WELLINGTON NETWORK TRACK CIRCUIT IMMUNISATION

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SUMMARY

Greater Wellington Regional Council is procuring new AC drive Electric Multiple Units (EMUs) for the Wellington rail network. It is essential that these new EMUs are compatible with the signalling system they are required to interface with. It was decided to replace some types of track circuit considered to be potentially susceptible to interference from AC drive EMUs, however it was hoped that many of the 50Hz double element track circuits could continue to operate safely in combination with the new EMUs.

Interfleet Technology was commissioned by ONTRACK to carry out susceptibility modelling of the 50Hz double element vane relay track circuits in the Wellington network. The work required the development of suitable computer simulation models of the track circuits, based on methodology developed over many years in the UK. The simulation models were developed to represent the unique nature of the Wellington track circuits and were validated against local measurement data, undertaken by ONTRACK staff.

Of a total of over 300 double element track circuits in Wellington, a subset of 18 track circuits representing the most susceptible configurations were individually modelled. This led to a set of susceptibility results for normal and failed infrastructure conditions of all 18 of these track circuits. A particular track circuit (1BGT) was identified as having an unacceptable level of susceptibility under failed infrastructure conditions due to a low voltage relay combined with other factors. This track circuit was recommended for modification or replacement. The remaining 17 track circuits had a wide variation of susceptibility limits for the normal infrastructure results. However, the failed infrastructure results were all much closer and it was therefore logical to set train design limits based on this remaining group of 17 track circuits.

These limits could not be declared in their entirety to the EMU manufacturer since multiple trains and other sources of 50Hz interference require the application of suitable safety margins.

The outcome of this work was the declaration of 50Hz limits (based on model limits with the addition of safety margins) suitable for use by the EMU manufacturer to enable them to design an AC drive train compatible with the 50Hz double element track circuits.

INTRODUCTION

Greater Wellington Regional Council (GWRC) have let a contract for the purchase of new Electric Multiple Unit (EMU) rolling stock for the Wellington Electrified Area (WEA). All existing EMU stock utilises low technology resistor/camshaft control, however, the new EMU stock will employ AC drive technology. The presence of significant AC currents in the rails has the potential to interfere with existing track circuits. Within the WEA there are a variety of track circuit types:

- AC/DC type (simple AC feed with a transformer/rectifier at the relay end to convert to DC to drive the track relay).
- AC Single Element vane relay type (on short track circuits).
- Coded type (the AC feed is pulsed on to the track at 80 or 120 Hz. The pulses are mimicked by a code follower at the relay end and fed through a transformer/rectifier to feed a DC track relay).
- AC 50Hz Double Element vane relay type configured as:
    - Capacitor Fed
    - Inductor Fed
    - Resistor Fed

  These track circuits may also be configured as follows:
    - Single Rail Traction return
    - Double rail traction return with both resonated and non-resonated impedance bonds (these are normally reactive fed)
    - Double rail traction return with auto impedance bonds (these are normally configured with feed and relay end capacitors)

The project team had already decided to replace AC/DC, AC Single Element and Coded type track circuits since it was known they would react to any AC in the rails and must be replaced.

The AC Double element track circuits require interference at the correct frequency (50 Hz) and phase to falsely energise, and must therefore be assessed for suitability for continued service.

Interfleet Technology was appointed by ONTRACK to carry out susceptibility analysis of the AC Double Element Vane Relay Track Circuits in the WEA. This has been achieved by developing a generic model of the track circuits that can be configured to the different installation arrangements utilised on WEA. The generic model has been validated against known data from the track circuits and then used to determine the susceptibility limits relevant to the WEA track circuits.

The outcome of this study enabled susceptibility limits (including safety margins) to be set for use by the manufacturer of the new rolling stock. It is expected that the train manufacturers will meet the susceptibility limits. However, if there are compatibility issues the study also provides ONTRACK with detail of the most sensitive types of track circuit installations leading to possible modifications or replacement of a limited number of track circuits.

NOTATION

AC	Alternating Current
DC	Direct Current
EMU	Electric Multiple Unit
GWRC	Greater Wellington Regional Council
IBJ	Insulated Block Joint
I_{int}	Interference current at 50Hz
WEA	Wellington Electrified Area
WSF	Wrong Side Failure

TYPES OF 50HZ DOUBLE ELEMENT TRACK CIRCUITS

Whilst there are other varieties of 50Hz track circuits – already listed in the introduction - this report is limited to an assessment of the 50Hz double element track circuits. They can be configured in a number of forms but all consist of a 50Hz feed at one end of a track section and a 50Hz double element vane relay at the other end of the circuit. With no train present the feed current passes through one rail to the relay returning via the other rail. This current energises the vane relay (causing the vane to lift) which closes the front contacts of the relay. If a train is in section the wheels and axles provide a low impedance path which connects the rails together, effectively shorting the relay. Current ceases to flow through the relay and the vane drops, which opens the front contacts. The state of the front contacts is used to provide an indication to the signalling system that the track is either unoccupied or occupied. Separation between adjacent track circuit sections is provided by insulated block joints (IBJs) in the rails.

There are three main configurations of the track circuits used in the WEA, and these are as follows:

- Single Rail, where traction current returns via one rail and insulated block joints are located in the other rail to separate track circuits.
- Double Rail Direct Feed, where IBJs (located in both rails) and impedance bonds are used to separate track circuits. The feed end is connected to rails directly via an adjustable resistor or inductor.

Impedance bonds can be either resonated or non-resonated.

- Double Rail Auto Connected where IBJs (in both rails) and impedance bonds are also used to separate track circuits. However, impedance bonds are connected in an auto configuration using tuning capacitors at feed and relay ends for bond resonance close to or on the inductive side of 50Hz.

These configurations are described in greater detail below.

1. Single Rail Track Circuits

This configuration derives its name from the fact that traction current returns via only one of the running rails (hence ‘single rail’), whilst the signalling current utilises both rails. Figure 1 below shows the main elements of this arrangement. The feed consists of a transformer converting the 110V or 240V 50Hz AC supply to a suitable track voltage (0-15V) 50Hz AC feed to the track. IBJs in the signal rail separate adjacent track sections. The I_{int} term in Figure 1 represents interference current at 50Hz generated by the train and the potential for influence on the track relay. All of I_{int} generated by the train returns via the traction return rail which drops a voltage along the length of rail between the train and the track relay. This voltage appears across the receiver $V_{receiver}$. If I_{int} is of sufficient magnitude and has the correct phase relationship to the reference supply of the relay, the track relay could be held energised even though the train is in section. This would constitute a wrong side failure. See Fig 1 below.

