COMPANY MAIN TOPIC [PRODUCT]

MODELLING OF EARTHING AND RETURN CURRENT SYSTEMS

OF ELECTRIC RAILWAYS

English

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Modelling of earthing and return current systems of electric railways

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For a safe and sustainable railway system it is essential to comply with the limits for body and touch voltages as well as for stray current criteria according to EN 50122. A design of railway systems and stray current monitoring arrangements in compliance with the standard can be supported by computer-based modelling of earthing and return current systems.

MODELLIERUNG VON ERDUNGS- UND RÜCKLEITUNGSSYSTEMEN ELEKTRISCHER BAHNEN
Für ein sicheres und nachhaltiges Bahnsystem ist die Einhaltung der Grenzwerte für Körper- und Berührungsspannungen sowie streustromrelevanter Kriterien gemäß EN 50122 unentbehrlich. Eine normgerechte Auslegung der Bahnanlagen und Erarbeitung von Maßnahmen zur Streustromüberwachung kann durch computerbasierte Modellierung von Erdungs- und Rückleitungssystemen unterstützt werden.

MODÉLISATION DE SYSTÈMES DE MISE A LA TERRE ET DE CIRCUIT DE RETOUR POUR LIGNES ÉLECTRIFIÉES
Pour l’exploitation d’un système ferroviaire sûr et durable, il est indispensable de respecter les valeurs limites des tensions de contact ainsi que les critères relatifs aux courants de fuite conformément à la norme EN 50122. Une conception des installations ferroviaires et l’élaboration d’un système de contrôle des courants de fuite en conformité avec la norme peuvent être assistées par une modélisation informatisée de systèmes de mise à la terre et de circuit de retour.

1 Introduction

In electric railway systems the current flows from the substation via the contact line to the electric traction vehicle and back over the return circuit to the feeding substation. In both d.c. and a.c. railways the return circuit connection to earth is unavoidable due to ballast conductance of the running rails involved in the return current conduction. In addition, as a rule, in a.c. railways the return circuit receives intentional connections to the earth via the mast foundations and structure earth. In d.c. railways such connections are normally avoided, or realised by means of voltage limiting devices, if necessary. However, the return circuit is still not completely isolated from the earth.

Therefore, in a.c. railways and, to intentionally limited extend in d.c. railways as well, it is unavoidable that part of the return current enters the earth and flows back to the substation via it. Touch voltages are caused in the places where the current enters and exits the earth. If the permissible levels for touch voltages specified in EN 50122-1 [1] and EN 50122-3 [2] are exceeded, these voltages can lead to a hazard due to electric shock.

The earth portion of the return current in d.c. railways shall be considered as stray current. The stray current can cause corrosion with subsequent damage of metallic structures in the railway environment. Overheating, arcing and fire are further potential risks due to the stray current with potential subsequent danger to persons. EN 50122-2 [3] defines limits for the leakage conductance and average stray current per unit length of the track, as well as potential shift between structure and earth caused by the stray current. If these stray current criteria are met, the design of the return circuit is assumed to be acceptable.

Provision of evidence of compliance with the limits according to [1] and [3] purely by means of measurements is both elaborate and costly and is only possible after the railway system construction is completed. In addition, some verifications by means of measurements are infeasible, such as when metallic structures at risk of corrosion are not accessible for the potential measurement.

Using a computer model for earthing and return circuit systems of electric railways (ERS), the compliance with the limits can already be checked during the planning phase. Corrective measures can be planned at an early stage in the event of noncompliance. Verification by means of measurements after completion of the system can be carried out at a few select locations and extrapolated to other locations using the computer model. As a result, the costs for a comprehensive measuring program and, depending on the measurement results, for subsequent corrective measures on an already installed railway system, can be reduced.

2 Modelling approaches

2.1 Basic approaches

Two basic approaches for the field calculation of ERS arrangements can be distinguished.

