Circuit Simulator for Prediction of Electromagnetic Induction up to Data Transmission Frequency in Railway Environment

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In the traction circuit, the feeding current causes inductive interference with metallic telecommunication lines. It is therefore necessary to reduce the influence of electromagnetic induction by the design using results of computer simulation. A circuit analysis program for the railway environment named ABTAC is available, although the calculation method is applicable only to low frequencies and conductors present in a structure are ignored. Nowadays, high speed data transmission systems by means of metallic telecommunication lines such as xDSL (Digital Subscriber Line) are being introduced and the frequencies used in these systems are higher than audio frequencies. Considering the electromagnetic screening effect of conductors in structures makes the prediction of electromagnetic induction more accurate. This study describes the development of a new circuit simulator. This tool will make it possible to take into account conductors in the structure and calculate voltage and current up to the data transmission frequency.

Keywords: inductive interference, electromagnetic screening, feeding system

1. Introduction

On electric railways, feeding voltage is applied and load current is flowing on the traction circuit. Then electrostatic induction and electromagnetic induction occur along the railway. The voltage and current induced by the phenomena causes inductive interferences with metallic telecommunication lines. When the induced voltage is high or the induced current is large, it leads to a deterioration in communication quality and an electric shock. Therefore, it is necessary to predict inductive interferences and reduce the influence of electromagnetic induction.

The circuit analysis program for the railway environment is called ABTAC and can calculate electromagnetic induction, however the calculation method is applicable only for a low frequency and conductors in structure are neglected. Nowadays, high speed data transmission systems by means of metallic telecommunication lines such as xDSL (Digital Subscriber Line) are being introduced and a higher frequency than the audio frequency is used by these systems. Considering the electromagnetic screening effect of conductors in a structure enables the prediction of electromagnetic induction to be more accurate.

This paper describes the development of a new circuit simulator. It can take conductors in a structure into account and can calculate voltage and current up to the data transmission frequency [1].

2. Electromagnetic induction in railway environment

2.1 Principle of electromagnetic induction in the railway environment

In the traction circuit, outward current flows through the contact wire and return current flows through the rail. If the return current is equal to the outward current, the magnetic field created by the alternating current will be cancelled, and the induced electromotive force will be low.

The rail is not grounded in Japanese feeding systems, but the rail return current leaks into the ground, and the magnetic field is not cancelled. For this reason, ground return current leads to inductive interferences along the railway as shown in Fig. 1.

![Fig. 1 Inductive interference along the railway](image)

2.2 Prediction and reduction of electromagnetic interferences

The circuit simulator named ABTAC was originally developed for the analysis of the complicated electrical behavior on AT (auto-transformer) feeding systems. The EMTP (Electro Magnetic Transients Program) and the SPICE...
are known examples of circuit simulators. ABTAC in particular, has a special function for calculating the current distribution depending on rail leakage conductance and train load location.

The acceptable value of induced voltages and currents is subject to limits set out in rules, such as the ITU-T Directives [2]. Thus, electromagnetic interferences must be predicted through simulation when installing and renewing telecommunication equipment, for example, on such occasions as the construction of a new railway. If the predicted induction level exceeds the acceptable value, it is necessary to reduce electromagnetic interference.

2.3 First improvement point of traditional simulators

Nowadays, in high speed data transmission systems such as xDSL, metallic telecommunication lines are used in addition to voice communication systems [3]. Therefore, it is possible for existing lines to utilize existing lines. A high frequency of about 1 MHz is used for the data transmission systems.

It is not possible however to predict the level of induced voltage and current at high frequencies using the ABTAC.

2.4 Second improvement point of traditional simulators

Electromagnetic screening is one of the ways to reduce the influence of electromagnetic induction. When a screening conductor is installed near the induced line, the induced current flows into the conductor. The current is called a screening current and it exerts a counter electromotive force on the line.

The cable includes a screening layer in the case of metallic telecommunication lines. When ground resistance of the screening layer of the cable is low, large screening currents flow into the screening layer and the influence of electromagnetic induction is small, as shown in Fig. 2.

Screening currents also flow into conductors in the structures, which reduces any influence [4, 5]. However, the screening effect of conductors in structures is disregarded or taken into account as only one equivalent conductor in an approximation model.

In addition, the quantity of induced voltage and current is estimated to be larger out of a margin for safety. As a result, countermeasures against electromagnetic induction based on predicted quantities are likely to be excessive.

