EMTP Modeling of a Distribution Line for Lightning Overvoltage Studies

Susumu Matsuura, Taku Noda, Akira Asakawa, and Shigeru Yokoyama

Abstract--Recently, the focus of lightning protection measures for distribution lines has moved to the direct lightning stroke. Studies of such countermeasures are generally carried out by digital simulation using the EMTP (Electro-Magnetic Transients Program). This paper first shows the surge response of a distribution line obtained by pulse tests using a reduced-scale distribution line model. The results of the pulse tests are simulated using the FDTD (Finite Difference Time Domain) method, and comparisons show that FDTD simulations give sufficiently accurate results. Finally, EMTP models of the distribution pole and wires, which can reproduce the transient overvoltages at the insulators, are proposed. The parameter values of the proposed models can be determined based on the pulse test or the FDTD simulation results.

Keywords: concrete pole, direct lightning stroke, distribution lines, EMTP modeling, FDTD method, ground wire, lightning channel, lightning overvoltages, and phase wires.

I. Introduction

Lightning-related overvoltages on overhead distribution lines can roughly be classified into the two types: overvoltages induced by a nearby lightning stroke and overvoltages due to a direct lightning stroke to the distribution line. Protection measures against the former type of overvoltages, which is commonly called lightning-induced overvoltages, have been taken and can be considered as almost completed [1], [2]. In Japan, the focus of lightning protection measures for distribution lines has moved to the latter type of overvoltages. Studies of such countermeasures are generally carried out by digital simulation using the EMTP (Electro-Magnetic Transients Program) [2], [3]. Thus, components of a distribution line must to be modeled appropriately in the EMTP for accurate simulations. Regarding the modeling of a distribution pole, the past studies [4], [5] focus only on the surge impedance of a stand-alone pole and do not consider the effects of a ground wire and phase wires.

Therefore, this paper first shows the surge response of a distribution line obtained by pulse tests using a reduced-scale distribution line model. The reduced-scale distribution line model includes a concrete pole, a ground wire, phase wires, and a lightning channel. The surge impedance of a distribution pole is evaluated considering the effects of a ground wire and phase wires. Voltage responses at various positions of the reduced-scale distribution line model are also obtained with varying the wavefront time of the current injected as a lightning stroke. The results of the pulse tests are simulated using the FDTD (Finite Difference Time Domain) method, and comparisons show that FDTD simulations give sufficiently accurate results. Finally, EMTP models of the pole and wires, which can reproduce the transient overvoltages at the insulators, are proposed. The parameter values of the proposed models can be determined based on the pulse test or the FDTD simulation results.

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II. Pulse Tests Using a Reduced-Scale Distribution Line Model

A. Experimental Setup

The reduced-scale distribution line model used in the pulse tests is shown in Fig. 1. The ratio of the actual distribution line to the reduced-scale one is 6.3 to 1. An aluminum cylindrical pipe (henceforth referred to as the pole) is used to model the reinforced-concrete pole [4], [5]. Its length is 2 m and diameter is 35 mm.

The experimental setup is shown in Fig. 2. A copper sheet is spread over the floor of the laboratory and is connected to the earth of the building. The copper sheet is sufficiently wide to consider as an infinite plane in the time range of this experiment. The ceiling in the laboratory is high enough to be disregarded. The surge current is generated by a pulse generator (Noise Laboratory INS-400L) placed at a distant point. The current passes through a coaxial cable (3D-2W) installed as shown in Fig. 2 and is injected into the top of the pole. At the end of the coaxial cable, a 540 Ω resistor is

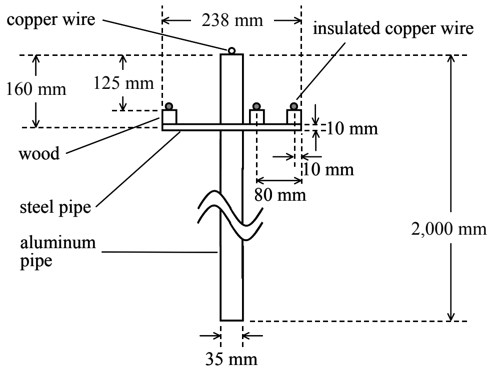


Fig. 1. Reduced-scale distribution line model.

