Development of a Lightning Surge Calculation Model for Level Crossing Signalling Equipment

Hideki ARAI, Ph.D.
Senior Researcher, Signalling Systems Laboratory, Signalling and Telecommunications Technology Division

Hiroyuki FUJITA
Researcher, Signalling Systems Laboratory, Signalling and Telecommunications Technology Division

Yuto ONO
Researcher, Signalling Systems Laboratory, Signalling and Telecommunications Technology Division

The development of the effective and economical lightning protection measures is very important for railway signalling systems because lightning damage causes railway transportation disruption. This paper proposes a calculation model for lightning overvoltages on railway level crossing equipment. The calculation model consists of a propagation model of lightning surge along the rails and an equivalent circuit model of equipment. The authors validated the calculation model by comparison with field test results. This model is applicable for quantitative estimation of lightning protection measures of railway signalling equipment.

Keywords: lightning overvoltage, calculation model, surge propagation, lightning protection measures, railway signalling equipment, level crossing

1. Introduction

Railway signalling systems have made remarkable progress in recent years with their components becoming increasingly compact and multi-functional due to the adoption of microcomputers and other electronic devices. However, lightning damage such as circuit burnout, system failure or malfunctions frequently affects railway signalling systems because of the vulnerability of electronic devices to lightning surges. Furthermore, railway signalling systems are generally located along the track forming a network through rail and cable connections. Consequently these systems are particularly vulnerable to lightning surges. Wide ranging problems arise because of lightning damage to railway signalling systems. As such cost effective and efficient countermeasures to prevent damage of this kind are important to avoid the social confusion resulting from cancelled and delayed trains.

Generally, trackside railway signalling systems are directly connected to the rails by means of cables. Rails can be a lightning surge entry point to the railway signalling system. Accordingly, clarifying the propagation characteristics of lightning surges along rails is essential the development of lightning protection measures for railway signalling systems.

The authors conducted field tests to investigate surge parameters along the rails [1, 2]. This paper proposes a calculation model for lightning surge propagation along the rails.

By way of example, this paper also proposes a calculation model for lightning overvoltages on railway level crossing systems. The latter model consists of a lightning surge propagation model along the rails and an equivalent circuit model of level crossing equipment. This paper describes the validation of the proposed calculation model by comparing its output values with the results of the field test. Moreover, this paper gives results from an evaluation of lightning protection effects by using the calculation model.

2. Surge propagation characteristics along the rails

2.1 Outline of field test section

Field experiments were carried out to measure rail surge impedance and surge propagation velocity along the rail which are key parameters to determine rail surge characteristics.

Three test sections with different ground resistivity were selected. All test sections were non-electrified and single track sections to reduce rail induced noise to a minimum which could otherwise influence measurements.

A cross section diagram of the test profile is shown in Fig. 1. The test track consisted of rails, wooden sleepers, ballasted rail bed, and track bed.

Test section conditions are shown in Table 1. Ground resistivity in Table 1 was measured utilizing the 4-electrode Wenner method. The field tests were performed in fine weather conditions when both the rail and rail bed were dry.

Fig. 1 Cross section diagram of the test profile

<table>
<thead>
<tr>
<th>Table 1 Conditions at test sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>
2.2 Measuring methods

Surge impedance and surge propagation velocity between the rail and the ground by measuring the injection current to the rail and the induced voltage on the rail when a steep-front current was injected into the rail. The outline of this measuring method is shown in Fig. 2.

The two measuring rails were insulated from adjacent rails by inserting insulated rail joints at both ends as shown in Fig. 2. A steep-front current generated by a pulse generator (PG) was injected into the sending end of a rail on one side (for example rail No. 1 in Fig. 2). Then, the injected current waveform (I), voltage waveform of rail No. 1 against the ground (V_m), and voltage waveform of rail No. 2 against the ground (V_m) were measured with an oscilloscope. The self-surge impedance of rail No. 1 (Z_{11}) and mutual surge impedance between rails No. 1 and No. 2 (Z_{21}) were calculated from measured waveforms.

The above-mentioned measurements were taken when the receiving end of the rail was both in open and short circuit position. The clear difference in reflection at the receiving end of the rail facilitated measurement of the surge’s round trip propagation time. The surge propagation velocity between rail No. 1 and the ground (c_1) was calculated from the round trip propagation time of the surge which was obtained with the measurement and the length of the test rail which was known.

Measurements similar to those described above were made applying a steep-front current injected into rail No. 2. The self-surge impedance of rail No. 2 (Z_{22}), mutual surge impedance between rails No. 2 and No. 1 (Z_{21}) and the surge propagation velocity between rail No. 2 and the ground (c_2) were calculated from measured waveforms.

