Simulations and measurements on electrical resonances on the Portuguese 25 kV network

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Abstract

The higher switching frequencies of modern traction converters can lead to resonances which can cause costly malfunctions, as the Eigen frequencies of traction power supply systems are relatively low and as dampening can be low as well. Unfortunately EMC standards like [1] nor traction power supply standards like [2] give guidance on this subject. The introduction of refurbished UTE-Silicio train sets on the Portuguese railway network by Comboios de Portugal (train operating company) led to resonance problems in the traction power supply network, which where in some locations thus severe that it resulted in damaged equipment, such as burned out transformers. The decision was made to change the switching frequency of the converters in the train from 450 Hz to 650 Hz, in order to avoid major modifications in the traction power supply systems. A project was started to calculate the frequency response of all 25 kV lines in the Portuguese railway network, as part of the homologation process for the refurbished UTE-Silicio train sets. Measurements were performed on many lines using a number of methods, to verify the simulation results. This paper discusses the results of the simulations and the measurements and these results will be compared. A further step will be a future project in which research will be performed to determine the technical and economical optimal solution for the problems caused by resonances. For instance changes in the switching frequency of rolling stock, or modification in the traction power supply system.

Project Background

In co-operation between REFER (infrastructure owner), Movares (consulting company) and Comboios de Portugal (train operating company), a project has been started to guide the homologation process of the refurbished UTE-Silicio train sets. The project consists of 3 parts:

\begin{itemize}
  \item[a)] homologation of the modified rolling stock with signalling and telecommunication installations;
  \item[b)] development and evaluation of a measurement system;
  \item[c)] modelling of the traction power supply system, including measurements to check on the accuracy of the simulations.
\end{itemize}

In the homologation process (a), it must be proven that:

\begin{itemize}
  \item[1.] The signalling equipment (and in particular the train detection layer, a safety critical system) is not influenced in a negative way by this change;
  \item[2.] The telecommunication equipment is not influenced in a negative way by the new trainsets;
  \item[3.] The traction power supply system has no Eigen frequencies in the proximity of 1.3 kHz.
\end{itemize}

Only after this process has finished with a positive result, the train receives permission to be used on the railway network.

Parts b) and c) of the project support the homologation process. By developing a measurement system (b) and using it to validate the simulation of the power supply system (c), it is not necessary to perform costly measurements on all parts of the network.

This paper will focus on the modelling of the system and the measurement results with regard to resonances.

Objective of research

Main objective of the research is to determine whether the change in switching frequency will solve the problems encountered in the past and will not lead to new problems. Due to the large diversity in the power supply configurations, both for the railway network itself as for the feeding high voltage network, a variety of aspects needs to be studied. For example, if the feeding high voltage network has a voltage of 150 kV or 220 kV, its influence is very small. In case of a 63 kV supply voltage, the impedance influences the behaviour of the line and the effects of a single or double circuit feeding the REFER substation become visible.

Those effects might be usable when resonance problems occur, for instance by using a single circuit at times when the load (and also the dampening) are low. The change in impedance causes the Eigen
frequency to shift to an area were (hopefully) no or lower harmonics are present so damage due to resonances can be avoided.

Another objective in the future is the setting up of rules for spectral management by the infrastructure owner. For the admission of rolling stock on the network, one must determine the allowable emission of harmonic currents. Some frequencies are not allowed because of possible interference with train detection systems, while other frequencies are not allowed because of power supply resonances. Modelling the infrastructure can help to limit the costs substantially, compared to doing measurements alone.

Modelling

The complete 25 kV traction power supply network of Portugal (21 substations and 1430 km of line) has been modelled in the frequency range 100 Hz – 10 kHz. Figure 1 and table 1 give an overview of the network. By modelling it is possible to study the effects of the change in switching frequency and the different configurations of the traction power supply system more efficient and more economical than by measurements.