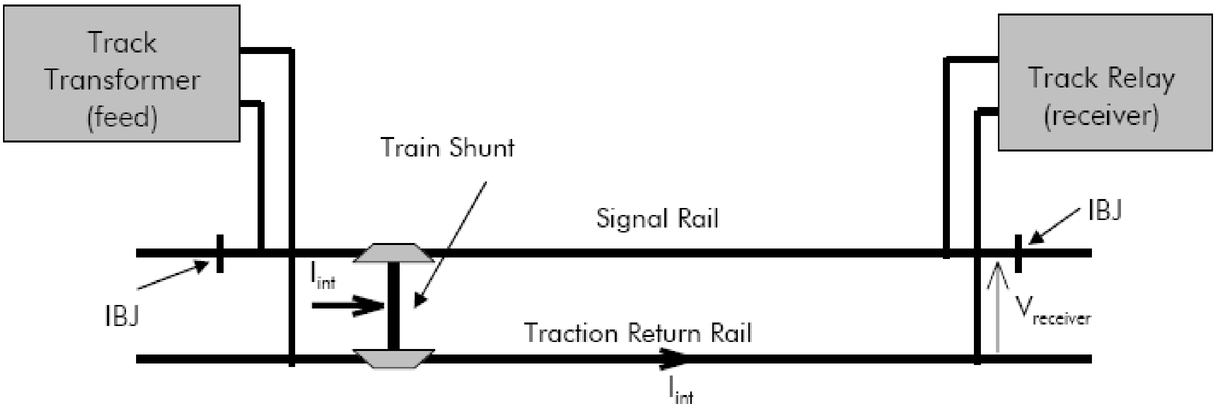


Figure 1 – Single Rail Double Element Track Circuit

2. Double Rail Direct Feed Track Circuits

The basic features of this track circuit configuration are shown in Figure 2 below. The reason these are referred to as direct feed track circuits is that the track transformer is connected directly to the rails via an adjustable resistor or inductor. This configuration utilises both rails for traction return current hence it is referred to as a double rail track circuit. IBJs are present in both rails and impedance bonds are used to allow passage of DC current between track sections whilst providing a high impedance to 50Hz current. The traction winding centre taps of adjacent impedance bonds are connected with each other. If the track circuit is perfectly balanced any current which enters at a train shunt (i.e. axle), at a centre-tap of a feed end impedance bond, or an intermediate impedance bond, will flow equally through both running rails and exit the track circuit at the centre-tap of the relay end bond. Any interference current at 50Hz (I_{int}) will also flow equally in both rails (I_{int} /2 in each rail). In practice there is likely to be some degree of imbalance, which will provide a mechanism to produce a small current flow through the relay. This current is dependent upon the balance of the track circuit as a whole.

The impedance bonds at both the feed and the relay ends of the track circuit are connected in resonated mode using the floating auxiliary winding with a nominal 10µF capacitor fitted across it. The configuration can also be used without the capacitors in a non-resonated manner.

Direct feed arrangements consume more power from the track circuit supply (usually 110V AC transformed to low voltage) than the auto configured (described in the next section) as the impedance bonds are fed in a less efficient way. In general, the direct feed double rail track circuit is suited to shorter length track circuits, where 50Hz power loss is less significant. See Fig 2 below.

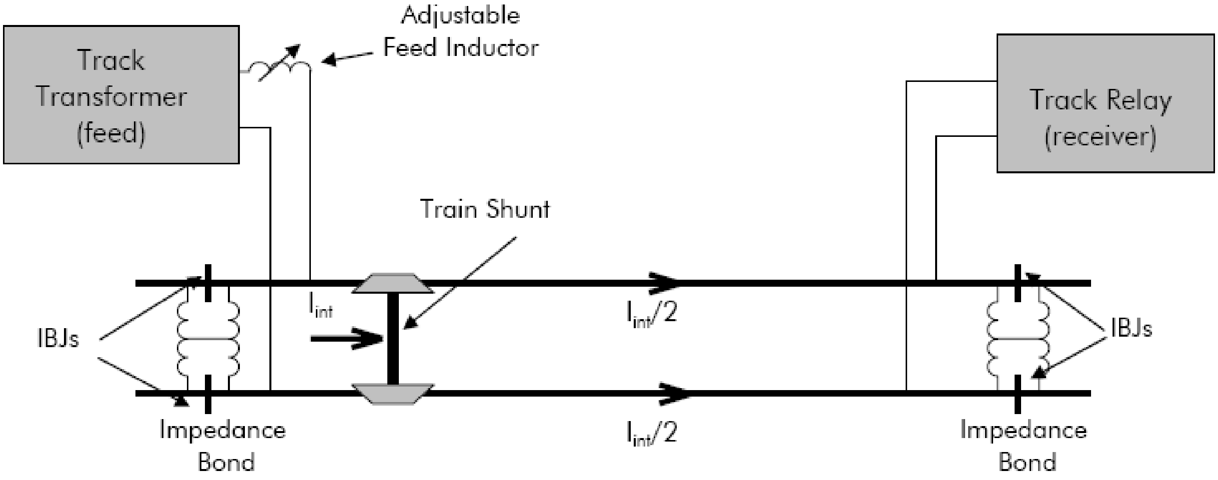


Figure 2 – Double Rail Direct Feed Double Element Track Circuit

3. Double Rail Auto Connected Track Circuits

The final track circuit arrangement is similar to the double rail direct feed type in that it is also a double rail type using both rails for traction return, has IBJs in both rails and impedance bonds to allow passage of DC current between sections. This arrangement is illustrated in Figure 3 below.

What is different, is the method of connecting the impedance bonds and the track transformer. It is referred to as auto connected because the impedance bonds are auto coupled by connecting the auxiliary winding in series with the traction coils. The track transformer feed is not connected directly to the track (as in the case of the single and double rail types, but by connection in series with the auxiliary winding and then transformer action between the auxiliary and traction coils. This provides an efficient means of introducing alternating current to or extracting it from the track circuit.