1. Simplified modelling and calculation with analytically solved equations from classical electrical engineering theory for elementary body shapes, such as earthing rods or strips, or for common earthing arrangements, such as earthing grids. In the process, the field problem is limited to a static problem. Although the conventional commercially available programs [4; 5], which work according to this principle, enable quick calculation, they offer very limited flexibility in the modelling of geometries and boundary conditions. The complexity of the ERS arrangements that can be handled with such programs is thus very limited.
2. Breakdown of all geometric structures, including earth, into small elements with subsequent assembly and common solution of the *Maxwell equations* for all these partial elements. Experience [6] has shown that the field problem must be limited to a static one for the purpose of a reasonable computing effort in most calculation cases. This field calculation approach is addressed in chapter 2.2.

The innovative method presented in chapter 2.3 combines the benefits of the two aforementioned principles, whereby an optimal relationship between precision, flexibility and effort in modelling and calculation for ERS is achieved.

2.2 Finite Element Modelling

From a mathematical perspective the *Maxwell equations* represent a system of partial differential equations of the first order, which can be solved numerically, for instance with the *Finite Element Method* (FEM). With this method, the investigated space is broken down into small finite elements such as triangles, squares, quadrilaterals, tetrahedra or hexagons. Linear or quadratic form functions are placed within these elements in order to approximate the field quantities which are sought [7]. These form functions are used in the differential equation to be solved and solved together with the boundary and transition conditions.

An important component of each FEM algorithm is the grid generation, so-called *meshing*, over all geometric structures of the model. On the one hand, the grid resolution essentially determines the precision of the results. On the other hand, the number of grid elements coheres heavily with the number of unknown factors in the equation system to be solved and essentially influences the computing time and memory requirements.

High flexibility in the modelling is the most important benefit of the FEM-based program. However, this is achieved at the cost of high demands on computing and memory capacity, as well as the field-calculation-specific qualification of the user.

The studies [6] have shown that the FEM-based programs, such as [8] and [9] quickly reach their limits when applied to ERS. Due to the large spatial dimensions of the typical ERS of a track section and the high number of ERS elements to be modelled, the computing and memory capacity of a conventional office computer are quickly used up. Moreover, large dimensional differences of individual model objects, such as the earth body and a rod of the earthing grid, result in numerical problems in the *meshing* algorithm.

Simplified modelling of selected ERS elements, as described under point 1 in chapter 2.1, with subsequent incorporation of such models in the FEM model could mitigate the indicated problems, however, this is usually not possible in standard FEM programs. Furthermore, it is not possible to combine FEM models for underground ERS elements and resistance network models of the above-ground ERS elements into an overall model.

Thus far, there has been no standard FEM program for the modelling of complex spatially expanded ERS which can provide an acceptable result with a reasonable modelling and computing effort. Nonetheless, it is possible to compute simple earthing arrangements with available FEM software and use them as a basis for verification of the new computing methods.

2.3 Earthing Modelling Method (EMM)

2.3.1 Requirements

As indicated in chapters 2.1 and 2.2, there is currently a need for a modelling and computing method which would satisfy the following requirements.

3. The method should be applicable for railway-specific, spatially expanded ERS consisting of numerous individual elements located some of them above and other below ground.
4. The method should model underground conductors of complex geometry with sufficient precision.
5. Above-ground ERS conductors with connections to underground ERS elements, such as return current wires and running rails with connections to mast foundations, influence the distribution of the earth current and therefore should be considered in the model by their resistances.
6. The considerable differences arising in railway applications between the dimensions of the underground conductors and the modelled track section should not result in any numerical problems for the method.
7. Computed sections of several hundred metres in length should be manageable with a conventional office computer. The computing effort should be optimised.
8. In order to achieve the optimal computing effort, the user should have as much control as possible

over the modelling process, even without an in-depth knowledge of numerical field calculation theory and programming.

The Earthing Modelling Method (EMM) [10] developed by Balfour Beatty Rail meets these requirements and combines the benefits of numerical field calculation methods with those of simplified analytical modelling.