inserted between the pole and the cable core. The current travels inside the coaxial cable until it reaches the top of the pole, and then, a portion of the current flows down the pole, and an opposite-polarity current travels up along the outer surface of the cable metallic shield. Therefore, the cable metallic shield can be regarded as the lightning cannel [6]. As a result, the impedance of the lightning cannel can be regarded as 1k Ω [7] when the reflection from the ground plane reaches the top of the pole.

B. Test Cases

Four test cases have been studied in the pulse tests. In Case 1, the surge impedance of a stand-alone pole, without a ground wire or phase wires, is measured. The injected current is the step waveform with a wavefront time of about 3 ns. Hereafter, it is referred to as the step current. When the step current is injected into the top of the pole, the voltage generated between the top of the pole and the zero-potential wire (henceforth referred to as the pole-top voltage) is measured. The surge impedance is defined as the maximum value of the pole-top voltage divided by the current at that time.

Case 2 examines the effect of phase wires. The surge impedance of the pole with three phase wires but without a ground wire is measured. The pole-top voltage and the voltage difference between a phase wire and the crossarm (henceforth referred to as the insulator voltage) are also measured when the wavefront time T_f of the injected current is varied as step, 16 ns (0.1 μs), 32 ns (0.2 μs), and 48 ns (0.3 μs). Here, the values in () denote T_f in the actual size distribution line.

Case 3 examines the effect of a ground wire and phase wires. The surge impedance of the pole with a ground wire and three phase wires is measured. Similar to Case 2, the pole-top and the insulator voltages are measured with varying T_f.

In Case 4, the coupling between the ground wire and a phase wire is clarified. When the step current is injected into the ground wire, the voltage generated between the ground wire and the zero-potential wire (henceforth referred to as the ground wire voltage) is measured without the pole. Also, the voltage generated between the phase wire and the zero-potential wire (henceforth referred to as the phase wire voltage) just below the current injected point is measured.

All measured waveforms shown in this paper are normalized so that the injected current converges into 1 A for comparison purposes.

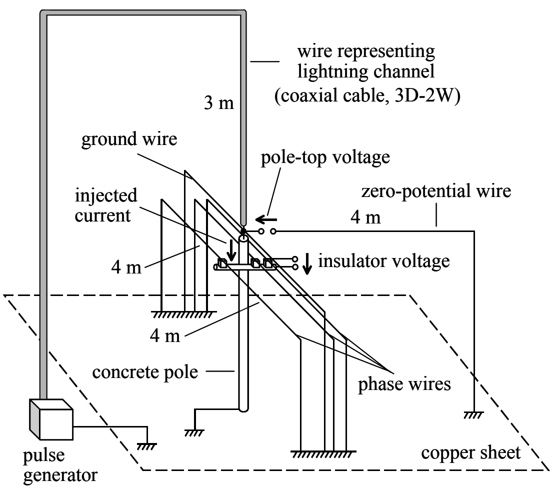


Fig. 2. Experimental setup.

C. Surge Impedance of Stand-Alone Pole

Fig. 3 shows the measured result of Case 1. The surge impedance of the stand-alone pole, without a ground wire or phase wires, calculated from the measured result for the step-current injection is 283 Ω.

D. Effect of Phase Wires

Fig. 4 shows the measured result of Case 2. The surge impedance of the pole with three phase wires but without a ground wire calculated from the measured result is 267 Ω,

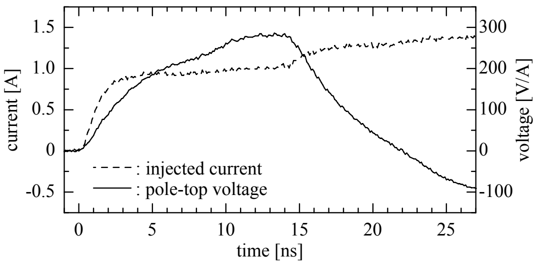


Fig. 3. Measured waveforms of Case 1.