Similar to the direct feed type, if the track circuit is perfectly balanced any current which enters at a train shunt (i.e. axle), at a centre-tap of a feed end impedance bond, or an intermediate impedance bond, will flow equally through both running rails and exit the track circuit at the centre-tap of the relay end bond. Since the currents in each traction half-winding of the relay end bond are equal and opposite, no net flux linkage of the auxiliary winding is produced and consequently, no component of the traction current is present in the relay control coil, even if it contains a 50 Hz signal. In practice, there is likely to be some degree of imbalance, which will provide a mechanism to produce a small current flow through the relay. This current is dependent upon the balance of the track circuit as a whole.

Tuning capacitors are not fitted within the bond, but are external and are adjustable – nominally 12µF at the feed end and 20µF at the relay end. By adjusting the feed and relay capacitors the overall circuit is tuned to resonate such that some amplification occurs at 50 Hz, although it is important that the relay circuit does not operate at the peak or on the capacitive side of resonance, as this can cause a low impedance sink for 50 Hz currents. This increases susceptibility to wrong side failure (WSF) from any source of 50Hz interference. Consequently this type of track circuit is always set up on the inductive side of resonance. See Fig 3 below.

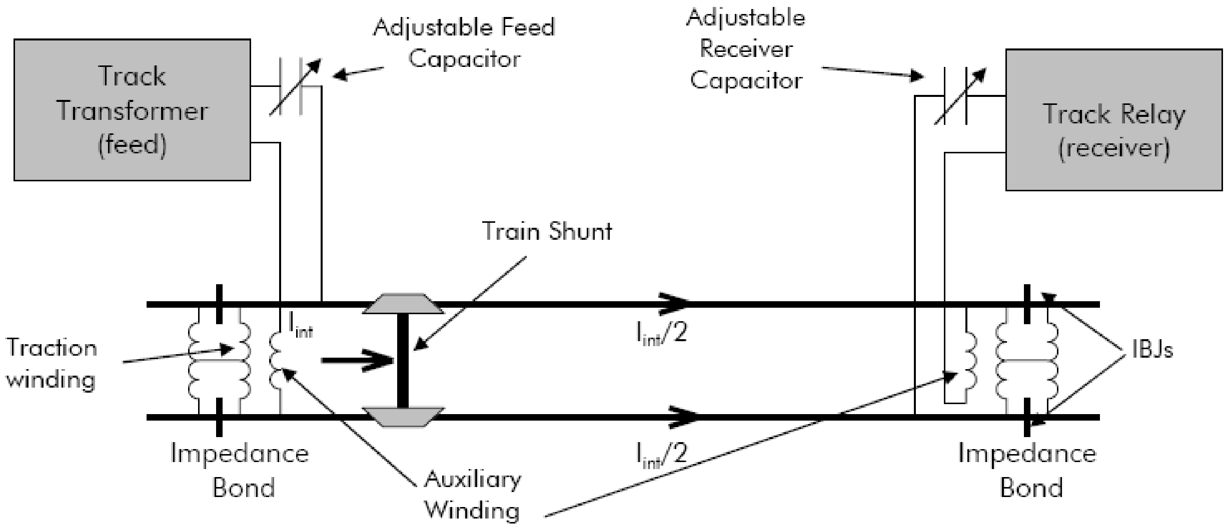


Figure 3 – Double Rail Auto Connected Double Element Track Circuit

4. Double Element Vane Relay

All three configurations outlined in section 3 above utilise the double element vane relay as the track relay. It contains an aluminium vane mounted on a shaft, which is mechanically linked to a number of movable relay contacts. The vane can freely move between two mechanical stops: the lower, or “back”, stop and the upper, or “front”, stop. The linkage is designed such that when the vane sits on the lower stop, the back contacts are closed, and when the vane sits on the upper stop the front contacts are closed. Two laminated iron cores are positioned around the vane, and on these the relay coils are wound, see Figure 4 below. There are two main coils: the local coil, which is supplied from the local 50Hz AC signalling supply, and the control coil, which is supplied from the track circuit. In some relay types there is also a tertiary coil, which is a second control core coil used to tune the effective control coil impedance to 50 Hz – these are referred to as resonated relays. Conversely other relay types do not have a tertiary coil and these are non resonated relays. See Fig 4 below.

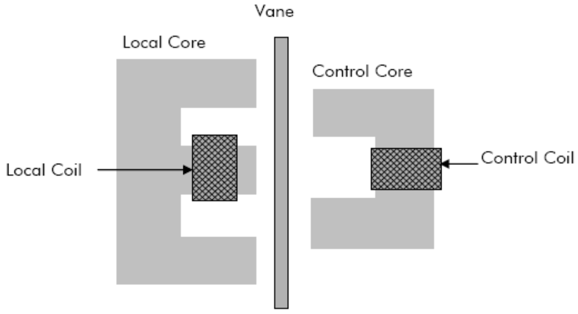


Figure 4 – Double Element Vane Relay

The currents in the local and control coils produce magnetic fluxes that link with the vane and induce eddy currents within it. Interaction of the eddy currents and fluxes produce a torque on the vane which is sufficient to lift it and thereby close the front contacts. To lift the vane there needs to be a correct phase displacement between the local and control voltages of nominally 90°, although the vane will pick-up over a range of positive phase displacements.

If the local voltage is connected in reverse (i.e. nominal phase displacement of -90°, the turning force on the vane is in the opposite direction, which only serves to force the vane against its back stops, resulting in no actual movement. The vane will only permanently pick if the local and control voltages are at the same frequency and with the correct phase displacement. Any other frequency will result in an oscillating torque (at the beat frequency) induced in the vane and the relay will attempt to alternately pick-up and drop.

For clarity, the phase displacements discussed above relate only to the vane relay. As far as the modelling each track circuit is concerned, the transmitter voltage is taken as the zero phase reference point.

TRACK CIRCUIT MODELLING

5. Background and UK Experience

Extensive studies and modelling of 50Hz track circuits has been carried out on UK railways over nearly two decades. This started in the late 1980’s when new forms of traction were first introduced – initially chopper technology and then in the early 1990’s, 3 phase drive inverter technology. This has resulted in two Network Rail standards which outline a suitable modelling methodology for single rail track circuits and double rail track circuits. The modelling work that has been carried out for ONTRACK is based on this methodology. However, there are a number of features unique to Wellington and the model had to be extensively modified, developed and validated to make it suitable for WEA railway. The key differences are that the WEA direct feed arrangement is not used in the UK, as well as a number of different impedance bond and relay types.