2.3.2 Assumptions and simplifications

Assumptions and simplifications are made in the EMM which make the modelling and calculating considerably easier without significantly distorting the results.

The earth is homogeneous and isotropic with permittivity of $\varepsilon = \varepsilon_0$ and specific electrical conductivity of γ_E. The boundary surface between the earth medium and the air medium is flat.

Conducting objects in the earth, meaning constructions, or parts of constructions which are directly involved in the distribution of the earth current are made of metal and have a specific electrical conductivity $\gamma_M >> \gamma_E$. Therefore, the assumption $\gamma_M = \infty$ is made in the EMM. Thanks to this assumption, the model consideration of the metal objects in the earth can be reduced from their volumes to their equipotential surfaces.

2.3.3 Physical principle

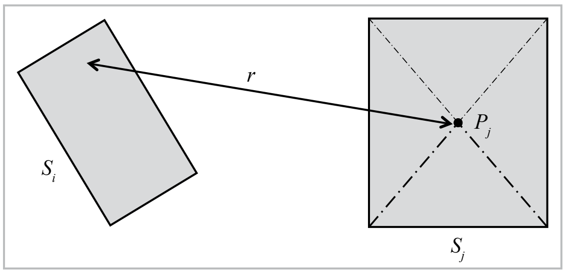
With the equations for the electrostatic field, electric potentials and electrical charges of objects are linked together, whereas potentials and leakage currents of objects can be linked together with equations for electric flow field. The analogy between the field types allows obtaining the equations for the flow field from the equations of the electrostatics by means of the following substitutions

$$C \rightarrow \frac{1}{R_E}; \quad Q \rightarrow I_E; \quad \varepsilon \rightarrow \gamma \tag{1}$$

with C, Q and ε as capacity, charge and permittivity in the equations for the electrostatic field, and R_E, I_E and γ as earthing resistance, leakage current and specific conductivity of the earth in the equations for the electric flow field.

Therefore, the following considerations are made for the electrostatic field first. Then the substitutions (1) are made and the calculations are carried out for the flow field.

A system of overall n conductive surfaces $S_1 \ldots S_n$ with charges $Q_{1 \ldots} Q_n$ and potentials $U_{1 \ldots} U_n$ is considered, wherein potentials and charges are linked over the matrix equation



$$|U|_{n\times 1} = |\alpha|_{n\times n} \cdot |Q|_{n\times 1} \tag{2}$$

with $|\alpha|$ as a matrix of the coefficients of potential α_{ji}, with $i = 1 \ldots n$ and $j = 1 \ldots n$.

Each coefficient of potential α_{ji} for $i \neq j$ can be approximated as

$$\alpha_{ji} = \alpha_{ij} \approx \frac{1}{4\pi\varepsilon S_i} \int_{S_i} \frac{\mathrm{d}S_i}{r} \tag{3}$$

with r as the distance from each point on the surface S_i to the geometric centre P_j of the surface S_j, (Figure 1). The approximation (3) becomes more exact as the dimensions of S_i and S_j become smaller in comparison to r

The following equation applies for the coefficients of self-potential α_{ii}

$$\alpha_{ii} = \frac{1}{4\pi\varepsilon S_i^2} \int_{S_i} \mathrm{d}S_i' \int_{S_i} \frac{\mathrm{d}S_i}{r}\,. \tag{4}$$

For the special case of flat rectangular surfaces S_i and S_j in the three-dimensional space, analytical solutions could be found for (3) and (4); see also [11].

For a system of surfaces $S_1 \ldots S_n$ in a conductive medium, such as in earth, (2) migrates into an equation system for electric flow field, that is to say for leakage currents $I_1 \ldots I_n$ of the surfaces and their voltages

$$|U|_{n\times 1} = |\alpha'|_{n\times n} \cdot |I|_{n\times 1}\,. \tag{5}$$

The elements α'_{ij} of the matrix $|\alpha'|$ are calculated according to (3) and (4) with performance of substitutions (1).