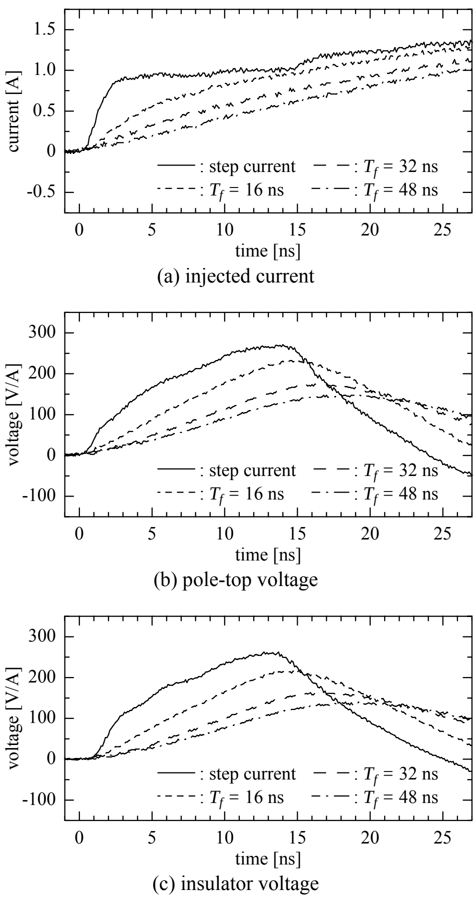


Fig. 4. Measured waveforms of Case 2.

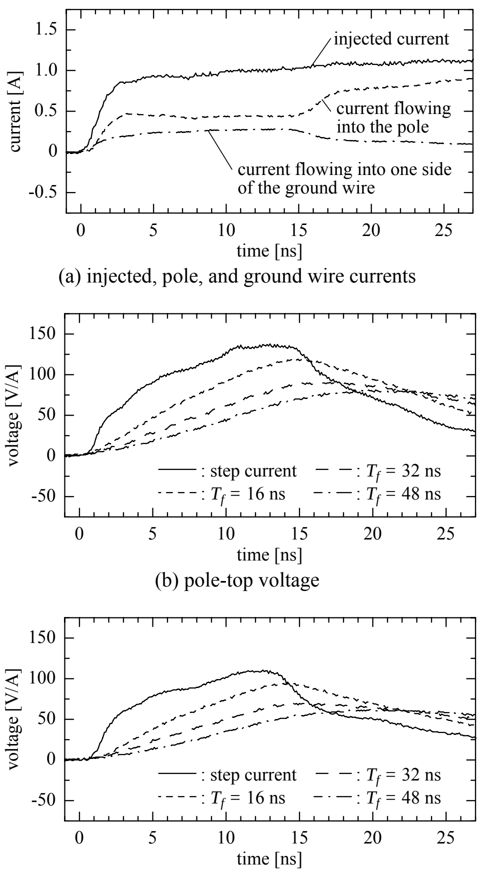
which is 16 Ω (6 %) smaller than that of Case 1. This may be due to the electromagnetic-field scattering by the presence of the three phase wires.

Comparing (b) with (c) in Fig. 4, the time taken to reach to the maximum value of the insulator voltage is about 1 ns earlier than that of the pole-top voltage. And the maximum value of the insulator voltage is slightly smaller than that of the pole-top voltage. The reason is that the reflection from the ground plane reaches the crossarm earlier than the top of the pole because the crossarm is closer to the ground plane than the top of the pole by 16 cm.

The effect of the wavefront time of the lightning current on the pole-top and the insulator voltages is as follows. As the wavefront time becomes longer, the pole-top and the insulator voltages become smaller.

