Modeling of Telecommunication Cables Installed with Distribution Lines for Lightning Overvoltage Studies

Kazuyuki Ishimoto, Taku Noda, Masatoshi Nakamura and Shunsuke Maru

***Abstract*– Due to the progress of information-oriented societies all over the world, telecommunication cables are often installed on concrete poles along with power distribution lines. When a lightning stroke hits a concrete pole equipped with an overhead ground wire and a telecommunication cable, the lightning current is split into the three paths: the concrete pole, the overhead ground wire, and the telecommunication cable. It is easily estimated that the existence of the telecommunication cable reduces the current through the concrete pole, and thus, reduces the voltages across the insulators which support the phase wires. However, its quantitative study has not yet been carried out. Considering the above, we have measured the surge impedance matrix of an actual-scale test distribution line equipped with an overhead ground wire and a telecommunication cable. Using this result, a method to model a distribution line with a telecommunication cable for lightning overvoltage simulations is proposed in this paper. Simulation results obtained by the proposed modeling method are compared with field-test results, and good agreement is obtained.**

***Keywords*: Field tests, Lightning overvoltage studies, Modeling, Simulation, Surges, Power distribution lines, and Telecommunication cables.**

I. Introduction

In Japan, the focus of lightning protection for 6.6-kV distribution lines has moved to overvoltages due to direct lightning strokes, because lightning-induced overvoltages can be ignored thanks to the progress of lightning protection measures [1]. Studies of protection measures for the direct-lightning-stroke overvoltages are in general carried out by an electromagnetic transient (EMT) analysis program such as the the EMTP (Electro-Magnetic Transients Program) [2]–[5].

Due to the progress of information-oriented societies all over the world, telecommunication cables are often installed on concrete poles along with power distribution lines [6]. When a lightning stroke hits a concrete pole equipped with an overhead ground wire and a telecommunication cable, the lightning current is split into the three paths: the concrete pole, the overhead ground wire, and the telecommunication cable. The effect of a wire installed under phase wires, like the telecommunication cable, on the suppression of lightning arrester failure was investigated in [7]. However, the ratio of the telecommunication cable current to the total lightning current and its effect to reduce the voltages across the phase-wire insulators have not yet been made clear. It is easily estimated that the existence of the telecommunication cable reduces the current through the concrete pole, and thus, reduces the voltages across the phase-wire insulators. Thus, these characteristics should be clarified quantitatively.

Considering the above, this paper first shows the measurement result of the surge impedance matrix of an actual-scale test distribution line equipped with an overhead ground wire and a telecommunication cable. Then, by comparing the measured result with theory, a method to model a distribution line with a telecommunication cable for lightning overvoltage simulations is proposed. For the validation of the proposed model, simulation results obtained by the proposed modeling method are compared with field-test results, and good agreement is obtained.

II. Pulse Test Using an Actual-Scale Test Distribution Line

A. Experimental Setup

The surge impedance matrix of a distribution line equipped with an overhead ground wire and a telecommunication cable was measured using an actual-scale test distribution line in Shiobara Testing Yard of CRIEPI. The layout of the test distribution line, consisting of nine concrete poles, is shown in Fig. 1. The arrangement of the conductors is shown in Fig. 2, where the overhead ground wire is designated by the symbol "G", the three phase wires by "P_1", "P_2" and "P_3", the telecommunication cable by "C", and its messenger wire by "M". The overhead ground wire is a 22 mm^2 steel wire, and the phase wires are 60 mm^2 polyethylene-insulated copper wires. In general, a telecommunication cable consists of an optical fiber and a copper tension member. Since the optical fiber is a good insulator, only the tension member plays an important role in the surge phenomena. Thus, an 8 mm^2 vinyl-insulated wire was used to represent the tension member and the optical fiber itself was ignored. The 8 mm^2 wire was fixed

K. Ishimoto and T. Noda are with Electric Power Engineering Research Lab., CRIEPI (Central Research Institute of Electric Power Industry), 2-6-1 Nagasaka, Yokosuka-shi, Kanagawa-pref. 240-0196, Japan (e-mail: ishimoto @criepi.denken.or.jp)
M. Nakamura and S. Maru are with Chubu Electric Power Co., Inc., 1, Toshin-cho, Higashi-ku, Nagoya-shi, Aichi-pref. 461-8680, Japan

Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

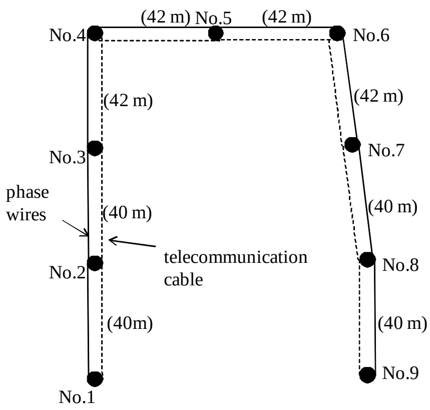


Fig. 1. Layout of the test distribution line.

