:** Structural bonding of a signal

The conductors that carry the traction current “back” to the FS are:

- RR to EW via overhead masts  
- EW to GME via mast foundations and mast-bonded structures  
- RR to RR via traction bonds and cross-track bonds in a multi-track corridor

Unintentionally, and in a variable measure, the following connection exists as well:

- RR to GME via ballast

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**Figure 2c:** Traction bonding via signalling equipment at FS (one track shown)

**Figure 2d:** Structural bonding in axle counter area (TSU = track-side unit)

**Figure 2e:** Bonding plan for a turnout: note the insulated rail (hairline)

The E&B connections are mainly “shunt” items, meaning that they are placed across the conductors that run parallel to the rail corridor. In a few cases they may run along the corridor, albeit for a short distance (< 1 m); for example an insulated joint which is not used anymore is
bridged along by a traction bond, to preserve the electrical continuity of the rail.

Figure 2 provides examples of E&B.

The aim of E&B is to offer a low impedance path to the current flowing back to FS in order to minimise the voltages found along the return path. These voltages must be contained because they are found on objects that can be accessed by personnel or livestock. Also, return path voltages cause interference with any equipment whose conductive parts are earthed.

An example of voltages on the return path due to a fault is given in Figure 3. A single track corridor energised with 2x25 kV system is assumed for clarity. The fault current flows from the catenary, which is initially energised at 25 kV to earth, into the mast structure. From here, it first finds its way back to the nearest ATs via the earth wire spans and the foundations of each mast along the faulted road, in both directions. If along the return path a structural bond is present, some current branches into the earth mat of the bonded item, which could be a signalling or telecommunication equipment metal building. When the current reaches a Z-bond, it finds its way into the rails as well, via the structural bond which connects the mast to the centre tap of nearby air core inductor.

At this point the return current flows via rails, earth wire, masts, bonds and earth mass until it reaches an AT, which is installed either at an AT site, FS or TSC. In proximity to the AT site, the current begins to be “attracted” to the centre tap of the AT. This is because the AT constitutes a low impedance path for the current to flow back into the 50 kV CC-FW circuit. The modelling of the AT and of the overhead line as a 2-phase system is covered in [3]. The low impedance path at the AT site is achieved by:

- Bonding the centre tap of the AT to RR and EW with a number of parallel bonds to minimise resistance and ensure redundancy in case of bond breakage
- Connecting the centre tap of the AT to its own substation earth mat, and connecting the mat to RR and EW

An earth potential rise (EPR) occurs at the AT site which is “reversed” (in opposite phase) to the EPR occurring at the fault point. However, the magnitude of the EPR at the AT site is lower than that at the fault site thanks to a better local earthing.

In Aurizon’s network there are also different overhead arrangements and energisations. For example, there are balloon loops and yards that are energised at 25 kV, where only CC and RR are present. This is the case of a stub-end feed: the fault current returns towards main line via RR and EW in one direction only, and then splits into two directions towards the nearest two AT sites.

The return path mechanism was explained using a fault as an example, but traction current absorbed by a train returns to the FS in a similar way. The difference is, apart from the order of magnitude, as traction current is very roughly 1/10 of a fault current, that traction current returns via RR until it finds a RR-mast bond or Z-bond, where it begins to flow also into EW. However, this path is followed also by a fault current caused by a dewirement onto a locomotive or wagon, where the fault current originates from a fallen CC touching a vehicle, flows through the chassis of the vehicle, and reaches RR.

3. INDUCED VOLTAGES

Traction power, telecommunication, and signalling conductors all run parallel along the railway corridor. This arrangement creates mutual inductive and capacitive coupling between them. Therefore, any current flowing through any conductor in the corridor induces a voltage along itself and along all the other conductors (inductive coupling). Also, any voltage between a conductor and the earth induces a current from itself to earth and from all other conductors to earth (capacitive coupling).
As the currents and voltages caused by inductive coupling within the railway corridor are, especially during a fault, much larger than those caused by capacitive coupling, only inductive phenomena are considered. As a rough guideline, capacitive coupling cannot be neglected in the following situations:

- Very long lines (> 500 km at 50 Hz)
- High frequency (kHz range)

These do not apply to the 2x25 kV electrification, unless harmonic distortion analysis is required. Also, during a fault, CC-RR voltage usually drops to a value lower than 25 kV, and currents increase by a factor of 10 with respect to nominal: therefore, in fault conditions, the amount of capacitive energy within the system drops in comparison to inductive energy by a factor > 100: this further reduces the influence of capacitive coupling.

