EMC aspects of voltage changeover areas

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Abstract

The standard electric traction system In the Netherlands is 1500 V_{DC}. However, two major new lines use 25 kV_{AC}, and both run close to existing 1500 V_{DC} lines. Dutch railway infrastructure manager ProRail commissioned a study on the interference that the 25 kV systems will cause to its existing infrastructure. The study included the areas where the new lines are connected to the existing infrastructure, known as voltage changeover areas (VCOs). In many cases, the VCOs are not ideally sited for avoiding electromagnetic interference. A new design was required to avoid mutual interference. This paper focuses on the final design of the VCOs of the Betuweroute and compares simulations with measurements.

Introduction

Two new major railway lines were recently built in the Netherlands: the HSL-Zuid (high-speed passenger line into Belgium) and the Betuweroute (dedicated freight line between Rotterdam and Germany). These new lines use 25 kV_{AC}. Both AC lines run close to existing 1500 V_{DC} lines in many areas (Figure 1). The combination of two different types of traction supply system in close proximity results in a zone of mutual influence:

1. AC→DC: The 25 kV_{AC} system generates step and touch voltages in the existing 1500 V_{DC} infrastructure and may interfere with the signalling and telecommunication systems.
2. DC→AC: Stray currents from the 1500 V_{DC} system may influence the operation of 25 kV components, such as transformers.


1500 V_{DC} 25 kV_{AC}

Figure 1: *1500 V_{DC} track next to 25 kV_{AC} track (HSL-Zuid)*

The emphasis of this paper is on the first aspect – interference to DC systems. A research project was initiated by HSL-Zuid and Betuweroute and managed by the Dutch railway infrastructure manager ProRail. The aim was to study the interference of the 25 kV_{AC} systems on the existing ProRail infrastructure, which is mainly 1500 V_{DC}. The scope is not limited to regions where both types of traction system run in parallel; it also include regions where the new lines are connected to the existing infrastructure. Studies on safety and possible interference to signalling and telecommunication systems were carried out to guarantee the following:

1. Personal safety (no unacceptable step and touch voltages on tracks, touch voltages on cables, etc.).
2. Safe operation of safety-related systems, especially train-detection systems.
3. No negative influence on availability.

Comprehensive studies were conducted, on safety and the possible interference to signalling and telecommunication systems, taking into account the following aspects:

- The two traction supply systems have different earthing philosophies. The existing infrastructure is floating, to avoid stray DC currents, whereas the 25 kV_{AC} system is solidly earthed. As a result, a significant fraction of the AC return current will flow though the earth during normal operation. Part of this current may return via the tracks of the 1500 V_{DC} system.
- Electronic equipment is usually sensitive to interference over a wide range of frequencies, even at low amplitudes. The interference to secondary circuits (at 50 Hz and other frequencies) is difficult to predict in practice. These voltages are determined by the source (the 25 kV_{AC} system), the coupling mechanisms and path, and the layout of the sink. In turn, these parameters depend on local circumstances. Models for calculating such interference to cables and track circuits were found not to be suitable for most cases. Most calculations use a two-dimensional model to calculate current distribution and interference voltages. They divide the network into independent sections and use lumped circuit elements to represent the mutual coupling between the various conductors. These frequency-dependent circuit elements are often based on Carson equations. In

regions where the E field has a radial component (e.g. near a substation or at ends), the 2D models may not form an adequate basis for solving the 3D Maxwell equations. More complex calculations may be necessary. However, one often takes a 2D approach to obtain an indication of the current distribution [2]. Uncertainties in both input parameters and the mathematical approach may cause significant deviations between simulation and measurement results.

- In total, over 200 different types of ProRail system had to be analysed. Some types of system in the 1500 V_{DC} infrastructure have been in use for decades. Response to 50Hz interference was unknown in most cases. Furthermore, the calculated safety margin proved to be very small for some systems.
- It was necessary to take account of various failure modes in the 1500 V_{DC} and 25 kV_{AC} systems, both during normal operation and under short-circuit conditions.
- Modifications and the development and implementation of new systems result in significant lead-time and costs. ProRail works with a large number of subcontractors. Standard solutions were therefore sought, and studies were carried out to minimize the number of systems to be modified.

While other countries also use multiple traction supply system, few case studies are available. Furthermore, it was not possible to adopt measures taken in other countries on ProRail infrastructure, as other counties use different signalling systems or operating frequencies.