E. Effect of Ground Wire and Phase Wires

Fig. 5 shows the measured result of Case 3. The currents splitting into the pole and the ground wire are shown in Fig. 5 (a) when the step current is injected. The surge impedance of the pole with a ground wire and three phase wires, which is defined as the maximum value of the pole-top voltage divided by the current flowing into the pole at that time, is 302 Ω. This value is 19 Ω (7 %) larger than that of Case 1 and 35 Ω (13 %) larger than that of Case 2. The surge impedance of the ground wire is calculated to be 495 Ω.



(a) injected, pole, and ground wire currents

(b) pole-top voltage

(c) insulator voltage

Fig. 5. Measured waveforms of Case 3.

The voltage rise of the pole-top and the insulator voltage are about 50 % smaller compared with that of Case 2, because part of the injected current flows into not only the pole but also the ground wire. In addition, the maximum insulator voltage is 27 Ω (20 %) smaller than the maximum pole-top voltage because of coupling between the ground wire and a phase wire, i.e., the voltage of the phase wire rises due to electromagnetic coupling with the current flowing into the ground wire.

Similar to Case 2, as the wavefront time becomes longer, the pole-top and the insulator voltages become smaller.

F. Coupling between Ground Wire and Phase Wires

Fig. 6 shows the measured result of Case 4. The ground wire voltage rises as time passes, and then, converges into about 250 V/A around 13 ns. On the other hand, the phase wire voltage shows a tendency to rise more slowly, and converges around 17 ns. Therefore, the coupling factor, that is calculated by the ratio of the instant value of the phase wire voltage to that of the ground wire voltage, has a relatively slow rise time. For instance, the coupling factor is only 24 % at 12.5 ns when insulator voltage reaches to its maximum value in Case 3, and then, it rises and converges into 29 % at 18 ns.

III. Surge Simulation Using the FDTD Method

In this Section, it is shown that FDTD simulations can be used instead of tests. FDTD simulations are a preferable choice over tests, because simulations with various conditions can easily be carried out. The pulse tests shown in Fig. 2 are simulated using a general-purpose surge simulation code based on the FDTD method, called VSTL (Virtual Surge Test Lab.) [8]–[10]. In the simulation, the current injection is represented by a parallel connection of a current souse and a 540 Ω resistance. A space step of 5 cm is used and an open space is assumed using second-order Liao formation. Fig. 7

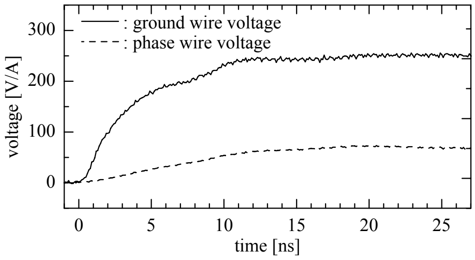


Fig. 6. Measured waveforms of Case 4.

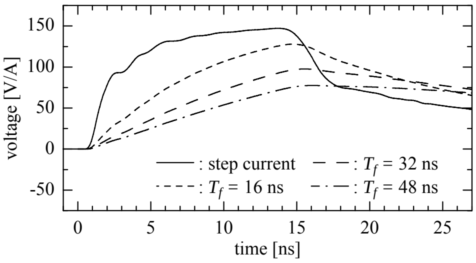


Fig. 7. Calculated results using FDTD method in Case 3.

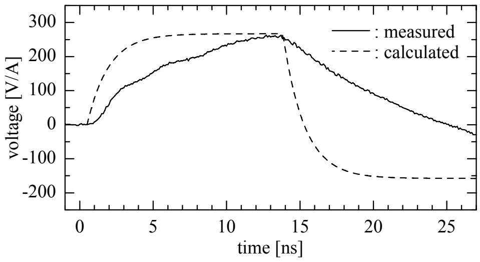
shows calculated results of the pole-top voltage in Case 3 and good agreement is found.