6. Model Development

The development of a steady state model required the main key elements shown in Figures 1, 2 and 3 to be suitably represented in a generic model, which can be reconfigured to represent different track circuit set ups. This allows key factors that influence susceptibility of a track circuit to be adjusted and compatibility current limits of various configurations to be established. Typical factors that affect track circuit susceptibility are:

- Relay type
- Track circuit length
- Impedance bond type
- Bonding arrangements
- Substation position
- Neighbouring track circuit type
- Single rail, double direct and auto impedance setups
- Normal and failed infrastructure conditions
- Double track and single track arrangements
- Distance between neighbouring tracks

Figure 5 below gives the basic block diagram of the generic track circuit model.

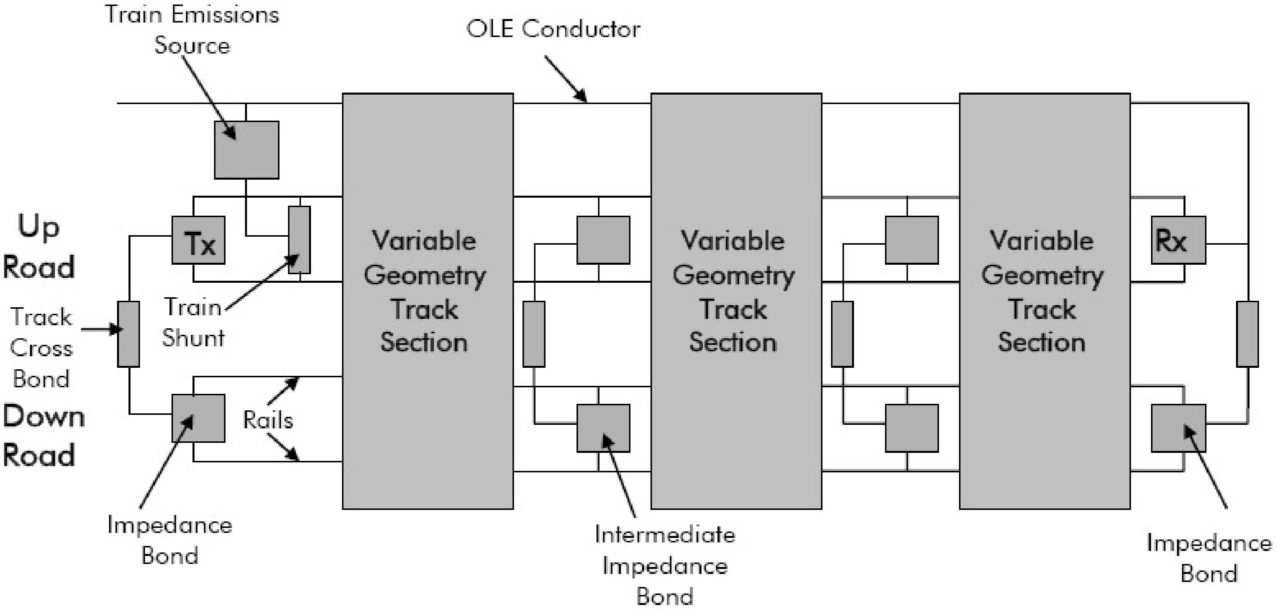


Figure 5 – Block Diagram of Generic Track Circuit Model

Each item of the block diagram has to be modelled and the detail of each item is discussed below.

7. 50Hz Vane Relay

Accurate modelling the dynamic behaviour of a 50Hz vane relay is not easy since it cannot be represented by a simple bandwidth filter characteristic. In addition to phase characteristics, the mechanical inertia of the vane itself makes it a complex dynamic device. However for the purposes of steady state susceptibility modelling it is adequate to model the relay in terms of its 50Hz impedance and operating voltage. The relevant relay parameters were determined from data and measurement of each of the relay types carried out by ONTRACK. Shown below in Figure 6 is an example of the generic model representation of a 50 Hz VT1 vane relay.

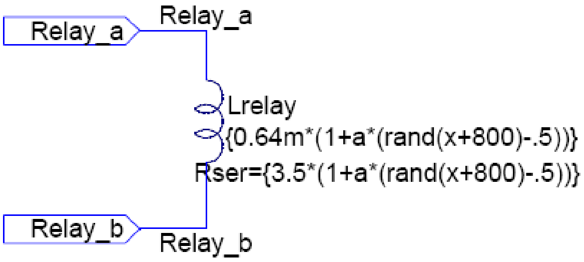


Figure 6 – Example of 50 Hz Vane Relay Model with Tolerance Parameters

8. Impedance Bonds

Impedance bonds require particularly high precision modelling because of the frequency dependent mutual interaction of the three windings and their dominant role in track circuit operation and behaviour. Modelling and validation of the wide variety of impedance bond types that are used in the WEA was therefore a complex task.

The first stage of the modelling was to build and validate the impedance bond model against known UK data. This was shown to provide accurate results for track circuit types that are common to both NZ and UK railways – for example single rail and double rail auto connected types. However, it was found unsuitable for modelling the direct feed types which are not used in the UK. The impedance bond model had to be further refined to more accurately represent the bond losses to enable the direct feed track circuit arrangement to be validated.

To validate an impedance bond model requires accurate measurement data relating to the bonds and this was not available for the WEA railway. The large number of parameters and the requirement for a high current source to replicate the traction current makes characterisation difficult, time consuming and costly. However, extensive data is available from characterisation work carried out on a variety of bonds used in the UK over a number of years. Some of these bond types are the same as those used in Wellington and it is appropriate to use this data as part of the validation process. Where bond types are not known from similar types in the UK an alternative approach is required. The criticality of the impedance bond required a methodology for managing valid alternatives that will not impinge on accuracy of susceptibility to 50Hz interference.

Confirmation of the adequacy of this methodology was that the final track circuit model gave credible results with the appropriate bond or substitute selected. This was part of the validation exercise which is discussed further below.