The ProRail project distinguished between areas where both systems run in parallel [1], and those where the new lines are connected to the existing infrastructure, the voltage changeover areas. Implementation of VCOs is difficult due to the limited amount of space available in the Dutch situation, and their location is not always conducive to avoiding electromagnetic interference. This aspect has to be reflected in VCO design, and a new design was required to minimize mutual interference. The present paper focuses on these design aspects and the influence of the 25 kV_{AC} system on the existing 1500 V_{DC} infrastructure. It is based on the locations: Vaanplein, the Sophiatunnel and Zevenaar (Figure 2).

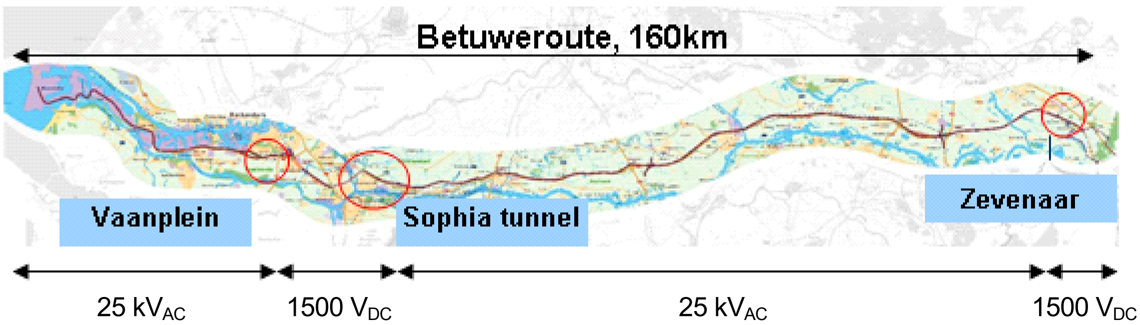

Figure 2: The Betuweroute, showing voltage changeover areas

The results of theoretical studies have already been published [3,4]. This paper presents:

- a description of the final design of the VCOs, discussing various design aspects;
- the most important parameters that determine the influence of the new 25 kV_{AC} system on existing infrastructure;
- measurement results and a comparison between measurements and simulations;
- analysis of the most important EMC aspects;
- an overview of practical measures taken in the existing infrastructure.

Final design of the voltage changeover area

The VCOs separate the AC traction power supply of the new lines from the DC power supply of the existing lines. The two systems have different earthing philosophies. The DC system is isolated from earth, to minimize stray currents, whereas the AC system is solidly earthed, to limit step and touch voltages. The separation of traction return currents is one of the most important design aspects. Typical characteristics of a VCO are as follows:

- On the Betuweroute, trains should be able to draw nominal traction power during most of the transition. The typical current per train is 500 A_{AC} or 4 kA_{DC}, and the short-circuit current is approx. 12 kA_{AC}.
- The zone where no traction is allowed should be as short as possible.

- Step and touch voltages should not exceed the limits of EN50122-1[5], either during normal operation or under short-circuit conditions.
- Leakage currents on both AC and DC sides should be as low as possible. At most VCOs, 75 Hz track circuits are located on adjacent 1500 V_{DC} lines and yards. Most of these are vulnerable to 50 Hz currents and expensive to modify or replace.
- Various failure modes have to be considered.

A single joint in the rails, exactly under the separation in the catenary, is not sufficient to achieve separation between the two supply systems (Figure 3).

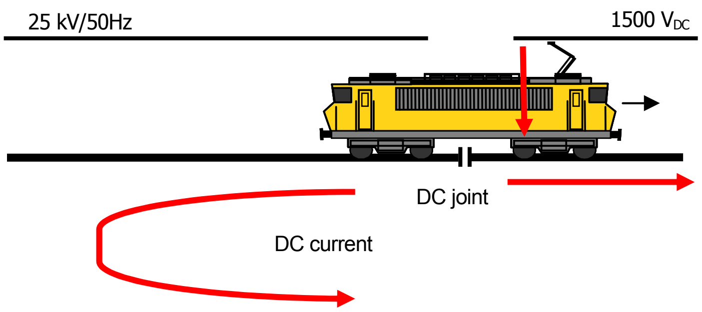

Figure 3: VCO with single joint. The train is moving in the direction of the DC system

Passing trains will bridge the joint and connect the AC and DC tracks via their wheels, bogies and underframes. A train passing from the AC to the DC side will inject a DC current into the AC rails as soon as the locomotive has passed the separation in the catenary and starts drawing power from the DC system. This current will continue to flow until the last vehicle has passed the joint. A similar effect occurs when a train passes from DC to AC. Transformers in the 25 kV_{AC} system might be damaged due to saturation of their cores.