2.3 Measuring results

By way of example, Fig. 3 illustrates the measured results obtained on test section B, described in Table 1.

Figure 3 shows waveforms of the injected current (I), the voltage of the injection rail against the ground (V_s), and the voltage of the induction rail against the ground (V_m) measured when a steep-front current was injected into rail No. 1.

The voltage waveforms of the injection rail (V_s) and the induction rail (V_m) in Fig. 3 are also shown for cases where the receiving end of the injection rail was either grounded or not.

From Fig. 3, the round trip propagation time of the surge in the rail, the self-surge impedance and the mutual surge impedance of the rail were calculated according to the method described below.

Table 2 shows the surge impedance matrix of the rail and the surge propagation velocities for the three test points. The mutual surge impedance of the rail for this period is defined as the voltage of the induction rail (V_m) dividing by injection current (I). In the same way, the mutual surge impedance of the rail No. 1 and the ground (V_m) measured when a steep-front current was injected into rail No. 1.

![Fig. 2 Outline of measuring surge parameters of rail](image)

![Fig. 3 Measured waveforms from test section B](image)
sections between the rail and the ground calculated by above-mentioned method.

As shown in Table 2, the surge impedance matrix is symmetrical and the surge propagation velocity against the ground for rails No. 1 and 2 is the same. The measured results are valid in consideration of the geometry of two rails shown in Fig. 1.

Table 2 illustrates that as ground resistivity increases surge impedance of the rail grows and the surge propagation velocity between the rail and the ground slows. Compared with an overhead line, the surge impedance of the rail is extremely low and the surge propagation velocity against the ground (S/m), G is the conductance (S/m), C is the capacitance (F/m), θ is the impedance phase angle (rad) and θ is the admittance phase angle (rad).

The calculated results of the four-terminal parameters (R, L, C and G) both between the rail and the ground and between rails are shown in Fig. 4, respectively. Figure 4 shows a sample of results obtained for test section C as described in Table 1.

As mentioned at section 2.3, rails are considered as a distributed line with extremely high leakage admittance, so we applied G and C to the calculation model.

Furthermore, G and C where it exists between the rail and the ground and between rails shown in Fig. 4 correspond to what would be expected in a circuit of the type shown in Fig. 5. We can calculate the true value of G and C, which exist between the rail and the ground from the measured values of G meas and C meas shown in Fig. 4 obtained with (5). In the same way, the true G and C values existing between the rails can be derived from the measured values G meas and C meas shown in Fig. 4 obtained with (5).

$$\Gamma(\omega) = \tan h^{-1}\sqrt{Z_s(\omega)/Z_o(\omega)/l}$$  \hspace{1cm} (2)

where $\Gamma$ is the propagation constant (1/m) and $l$ is the length of the rail (m).

$$Z(\omega) = Z_i(\omega) \cdot \Gamma(\omega) \hspace{1cm} Y(\omega) = \Gamma(\omega)/Z_i(\omega)$$  \hspace{1cm} (3)

where Z is the impedance ($\Omega$/m) and Y is the admittance (S/m).

$$R(\omega) = Z(\omega) \cdot \cos \theta \hspace{1cm} L_s(\omega) = Z(\omega) \cdot \sin \theta / \omega$$  \hspace{1cm} (4)

where $R$ is the resistance ($\Omega$/m), $L_s$ is the inductance (H/m), $C_s$ is the conductance (S/m), and $\theta_s$ is the admittance phase angle (rad).

3. Calculation model of lightning surge propagation along the rails

3.1 Distributed parameters of the rail

The calculation models for the lightning surge propagation along the rails were designed utilizing EMTP (Electro-Magnetic Transients Program) which enable reasonable prediction of the experiment results expressed in chapter 2.

The electric circuit, comprising a sending and receiving end of a rail as shown in Fig. 2, can be considered as a two-port circuit composed of distributed-parameter lines such as rails. Investigations were carried out using the frequency-dependent four-terminal parameters (resistance $R$, inductance $L$, conductance $G$ and capacitance $C$) of the rails and the ground to determine the distributed parameters to be adopted in the calculation model for measuring the open circuit impedance and the short circuit impedance through non-grounding or grounding at the receiving end of the rail, respectively. In the same way, we measured the open/short circuit impedances between rails.

The different phases, rail voltage and current were measured while a sine wave voltage of 1-100 kHz was dispatched from the sending end of the rail along the rail on one side and the ground or between rails.