An example of an impedance bond model is shown below in Figure 7.

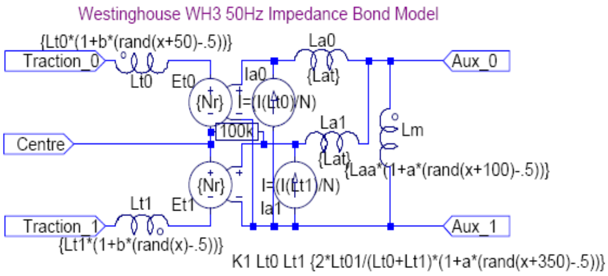
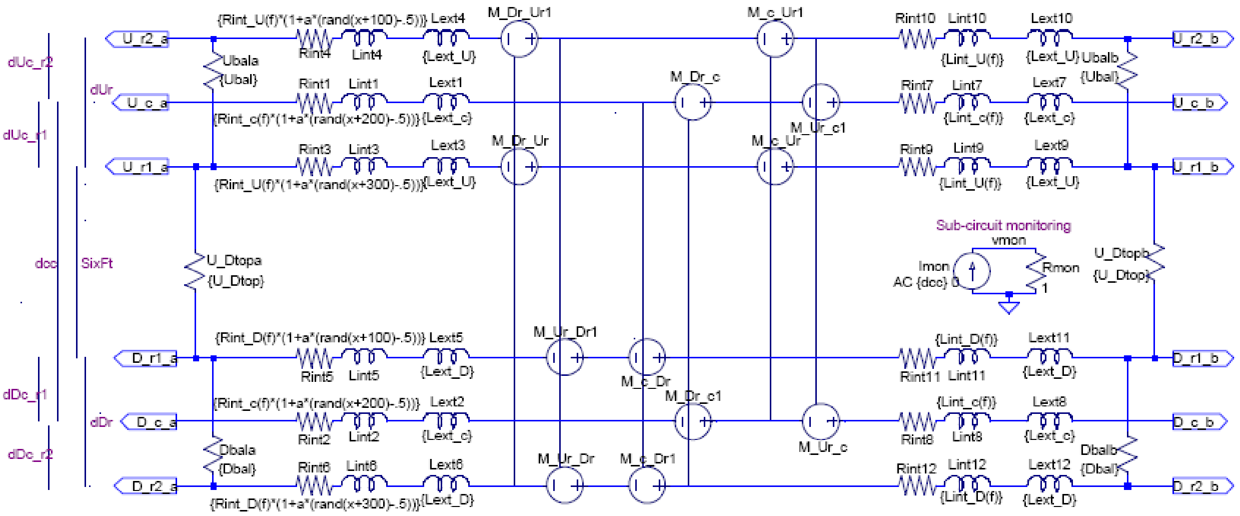


Figure 7 – Example of Impedance Bond Model

9. Variable Geometry Track Section

An example of a variable geometry track section is shown in Figure 8 below. It can be seen that this consists of main conductors – running rails and overhead cable, as well as mutual and resistive cross connections. The rails and overhead cable consist of resistance, self and external inductance. There are also mutual inductance terms for the coupling between the conductors, ballast resistance and earth resistivity. These parameters are defined at 50Hz for this modelling.

It can be seen that this generic section is double track, but it can be easily modified to represent any arrangement found on the WEA. For example, modifications can be made to the model by setting mutual parameters to zero where there is no cross coupling for a particular section. Alternatively, all terms in the second track may be set to zero for single track representation.



```
.param Lext_c=1e-7*L*ln(abs(dcc/r_c))
.param Lext_D=1e-7*L*ln(dDr/r_D)
.param Lext_U=1e-7*L*ln(dUr/r_U)
.param c_Ur=(dUc_r2h*dDc_Ur1h)/(dUc_r1h*dDc_Ur2h)
.param c_Dr=(dDc_r2h*dUc_Dr1h)/(dDc_r1h*dUc_Dr2h)
.param Dr_Ur=(dDr1_Ur2*dDr2_Ur1)/(SixFt*dDr2_Ur2)
.param Dbal=1.27*rho_bal*ln(dDr/r_D)/L
.param Ubal=1.27*rho_bal*ln(dUr/r_U)/L
.param U_Dtop=1.27*rho_top*ln(2*SixFt/(r_D+r_U))/L
```

```
.param dcc=SixFt+dUc_r1+dDc_r1
.param dUc_Dr1=SixFt+dUc_r1  dUc_Dr2=dUc_Dr1+dDr  dUc_r2=dUr-dUc_r1
.param dDc_Ur1=SixFt+dDc_r1  dDc_Ur2=dDc_Ur1+dUr  dDc_r2=dDr-dDc_r1
.param dDr1_Ur2=SixFt+dUr   dDr2_Ur1=SixFt+dDr   dDr2_Ur2=dDr2_Ur1+dUr

.param dUc_r1h=sqrt(dUc_r1*dUc_r1+H*H)  dDc_Ur2h=sqrt(dDc_Ur2*dDc_Ur2+H*H)
.param dUc_r2h=sqrt(dUc_r2*dUc_r2+H*H)  dDc_Ur1h=sqrt(dDc_Ur1*dDc_Ur1+H*H)
.param dDc_r1h=sqrt(dDc_r1*dDc_r1+H*H)  dUc_Dr2h=sqrt(dUc_Dr2*dUc_Dr2+H*H)
.param dDc_r2h=sqrt(dDc_r2*dDc_r2+H*H)  dUc_Dr1h=sqrt(dUc_Dr1*dUc_Dr1+H*H)
```

```
.func Lint_c(x) 2.5e-8*L
.func Rint_c(x) 0.5*L*(2.62E-8*(x)+5.60E-9/(r_
.func Lint_D(x) 5e-7*L*(4.03/sqrt(x)+0.02)
.func Rint_D(x) 0.5*L*(1.63e-5*sqrt(x))
.func Lint_U(x) 5e-7*L*(4.03/sqrt(x)+0.02)
.func Rint_U(x) 0.5*L*(1.63e-5*sqrt(x))
```

BS95R Track Model

Figure 8 – Example of Variable Geometry Track Section Model

10. Other Track Circuit Modelling Parameters

In addition to the 50Hz relay parameters detailed above, and other fixed parameters such as known feed inductors and capacitors, there are a large number of other parameters that are required for the model. These have been selected according to values quoted by ONTRACK where these are known or other sources from UK modelling work. These include the following:

- Rail resistance (continuously welded and joined rail)
- Track and rail dimensions
- Ballast resistance
- Surface earth resistivity

11. Model Validation

The first stage of model validation was to construct the model using elements identified in the previous sections. Based on known data from actual track circuit measurements (from UK data), the model was run to confirm that good agreement between predicted results and actual track circuit measurements was found.