If the entirety of surfaces $S_1 \ldots S_n$ forms the surface of a metallic earth electrode to which the potential U_E is applied, the leakage current of the earth electrode I_E can be calculated as the sum of the leakage currents of individual surfaces from (5):

$$I_E = |1|_{1\times n} \cdot |I|_{n\times 1} = |1|_{1\times n} \cdot |\alpha'|_{n\times n}^{-1} \cdot |1|_{n\times 1} \cdot U_E \tag{6}$$

2.3.4 Modelling process

The modelling process for an ERS is implemented using *MATLAB®* and consists of the following steps:

9 Identification of all conductive objects of an earthing system having their surfaces in contact with the earth

10 Breakdown of the objects under step 1 into rectangular partial surfaces, as shown in Figure 2 on the example of the piling pipe foundations of two masts, and creation of a database with coordinates and dimensions of all these partial surfaces

11 Reflection of partial surfaces from step 2 above the earth surface for consideration of the field boundary conditions on the earth/air boundary surface

12 Formation of the matrix equation (5) and calculation of coefficients α'_{ij} according to (3), (4) and (1) from the coordinates and dimensions of individual partial surfaces from steps 2 and 3
13 Formation of the boundary conditions equations for currents and voltages of the objects:
  – Equalisation of the potentials of all partial surfaces belonging to the same object
  – Assignment of current or voltage values to selected objects
  – Formation of node equations for the linkage of currents and voltages of all objects which are interconnected with resistive elements of the return current circuit
14 Common solution of the equations under steps 4 and 5
15 Summation of currents of individual partial surfaces by object for all objects identified under step 1 and output of the calculated voltages and leakage currents of the objects
16 If necessary, calculation of potentials at the selected points of the earth surface using the coefficients of potential analogously to (3), (1)

In step 2 the user determines the modelling precision and thus the computing effort by defining the fineness of the breakdown of object surfaces into partial surfaces.

The computing effort can be further optimised with omission of the surface breakdown for selected rod-shaped conductors. Coefficients of potential for these conductors can be determined on the basis of classical equations from the theory of the electrostatic field with incorporation of (1). As a result, the dimension of (5) can be reduced. This procedural approach can be particularly beneficial for ERS containing earth grids made of rod-shaped conductors.

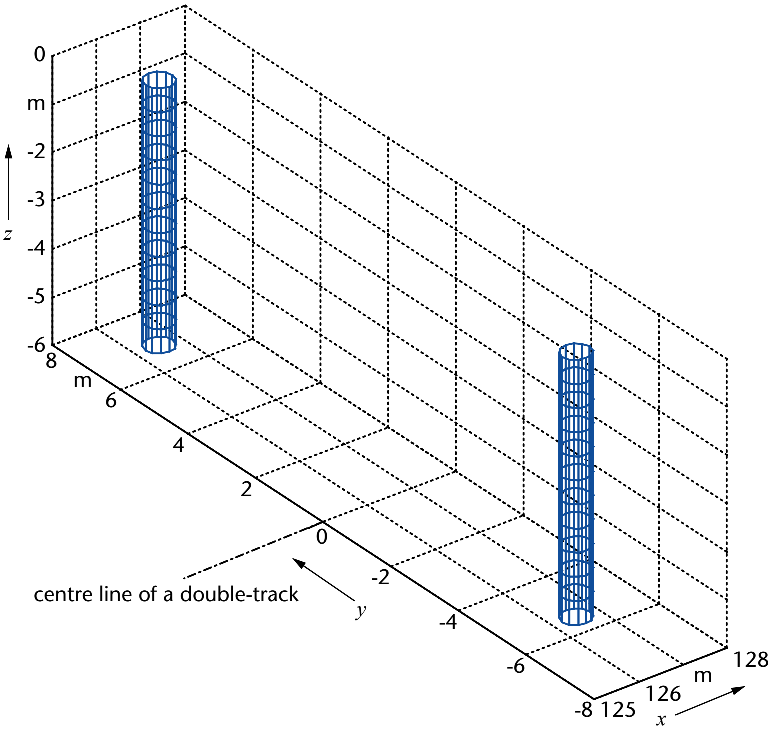


Figure 2:
Modelling of piling pipe foundations of masts in EMM.

