Simulation studies of 50Hz locomotive impedance and DC substation interference sources

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Abstract

The requirements specified in the locomotive acquisition specifications for compatibility with the 50 Hz train detection systems usually result in severe design restrictions on the electric powered vehicles (EPV). They require bulky inductors and capacitors in the input filters of power electronic converters with associated weight and space problems. Usually the impedance of the locomotive is specified which implies a worst case 50 Hz substation supply voltage. This paper investigates the conditions necessary for this voltage to be present and presents simulation results obtained with the study. Simulation is also performed on proposed measurement setups to be employed during the practical measurement of locomotive impedance.

1 Background

Even today after much research and publishing on the subject of power frequency track circuit interference [1-3], severe design restrictions is placed on the design of locomotive power electronic drive systems. In South Africa the locomotive acquisition specifications call for a total train impedance of more than 1 Ohm at 50Hz which translates to 4 Ohm per electric powered vehicle, when the train consist is made up of 4 powered units.

Some investigation into the origin and reasons for these severely restricting requirements indicated that these were derived from the characteristics of the rheostatic controlled electric powered vehicles. When chopper controlled vehicles were offered, a specification was required to ensure that no interference would occur with the introduction of this “new technology”. In the presence of fail safe (vital) systems this is indeed a huge and difficult task [4]. Therefore the
engineers at the time opted for the less time consuming and “safer” path. This entailed determining the input impedance of a train employing rheostatic control and specifying this as the lower limit for future trains. Since 50 years of experience with these technologies has proven that the systems were electromagnetically compatible, the safety requirements could also be met in this way. The specification simply required that the electric powered vehicle (EPV) input impedance be more than 4 Ohm at 50 Hz and that it should not interfere with the track circuits installed at the time, and a list of these equipment were provided.

Although this approach is a very responsible one, these requirements resulted in bulky inductors and capacitors of the input filters in front of power electronic converters with associated weight and space problems. This is especially true in the case of metro rolling stock where space is very limited. In order to seek a more optimised solution an investigation was conducted to determine the parameters which could be specified to relax the constraints placed on the power electronic designer, and still not compromise the required safety levels.

2 Electromagnetic compatibility specifications

2.1 Requirements originating from the signalling system

From a signalling point of view the frequency content of the traction return current in the rail is the most important parameter when EMC is considered.

![Figure 1: AC track relay susceptibility limits](image)

Figure 1: AC track relay susceptibility limits (a) Voltage, (b) Traction current.

These specified current limits originate from the interference characteristics of the power frequency track circuits under wrong-side and right-side failure conditions [5, 6]. Figure 1a gives an example of the susceptibility limit applicable to a 50 Hz AC track relay, in terms of the relay terminal voltage. The graph in Figure 1b presents the susceptibility of the track circuit relay when
transformed into an equivalent traction return current [7]. The track circuit relays are also sensitive to the phase angle of the current relative to the local mains supply but since there are too many variables determining this, it is not taken into account. Thus from a signalling point of view the limits as shown above is the only requirement specified to ensure EMC.

2.2 Additional requirements necessary for rolling stock design

Although the current limit is the only requirement imposed by the signalling system, other parameters in the traction system needs to be specified in order to complete the locomotive design requirements.

On power electronic controlled electric vehicles an input filter is required to reduce the harmonics current of the fundamental switching frequency because of audio frequency track circuits. This configuration reduces the input impedance of vehicle significantly and the only way to raise the input impedance is to select a relatively large inductor value. Furthermore the filter resonant frequency needs to be as far below 50 Hz to increase the impedance, but should be high enough to separate the electrical and mechanical resonant frequencies from each other.

Since conditions in the electrical traction supply system is outside the control of the locomotive designer, one of two factors needs to be specified by the railways. This is the locomotive input impedance at 50 Hz, or the worst case 50 Hz voltage at the substation terminals. In order to allow the locomotive designer the most freedom, specification of the traction supply voltage is further investigated.