IV. Distribution Line Models for EMTP Simulation

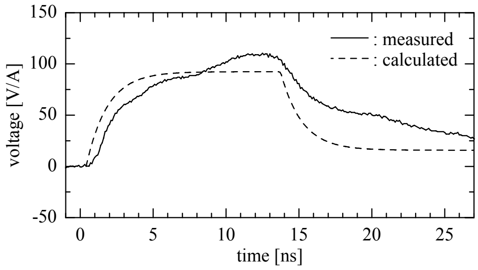
A. Problems of Conventional Model

As shown in Sections II and III, the moment a lightning stroke hits a distribution pole, an overvoltage is generated due to the surge impedance of the pole in a short time range, and this can be a cause of insulator flashovers. In this short time range, electromagnetic fields around the pole are still in the process of formation. Therefore, the transient overvoltages generated at the insulators cannot accurately be reproduced by representing the pole by a distributed-parameter line model in the EMTP, since it assumes a TEM (Transverse Electro-Magnetic) mode of propagation for the calculations of traveling waves, i.e., ignores the process of electromagnetic field formation. This means that a special treatment is required in order to represent the transient response of the distribution pole and wires in the EMTP.

Fig. 8 shows the comparison between results of the pulse tests and EMTP simulations with the conventional model mentioned above where the pole is represented by a single lossless distributed-parameter line model [2], [3]. Figs. 8 (a) and (b) show the insulator voltages in Cases 2 and 3 when the step current is injected. In Fig. 8 (a), the measured and calculated waveforms do not agree in the rising process at the wavefront. On the other hand, in Fig. 8 (b), the difference around the wavefront is small, however, the maximum values do not agree.



(a) Case 2

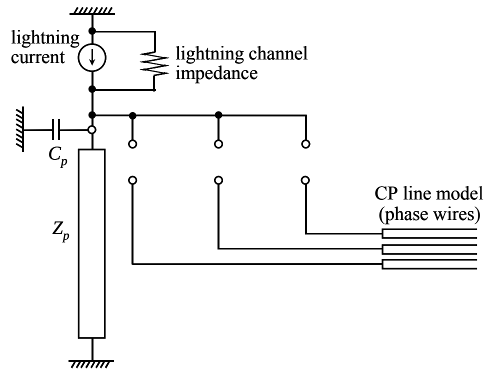


(b) Case3

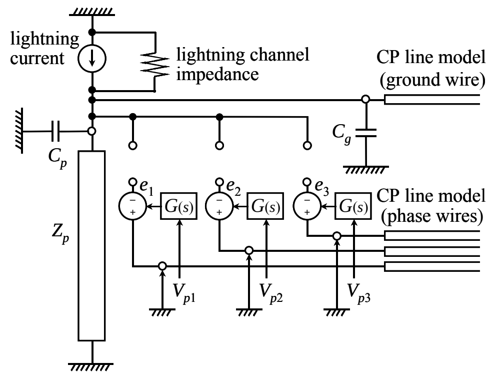
Fig. 8. Calculated results using the conventional EMTP model.

B. Main Framework of the Proposed Models

In this paper, two models for EMTP simulations are proposed: one is for modeling a pole equipped with phase wires but without a ground wire, and the other is for a pole equipped with a ground wire and phase wires. Hereafter, the former is referred to Model A, and the latter to Model B. The proposed models are shown in Fig. 9, where the ground wire and the phase wires at both sides of the pole are shown on the right-hand side. The distribution wires (the ground and phase wires) are represented by the CP-Line (constant-parameter line) model in the EMTP-RV [11] and the pole is represented by a single lossless distributed-parameter line model. The resistance representing the impedance of a lightning channel is connected in parallel with the current source representing a lightning current. The two models are described in the following two subsections.



(a) Model A



(b) Model B

Fig. 9. Proposed EMTP models of a distribution line.