There are several ways of preventing DC current entering the AC system:

1. Avoid the use of DC traction where the joint is bridged. This requires a much longer zone where no traction is allowed. This option is not acceptable on the Betuweroute, as the VCOs may be located where traction power is required.
2. Block DC current in the rails.

In view of the design rules and constraints, the second option was chosen. Because the resulting stray DC currents are of short duration, the corrosion effects may be acceptable.

In theory, resonant filters set to block 50 Hz currents could be used to reduce AC currents in the DC system [3]. In practice, this design has several disadvantages (transient behaviour, size and cost), with limited advantages. As the primary victims on the DC side are the signalling systems operating at 75 Hz, and as these are safety-related systems, a fail-safe situation must be created. All failure modes have to be taken into account. If a joint becomes defective, the resonant filters cease to function. This means that even if filters were to be installed, one would have to take into account the behaviour of the system without filters. Once this point had been studied it became apparent that the advantages did not outweigh the disadvantages. Filtering was therefore not used. The final design is shown in Figure 4.

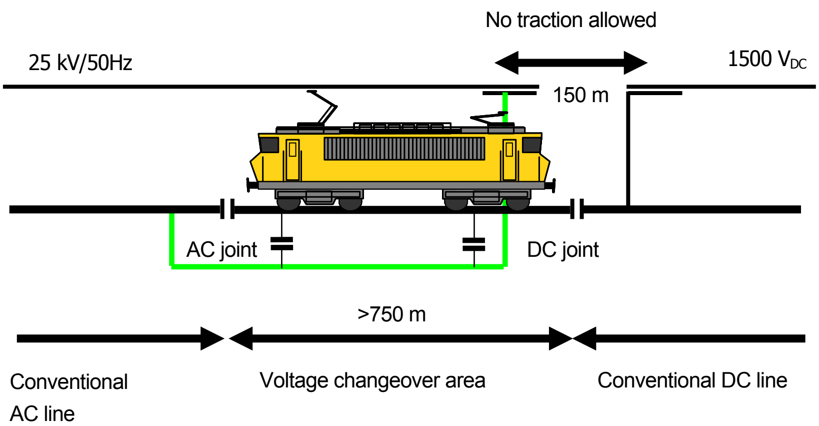

Figure 4: Final design of the voltage changeover area

There are two joints in the rails, at a distance greater than the maximum train length of 750 m. Two capacitor banks are installed in the VCO, between the tracks and the earthing system. The capacitors allow AC current to return, while blocking DC currents.
The driver must lower the pantograph while passing the separation in the catenary. On either side of this separation, there is a zone in which no traction is allowed. To prevent damage to the train and/or infrastructure, a second contact wire is added in parallel with the main one. This second contact wire is connected to the earthing system on the AC side and to the running rails on the DC side. If the driver fails to lower the pantograph, it touches the two parallel contact wires simultaneously, resulting in a short-circuit. As a result, traction power is switched off on both sides.

Influence on existing infrastructure

Given the final design, it is necessary to determine both the influence of the new system on the existing infrastructure and the measures required. Figure 5 shows the characteristic parameters.

1. The 50 Hz rail potential (V_{CM}) at the DC joint.
2. Total 50 Hz leakage current trough the tracks in the DC area (I_{CM}) at the DC joint.

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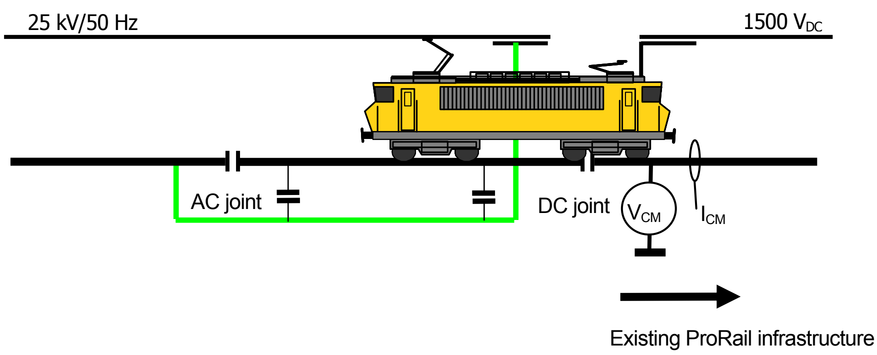

Figure 5: V_{CM} and I_{CM}: a train drawing AC power bridges the DC joint, inducing a voltage in the existing ProRail DC infrastructure

All other interfering voltages and currents in the existing infrastructure are derived from these parameters. The parameters V_{CM} and I_{CM} are determined by a number of aspects.