3 Factors influencing the worst case supply voltage

3.1 Failure modes, effects and criticality analysis of DC substation

In order to establish a departure point for studying the factors influencing the worst case 50 Hz supply voltage a Failure Mode Effects and Criticality Analysis (FMECA) was performed on a typical substation configuration (see Figure 2). Three dimensions were defined in the FMECA namely: probability, detectability and severity. Each of these dimensions was rated on a scale and then the criticality of the failure mode could be found by the product of the three dimensions. Many of the failure modes in the substation could be eliminated by virtue of inspection or experience. Some of the failure modes identified could definitively have an influence on the 50 Hz voltage but the effects could not be directly characterised. In order to achieve this, a simulation model of the substation was developed.

3.2 Simulation model to investigate failure states generating 50 Hz components

The Electromagnetic Transient Program (EMTP) was used to develop a model of the DC substation, line and EPV. With this model, different failure modes were investigated that could cause a 50 Hz voltage component on the DC side of
the rectifier. This method had a two fold result. Firstly, a calibrated model assists in adding or improves a severity index in the FMECA of the substation discussed in section 3.1. Secondly, the simulation is used to decide on a safe method of introducing a fault in the substation on purpose to generate a 50 Hz voltage component on the DC side. This 50 Hz component is then used firstly to further calibrate the model and secondly to measure the input impedance of the EPV at 50 Hz while in normal operation.

3.2.1 Simulation of fault conditions
A diagram of a typical DC substation layout is shown in Figure 2. The substation consists out of two three-phase transformers (a star-delta and a star-star transformer) that are simulated by 2 sets of three-phase, delta-connected, pure 50 Hz voltage sources of which the phase angles are set accordingly. A 12-pulse diode rectifier, a series inductor, and two resonant filters at 600 and 1200 Hz are coupled to the transformer. Each diode shown in Figure 2 consists of a set of parallel and series diodes. Diodes in series have resistor divider networks to balance the reverse voltage across them, and across each diode is usually an RC snubber circuit. Following the two parallel filters is a series impedance which corresponds to the line impedance from the substation to the EPV. As a first attempt, the EPV is modelled with only a resistor, to act as a DC load to the substation.

In some DC substations, there are large inductors in the AC lines connected to the rectifier – in Figure 2 denoted by $L_{ac}$. They date back to the days when mercury arc rectifiers were used, and in some substations, the inductors are still present. One of the attempts at generating a 50 Hz voltage component at the DC side of the rectifier was to simulate an unbalance on the AC side. A source of unbalance could be transformer leakage and mutual inductance unbalances due to inherent unsymmetrical transformer construction. This was simulated by

![Figure 2: Typical DC substation configuration.](image-url)
simply short-circuiting one of the $L_{ac}$ inductors on the AC side. However, due to the full-bridge rectification by the 12-pulse rectifier, the unbalance on the AC side resulted in 100 Hz (and integer multiples thereof) voltage components on the DC side, but no 50 Hz components. It might be conceived that an unbalanced 25 Hz voltage component (due to flicker) on the AC side or a balanced 25 Hz voltage component with unbalanced impedances could cause 50 Hz voltage components on the DC side of the rectifier. However, the magnitude and likelihood of such an event needs further investigation.

Since each diode in the rectifier is on for a short while only once every 50 Hz period, the failing of a diode will generate a 50 Hz voltage at the DC side. Most of the time, diodes fail to a short-circuit state. When one of the diodes in a two-series diode set fails to a short circuit, an unbalance exists. However, simulation at 300 A DC current showed that this unbalance is too small to generate a significant 50 Hz voltage on the DC side: 1.6 V in this case, but depends on the on-resistance of diodes. When both series diodes fails to short circuit however, a very large 50 Hz component is generated: 800 V, 50 Hz for 300 A DC. This component is almost of the same order as the DC voltage so that large and unsafe voltage levels will occur. The same happens when one of the diodes fail to an open circuit. If there are parallel sets of diodes and one diode fails to a short circuit, the 50 Hz voltage component is again small, 0.5 V, while the same result as previous holds for one diode failing to an open circuit.