C. Model A

As shown in Case 2, the voltage rise of the pole, which is a vertical conductor, rises as time passes. To reproduce this transient response approximately, the capacitance C_p is connected in parallel with the pole in Model A. The value of C_p is determined by the time constant τ_p of the pole-top voltage waveform, when the waveform of the injected current is step in Case 2. The injected current $i(t)$ in the pulse tests can be approximated by

$$i(t) = i_0\{1 - \exp(-t/\tau_i)\} \tag{1}$$

where i_0 and τ_i is the converged value and the time constant of $i(t)$. Then, the pole-top voltage $v(t)$ is given by

$$v(t) = v_0\left\{1 - \frac{\tau_i}{\tau_i - \tau_p}\exp\left(\frac{-t}{\tau_i}\right) + \frac{\tau_p}{\tau_i - \tau_p}\exp\left(\frac{-t}{\tau_p}\right)\right\} \tag{2}$$

where v_0 is the converged value of $v(t)$. τ_i is determined to be 1 ns so that the step current waveform in Fig. 4 (a) satisfies (1). Also, τ_p is determined to be 4 ns so that the pole-top voltage waveform in Fig. 4 (b) satisfies (2). The pole surge impedance Z_p is set to 267 Ω from the result of Case 2. Therefore, C_p is calculated by

$$C_p = \tau_p / Z_p = 15\,\text{pF}\,. \tag{3}$$

D. Model B

The voltage rise of the ground wire, which is a horizontal conductor, also rises as time passes, and then, converges into the value obtained by assuming a TEM mode of propagation as shown in Fig. 6. In Model B, the capacitance C_g is connected in parallel with the ground wire in addition to C_p to reproduce this transient response approximately. First, the total surge impedance Z_t of Z_p and the ground wire surge impedance Z_g is calculated by

$$Z_t = \frac{Z_p Z_g / 2}{Z_p + Z_g / 2} = 136\,\Omega \tag{4}$$

where Z_p and Z_g are 302 Ω and 495 Ω from the results of Case 3. The total capacitance C_t of C_p and C_g

$$C_t = C_p + C_g \tag{5}$$

is determined by the time constant τ_t of the pole-top voltage waveform injected the step current in Case 3. Similar to Model A, τ_t is determined to be 3 ns so that the pole-top voltage waveform shown in Fig. 5 (b) satisfies (2). Therefore, C_t is calculated by

$$C_t = \tau_t / Z_t = 22\,\text{pF}\,. \tag{6}$$

Next, C_p and C_g are calculated from C_t in the following way. If we assume that τ_p is equal to the time constant τ_g of the ground wire voltage waveform, we obtain

$$C_p Z_p = C_g Z_g\,. \tag{7}$$

Finally, C_p and C_g are calculated by

$$C_p = \frac{Z_g C_t}{Z_p + Z_g} = 14\,\text{pF},\ C_g = C_t - C_p = 8\,\text{pF}\,. \tag{8}$$

Coupling between conductors is instantly generated in a line model in the EMTP, since it assumes a TEM mode of propagation. Therefore, the time variation of the coupling factor between the ground wire and the phase wires cannot be reproduced in straightforward EMTP simulations. To eliminate the difference between the measured and calculated insulator voltages, the voltage sources e_1, e_2, and e_3 are inserted in series with the phase wires as shown in Fig. 9 (b). With these voltage sources, the coupling between the ground wire and the phase wires converges slowly into the TEM value with the time constant τ_c. τ_c is the time when the phase wire voltage takes $1-e^{-1}$ times of its maximum value in Fig. 6 and is determined to be 9 ns. The phase wire voltages V_{p1}, V_{p2}, and V_{p3} are inputted to the transfer function $G(s)$, which has the response

$$G(s) = 1 - \frac{1}{1 + \tau_c s}\,. \tag{9}$$

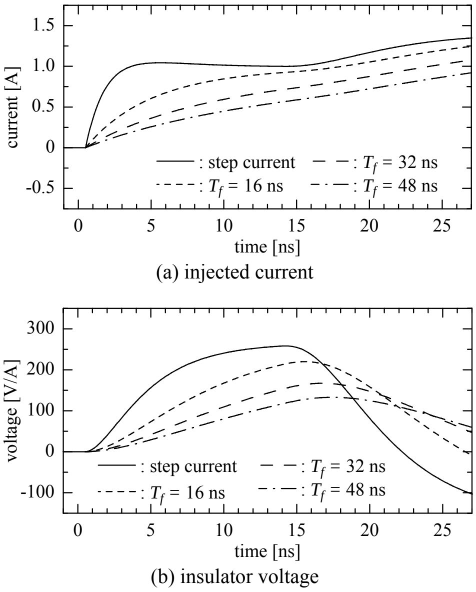


Fig. 10. Calculated results using the proposed EMTP model in Case 2.