In literature there are various formulas for voltage induced in telecommunication and signal circuits by overhead currents [1]. However, most publications lack a clear step-by-step derivation of the formula, which would make it useful to adapt, for example, to particular feeding or track arrangements. In the next section, an example of modelling of a double track section is provided. Although the topic of induced voltage will not be covered, the model presented can be easily adapted to the calculation by adding to the matrix an additional conductor to represent the parallel circuit.

4. MODELLING RESULTS

A Matlab model of a double track feeding section from FS to TSC was developed with the aim of calculating the EPR at the fault point, and also the voltage induced along a conductor running parallel to the track by adding a conductor to the matrix.

The numerical approach is required to validate approximated formulas that are presented as well. The formulas avoid the burden of creating a model for every electrical section, and simplify the design process.

Figure 5 shows a schematic of the electrical section. The section comprises a FS, a faulted mast (CC-EW fault), two AT sites, and terminates on a TSC. On the other side of the FS and TSC the track is continued, however without the CC and FW conductors, to represent the continuity of RR and EW. The whole model as it appears in SimPowerSystems is not shown as this would not be practical and clear enough.

All conductors are included, as showed in Figure 6. Catenary and contact are already grouped into CC when the transmission line matrices are computed [Carson’s equations, and 7, 8], as these conductors are continually connected to each other along the entire track.

The section where the fault is applied is modelled in more detail, and each span is assigned a separate 50 m long transmission line block, as visible in Figure 6. This is necessary if EPR at each mast needs to be evaluated. Also, this arrangement allows to model bonds as described in Section 2. Bonds can be altered in connections and resistance, so that the effect of various levels of bond degradation can be assessed.

As a standard practice in Aurizon [5] every 400 m rail-rail, track-track and track-mast bonds are installed, unless Z-bonds for signalling equipment are installed equivalently; 400 m correspond on average to 8 spans (50 m/span).

![Figure 5: schematic of modelled section](image1)

![Figure 6: schematic of \( \Pi \) model of track and overhead line between pairs of masts](image2)
to the currents in all the other conductors multiplied by their respective coupling coefficients.

The calculation is carried out in the phasor domain, as it is much faster and because the evaluation of transients is not required.

As the scope includes finding approximate formulas that can be used to calculate EPR and induced voltage and validate numerical models, the distribution of the fault current among the conductors must be understood. The Matlab model is a convenient way for doing so.

Current measurement points are therefore set up along the conductors at different locations. Two are set up at each side of the faulted mast, to measure fault current split, and another two after the bond locations, to measure the change in current distribution among the conductors and the expected change in EPR of the masts.

Values used for the model are:

- Soil resistivity = 100 ohm.m
- Mast foundation R = 17.2 ohm
- Mast-mast R = 160 ohm (across tracks)

### Table 1: values of X and R in complete and reduced matrices for a double track section [ohm/km]

<table>
<thead>
<tr>
<th>R</th>
<th>DL FW</th>
<th>DL CC</th>
<th>DL EW</th>
<th>DL or</th>
<th>DL ir</th>
<th>UL ir</th>
<th>UL or</th>
<th>UL FW</th>
<th>UL EW</th>
<th>UL CC</th>
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<tr>
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</table>

or = outer rail; ir = inner rail; UL = up line; DL = down line

| Table 2: reduced values of X and R for a double track section [ohm/km] |

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<tr>
<th>X reduced [ohm/km]</th>
<th>DL FW</th>
<th>DL CC</th>
<th>DL UL e</th>
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</table>

Current measurement points are therefore set up along the conductors at different locations. Two are set up at each side of the faulted mast, to measure fault current split, and another two after the bond locations, to measure the change in current distribution among the conductors and the expected change in EPR of the masts.

Values used for the model are:

- Soil resistivity = 100 ohm.m
- Mast foundation R = 17.2 ohm
- Mast-mast R = 160 ohm (across tracks)
A fault is applied at 2.9 km from the FS, between CC and EW. Figure 5 shows a schematic of the section, and Figure 8 the EPR for the first 12 masts at the left and right of the faulted structure (with bond resistance degraded at 0.1 ohm).

It is interesting that the curve that joins the EPRs of the masts becomes less steep as soon as the fault return current reaches the cross-rails and cross-track bonds. This is because the return path is not the EW alone anymore, but all the tracks and the two EW together. This shows how important rail-rail, track-track and track-mast-EW bonding is to maintain low values of EPR.

If all the values of current on the return path are added and compared with the sum of the currents on the other conductors, especially the faulted CC, it is noticeable that there is a "two way" distribution in the currents: forward path to the fault, and backward path to the FS and AT site.