3. Prediction of electromagnetic induction in the railway environment

3.1 Analysis method for railway environment

Leakage conductance values rise or fall depending on track surface conditions. The traction circuit component changes in accordance with train load location. Computer applications used in the railway environment must accommodate these features.

The rail on the ground is continuously grounded through leakage conductance. This means that the calculation model must be divided into many pieces and be large scale.

Therefore, computer aided circuit analysis is suitable for the prediction of electromagnetic induction in the railway environment. In ABTAC the nodal analysis approach of circuit analysis is used. In the new simulator a similar approach of circuit analysis is also used.

The circuit analysis consists of three steps. The first is electrical circuit modeling, the second is formulating simultaneous equations, and the third is solving the simultaneous equations.

3.2 Modeling of distributed constant lines

The traction circuit and the metallic telecommunication lines along the circuit are distributed constant lines whose voltage and current depend on location. The modeling method of the system divides the circuit into sections and replaces the sections with a pi-type equivalent circuit. The system is represented as multiwire networks through this process as shown in Fig. 3 [6].

The impedance in longitudinal elements such as rails, contact wires, and telecommunication lines is in series. Cross elements such as substations, auto-transformers, and train loads have shunt admittance. The pi-type equivalent circuit is obtained by putting distributed constant lines into lumped parameter circuits. The circuit of one line is shown in Fig. 4.

Any line in the multiwire system is coupled electrically with the others, and the pi-type equivalent circuit depicting multiwire networks is shown in Fig. 5.

The simultaneous equation of the nodal analysis approach is (1).
impedance in consideration of the skin effect and ground return impedance. The conductor internal impedance is given by Schelkunoff’s formula containing a Bessel function [7]. The ground return impedance is given by Carson’s formula containing infinite integration [8]. These formulas are described by infinite series expansion.

However, the error in the expansion may be large or the value of the expansion may diverge when the frequency is high. The permeability in Schelkunoff’s formula changes depending on the current in the conductor such as the rail and the screening layer of the cable. Carson’s formula is derived from the assumption that the actual earth is replaced by a plane homogeneous semi-infinite solid. Thus, approximate formulas can satisfy the required degree of precision.

The approximate formulas of series impedance such as Ametani’s formula [9] and Deri’s formula [10] have been put to practical use and are numerically stable. In the new simulator these approximate formulas are adopted and series impedance can be calculated stably at high and low frequencies.

The replacement of the pi-type equivalent circuit with lumped parameter circuits is based on the following approximation (2)

\[
\begin{align*}
\frac{\Gamma}{v/2} \cosech(\frac{\Gamma}{v}) \approx 1 \\
\frac{\Gamma}{v/2} \tanh(\frac{\Gamma}{v/2}) \approx 1
\end{align*}
\]

where \(v/\Gamma\) is sufficiently small; \(\Gamma\) : voltage propagation constant; and \(l\) : length of one section.

The higher the frequency, the larger the propagation constant. The calculation model must be divided into short sections in order that (2) may be established. As a result, there is an increase in the number of sections in the calculation model.

### 3.4 Formulating the simultaneous equation

Each of the circuit analysis approaches necessitates the formulation of its respective simultaneous equations [11, 12, 13]. The equations for the nodal analysis approach are composed of fewer formulas, which results in smaller computational loads. The equations of the modified nodal analysis approach can describe ideal voltage sources whose internal resistance is zero. The equations of the sparse tableau approach are suitable for nonlinear analysis and timedomain-analysis including the processing of updates in the constants.

In the new simulator, the nodal analysis approach is used in order to enable comparisons with the ABTAC in which it is used. In future work, a simulator will be developed which can solve the problem in the time-domain and switch between approaches for various analyses.

### 3.5 Solving the simultaneous equation

The numerical solution of the linear equations are classified as either a direct method or a relaxation method. It is easy to perform parallel computing in the relaxation method, but the convergence of solutions is determined by the nature of the matrix. Hence, preconditions and algo-
4. Development of a new simulator

4.1 Performing parallel computing

The increase in the number of sections at high frequencies and that of conductors resulting from taking structures into account cause the computational loads to become high. Using the workstation having a multi-core processor and large memory enables us to perform parallel computing and to calculate a large scale model.

In the developed simulator, the MUMPS (Multifrontal Massively Parallel sparse matrix Solver) [14] is used as a numerical calculation library for the solution of linear equations. The library solves linear equations by the direct method and it is possible to calculate a large scale model by performing distributed-memory parallel processing.