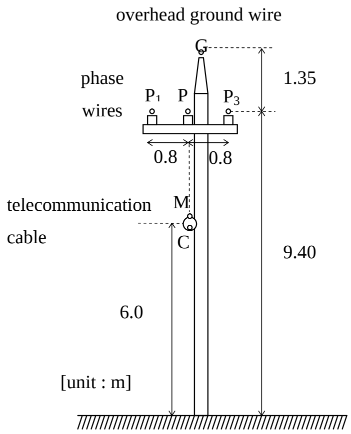


Fig. 2. Arrangement of conductors.

by cable hangers at an interval of 60 cm and hung along the messenger wire, which is a 38 mm^2 steel wire. The cable hanger is shown in Fig. 3.

B. Surge Impedance Matrix

In this section, the measured surge impedance matrix is compared with calculated one. The overhead ground wire, the three phase wires, telecommunication cable and its messenger wire are considered as a six-phase distributed-parameter line. Thus, the size of the surge impedance matrix $[Z_0]$ is six by six.

Fig. 4 shows the circuit used to measure the surge impedance matrix. Both ends of the test distribution line are open-ended. In this measurement, pole No. 1 was called the sending end, and No. 9 the receiving end. At the sending end, a step current was injected to one of the six conductors through a 500-Ω resistor by a pulse generator (PG). Since the total length of the test distribution line is 328 m, the current reflected at the receiving end comes back to the sending end in about 2.2 μs. Thus, during this 2.2 μs, step voltages are observed on these six conductors at the sending end. Voltage values observed on the six conductors divided by the injected current value give a column, which corresponds to the injected phase, of the surge impedance matrix $[Z_0]$. By repeating this procedure for all six conductors, we finally obtain all entries

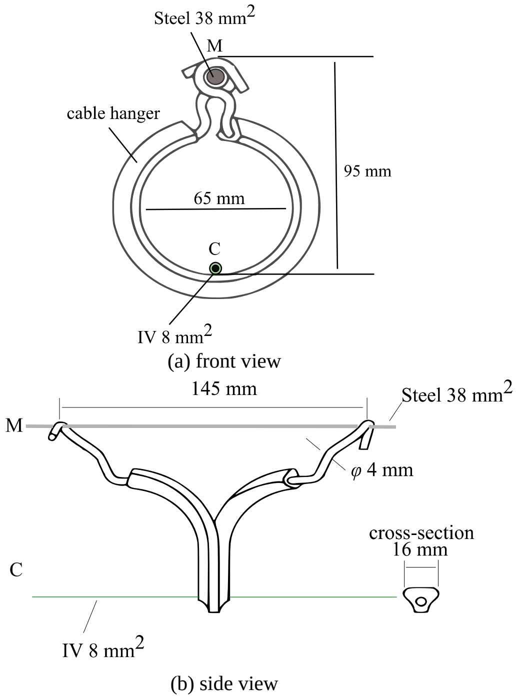
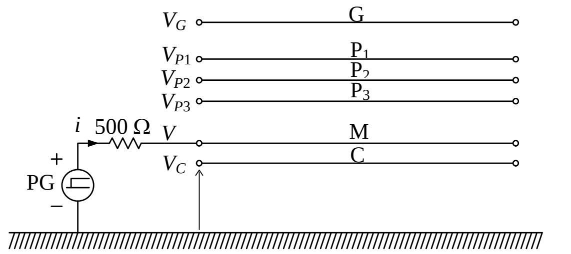


Fig. 3. Cable hanger used to support the telecommunication cable.



F

ig. 4. Measurement circuit of the surge impedance matrix.

of $[Z_0]$. Meanwhile, in an actual lightning stroke, quite bigger voltage than the voltage generated by PG generates, and corona discharge generates around the power wires. However, the corona discharge voltage of 60 mm^2 power line is about 150 kV, and although the flashover voltage of the insulator (about 150 kV) or discharge voltage (about 30 kV) of lightning arrestor for power distribution lines are lower than this. Thus, when the corona discharge begins, the insulator flashovers or the lightning arrester discharges. That is, the value measured with PG can use it as it is.