The next stage was to validate the model against actual WEA infrastructure detail. An example track circuit of each main type was selected for validation purposes to include a single rail, double rail direct and double rail auto configuration. The generic model was adjusted to include the specific infrastructure detail derived from WEA bonding diagrams, S&I signalling diagrams, track circuit listings, and measured parameters from track circuit record cards. The appropriate bond model was selected based on the methodology described in section 8 above.

The validation results showed that extremely close correlation was achieved for the single rail model. The double rail direct and auto configurations are more complex to model given the use of impedance bonds, but good correlation between model results and track circuit records was achieved. To provide further confirmation of the credibility of the results, Monte Carlo analysis was carried out. This analysis takes the credible variation of each important parameter (typically ±3% or ±5% where appropriate), and randomly selects a value between these extremes for each parameter. The model runs some 100 iterations for the various random values and produces a spread of credible results. Provided the measurements lie within this spread and not at the fringes, this provides a strong indication that the results are credible and the validation supported.

The records against which the model results were compared were taken from the actual track circuit record cards kept within the signalling locations for the particular track circuits. These are real measurements taken of the track circuits on a periodic basis (usually annually). This is part of the maintenance regime to ensure that the track circuits are still operating within acceptable tolerances. Given that these are actual measurements they provide strong evidence of the credibility of the model results.

The results provided the evidence to confirm that the model was well developed and suitable for modelling all the track circuit types present in Wellington. This includes single rail, double rail auto and double rail direct configurations.