This current distribution can be exploited to find an approximated formula to calculate EPR of the faulted structure. This is very important information as it determines the requirement for insulation of signalling and telecom equipment which may come in contact with structure potential and remote earth potential simultaneously. It is also important for determining the requirement for grading rings to protect personnel from step and touch potentials.

The current sources inject a net current only in the first and last nodes, as all the way in between the induced currents cancel each other out. Therefore the source vector has only non-zero first and last element. Note also how the impedance depends on $Z_r-Z_m$, which shows how the voltage induced by the forward current on the return path lowers its apparent impedance.

As the matrix is tri-diagonal, the system of equations offers itself to be solved in an iterative fashion such as Gaussian elimination. The matrix can be transformed in an upper diagonal. The last voltage $V_n$ can be found by calculating diagonal elements $y_n$ and source vector elements $s_n$ via these recursive formulas:

$$y_1 = a \quad s_1 = -1$$
$$y_{k+1} = b - \frac{1}{y_k} \quad s_{k+1} = \frac{s_k}{y_k} \quad (2)$$
$$y_n = a - \frac{1}{y_{n-1}} \quad s_n = 1 + \frac{s_{n-1}}{y_{n-1}}$$

The EPR at the faulted mast is equal to:

$$V_n = (Z_e - Z_m) \cdot I_s \cdot \frac{s_n}{y_n}$$

And all the other voltages up to the beginning $V_1$ can be found by working backwards from that value. However, $V_n$ is usually the one of interest being the highest.
unchanged. This is because the number of spans between the start and the fault is, in this case, sufficient for avoiding any mutual influence: in other words, there is a zone at almost zero potential between fault and return current site. For Aurizon’s double track arrangement, the equivalent impedance is about 0.15 ohm, constant for a sufficient number of masts (roughly > 200).

Once the equivalent impedance of the masts and EW-RR is known, in order to calculate the EPR, it is necessary to find the value of the fault current either via the Matlab model or by performing hand calculations. The latter, although it leads to approximated results, is preferable, as it is adaptable with little change to many different situations and is a good validation tool for computer based analysis.

As discussed in [3] and [7, 8] the 2-phase 2x25 kV traction power system can be represented by zero- and positive-sequence components, as done for 3-phase systems. The section of Figure 5 can be represented in the sequence domain by the networks of Figure 13a and b.

Most of the sequence impedances are calculated as per [3, 7, 8], and in this case, their values are:

- \( V_{\text{source}} = 50 / \sqrt{2} = 35.36 \text{ kV} \)
- \( Z_{\text{1,PT}} = j6.9 / 2 = j3.45 \text{ ohm} \)
- \( Z_{\text{1,source}} = 0.85 + j3.36 \text{ ohm} @ 132 \text{ kV} \)
- \( Z_{\text{0,AT}} = 2\times Z_{\text{short,secondary}} = 2\times (0.09+j0.25) = 0.18+j0.5 \text{ ohm} \)
- \( Z_{\text{0,masts}} = 2\times 0.15 = 0.3 \text{ ohm} \)

Note that the \( Z_{\text{epr}} \) is multiplied by two, as it is a “single phase” network which is connected to the 2-phase network via the centre taps of the ATs. In the 3-phase case, the single phase impedances connected on the neutral terminals are multiplied by 3 when they are included in the 0-sequence network.

If a fault resistance for earth fault needs to be included, it is multiplied by 2 and connected in the series with the 0- and 1-sequence networks (Figure 11).

The zero sequence impedance of the line is more difficult to calculate, and it is based on the reduction of the line matrix for earth wires, as done in [9].

The hypothesis that underpins this reduction of the matrix is that the voltage between ends of the earth wire is almost zero: this is true for good earthing of the AT and FS (or AT and TSC). Also, along each span, the voltage drop is mostly low, apart from the spans closer to the fault. For these spans, however, the approximation is quite crude.