<table>
<thead>
<tr>
<th>Substation</th>
<th>Supply Voltage [kV]</th>
<th>Installed Power [MVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrantes</td>
<td>63</td>
<td>10</td>
</tr>
<tr>
<td>Alfarelos</td>
<td>63</td>
<td>2 × 16.2</td>
</tr>
<tr>
<td>Amadora</td>
<td>63</td>
<td>2 × 16.2</td>
</tr>
<tr>
<td>Entroncamento</td>
<td>63</td>
<td>2 × 10</td>
</tr>
<tr>
<td>Ermidas</td>
<td>150</td>
<td>12</td>
</tr>
<tr>
<td>Pogueteador</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>Gouveia</td>
<td>220</td>
<td>16.2</td>
</tr>
<tr>
<td>Irivo</td>
<td>220</td>
<td>20</td>
</tr>
<tr>
<td>Litém</td>
<td>63</td>
<td>10</td>
</tr>
<tr>
<td>Luzianes</td>
<td>150</td>
<td>12</td>
</tr>
<tr>
<td>Monte Novo</td>
<td>150</td>
<td>12</td>
</tr>
<tr>
<td>Mortagua</td>
<td>220</td>
<td>16.2</td>
</tr>
<tr>
<td>Pegões</td>
<td>150</td>
<td>16.2</td>
</tr>
<tr>
<td>Quinta Grande</td>
<td>150</td>
<td>16.2</td>
</tr>
<tr>
<td>Rodão</td>
<td>150</td>
<td>16.2</td>
</tr>
<tr>
<td>Salreu</td>
<td>63</td>
<td>2 × 16.2</td>
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<tr>
<td>Santiago do Cacém</td>
<td>63</td>
<td>12</td>
</tr>
<tr>
<td>Sobral</td>
<td>220</td>
<td>16.2</td>
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<tr>
<td>Travagem</td>
<td>63</td>
<td>2 × 16.2</td>
</tr>
<tr>
<td>Tunes</td>
<td>63</td>
<td>12</td>
</tr>
<tr>
<td>Vila Franca de Xira</td>
<td>63</td>
<td>2 × 16.2</td>
</tr>
</tbody>
</table>

Table 1 List of 25 kV substations

Names of substations on which off-line measurements have been performed are indicated in red. Names of substations on which on-line measurements have been performed are indicated in blue.

Figure 1 Overview of Portuguese railway network
For a number of substations, measurements have been done to verify the simulation results. Substations with complex track layouts or substations for which the simulation predicts resonances close to 1.3 kHz are preferred as measurement locations, but accessibility and availability of the track play a major role as well.

The simulations are done with SimspoG, a simulation tool developed by Movares for modelling systems of parallel conductors such as railway lines or high voltage lines [3]. The model uses the Carson - Pollaczek equations to calculate the electrical parameters of the line (self and mutual impedance per conductor). The capacitance between the overhead conductors and ground are added to the model, as well as the parasitic capacitance in other components, e.g. switchgear, current and voltage transformers and surge arrestors. A model of the substation transformers and the feeding high voltage network is also added to the model. A typical result is shown in figure 2. The first parallel resonance (peak at 1.6 kHz) is mainly determined by the stray inductance of the substation transformer and capacitance of the line and is independent of the position along the line. One of the problems with the modelling is the estimation of the values of all parasitic capacitances, as these parameters are usually not regarded as important and therefore often not well known.

Measurements

In order to validate the simulation model, measurements have been done using the following techniques:
- Using harmonics produced by rolling stock;
- off-line injection;
- on-line injection.

Harmonics produced by rolling stock

The harmonics measurements were done by recording the current through the train and the catenary voltage. Differentiating/Integrating measurement techniques were used [4], [5] as well as in all other cases. By using the transferimpedance concept for the measurement chain [6], reliable measurements are present in the dirty EM environment of a railway system. The advantage of this method is that no equipment is required to generate the currents at higher frequencies; the harmonic content of the rolling stock itself is used. Only measurement equipment is required to measure the currents through the train and the voltage on the catenary for frequencies between approximately 500 Hz and 2 kHz. The measurements can be done during normal operation while other trains are running or when the line is out of service. The latter may ease the understanding of the results (and is therefore usually the preferred method), while the first situation may yield more realistic results.

There is however a major disadvantage with this measurement technique: the impedance can only be calculated for frequencies that are emitted by the train from which the measurements are done. This means that in general, only a few discrete harmonic frequencies can be measured, while a continuous
spectrum is necessary to find the Eigen frequencies. This is illustrated by the graph in figure 3. If the impedance of the network is only known for a few discrete frequencies, it is impossible to determine the exact Eigen frequencies. For a given set of discrete points, a number of continuous spectrums can be fitted on them.

![Figure 3 Two possible frequency response curves](image)

**Off-Line Injection**

In order to overcome this disadvantage, an off-line injection set-up has been developed in co-operation between REFER and Movares. The set-up is shown in figure 4. A sine wave generator feeds into an amplifier and this signal is injected into the catenary. A transformer is used to match the impedance of the line to more suitable levels for the amplifier. A resistor is connected in series to provide a minimum impedance in case a parallel resonance is found and the impedance of the line approaches zero Ohm. Also an over voltage protection consisting of diodes and zener diodes is present, as well as a 700 V voltage fuse between catenary and running rails. By measuring the current and voltage, the impedance as a function of the frequency can be found. This method requires the catenary system to be disconnected from the high voltage network, and be floating, otherwise the amplifier will suffer from a large 50 Hz voltage at its output terminals. While this set-up can be used to validate the major part of the model, it cannot be used to identify the Eigen frequencies of the line under normal operating conditions, because the influence of the high voltage network is absent. This is mostly an issue for REFER substations that are fed from the 63 kV HV network. The influence of the 150 kV and 220 kV networks is very small and negligible in most cases. An example of the influence of the feeding HV network for a substation fed from 63 kV can be found in Figure 5, simulations are given for the situation where the HV network is connected and for the situation where the substation transformer is disconnected at the HV side and grounded, as is the case during an off-line measurement. More information can be found in [7].