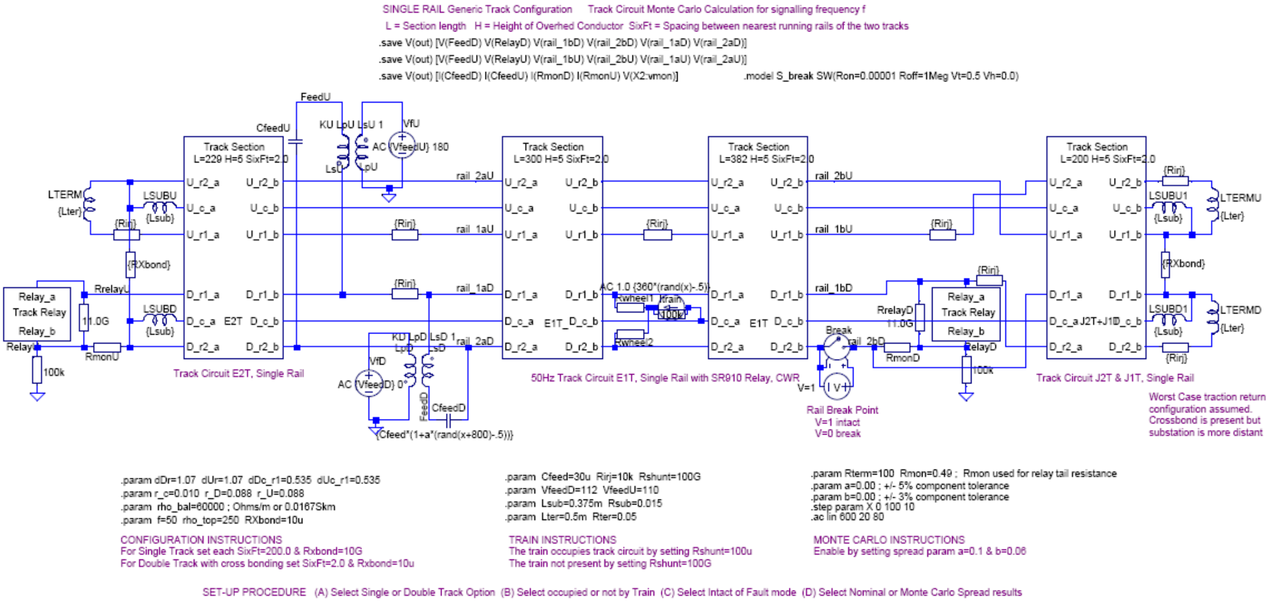


Figure 9 – Model Validation Schematic for Track Circuit E1T at Paekakariki

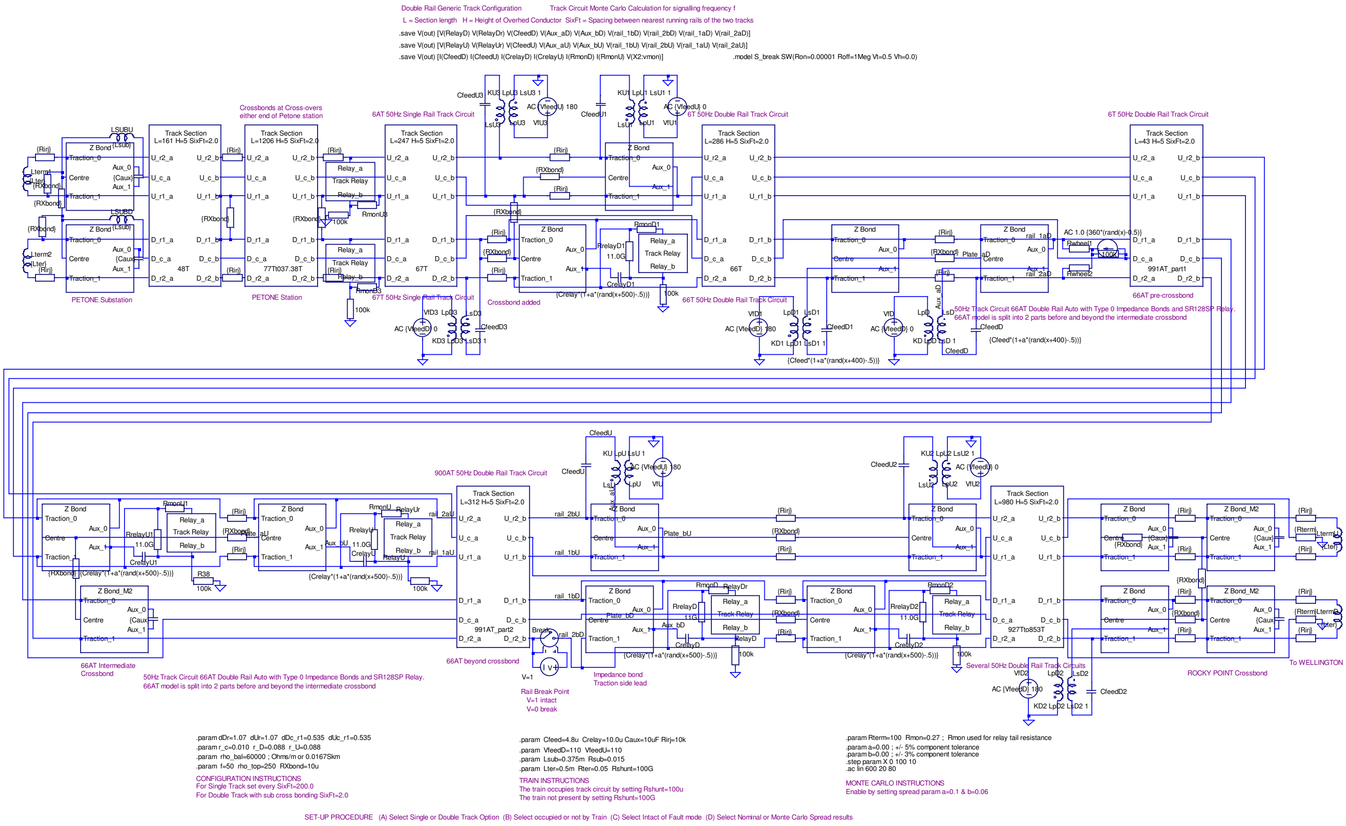


Figure 10 – Track Circuit Top Level Schematic

12. Track Circuit Susceptibility Analysis

Using the validated model it was then possible to configure it to represent any particular track circuit in WEA. However, it was not practical to model every single one given that there are over three hundred 50Hz double element vane relay track circuits. The next aim of the analysis was to select a representative sample of the most probable susceptible track circuit set ups, each of which was then individually modelled. This enabled susceptibility limits to be set that encompassed all track circuits. A total of 18 track circuits were selected and agreed with ONTRACK, which covered the potentially most susceptible arrangements of each of the track circuit configurations.

13 Development of Target Limits

The susceptibility limits determined by the modelling define the worst case level of interference current from any traction (or other) source that is tolerable, thus preventing the risk of wrong side failure of the signalling system.

Given that multiple sources of interference may be present on the railway network it is not possible to ascribe the entire infrastructure susceptibility limit to a single traction source (normally one train). However, it is possible in critical scenarios to envisage the presence of a dominant source, based on the proximity of the sources to the susceptible infrastructure. The infrastructure controller decides the proportion of the infrastructure susceptibility limit that may be allowed per train. Typically the train limit may be up to 50% of the infrastructure limit, although lower train limits are often applicable in heavy traffic conditions with short headways. However, some systems that employ sophisticated coding or high voltage receivers may only need a small safety margin. Measurements of track interference for single and multi-train operations can demonstrate the validity of safety factor assumptions, although theoretical arguments are often sufficient.

Having established the per train limit of the normal infrastructure, it is also necessary to consider failure modes of the system, both fixed and train borne. Figure 11 is a diagram of a recommended approach to absorb credible infrastructure faults into train limit specifications from UK standard GE/RT8015.

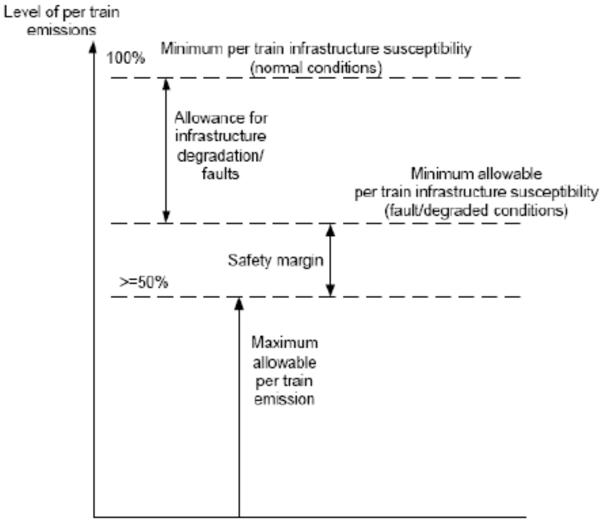


Figure 11 – Setting of Maximum Allowable Train Emission Limits

However, where this requires further reduction of up to 2 in the allowable train emissions, it is often impractical to retain a single per train limit that is applicable in all circumstances. In situations where exceedance of the failed infrastructure target might impinge on operational reliability, alternative compatibility solutions should be sought. This will vary according to the nature of the infrastructure system under threat and the mechanism of interference. The mechanisms of interference are classified as conducted (steady state and transient), inductive and radiated. The threat from transients is generally from conducted paths (although other mechanisms should not be ignored), so may be considered as short term conducted interference. Higher limits are normally tolerable for a short durations.

The conventional way to handle the consequences of infrastructure failure is to prove that the risk remains acceptably low. An important underlying premise for this proof is that the existing railway is already a safe and operational system in electromagnetic compatibility terms. Hence, a predictive method based on measured probability of any given magnitude and frequency, to confirm tolerable exceedance rates with failed infrastructure is recommended. The train manufacturer will also need to predict that train failure modes are tolerable and ALARP.

From this information it is possible to derive a second set of results that covers various mechanisms across the infrastructure susceptibility spectrum for the 50Hz double element vane relay track circuits.

> In addition to the current limits that relate to permitted 50Hz emissions that a train could return via the running rails, there is another mechanism to consider. This mechanism can affect 50Hz track circuits where there are parallel paths to adjacent tracks due to 50Hz longitudinal voltage drop along the length of a train between any two of its axles. This usually only results from a train fault condition, caused by earth faults on 50Hz power supply lines that are bussed down the train. It is usual to set an axle to axle limit for a train to 50% of the lowest drop away voltage of any of the relays. This led to an axle to axle limit of 0.2V.

