Modelling Electromagnetic Fields Propagated from an AC Electrified Railway Using TLM

Ade Ogunsola, Ugo Reggiani, Leonardo Sandrolini

Abstract—This paper provides an application of the transmission-line modelling (TLM) method to the calculation of the electromagnetic field from an ac-electrified railway. The complexity of such environment requires proper management and understanding of the electromagnetic interference (EMI) that may jeopardize the safety and operational integrity of the railway system, leading to the application of modelling methods to support measurements. The presented model, although simplified, can assist the designer of wayside installations to evaluate the compatibility of the whole system with applicable norms, standards and regulations.

Key words: AC Electrified Railway, Signalling, Electromagnetic Field, Electromagnetic Interference, TLM.

I. INTRODUCTION

There are many practical instances when one is interested in the electromagnetic field propagated from an electrified railway as well as the distribution of leakage currents due to train movement. An understanding of these issues is important in the estimation of the EMI risk to sensitive signalling and telecommunication circuits which are to be installed wayside. The dynamics of railway operations and upgrades implies the need to assure the design and equipment performance with respect to signaling compatibility prior to any wayside trail and installation. Cable management systems have to be designed taking into consideration the potential coupling from the electrified railway and the need to install signaling and control services close the railway track.

An ac-electrified railway is a complex distributed system consisting of long lengths of parallel conductors. The catenary — rail/ground configuration can be represented as two coupled transmission lines. In such a system, energy transfer takes place through the surrounding electric and magnetic fields, which are perpendicular to the railway line direction. The primary line distributed components are the self and mutual impedance and admittance.

This paper provides an example of the application of TLM to predict the electromagnetic field near an ac-electrified line. Results are presented and discussed for a 10 km railway line.

II. EMI MODELLING IN TRACTION SYSTEMS

A. EMI in traction systems

An electrified railway is an environment that contains several sources and victims of EMI and where the risk of electromagnetic compatibility (EMC) issues is particularly high because of all the mixing of power, information and communication signals in space, time and frequency [1]. Furthermore, the risk is aggravated as electromagnetic energy couples between source and victim systems by all means; as conducted as well as radiated coupling mechanisms can be present at the same time [2]. The main EMI sources can be electric substations (either dc or ac), the traction line and rails (for the arcs between line and pantograph or between contact shoes; moreover, the traction return current creates unbalanced magnetic fields), the rolling stock (power electronic converters generate high-frequency currents and voltages), and signalling systems.

On the other side, the main victims of EMI in an electrified railway can be catenary and running rails, traction drives (rectifiers, choppers, inverters), signalling systems (track circuit receivers, electromechanical relays). In such a complex environment, EMI can be classified as:

- Internal, viz., from the traction power supply and drives to the signalling system;
- Inward, viz., from power lines or radio frequency interference to railway communication and safety signalling systems; and
- Outward, viz., from the railway to external installations.

The complexity of the environment requires proper management and understanding of the EMI that may compromise the safety and operational integrity of the railway infrastructure. The analysis of all possible failures due to EMI, under normal or abnormal operation, leads to the application of modelling methods to support the measurement efforts. Simulation-based techniques are also needed to evaluate the compatibility of the whole system with the applicable norms, standards and regulations.

B. EMI Modelling

In general, to identify how EMI propagates in traction systems requires modelling of the following elements: distribution of the traction return current, tracks, track circuits, substations, and traction equipment (rectifier, de link, inverter, induction motor). The traction line can be suitably represented with a multiconductor transmission line (MTL) model. To analyse such model, the per-unit-length parameters of inductance, capacitance, resistance and conductance for the given line must be determined. Traditionally, Carson’s theory has been applied to calculate the per-unit-length inductance and...
resistance, whereas image theory is usually adopted to determine the capacitance; the conductance is determined from the experience and standard average values. However, the chosen parameters may result in inaccuracies, as they can be frequency- or geometry-dependent, nonlinear and dependent on earth characteristics. The MTL model would indeed benefit from the use of numerical methods such as the finite element method (FEM) to determine the electrical parameters of the traction line, although environmental conditions may affect their values.