![Figure 4 Measurement set-up](image)
Figure 5 Influence of HV feeding network (substation Entroncamento)

Figure 6 below shows the set-up during one of the measurements. In the foreground two transformers can be seen. The amplifier and sine wave generator are in the middle, while the measurement equipment can be seen in the background.

On-Line Injection

A third set-up has been developed by Eindhoven University of Technology that measures the impedance while the line is connected to the high voltage network. This on-line injection method is able to provide data that can be used to validate the entire model as well as identify the Eigen frequencies of the system under normal operating conditions. The on-line injection set-up consists of the following parts:
- Relay board;
- IGBT stack & capacitor bank;
- Transformer 25 kV / 220 V, 10 kVA;
- Electronic control unit.
The capacitor bank is charged/discharged by IGBT semiconductors at a frequency that can be adjusted from 200 Hz up to 2 kHz, pulse width can be modulated to control the current. Apart from this basic frequency several higher harmonic families are generated, thus it is possible to perform measurements until 10 kHz. A relay board is used to switch the equipment on and off and to discharge the capacitor bank after each measurement. The whole set-up is controlled by an electronic control unit. The set-up is designed to work at 230 V 50 Hz, but with some software modifications in the control unit, it can also be used with 16.7 Hz power supply systems. The unit is connected to the secondary winding of a 25 kV / 220 V, 10 kVA transformer that is normally used to feed track side signalling or other equipment. At 25 kV level, harmonic currents can be injected with an amplitude of about 0.1 to 1 Ampere, depending on the impedance of the line.

Figure 7 shows the main electrical diagram of the system. Relays K1, K2 and K3 are used to start & stop the system in a controlled manner. The control unit switches the IGBT's in such a way that the harmonic content in the line current is as large as possible. The switching frequency can be adjusted between 200 Hz and 2 kHz, which is sufficient for the purpose of this set-up.

Figure 8 and 9 show the simulated current on the low voltage side of the transformer in the time and frequency domain. An overview of the set-up as it was actually used can be found in Figure 10. For ease of transport the transformer is mounted in the back of a small pickup truck (left), relay board and IGBT stack on the right.
The On-Line Injection set-up was used for the first time in Pragal (just south of the tunnel entrance, western track) testing substation Fogueteiro, one transformer was feeding the section towards Alvito (North). Typical results can be found in Figure 11. Although the main frequency of the current injected is 536 Hz, the voltage signals shows high values at 250 Hz, 350 Hz, 550 Hz, 650 Hz, 850 Hz and 950 Hz, which correspond with 5th, 7th, 11th, 13th and 19th harmonic, which are injected into the railway system by the energy supply company. Measurements were performed using a digital signal analyser. For the voltage measurement system a double T band-notch filter was used to suppress the 50 Hz component, in order to obtain a larger dynamic range for the higher harmonics, which are of more interest.
Comparison between Simulations and Measurements

Figure 12 shows the results of a simulation and of a measurement (using harmonics produced by rolling stock) for a substation (Litém) that is fed from the 63 kV network. It can be seen that these match fairly well.

Figure 13 shows the results of a simulation and of a measurement (with the off-line technique) for a substation that is fed from the 150 kV network. It can be seen that these match fairly well. So far 10 out of 21 substations have been tested using the off-line technique, in all cases the model predicts the reality well. The amplitude is not correct, this is probably caused by dampening that is present in reality but absent in the model. For instance in reality a number of transformers are connected to the catenary to supply secondary installations, which leads to a higher damping of resonances than predicted by the model. For reasons of simplicity of the model, these transformers have been omitted. However the Eigen frequency matches well, which is the most important characteristic, as the correct
prediction of the values of Eigen frequencies (especially parallel resonances) is much more important than the absolute value of the impedance at a parallel resonance.

**Figure 13** Comparison between off-line measurement and simulation (substation Rodão)

In Figure 14 a comparison can be found between a simulation and an injection using the on-line measurement technique. Due to limited time available during the interdiction it was not possible to obtain a more complete curve, however the measurement results which are available match well. Also it should be noted that the simulation does not exactly match the situation in which was measured, a large yard was coupled off during the measurements.