Another practical approach considering the screening effect of conductors in structures is computational complexity reduction by ignoring the conductors in which the current flow is so small as to have minimal influence on inductive interference.

4.2 Interface and execution of the developed application

The routines for electrical circuit modeling and formulating the simultaneous equations were developed on the basis of a previous study, and MUMPS was used for solving the simultaneous equations. The developed simulator was built using programs such as those shown in Fig. 6.

Input data for running the simulator were based on the properties of the longitudinal elements and cross elements. The longitudinal elements are rails, contact wires, and telecommunication lines. Their properties comprise radius or diameter, conductivity, and permeability. The cross elements are substations, auto-transformers, and train loads. Their properties include location, impedance, voltage or current of sources, and so on.

MUMPS was used as the numerical calculation library for solving linear equations runs on Linux operating systems. Consequently, input data was described in text files. Some input data can be manipulated through the graphical user interface on Windows operating systems.

The calculation result was output into text files after running analysis processing including the input data files on the command line. The contents of the output files indicate voltages and currents. The induced voltages on metallic telecommunication lines and induced currents on rails according to train load location were then shown by converting output data to the CSV (Comma-Separated Values) format.

The user interface will be improved continuously to facilitate the input and output process.

5. Results of the validation

5.1 Electromagnetically induced voltage at low and high frequencies

This procedure aimed to validate the extension of the frequency range from the audio frequency band of 4 kHz up to the data transmission band of 1 MHz, in the new simulator. The model for the validation of electromagnetically induced voltage is shown in Fig. 7.

The validation set up was composed of an induction loop circuit and an induced line with a longitudinal length of 5 m. It was divided into 100 sections fine enough to establish the replacement by a pi-type equivalent circuit.

The predicted voltages on the induced line according to the ABTAC and the new simulator were compared as shown in Fig. 8.

The frequency and the mutual impedance were proportional and their correlation was displayed on a linear graph. The new simulator can be used to calculate the induction voltages and currents. The induced voltages on metal telecommunication lines and induced currents on rails according to train load location were then shown by converting output data to the CSV (Comma-Separated Values) format.
quantity of electromagnetic induction at high frequencies up to about 1 MHz. The two calculated values from the ABTAC and the new simulator were consistent with each other at the audio frequency band up to 4 kHz. Therefore, the new simulator can replace ABTAC.

5.2 Screening effect of conductors in structure

This second validation was to check the simulator’s ability to reflect, in detail, the installation conditions of a structure and the screening effect of conductors in the structure. The model for the validation of the screening effect of conductors in a structure is shown in Fig. 9.

The validation set up was composed of a viaduct, and inducing and induced lines in its vicinity. The length of the viaduct was 100 m and the number of longitudinal reinforcing rods in it was 238.

The measured value of the voltage affected by the screening effect on the induced line and those calculated values through the ABTAC and the new simulator were compared; the results of the comparison are shown in Table 1.

The predicted quantity of the new simulator is 10% lower than that of the ABTAC. This indicates that the screening effect of conductors in structures can be simulated with greater precision.

Table 1  Validation of screening effect of conductors in structures

|               | Induced voltage |
|---------------|-----------------|
| Measured value| 3.77 mV         |
| Calculated value (ABTAC) | 4.95 mV (+31%)  |
| Calculated value (New Simulator) | 4.50 mV (+19%)  |

Incidentally, there was in fact more screening current flowing in the viaduct poles to the ground. However, since there was uncertainty about the ground resistance and the quantity of electromagnetic interference needed to be overestimated to ensure a safety margin, the calculated voltages obtained by ignoring the connection to the ground through the viaduct poles were higher than the measured voltages.

6. Conclusions

In this study, a new induction prediction simulator was developed, which is applicable to frequency bands exceeding audio frequencies and is capable of considering multiple conductors in structures.

The new simulator extends the frequency range from the audio frequency band of 4 kHz up to the data transmission band of 1 MHz. Since the new simulator is no longer bound by the old simulator limit of several dozen longitudinal conductors, installation conditions can be considered in detail and the screening effect of conductors in structures can be simulated.

The simulator will make it possible to quantitatively evaluate the reduction of induced voltage and induced current on telecommunications lines, when upgrading or installing new power equipment or new wire-based telecommunications equipment. It can also be used for predicting voltage and current induction in rails.
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