In theory, on the other hand, the diagonal entries Z_{0ii} (self impedances) and the off-diagonal entries Z_{0ij} (mutual impedances) of $[Z_0]$ are given by

$$Z_{0ii} = 60 \ln\left(\frac{2h_i}{r_i}\right), \quad Z_{0ij} = 60 \ln\left(\frac{D_{ij}}{d_{ij}}\right), \tag{1}$$

where r_i is the radius of the ith conductor, h_i and h_j are the heights of the ith and the jth conductor, and y_{ij} is the horizontal distance between the two conductors. d_{ij} and D_{ij} are calculated by

$$d_{ij} = \sqrt{\left(h_i - h_j\right)^2 + y_{ij}^2}\ ,\quad D_{ij} = \sqrt{\left(h_i + h_j\right)^2 + y_{ij}^2}\ . \qquad (2)$$

From the geometrical arrangement shown in Figs. 2 and 3, the surge impedance matrix [Z_0] in the phase domain is calculated by (1) and (2). Table 1 shows the measured and the calculated values of the surge-impedance matrix and their deviations. Comparison between the measured and the calculated values shows that the elements in the rows and the columns corresponding to the three phase wires and the overhead wire are in good agreement. However, the calculated values in the rows and columns of the telecommunication cable and its messenger wire are larger by 30 % than the corresponding measured ones. The following two points are considered as the reasons of this difference. (i) The capacitance to ground of the messenger wire has increased due to the fact that it is electrically connected to the cable hangers whose diameter is about 10 cm. (ii) The 8 mm^2 wire representing the tension member of a telecommunication cable is physically in contact with the cable hangers through the two dielectric layers: the insulating vinyl jacket of the 8 mm^2 wire and the insulating coating of the cable hangers. Thus, the capacitance between the 8 mm^2 wire and the cable hangers that is electrically connected to the messenger wire has increased. The following (i) and (ii) are thought as this reason. (i) The earth capacitance of the messenger wire has increased since the messenger wire is connected electrically with cable hanger whose diameter is about 10 mm. (ii) Since the tension member contacts with cable hanger across two layer insulation (the insulated layer of the vinyl coating copper wire and the insulated layer of the cable hanger), the capacitance between tension member and cable hanger has increases.

Table 1. Comparison of the measured and the calculated values of the surge impedance matrix.

(a) measured [unit : Ω]

	G	P1	P2	P3	M	C
G	553	152	153	142	78	85
P1	152	489	176	144	89	96
P2	153	177	485	192	92	99
P3	144	146	191	486	90	98
M	81	92	93	93	370	214
C	85	97	99	99	212	465

(b) calculated [unit : Ω]

	G	P1	P2	P3	M	C
G	540	153	162	153	76	74
P1	153	502	189	148	89	87
P2	162	189	502	189	91	89
P3	153	148	189	502	89	87
M	76	89	91	89	482	287
C	74	87	89	87	287	527

(c) deviation [unit : %]

	G	P1	P2	P3	M	C
G	2.3	0.8	6.0	7.9	3.1	12.9
P1	0.5	2.6	7.6	2.8	0.1	9.3
P2	6.0	7.0	3.5	1.3	1.5	10.6
P3	0.1	1.4	0.8	3.3	1.1	11.2
M	6.6	3.2	2.5	4.2	30.2	34.1
C	12.9	10.2	10.6	12.0	35.4	13.4

III. Modeling of a Distribution Line Equipped with a Telecommunication Cable

This chapter proposes a method for modeling a distribution line equipped with a telecommunication cable. In the proposed method, the increase of the capacitance to ground of the messenger wire is reproduced by equivalently making the diameter of the messenger wire larger than its actual size in the line constants calculation. The increase of the capacitance between the 8 mm^2 wire (representing a telecommunication cable) and the cable hangers is taken into account by adjusting the corresponding surge impedance and the capacitance value utilizing the measured data.