**Figure 14** Comparison between on-line measurement and simulation (Substation Fogueteiro)

**Discussion**

It is clear that all three measurement techniques give results which are in good agreement with the simulations, which gives confidence in the simulation tool used. An overview of the major advantages and disadvantages of the three measurement methods used can be found in table 2. As it can be seen on-line and off-line injection are normally most suited. In case of substations fed by 150 kV or 220 kV HV networks, off-line injection is the preferred method, as it is more easy than on-line injection and as the influence of the HV feeding network can be neglected in this case. In case of substations fed by 63 kV or if the influence of the short-circuit impedance of the feeding HV network can not be neglected (can be checked by simulation), on-line injection is the preferred method. Injection using the harmonics produced by rolling stock are normally not be preferred as the amount of information gathered is limited. The latter can be (partly) avoided by using rolling stock like FLIRT, however this solution is always very expensive and requires a large effort with respect to organisation needed, moreover due to different gauges it cannot be used in Portugal.
### Table 2 Overview of major advantages and disadvantages of various measurement techniques

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Harmonics injected by rolling stock | • Can in theory be used without interdiction  
• Simple  
• Limited measurement equipment needed  
• Effects of HV feeding network are taken into account | • Spectrum not fully covered  
• Can be problematic to arrange suitable rolling stock  
• Multiple interpretations possible (see Figure 3)  
• Results difficult to understand due to other interference sources  
• Interdiction needed in case other interference sources need to be excluded |
| Off-line injection               | • Relatively simple injection circuit  
• Operates at low voltage  
• Complete spectrum can be covered  
• Interpretation of results is easy | • Interdiction is needed  
• Effects of HV feeding network are not taken into account |
| On-line injection                | • Complete spectrum can be covered  
• Effects of HV feeding network are taken into account  
• Interpretation of results is easy | • Complex interdiction is needed  
• Complex injection circuit  
• Operates (partly) at High Voltage  
• Harmonics injected by HV network need to be filtered out |

**Conclusions**

Simulations can be used to predict the Eigen frequencies of railway lines. The combination of modelling the complete network with measurements on a small number of substations has proven to be very effective. When used in a homologation process, simulations can be used to support the process and reduce costs for measurements. It is possible to determine frequency ranges where no harmonics are allowed, prior to putting new rolling stock in service, as well as to study mitigating measures when problems do occur. Simulation results match well with measurement results.

**Acknowledgments**

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**References**


Author’s Biography

M.F.P (Maurice) Janssen studied Electrical Engineering at the Eindhoven University of Technology. Since 1998 he is employed as consultant by Movares (formerly Holland Railconsult) in Utrecht, the Netherlands. He has experience in EMC and earthing systems in the railway environment, as well as in simulation techniques and high voltage engineering.

P.G. (Paulo) Gonçalves studied Electrical Engineering at the Technical University of Lisbon. Since 1989 he is employed as a Signalling & EMC Engineer at CP (Portuguese Railways) and later in REFER (Portuguese Railway Infrastructure) in Lisbon, Portugal. Fields of interest are EMC and Traction-Power Supply Systems. Main areas of concern are the interaction between Traction-Power Supply, Signalling and Telecommunication Systems and rolling stock. Responsible for EMC Lab within REFER and projects in the area of Traction Return and Grounding for a.c. systems.

R.P. (Rui) Santo studied Electrical Engineering at the Technical University of Lisbon. Since 2006 he is employed as EMC engineer by REFER, the Portuguese railway infrastructure manager, Lisbon, Portugal. The fields of interest are traction-power supply systems and EMC. Main area of concern is the interaction between traction-power supply systems with signalling installations, as well as traction current return and grounding systems.

H.W.M. (Erwin) Smulders studied Electrical Engineering at the Eindhoven University of Technology. Since 1997 he is employed as senior consultant by Movares (formerly Holland Railconsult), Utrecht, The Netherlands. Fields of interest are Traction-Power Supply Systems and EMC. Main area of concern is the interaction between Traction-Power Supply Systems, Signalling and Telecommunication equipment, stray currents and step and touch voltages. Since 1999 involved in the design and analysis of Voltage Change Over Areas. Responsible for projects in The Netherlands, Ireland and Portugal. Member of Cenelec SC9XWGC1, responsible for drafting the EU standard on mutual interaction between a.c. and d.c. systems, Member of IEC/TC9/MT62236 responsible for maintenance of IEC standard IEC-62236-1/5, Member of IEC/TC9/WG62128 responsible for amendment of IEC standard IEC-62128-1.