III. NUMERICAL MODELLING USING TLM

The application of analytical methods to evaluating the electromagnetic problem described in the previous Section becomes limited as the complexity of the railway configuration increases. There are numerous numerical methods that can be applied to compute the electromagnetic problem described previously, however the degree of accuracy will depend on the method employed, the assumptions made and the accuracy of the model employed. The benefit of using numerical methods is the ability to compute the inductive and conductive coupling to nearby buried metallic conductors as well as the electromagnetic field in three dimensions. This is of particular importance during the design and installation of re-signalling works and/or the location of other services wayside to the track.

Numerical modelling is concerned with the representation of physical systems by specific quantities, which are obtained by numerical methods. For electromagnetic systems, it is generally required to obtain the electric and magnetic fields within a volume of space, subject to appropriate boundary conditions.

A. TLM and Railway Modelling

The common form of coupling in a railway signalling environment is inductive and conductive coupling. Capacitive coupling is deemed to be negligible. It is typical to analyse this coupling (inductive and conductive) mechanism using discrete lumped circuit components, which are estimated by means of practical EMC measurements [3]. The structure of TLM with its emphasis on field description in terms of transmission lines is a natural choice for incorporating models of circuits and cables, and thus is ideal for studying, in a unified manner, coupled field and circuit problems within a railway environment. Calculating the inductively and conductively coupled currents and potentials in buried metallic structures in the vicinity of a railway line can be viewed as an electromagnetic field problem.

The electric and magnetic fields in the ground originating from the currents in the railway installation are the source of these coupled currents and potentials. The magnetic field will be present along the whole length of the railway line, while the electric field caused by leakage currents from the rails is connected to the current transfer zones.

The current distribution in the traction current return path of an ac-electrified railway is a quasi-stationary problem. This is a three dimensional problem since the electric field potential will vary in all three dimensions. The railway system can be described as a coupled multiconductor transmission line; such a model must include the running rails, the overhead line and signalling/telecommunication cables (and parallel electric power rails and cables for dc traction system).

B. Railway Model

A 10 km railway line was chosen as the test case. The railway line was modelled as a simple railway configuration in which the current return path is the running rails [4]. The load (train) is modelled as a current source located arbitrarily along the line. The actual load condition is achieved by controlling the catenary current, which was set to 300 A for normal operation, a representative value for mainline service in the UK.

In TLM only the dimensions and material properties of the railway are required. The physical dimensions and material electrical and magnetic properties of the conductors as used in TLM are shown in Table I.

<table>
<thead>
<tr>
<th>Property</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tramway</td>
</tr>
<tr>
<td>Conductor outer radius (mm)</td>
<td>48</td>
</tr>
<tr>
<td>Conductors inner radius (mm)</td>
<td>0</td>
</tr>
<tr>
<td>Conductivity (S/m)</td>
<td>5.62x10⁹</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>1</td>
</tr>
</tbody>
</table>

The rails are modeled as two separate conductors bonded together at each end of the track. In real railway installations, the tracks will be regularly bonded – by impedance bonds – to ensure an even distribution of the traction current between the rails. In the model, impedance bonds are replaced with simple copper connections between the rails. For simplicity, the radius of the other conductors is assumed identical to the equivalent radius of the rail. In the model, only the catenary is modeled. Booster transformers are not included even though in reality these would be installed every 3 – 5 km along the line. The running rails and catenary are modelled as solid cylindrical conductors of section $A_{\text{rail}}$ having an equivalent radius

$$ r_{eq} = \sqrt{A_{\text{rail}} / \pi} \quad (1) $$

The feeder station is modelled as 25 kV voltage source with appropriate line impedance to provide the desired catenary current of 300 A at 50 Hz. Figs. 1(a) and 1(b) illustrates two basic models of the railway.