![Fourier components of DC voltage with no fault and with one diode short circuit](image)

Figure 3: Fourier components of the rectified and filtered voltage (a) with no fault, and (b) with one diode failed so a short circuit.

### 3.2.2 Simulation results – fault condition

The transient simulation in EMTP is run until steady-state is reached. Then Fourier analysis is used to determine the 50 Hz voltage component on the DC side of the rectifier. As an example a simulation was performed for the case where one of the series diodes in a two-series diode set in a rectifier leg failed short circuit. The results of this simulation are shown in Figure 3. The Fourier components of the DC voltage on the track side of the two filters (thus the output voltage of the substation) are shown in Figure 3a with no fault, and in Figure 3b...
with one diode failed to a short circuit. In both graphs, the smaller harmonic components have been zoomed into – the DC component is approximately 3100 V and off the scale in Figure 3. Also shown in both graphs of Figure 3 are the 12th and 24th harmonic components that are characteristic of a 12-pulse rectifier. The additional harmonics (of which the 50 Hz component is the largest) caused by the failed diode can be seen in Figure 3b.

From the simulations it was found that normal failure of all the diodes in a rectifier leg will either generate very large, unsafe levels of 50 Hz voltages or 50 Hz voltage in the region of 1.5 V or less with a single diode short circuit failure.

3.2.3 Simulating conditions to generate 50 Hz for test purposes
For the second objective (to measure the input impedance at 50 Hz of the EPV) the aim was to create an unbalance inside the rectifier which generates a useable, safe 50 Hz voltage on the DC side. Simulation showed that placing a small ohmic impedance in series with one of the diode sets generates a 50 Hz voltage of which the level could be set be changing the value of the impedance. The position of the impedance in the rectifier is shown in Figure 4. Also shown in Figure 4 is the measuring equipment which could be used to measure the generated voltage. Measurement results obtained is presented in a separate paper in these proceedings [8].

![Figure 4: Impedance in series with diodes (resistor setup).](image)

The unbalanced created by this resistor generates an arbitrary chosen 50 Hz voltage component superimposed on the DC voltage for a certain DC current which is drawn from the rectifier. Also superimposed on the DC voltage are a host of harmonics – integer multiples of the 50 Hz component, but all of them smaller in amplitude than the 50 Hz component. For example, a simulation was performed for the substation shown in Figure 4 having an unbalance resistance.
of 0.05 Ω with 300 A DC current drawn from the rectifier. This resulted in a 7.5 V, 50 Hz component superimposed on the 3100 V DC as shown in Figure 5. The Fourier components of the rectified voltage in this case is shown in Figure 5a. The 50 Hz component can clearly be seen. The DC voltage with the big 50 Hz oscillations can be seen in Figure 5b.

![Fourier components of DC voltage with unbalancing resistor](image)

![DC Voltage against time with unbalancing resistor](image)

Figure 5: (a) Fourier components of the rectified, filtered voltage with the unbalanced resistance, and (b) the DC voltage with oscillations against time.

4 Conclusion

A model of a DC substation was develop to investigate 50 Hz interference sources originating within the substation. This model will aid in setting severity indexes for the different faults which are considered in the FMECA study. The consequence of some of these faults is too dangerous to test experimentally.

It was seen that an unbalance in the rectifier part of the substation will generate a 50 Hz voltage component on the DC side. A small ohmic resistance was placed in series with one of the diodes to test this and was also used as a safe mechanism to generate 50 Hz voltage to be used when measuring the 50 Hz input impedance of some EPVs.

The simulation model was calibrated with experimental results [8] and can now be employed to assist with the development of a specification of the worst case substation voltage which can be safely used in the EPV electromagnetic compatibility specifications.

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References