CONCLUSIONS

A generic computer simulation model has been developed and successfully validated for use in modelling 50Hz double element track circuits in WEA.

From over 300 double element track circuits present in WEA, a subset of 18 track circuits representing the most susceptible set ups have been individually modelled. This has lead to a set of susceptibility results for normal and failed infrastructure conditions. Of the 18 track circuits, there was one example of the use of the most sensitive relay type, which lead to an extremely low susceptibility limit due to a number of factors for the failed infrastructure case..

To use this value as the basis of train design limits would lead to unacceptably low values that would be impossible to achieve by the train designer. For this reason it was recommended that this worse case example be considered as a unique case to be modified or replaced. The remaining 17 track circuits have a wide variation of susceptibility limits for the sound infrastructure results, however, the failed infrastructure results are more closely grouped. It was therefore logical to set limits based on this remaining group of 17 track circuits. All further concluding comments therefore apply to the group of 17 track circuits, excluding the worse case example detailed above.

By taking the lowest susceptibility limit from all of these 17 results and then applying suitable safety margins, it has been possible to define train limits and targets. These are suitable for use by the train designers to assist in designing an EMU compatible with the double element track circuits it is required to operate over in WEA.

One of the outcomes of the modelling was a better understanding of factors that effect the susceptibility of the track circuits leading to possible actions that could be carried out to improve their susceptibility. However, as the results demonstrated there is no one clear type of 50Hz track circuit that is always more susceptible than another, or no general actions that will significantly improve the susceptibility of all track circuits of that type. This is because there are many interdependent factors that affect track circuit susceptibility. Hence a starting premise that long track circuits are more susceptible than shorter ones, whilst often true, is not inevitably the case.

For example, it is useful to look at two auto connected track circuits comparing a long (1393m) circuit with a shorter (215m) circuit, under no fault conditions. The no fault scenario does indeed give a much higher susceptibility limit for the shorter track circuit, 46.7A compared to only 5.45A for the longer circuit. However, when considering fault conditions their susceptibility is virtually identical, 0.79A and 0.8A respectively.

Also, when looking at two single rail track circuits, a longer (682m) circuit has a higher susceptibility limit (7.99A no fault, 1.08A fault), compared to the shorter (432m) circuit, which is only 3.54A no fault, 0.77A fault. This is due to other factors such as the presence (or not) of parallel paths. The longer circuit has a parallel path due to bonding at both ends, whereas the shorter circuit does not.

In fact, many factors (often interrelated for any particular track circuit) that affect track circuit susceptibility include the following:

- Relay Type

  Generally the lower the operating voltage (and in particular the drop away voltage) of the relay the lower the susceptibility of the track circuit.

- Track Circuit Length

  In general susceptibility increases with length for sound infrastructure.

- Impedance Bond Type

  Modelling of impedance bonds is sufficiently detailed to include imbalance due to manufacturing design between the main traction windings and the auxiliary winding. Since the imbalance varies between impedance bonds so the susceptibility of a track circuit will be affected.

- Bonding Arrangements

  The presence of multiple connections between neighbouring tracks (due to cross bonding or points and crossings), providing parallel paths for traction return current improves the no fault susceptibility of a track circuit. However, it can make the fault mode worse since it is less likely to be revealed due to the parallel paths.

- Substation Position

This determines the principal direction of return traction current flow. The worst scenario is when the local substation is just beyond the track relay.

- Neighbouring Track Circuit Type

  Transmitter breakthrough into circuits from neighbouring track circuits is not negligible, particularly for direct feed double rail circuits, where the feed current is greater.

- Single Rail, Double Direct and Auto Impedance set ups.

  Under no fault conditions double direct types are the least susceptible, but under fault conditions all three types are similar.

- Normal and Failed Infrastructure Conditions.

  All failed infrastructure conditions degrade the susceptibility of a track circuit. The worst case site for a train within a circuit is not automatically the same between track circuits, and the introduction of a failure mode moves the site.

- Double Track and Single Track Arrangements.

  Single rail track circuits on single track railway are generally more susceptible than an equivalent one on double track as there can be no parallel paths due to cross bonding. However, for infrastructure fault scenarios only, the parallel track unbalances the double rail track circuit, making double track railway generally more susceptible than an equivalent single track.

- Distance Between Neighbouring Tracks

  The closer the distance the greater the coupling effects, increasing relay current from parallel paths. In general this increases susceptibility, so a worst case minimum separation is assumed. However, for some single rail circuits and other unusual track configurations the effect can be opposite.

Notwithstanding the above statements there are some general conclusions than can be deduced about the different track circuit configurations (single rail, double direct and double auto connected).

- ❖ Under no fault conditions single rail track circuits are generally more susceptible than double rail types. From the results, susceptibility limits for single rail are generally below 10A and often between 3 - 4A.
- ❖ Under no fault conditions auto connected double rail types are the next most susceptible type, the lowest limit being 5.45A, but levels often being in the region between 10 - 20A.
- ❖ Under no fault conditions the direct feed double rail type are the least susceptible arrangement with the lowest limit being 10.2A, with levels often being in the region of 50 -100A and above.
- ❖ Under fault conditions there is much less difference in susceptibility between the track circuit configurations. Single rail range from 0.63A - 2.86A, Auto connected from 0.77A - 1.48A and Direct connected from 1.58A - 7.14A.

As discussed in section 13 there is a further mechanism that can effect 50Hz track circuits where there are parallel paths to adjacent tracks. An axle to axle limit of 50% of the lowest relay drop away voltage has been set, leading to a limit of 0.2V.

In summary, the results from all modelled configurations (with one exception requiring track circuit modification) were considered in the train limits declared. By the careful selection of appropriate track circuits to analyse in detail, the results encompass all track circuits found on WEA and are therefore represent suitable limits for train design.

Should it prove necessary to improve the susceptibility of some of the more susceptible track circuits on WEA if the train design does not meet the declared limits, this would be feasible.

However, as evidenced by this paper there are no simple single actions that will significantly improve the overall susceptibility limits. A number of different actions would require implementation to improve track circuit susceptibility, judged on a case by case basis with further detailed study.