The four-terminal parameters ($R$, $L$, $G$ and $C$) of the distributed line can be derived from (1)-(4). The open/short circuit impedances obtained with the above-mentioned method is input to (1) and (2).

$$Z(\omega) = \sqrt{Z_o(\omega) \cdot Z_i(\omega)}$$  \hspace{1cm} (1)

$$\omega = 2\pi f$$

Table 2  Surge impedance and surge propagation velocity of the rails

<table>
<thead>
<tr>
<th>Test section</th>
<th>Surge impedance ($\Omega$)</th>
<th>Surge propagation velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ($\rho=1,043\Omega \cdot m$)</td>
<td>(57 43) (43 56)</td>
<td>55</td>
</tr>
<tr>
<td>B ($\rho=534\Omega \cdot m$)</td>
<td>(45 28) (28 43)</td>
<td>70</td>
</tr>
<tr>
<td>C ($\rho=1,465\Omega \cdot m$)</td>
<td>(40 14) (14 38)</td>
<td>92</td>
</tr>
</tbody>
</table>

(* The two rails were the same)
\( G_{c,\text{meas}} \) is the measured value of conductance between the rail and the ground (S/m), \( G_{s,\text{meas}} \) is the measured value of conductance between rails (S/m), \( G_s \) is the capacitance between the rail and the ground (F/m), \( G_s \) is the capacitance between rails (F/m), \( C_{c,\text{meas}} \) is the measured value of capacitance between the rail and the ground (F/m) and \( C_{c,\text{meas}} \) is the measured value of capacitance between rails (F/m).

The calculation model for lightning surge propagation along the rail is shown in Fig. 6. As shown in Fig. 6, the model divides the rail into 8 lengths. The reason for so many sections is that if the number is too low, the admittance component of the rail is added as a concentrated constant in 1 place. On the other hand when number of partitions is too high, the model becomes impractical.

**Table 3 Geometric and electric properties of 50N rail**

<table>
<thead>
<tr>
<th>Items</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent cylindrical body radius</td>
<td>93.9 mm</td>
</tr>
<tr>
<td>Distance of between rails</td>
<td>1,067 mm</td>
</tr>
<tr>
<td>Placement height of rail</td>
<td>Surface of ground</td>
</tr>
<tr>
<td>Specific resistance</td>
<td>( 20.3 \times 10^6 ) ( \Omega \cdot m )</td>
</tr>
<tr>
<td>Relative magnetic permeability</td>
<td>70</td>
</tr>
</tbody>
</table>

**Table 4 Admittance applied to the model**

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>( G_s ) (( \mu )S/m)</th>
<th>( C_s ) (nF/m)</th>
<th>( G_c ) (( \mu )S/m)</th>
<th>( C_c ) (nF/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>117.46</td>
<td>0.31</td>
<td>8.67</td>
<td>0.08</td>
</tr>
</tbody>
</table>

3.3 Surge propagation analysis utilizing model calculations

We simulated the current and voltage characteristics of the rail when a steep-front current was injected into the sending end of the rail by using the calculation model shown in Fig. 6.

The calculated results obtained reproducing the experiment described in chapter 2 are shown in Fig. 7. Furthermore, at the time of analysis, the ground resistivity was 146 \( \Omega \cdot m \), i.e. the same as the condition of field tests on section C in Table 1.

On comparison of calculated results in Fig. 7 and experiment results in Fig. 8 obtained for test section C, the calculated results from the lightning surge propagation model shows a smaller current value flowing into the rail than the experimental result while the voltage waveform in both cases almost agree.

Surge impedance is however higher by the model calculation method than the experiment results, as shown in Table 5. On the other hand, the same Table 5 shows that model calculation of the surge propagation velocity is about 91 m/\( \mu \)s which is similar to the experiment results.
The fact that results for surge impedance and surge propagation velocity with the proposed calculation model and through experiments almost agree, demonstrates that the calculation model for lightning surge propagation along the rails is valid.

4. Calculation model for lightning overvoltages on a level crossing system

4.1 Equivalent circuit model of signalling equipment in a level crossing system

The equivalent circuit model can be estimated by measuring the input impedance of the equipment [4]. This paper describes how to estimate the equivalent circuit model.
of this type of signalling equipment such as, for example, electronic train detectors for level crossings. The electronic train detector is one of the most vulnerable pieces of equipment in Japan, in case of lightning.