Then, the output of $G(s)$ is generated by the voltage sources e_1, e_2, and e_3 in the direction designated in Fig. 9 (b).

E. Calculated Results Using Proposed Models

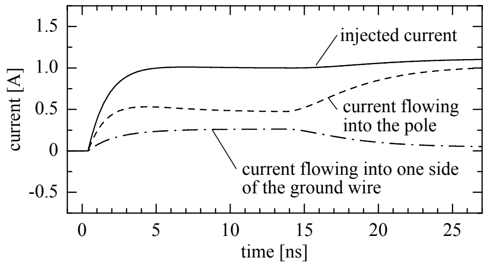
The calculated results obtained using the proposed models are compared with the measured results. The calculation conditions are described as follows. The value of the resistance representing the impedance of a lightning channel is 1k Ω [7]. The waveform of the current source is set by (1). The value of the ground resistivity is set to 1.69×10^{-8} Ω m for simulating the copper ground plane. The pole surge impedance is set to one of the values obtained in the tests according to a case of interest. Figs. 10 and 11 show Cases 2 and 3. It is clear that the calculated results agree well with the measured results in terms of the maximum values and the transient responses.

V. CONCLUSIONS

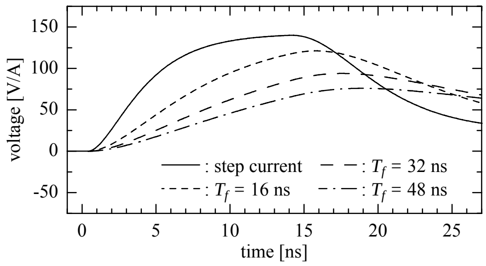
This paper has presented the surge responses of a distribution line obtained by pulse tests using a reduced-scale distribution line model. As a result of the pulse tests, it was found that the surge impedance of a concrete pole changes depending on the presence of the ground and the phase wires, and the coupling between the ground wire and the phase wires has the time variation and converges slowly into the TEM value.

Then, two EMTP models, one for without the ground wire and the other for with the ground wire, which can reproduce the transient overvoltages at the insulators, are proposed. The parameter values of the proposed models can be determined based on pulse test or FDTD simulation results. The special treatment of the proposed models is summarized as follows:

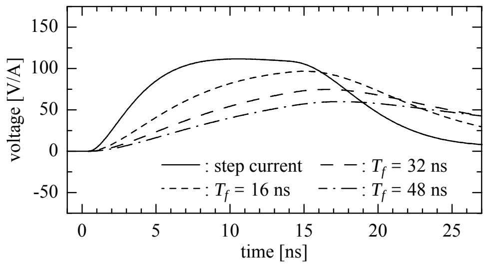
▪ In the model without the ground wire, a capacitance is connected in parallel with the pole top to reproduce the



(a) injected, pole, and ground wire currents



(b) pole-top voltage



(c) insulator voltage

Fig. 11. Calculated results using the proposed EMTP model in Case 3.

transient voltage rise of the pole.

▪ In the model with the ground wire, in addition to the capacitance connected to the pole top, a capacitance is connected in parallel with the ground wire to reproduce the transient voltage rise of the ground wire. And to represent the time variation of the coupling between the ground wire and the phase wires, voltage sources are inserted in series with the phase wires.

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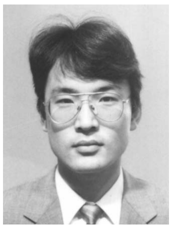

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