A. Equivalent Diameter of the Messenger Wire

As mentioned above, the increase of the capacitance to ground of the messenger wire is caused by the cable hangers which are electrically connected to the messenger wire. That is, the cable hangers are electrostatically a part of the messenger wire, and thus, the effective diameter of the messenger wire becomes larger than its actual size. If the cable hangers were attached to the messenger wire continuously over the total length, the effective diameter would be equal to the diameter of the cable hangers. In reality, as mentioned earlier, the cable hangers are attached to the messenger wire at an interval of 60 cm, and thus, we can guess that the effective diameter of the messenger wire is larger than 7.8 mm which is the actual diameter of the messenger wire itself and smaller than 95 mm which is the diameter of the cable hangers. Considering this, we search for the effective diameter that matches the measured surge

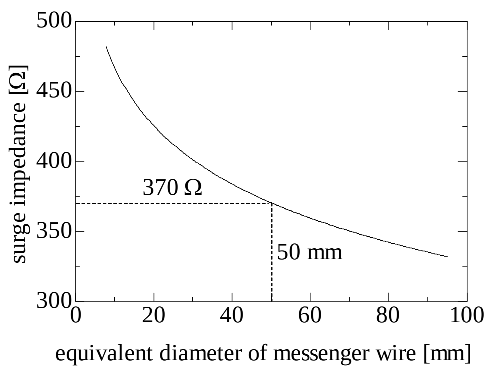


Fig. 5. Relationship between the equivalent diameter of the messenger wire and its surge impedance.

impedance value within the range between 7.8 mm and 95 mm. Fig. 5 shows the self surge impedance Z_{0MM} of the messenger wire calculated by (1), when the diameter is varied within that range. As indicated in Fig. 5, when the diameter is set to 50 mm, the calculated value becomes equal to the measured one, 370 Ω. Thus, the effective diameter of the messenger wire with the cable hangers, shown in Fig. 3, is determined to be 50 mm. Of course, if one or both of the diameters of the messenger wire and the cable hangers or the interval to attach cable hangers are different, the effective diameter obtained is no longer valid and the procedure above has to be repeated to obtain an effective diameter. It should be noted however that the effective diameter obtained here is valid even if the installation height is different, since it is obtained in the form of a diameter. Since the diameters of the messenger wire and the cables hangers and the attachment interval used in this paper are widely used in Japan, the effective diameter obtained is a meaningful value and can be often used. The effective diameter obtained will be used when the line constants of a distribution line is calculated in the proposed modeling method.

B. Capacitance between the Tension Member of the Telecommunication Cable and the Cable Hangers

The capacitance between the tension member of the telecommunication cable and the cable hangers has an influence on the mutual surge impedance between the two conductors and the self impedances of both conductors. We fist consider the mutual impedance. The values of the mutual impedances Z_{0CM} and Z_{0MC} are considered almost constant regardless of the installation height of the telecommunication cable. This is because the relative positions of the two conductors do not change even if the installation height is changed. From Table 1 (a), the measured values of the mutual impedances Z_{0CM} and Z_{0MC} are respectively 214 Ω and 212 Ω. In theory, these two values should be the same since the surge impedance matrix $[Z_0]$ is symmetrical. The difference is supposed to come from measurement errors. Thus, we can conclude that the mutual surge impedance between the tension member of the telecommunication cable and the cable hangers is 213 Ω, which is obtained as the mean value of 214 Ω and 212 Ω, regardless of the installation height. This value will replace the corresponding entries of the calculated surge impedance matrix in the proposed modeling method.

Next, we consider the self impedances Z_{0CC} and Z_{0MM}. Since Z_{0MM} has already been adjusted in Section III-A, we now have to adjust Z_{0CC}. It apparently depends on the installation height, and thus, we calculate the increase of the self capacitance of the tension member by subtracting the calculated value from the measured one. Since the increased amount is independent from the installation height, the value will be added to the corresponding calculated value in the line constants calculation of the proposed modeling method.

The capacitance matrix (per unit length) of a distribution line is calculated from the surge impedance matrix by the following equations.

$$[P] = \frac{1}{60}[Z_0] \tag{3}$$

$$[C] = 2\pi\varepsilon_0 [P]^{-1} \tag{4}$$

Note that $[P]$ is the potential matrix. Using (3) and (4), the capacitance matrix is calculated from the measured data, and we refer to the obtained capacitance values as measured ones. In the case of the distribution line under investigation, the measured and the calculated self capacitance of the tension member of the telecommunication cable are

Measured value: 10.4 pF/m
Calculated value: 9.44 pF/m

Finally, we obtain the increased amount as the difference of the two values, 0.96 pF/m. In the same way as the mutual impedance case, this value is valid for different installation heights and added to the corresponding calculated value in the constants calculation of the proposed modeling method to reproduce a correct value of Z_{0CC}.