Balfour Beatty Rail has issued a Declaration of Conformity for the EMM [14] on the basis of the validation results.

Conventional office computers were used for both the EMM- and *Maxwell*-based calculations. The major advantage of the EMM in regard to the computing effort was clearly recognisable in time needed for computing, which was a matter of minutes for the EMM and a matter of hours for *Maxwell*.

3 Validation

Since validation of the EMM by measurement is very problematic and elaborate, the validation was performed on the basis of a comparison with *ANSYS® Maxwell®* [8]. Balfour Beatty Rail defined several models which could be handled with a reasonable computing effort in *Maxwell* and calculated them using the EMM. The same models were then calculated by the Electric Railway Systems Professorship of TU Dresden using *Maxwell* [12]. The validation report [13] shows a good match of the calculation results from the EMM and *Maxwell*. The deviations were <2 % for the calculated earthing resistances and <7 % for the stray current flow. It should be emphasised that both the FEM method on which *Maxwell* is based and the EMM, as numerical field calculation methods, do not provide physically exact results as a basic principle. However, with a good model and good data quality a good approximation can be achieved.

4 Application

The EMM was used for the first time in the new line construction project VDE 8.1 Ebensfeld – Erfurt, sections 3100 and 3200, with a total length of about 44 km. Balfour Beatty Rail was commissioned with planning services by IVV Ingenieurgesellschaft für Verkehrsplanung und Verkehrssicherung GmbH. The scope included computer verification of the adherence to the values defined in [1] for touch voltages in these sections. The verification was required in the scope of the application for the EC testing process, module SG – Evaluation of the energy subsystem.

Using the EMM, models for the ERS at select track locations were created and the touch voltages were calculated for normal operation and for short-circuit cases. Figure 3 shows the calculated distribution of the earth surface potential for the case of a short-circuit due to flashover of an insulator on the mast. The potential distribution in the region of the affected mast

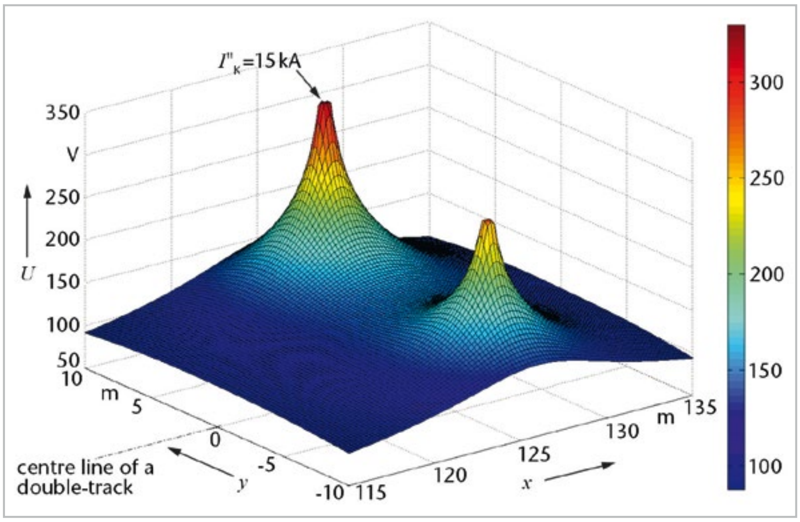


Figure 3:
Distribution of the earth surface potential in case of short-circuit calculated with EMM.

of the first track and the opposite mast on the second track at the same support point location is shown.

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