The *position* and *load current* of trains in the VCO/25 kV system: as the distance to the existing infrastructure increases, V_{CM} and I_{CM} decrease (Figure 6).

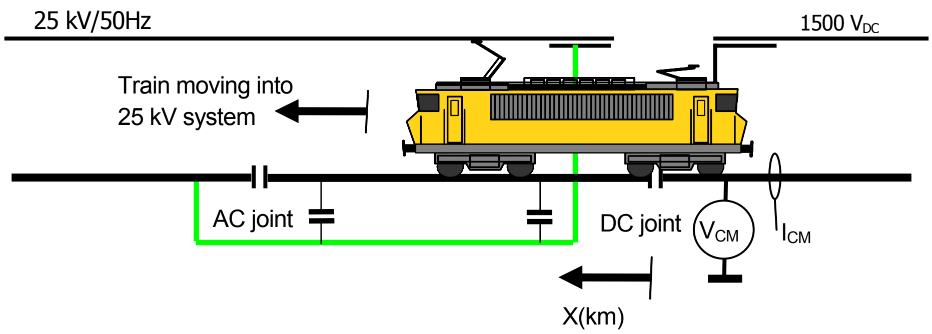

Figure 6: V_{CM} and I_{CM}: a train drawing AC power bridges the DC joint, inducing a voltage in the existing ProRail infrastructure

The *distance* between the signalling or other system under consideration and the DC joint. The AC current flows through the 1500 V system over a number of kilometres (Figure 7). Results of preliminary tests on this point have been published in [6].

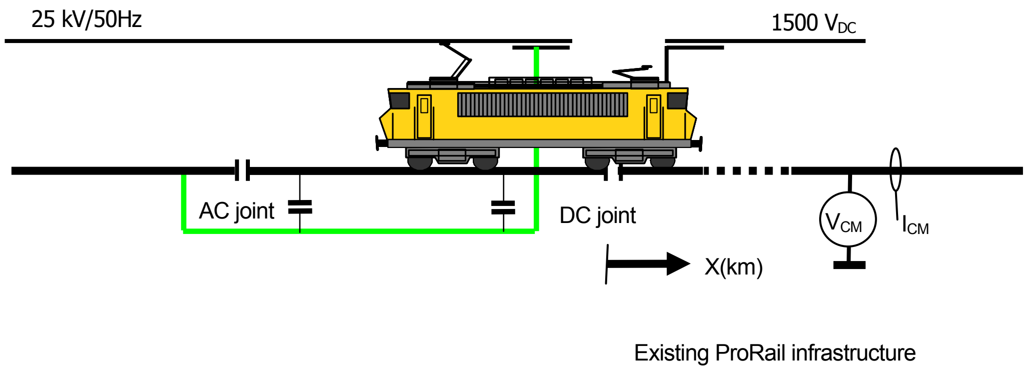

Figure 7: V_{CM} and I_{CM}: a train drawing AC power bridges the DC joint, inducing a voltage in the existing ProRail infrastructure

Failure modes: Various failure modes were considered, in both the 25 kV system and the existing DC infrastructure. The analyses included short-circuit conditions. System characteristics determine the most dominant failure mode, and differ for each system. In general, one of the most dominant effects is the loss of a capacitor bank (Figure 8). Under such conditions, I_{CM} and V_{CM} increase by approx. 50% compared with normal operation. Other failure modes were also analysed, such as a broken rail in a rail track circuit.