The two earth conductors and the four rails are grouped together to create “E”, and so are catenary and contact to create CC. So the matrix to be reduced, for two tracks, is a 5x5, and it will be reduced to a 4x4: however, here only one track is shown as the result for the other is identical.

\[
[Z] = \begin{bmatrix}
Z_{\text{CC}} & Z_m & Z_{\text{me}} \\
Z_m & Z_F & Z_{\text{me}} \\
Z_{\text{me}} & Z_m & Z_E
\end{bmatrix} \begin{bmatrix}
Z_{\text{line}} \\
Z_{\text{ph}} \\
Z_{\text{op}} \\
Z_E
\end{bmatrix}
\]

(3)

As per [8, 9] the reduction is operated as:

\[
[Z]_{\text{red}} = [Z]_{\text{line}} \cdot [Z]_1^{-1} \cdot [Z]_p
\]

(4)

The result is:

\[
Z_{\text{CC}} = Z_{\text{CC}} - Z_{\text{me}}^2 / Z_e \\
Z_F' = Z_F - Z_{\text{me}} / Z_e
\]

(5)

So all impedances are reduced by the same amount. This does not change positive sequence impedance, but reduces zero sequence impedance:

\[
Z_1 = \frac{Z_{\text{CC}} + Z_F - Z_m}{2} - \frac{Z_{\text{CC}} + Z_F - Z_m}{2} = \frac{Z_{\text{CC}} + Z_F - Z_m}{2}
\]

(6)

\[
Z_0 = \frac{Z_{\text{CC}} + Z_F - Z_m}{2} + Z_m = \frac{1}{2} \left( Z_{\text{CC}} + Z_F - \frac{2Z_{\text{me}}}{Z_e} \right) +
\]

\[
+ \frac{Z_m - Z_{\text{me}}^2}{Z_e} = \frac{Z_{\text{CC}} + Z_F}{2} + Z_m - \frac{2Z_{\text{me}}^2}{Z_e}
\]

Hence:

- \( Z_{\text{1, line}} = 0.1032+0.3188 \text{ ohm/km} = 0.3351 \text{ ohm/km} @ 72.1^\circ \)
- \( Z_{\text{0, line}} = 0.1684+0.5099 \text{ ohm/km} = 0.5370 \text{ ohm/km} @ 71.7^\circ \)

If the \( Z_1 \) and \( Z_0 \) are calculated from a non-grouped matrix which includes separate CC, FW, EW for each track and 4 separate rails, the values are marginally different:

- \( Z_{\text{1, line}} = 0.1083+0.3121 \text{ ohm/km} = 0.3304 \text{ ohm/km} @ 70.9^\circ \)
- \( Z_{\text{0, line}} = 0.2043+0.4838 \text{ ohm/km} = 0.5252 \text{ ohm/km} @ 67.1^\circ \)

The smaller values can be used as they are more conservative for fault calculations.

The faulted section is transformed in sequence networks and it appears in Figure 13. The fault current is calculated as:

- \( I_1 / \sqrt{2} \) for CC-FW fault \((I_0 = 0)\) \quad (7)
- \( I_0 / \sqrt{2} \) or \( I_0 / \sqrt{2} \) for a CC-E fault \quad (8)
For a CC-F fault the fault current equals to:  
\[ I_{FCh-FW} = \frac{1}{\sqrt{2}} \sqrt{V_i Z_{source} + Z_{PT1} + Z_{line1}} \]
\[ = 0.454 - j5.18 \text{ kA} = 5.2 \text{ kA} @ -85^\circ \text{ (Matlab: 5.17 kA @ -84 }^\circ) \]

For a CC-EW fault the fault current equals to:  
\[ I_{FCh-E} = \sqrt{2} I_{f1} = \sqrt{2} \frac{V_i}{Z_{source} + Z_{PT1} + Z_{line1} + Z_0} \]

Where:  
\[ Z_0 = \frac{Z_{masts-earth} + Z_{AT0} + Z_{line0}}{2} = 0.644 + j1.1674 \text{ ohm}; \text{ so } I_{RCC-E} = 1.4526 - j8.1335 \text{ kA} = 8.262 \text{ kA} @ -80^\circ \text{ (Matlab: 8.633 kA @ -81}^\circ, +4\%) \]

The earth fault current is slightly below the value calculated with Matlab. This is due to the various approximations introduced, chiefly neglecting the unbalance in the CC-FW line and having discarded the sequence-coupling terms [3]. The approximation is deemed to be acceptable as a margin is usually introduced in fault calculations.

Finally, the EPR can be calculated by using the equivalent earth resistance of all masts on each side. The two values are connected in parallel as the fault current will flow in both directions.

Actual values (not sequence components) are:

- 58 masts: \( Z_{masts} = 0.0877 + j0.0757 \text{ ohm} \)
- 104 masts: \( Z_{masts} = 0.1270 + j0.0565 \text{ ohm} \)

The parallel of the two is:

\[ Z_{eq\_masts} = 0.053 + j0.035 \text{ ohm} = 0.0639 \text{ ohm @ 45 }^\circ, \text{ for } 2x\text{EW} + 2x\text{RR} \text{ in parallel} \]

However, the simulation in Matlab is based on a fault occurring between two sets of cross-rail bonds, which are at +200 m (+4 spans) from the faulted mast. Over this distance the fault current uses the earth wire alone as return conductor.