C. TLM Model Parameters

The numerical accuracy obtained from TLM is determined by the model parameters and simulation time. Increased accuracy is achievable but at the expense of increased computational time. In the simulation, an absorbing boundary condi-
tion was used for all sides except the ground, whose behaviour was modelled with an electric wall. The maximum and minimum cell size were 10,000 mm and 48 mm, respectively. The total number of cells for the basic model was 2,612,688 and the total number of timesteps was 27,439 million. The simulation was performed on a 4 GB RAM, dual AMD K6 processor computer running 64 bit Windows OS. The CPU run time was 38 hours for a maximum frequency of 1 kHz, although the CPU run time increased to over 80 hours with increasing model complexity.

IV. RESULTS AND DISCUSSION

The basic model parameters were adjusted until the line current at the fundamental frequency was as close to 300 A as reasonably possible. An impulse excitation from dc to 1 kHz was used to introduce energy into the model; convolution was then used to obtain the response of the model to a current sinusoidal waveform having equation $A \sin(2\pi f t)$, with $A = 2.25$ A and $f = 50$ Hz. The amplitude of the convoluted sinusoidal waveform was chosen to obtain the desired catenary current.

Fig. 2 shows the line current amplitude of the model in the frequency domain, while Fig. 3 illustrates the convoluted catenary current in the time domain. As shown in Fig. 4, the catenary current and the continuous rail current are both equal (i.e. the amplitude of the current is approximately 300A).

Figs. 4 and 5 show the rail surface current distribution obtained for the basic railway models (as shown in Figs. 1(a) and 1(b)). As can be seen, the continuous rail current is approximately 300 A as is the catenary current. The signal rail current is low as a result of the section gap included in the basic model. The basic railway model with a train modelled as a 1 A current source located 0.1 km from the section gap was simulated. In this case, the rail current distributed equally, flowing through both running rails from the train location back to the substation. The model predicts that the magnetic field propagating in the railway line direction could be as high as 230 A/m at a distance of approximately 1.8 m from the signal rail.

It is desirable to predict the electromagnetic field along a railway line with respect to a moving train. There is no way of implementing this within Microstripes™, the commercial software used, however it is possible to provide a quasi-static response by manually changing the load position within the model and re-running the simulation. Fig. 6 shows the current distribution and magnetic field with the load moved 0.6 km forward. In Fig. 6, the load was positioned at a location slightly ahead of the rail gap, as obtained from the simulation the current return path to the substation is via the continuous rail. In this scenario, the magnetic field is generated via the substation- catenary wire – load - section of the continuous rail. As discussed in Section II, the determination of interference effects in a typical railway right-of-way is a complex mathematical problem requiring knowledge of the physical and electrical parameters of the system space including a good representation of the soil structure. Potential impact of induc-
tive interference to buried metallic conductor is one of potential damage/mal-operation of equipment, and may result in injury or loss of life. It is desirable to use numerical tools such as TLM to assess the impact of right of way, the robustness of a cable layout (and cable management system) and the impact of induced fields on nearby buried metallic services including signalling and communication cables. This is particularly important as signalling and communication cables tend to be installed very close to the track.

Fig. 4: Current distribution (at 50 Hz) of basic railway model

Fig. 5: Current distribution (at 50 Hz) of basic railway model with a train in section

Fig. 7 shows the magnetic field due to the railway at an observation point some distance away. From the figure, magnetic field amplitudes between 20–26 A/m at a distance of 1 m from the track are predicted. Care must be taken in the interpretation of this result since the model is an over simplification of the problem. However, the model does give an indication of the severity of the magnetic field as a function of separation distance between the railway and the observation point; for example, at a distance of about 2m from the rail, a magnetic field amplitude of 6.5–13 A/m is likely to be observed.

V. CONCLUSION

The electromagnetic field from a simple railway model has been evaluated with a three dimensional TLM code. The simplicity of the model implies that detailed evaluation of the electromagnetic coupling is not possible, however the simple model is useful as a first approximation of the electromagnetic field in the vicinity of the railway and thus can be used to assist in the design of wayside installations.

REFERENCES