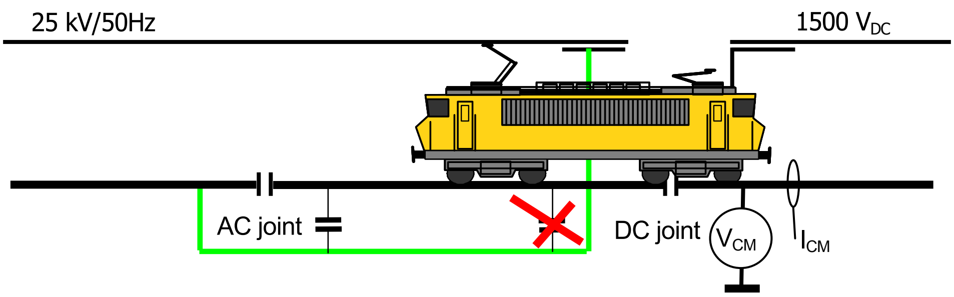

Figure 8: One of the most dominant failure modes is the loss of a capacitor bank

Given the final design, measures were determined for each location to avoid any negative influence on the existing infrastructure. The most important measures were:

- Replacing single-rail track circuits by double-rail track circuits.
- Applying special safety measures to personnel working in certain zones.
- Limiting maximum circuit length.
- Using fibre optic cables for telecommunication at certain locations.

Measurements

Correct prediction of interference voltages depends not only on a correct mathematical algorithm, but also on the reliability of the input parameters. One needs to have an exact overview of the as-built situation:

- The surrounding network has a great influence on the effect of interference. Any metal structure/cable in the soil near the substations will influence the current distribution, and the person making the predictions is often unaware of such structures and cables.
- Installation details, such as the way cables are installed, can have a significant influence on the interference voltages.
- In the case of structures with steel elements, such material parameters as magnetic permeability may play an important role at higher frequencies.

For some of the systems considered, the calculated safety margin was very small. During the final phase of the project, measurements were therefore carried out to verify the effects of the proposed measures.

An efficient test programme was required, given the limited amount of time available to prepare and perform the tests. Both test methods and measurement techniques played an important role. Several test methods were considered, of which three were used:

1. Tests with generators (Appendix 1): a 48 Hz current simulates the load current of a train in the 25 kV system. The influence is measured.
2. Short-circuit tests (Figure 9a): these types of tests give insight into non-linear phenomena (e.g. insulation defects and effects on overvoltage protection).
3. Tests with rolling stock (Figure 9b): this relatively inefficient method was used to test all aspects that could not be tested by either of the other two methods (traction harmonics, etc).

Methods 2 and 3 include the effects of the EMI produced during switching operations.

Figure 9a: Short-circuit tests

Figure 9b: Rolling stock

Measurement results

Typical measured values of I_{CM} and V_{CM} for a train at the DC joint are 5% of the load/short-circuit current and 30-35 V/kA during normal operation. The exact values depend on local parameters. In general, tests confirm an almost linear relation between the load/short circuit current and these parameters. Figures 10a and 10b show:

a) The measured values of V_{CM} and I_{CM} at the DC joint as a function of train position (see also Figure 6). The train is moving in the direction of the 25 kV system. The values measured are connected by straight lines. Additional analysis is performed to obtain more detailed information.

b) The measured values of V_{CM} and I_{CM} as a function of distance to the DC joint, with the train position fixed at the DC joint (see also Figure 7). The sum of all currents is shown; the exact current per track depends on local parameters.

Both parameters depend on the conductance of the tracks to earth, which is closely related to weather conditions. To calibrate the model, this parameter was measured each day at a number of locations.

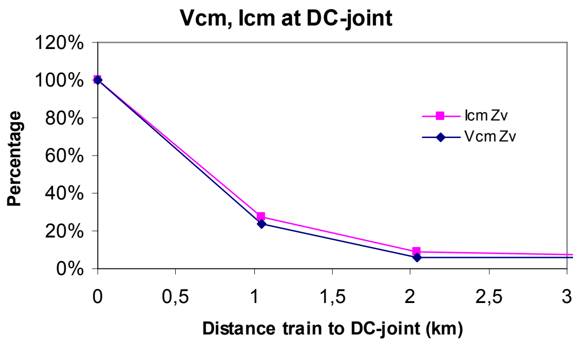

Figure 10a: Rail potential and leakage current into the DC tracks when the train moves from the DC joint

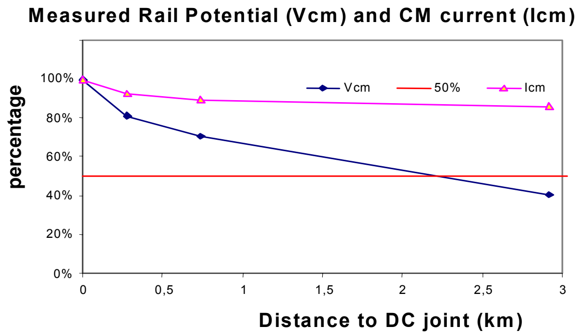

Figure 10b: Rail potential (V_{cm}) and leakage current (I_{cm}) in the DC tracks. The train position is fixed at the DC joint

No negative influence was reported in the secondary circuits during switching operations.