If the \( Z_{masts} \) is evaluated for the earth wire only, for 12 masts the value is:

\[ 12 \text{ masts EW alone: } 0.109 + j0.121 \text{ ohm} = 0.163 \text{ ohm @ 48 }^\circ \]

EPR = \( Z_{masts} / 2 \times I_{fault\_cc\_e} = 0.163 / 2 \times 8.26 \text{ kA} = 673 \text{ V (Matlab: 707 V, +5\%)} \)

If the fault occurs in an area where only the EW can carry the fault current, then a higher EPR must be expected.

For a very high number of masts (200, or 15 km of 50 m spans), the impedance \( Z_{masts} \) stops increasing and saturates to an almost constant value as shown in the graph of Figure 12.

5. MEASUREMENTS

Rail EPR measurements were performed in the past and are currently underway at the time of writing. Measuring the rail EPR following a fault is very difficult, as a fault can occur anywhere, but a datalogger can only monitor one structure on one road. So it is very unlikely that the structure whose voltage is being measured is faulted and voltage is recorder.

The more practical way of measuring EPR is to wait for a train to pass the metered mast, and measure the EPR then. However, some conditions on the current drawn by the train shall be met:

1. it is substantial
2. it is known or can be estimated
3. the locomotive absorbing it shall be at the structure

And also:

4. EPR varies substantially according to the location of the closest bonds: the structure must be chosen with this in mind

The first condition is for accuracy: if the train is coasting and only auxiliaries and air brake compressor are running in the locomotives the current may not be enough to change EPR significantly to be able to distinguish it from induced voltage due to another load in the section.
The second condition is self-explanatory: for a train it can be difficult, unless one is sure that the train is accelerating at maximum notch. Usually a good pick is a mast at a signal on the path of a loaded train. However, the structure at the signal shall be well bonded, so a high EPR is not expected. Measurements like this were performed, but EPR did not show very high values.

The third condition is important: if the locomotive is a few spans away, say ten, from the structure, EPR can be a fraction of the maximum (see Figure 10).

The fourth condition is on the type of structure which needs to be investigated: EPR in axle counter territory near a cross-track and cross-rail bond to masts and earth wire will be very different from EPR in a single traction rail section, half way between turnout signal bonds.

5.1 EPR at signal

For example, the lead electric locomotive of a loaded train in the Blackwater coal system absorbs about 170 A at full power. This current flows from CC into the rail. Measurement of EPR on a signal at the start of a turnout was performed on 6/11/2015. The values varied considerably and oscillated during measurement while the train was going over the insulated joint. The maximum EPR voltage that was measured was about 20 V: this corresponds to an equivalent impedance of:

\[ Z_{eq} = 20 \text{ V} / 170 \text{ A} = 0.12 \text{ ohm} \]

The value is in same order of magnitude of the result of the calculation presented in this article, a bit lower as the location of the measurement was well bonded, being a signal at a turnout.

5.2 EPR at location case 1

![Figure 13: setup to measure EPR](image)

Figure 13: setup to measure EPR

Rail potential rise and induced voltage along a track repeat circuit were performed at a location case (LOC). Figure 13 shows the measurement setup. The LOC is in an area where trains predominantly coast, so no significant current absorption is expected. Also, the bonding connects the two tracks and the two earth wires together: a small EPR is expected to occur. It is difficult to establish how much current a train would absorb in this part of the network, but it is expected not to be high.

![Figure 14: train EPR, LOC1](image)

Figure 14: train EPR, LOC1

![Figure 15: fault EPR, LOC1](image)

Figure 15: fault EPR, LOC1

![Figure 16: train EPR, LOC2](image)

Figure 16: train EPR, LOC2

Figure 14 shows the waveform of the EPR at the passage of a train. It can be seen that the value is negligible (6 V peak). If the power absorbed by the locomotive is estimated to be about 1 MW, corresponding to 1 MW / 25 kV = 40 A, the equivalent impedance is about:

\[ Z_{eq} = (6 \text{ V} / 1.41) / 40 = 0.1 \text{ ohm} \] (11)
This is a value lower than the 0.18 ohm estimated above. This can be partly due to the presence of the bonds.

It is therefore necessary to evaluate on a case by case basis the EPR to be expected on a structure. A worked example with both a numerical model and closed formulas was presented.

7. REFERENCES


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