In this present work, the input impedance between the terminals and frame case of the electronic train detector is measured and the parameters for an equivalent circuit model are estimated through least square approximation against the measured value. The parameters of equivalent circuit model at 100 kHz were applied, in the same way as the calculation model for surge propagation along the rails. For example, the measured result of the input impedance on the terminal of the electronic train detector, called “Rail (s) –”, is shown in Fig. 9. The calculated result of the equivalent circuit as shown in Fig. 10 is also shown in Fig. 9.

The equivalent circuit model related another terminal on the electronic train detector was estimated by the above mentioned same way.

The calculation model for lightning overvoltages on level crossing systems consists of the rail model above mentioned in chapter 3 plus the equivalent circuit model of the signalling equipment.

4.2 Field tests to confirm validity of the model

As shown in Fig. 11, a temporary installation of actual railway level crossing equipment was set up to reproducing typical trackside electronic signalling equipment in order to perform field lightning surge tests, and measure the lightning overvoltages on the level crossing equipment in case of a potential rise in the rail to validate the calculation model for lightning overvoltages on level crossing equipment [2]. A potential rise of the rail was caused by injecting a 1/100 µs lightning surge current of 3 A generated with an impulse generator (IG).

There are differences between natural lightning current and the generated current by IG. Natural lightning is considered to be an impressed current source. Field tests were therefore conducted ensuring that flashovers on the equipment would be avoided. Namely, a linear characteristic was assumed between the overvoltages on the equipment and the impressed current.

Field tests were conducted on test section C as shown in Table 1. At the time of analysis, the ground resistivity was 146 Ω·m, the same as in field tests on section C.

4.3 Comparison of the field test and calculation results

Figure 12 shows the comparison of the calculated results and the experimental results for lightning overvoltages after lightning surge current injection into the rail. The lightning overvoltage waveforms for both the “Rail (s) –” terminal connected to the injection rail and the terminal “Rail (s) +” connected to the induction rail are shown in Fig. 12, respectively. Figure 12 shows that the proposed model is almost correct because of the agreement with the experimental results. The wave front from the calculated result was especially similar to the experimental result.

Hence, the calculation model for lightning overvoltages on railway signalling equipment is valid and applicable to the development of lightning protection measures for the railway signalling systems.
Lightning protection measures were evaluated as shown in Fig. 13 by using the calculation model for lightning overvoltages on railway level crossing systems. The effects of lightning protection measures on the electronic train detector for level crossings shown in Fig. 13 were verified experimentally [5].

In the simulation to test the effect of lightning protection measures, lightning overvoltages on electronic train detector terminals in case of the lightning surge current injection into the rail were calculated as a parameter of the SPD (Surge protection device) grounding resistance. SPDs in Japan are still not grounded because stray current through grounding lines may cause interference with railway signalling equipment and because grounding effects have still not been confirmed. Figure 14 shows the simulation results.

At the time of analysis, a lightning surge current of 1/100 µs, 400 A was injected into the rail. The calculated results for conventional protective measures are also shown in Fig. 14.

Figure 14 illustrates that lightning overvoltages can be suppressed utilizing the proposed protection measures as the SPD grounding resistance falls. Applying the proposed measures with a grounding resistance of 20 Ω reduces lightning overvoltages on the electronic train detector by approximately 1/2 compared to conventional protective measures.

6. Conclusions

This paper described a calculation model for lightning surge propagation along rails and a calculation model for lightning overvoltages on a typical example of trackside signalling equipment, namely a level crossing system. Moreover, this paper described the evaluation results for the effectiveness of lightning protection using the calculation model.

The main conclusions are summarized as follows:
(1) The self-surge impedance between the rail and the ground is about 50 Ω, the mutual surge impedance between the rails is about 30 Ω, and the surge propagation velocity between the rail and the ground is about 70-90 m/µs. In general, the
14

The surge impedance of the rail is much smaller and the surge propagation velocity of the rail is much slower than over-head conductors.

(2) A proposal was made for a calculation model for lightning surge propagation along the rails. The calculations of surge impedance and surge propagation velocity utilizing the proposed model almost agree with experiment results.

(3) A calculation model was then proposed for lightning overvoltages on level crossing systems. The calculation model consists of a rail model and an equivalent circuit model of the signalling equipment. The calculation model is valid because results correspond with those of field tests. The calculation model is therefore applicable to lightning protection measure development for railway signalling systems.

(4) The calculation model was employed to evaluate the proposed lightning protection measures for railway level crossing systems. Simulation results for the proposed measures with a grounding resistance of 20 Ω demonstrated that the lightning overvoltages on the electronic train detector were cut by approximately 1/2 compared with conventional protection measures.

References