Concluding remarks

The 25 kV_{AC} system is connected to the existing 1500 V_{DC} infrastructure at the voltage changeover areas. In the Netherlands, the locations of these areas are often not conducive to avoiding electromagnetic interference. A new design was required to avoid mutual interference between the two traction supply systems.

The paper demonstrates that the proposed design satisfies the EMC requirements of all the systems involved. It describes the design of VCOs of the Betuweroute and compares simulations with measurements. Most deviations between simulation and measurement are caused by deviations in the input parameters. The combination of a 2D model and selective measurements resulted in an optimal set of mitigating measures. The modifications have already been implemented, and the VCOs are now in full operation.

Acknowledgements

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Appendix 1: Measurement techniques

An efficient test programme was required, given the limited amount of time available to prepare and perform the tests. A generator setup was used to perform most of the test. This Appendix describes this system, which was built and operated by the Dutch power utility Nuon. A similar method had been used for earlier tests on the Nuon grid [7].

The maximum permissible signals in equipment such as track relays are small (a few hundred mA). To measure these signals, a current comparable to a load current was required in the 25 kV system.
Figure A1 gives a schematic overview of a typical feeding arrangement. The generator (Vb) is located at the substation and is connected to the 150 kV connection of the substation transformer. A connection between the catenary and the tracks is made in the 25 kV system, to simulate a train. The switch S is used to connect and disconnect the generator.

Before the system was designed, an estimate was made of the impedance at the traction transformer (Figure A2).

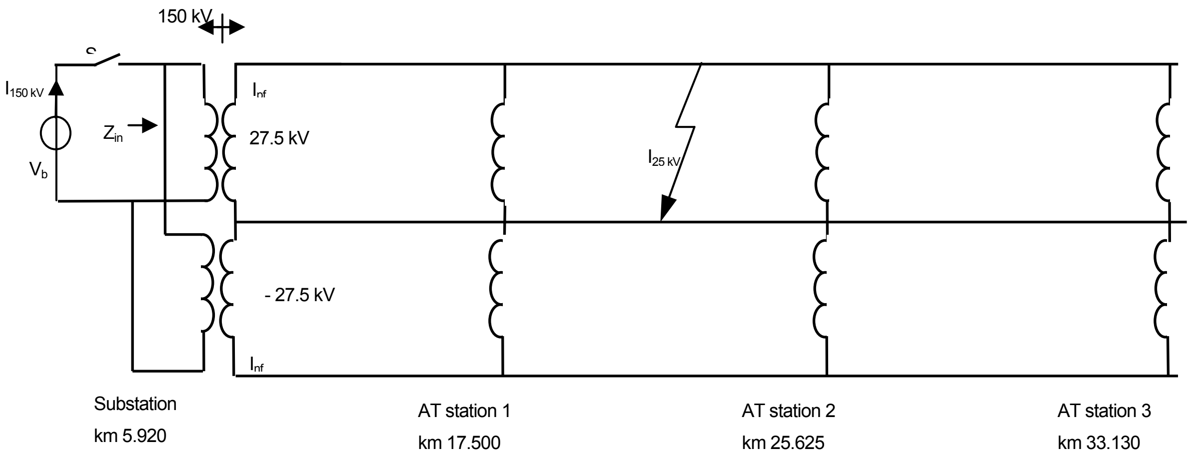

Figure A1: Schematic overview, typical feeding arrangement

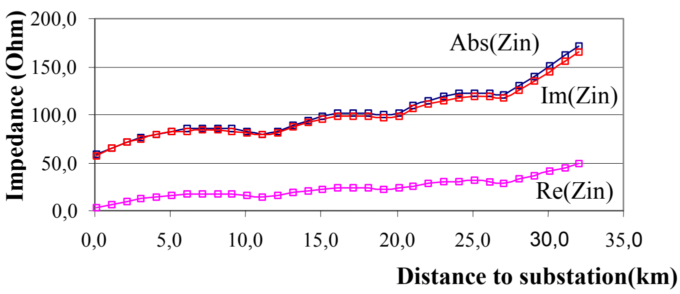

Figure A2: The train is replaced by a short circuit during the tests. This figure gives the estimated impedance Zin as a function of the short-circuit position. The AT-stations are located at a distance of 11.6, 19.7 and 27.3 kilometres from the substation.

Figure A3 gives further details of the generator setup. It consists of 400 V generators connected to two or three 400 V/10 kV transformers, of the type normally used in power grids. By connecting the transformers in series or in parallel, various different supply voltages can be obtained. The generator is connected to the LV side of the transformers.

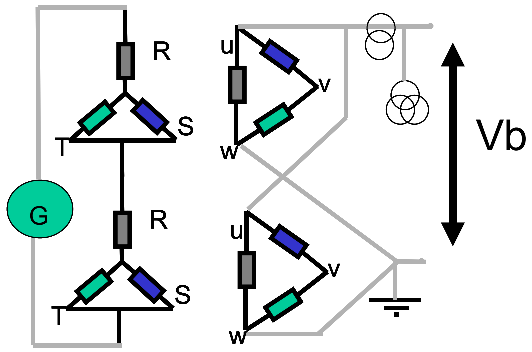

Figure A3: The 400V generators are connected to distribution transformers. The voltage V_b at the medium voltage side is connected to the substation transformers. This figure shows one of the configurations used.

Figure A4: The generator setup

This method has several advantages:

- Personal safety: the current in the 25 kV systems is limited to approximately 400 A and there is no risk of a 25 kV short-circuit current. The induced voltages in both traction supply systems are low.
- Efficient: a large number of configurations and the 50 Hz failure effect modes can be tested in a short period of time, to verify the 50 Hz model:
  - the time for start-up is relatively short;
  - compared to other test methods (such as the use of rolling stock), a relatively large number of configurations can be tested during one possession;
  - there is no risk of damage/insulation defects due to overvoltages since the current is limited, so no checks are required after the tests, which increases the time available for testing;
  - the setup is easy to operate with a limited number of personnel.
- Selective measurements: the operating frequency is 48 Hz (which gives minor deviations from 50 Hz), and the position of the “train” is well-known. MATLAB filters the 48 Hz component from the measurement signals.
- GPRS is used to transmit the measurement data during the tests. Analysis is performed on site.

Authors' biographies

Dr. J. B. M. (Jeroen) van Waes received his PhD in 2003 from Eindhoven University of Technology. His thesis was entitled *Safety and EMC aspects of grounding, experimental studies in high-power systems*. The research project was a co-operative venture with Dutch power utility Nuon. It involved detailed simulations and various full-scale field measurements on 150 kV, 10 kV and low voltage grids. For this project, Jeroen received the 2004 Hidde Nijlandprijs at Delft University of Technology. Since 2001, he has been a consultant/lead engineer at Movares (formerly Holland Railconsult) in Utrecht, the Netherlands. He is currently carrying out EMC projects on the HSL-Zuid and Betuweroute for ProRail, the Dutch railway infrastructure manager. These cover both studies and measurements related to 25 kV and 1500 V traction supply systems. His fields of interest include interaction between telecommunication, signalling and traction supply systems.

M. F. P. (Maurice) Janssen studied electrical engineering at Eindhoven University of Technology and has been with Movares since 1998. He has experience in EMC and earthing systems in the railway environment, along with simulation techniques and high voltage engineering.

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, Signaling 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.

J.P. (Jan) van Oostveen was born in Amstelveen, The Netherlands. He received his M. Sc. degree in 1993 from the Eindhoven University of Technology (TU/e). He started his career on the High Voltage Laboratory of NKF cable in Delft. Special objects of interest were high voltage cables with integrated optical fibres and cable terminations for factory prepared cables. He continued his career as a system engineer for high voltage cable systems (50-150 kV). Since 1999 he is working on the introduction of a 25 kV traction grid in the Netherlands. As a project manager, he started with the development of procedures and equipment for emergency services. Since 2001 he is as project manager for ProRail responsible for the EMC studies and tests for the interaction from a 25 kV traction system (Betuweroute and HSL-Zuid) on the existing ProRail railinfrastructure.