C. Modeling Procedure

The procedure for modeling a distribution line equipped with a telecommunication cable described above in detail is summarized here.

Step 1: The line constants of a distribution line with a telecommunication cable are calculated with the equivalent diameter (50 mm), mentioned in Section III-A, of the messenger wire of the telecommunication cable. The surge impedance matrix $[Z_0]$ is obtained as one of the line constants.

Step 2: Among the elements of $[Z_0]$, the mutual surge impedances Z_{0CM} and Z_{0MC} between the tension member of the telecommunication cable and its messenger wire are replaced with the value (213 Ω) obtained by measurement as mentioned in Section III-B.

Step 3: The surge impedance matrix modified in Step 2 is converted into the capacitance matrix $[C]$ using (3) and (4), and then, the increased amount (0.96 pF/m), mentioned in Section III-C, of the self capacitance of the tension member is added to the corresponding element of $[C]$. Then, this is converted back into the surge impedance matrix to be used in the line model.

The values shown in parentheses above are obtained by the surge impedance measurement of the specific telecommunication cable used in this paper. However, these values are usable, since the same telecommunication cables are often used in Japan and the values are in quantities independent from a conductor arrangement. With these three steps, the surge impedance matrix, taking into account the existence of cable hangers, is obtained and it will be used in the line model in lightning-overvoltage.

IV. Comparison with Field Test

In this chapter, simulation results obtained by the proposed model are compared with corresponding field test results for the accuracy validation. The field test results were obtained using the actual-scale test distribution line in Shiobara Testing Yard of CRIEPI.

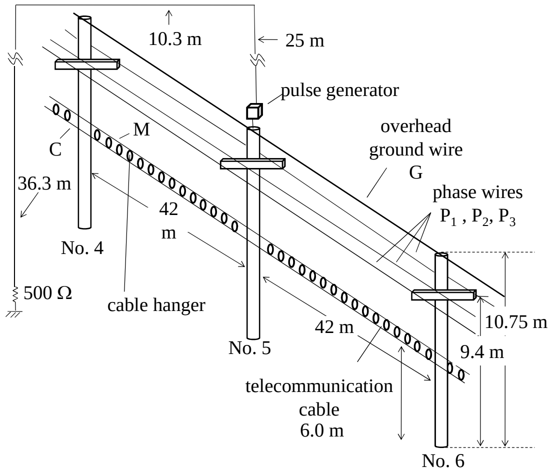


Fig. 6. Experimental setup.

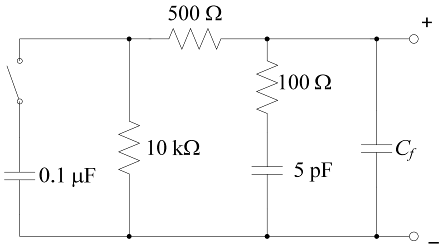


Fig. 7. Equivalent circuit of the pulse generator (PG).

A. Field test Results

A lightning-surge test was carried out using the experimental setup shown in Fig. 6. A lightning stroke to pole No. 5 (see Fig. 1) is assumed, and both ends of the distribution line are terminated by matching resistors for eliminating reflections from the ends. A pulse generator (PG), whose circuit diagram is shown in Fig. 7, is placed at the top of pole No. 5, and a surge current is injected from the 2-mm^2 vinyl-insulated wire representing a lightning channel to the concrete pole. By setting the series resistor of the PG to 500 Ω, the total impedance of the lightning channel seen from the pole top is 1 k Ω, which corresponds to the lightning channel impedance recently obtained by observations [8], [9]. The remote end of the 2-mm^2 wire is terminated by a 500-Ω resistor also for eliminating reflections. The capacitor C_f in the PG is used to adjust the wavefront duration T_f of the injected current. The values 50 pF, 700 pF and 1,500 pF of Cf respectively give the wavefront duration values 0 μs (hereafter referred to as the step current), 0.5 μs and 1 μs. For these three wavefront durations, the waveforms of the injected current, the voltage across the insulator that support the phase wire P_1 (hereafter, simply referred to as the insulator voltage), the current flowing into the overhead ground wire, and the current flowing into the messenger wire of the telecommunication cable were measured. Fig. 8 shows the measured waveforms. It is found that about 20 % of the injected current flows into the messenger wire.

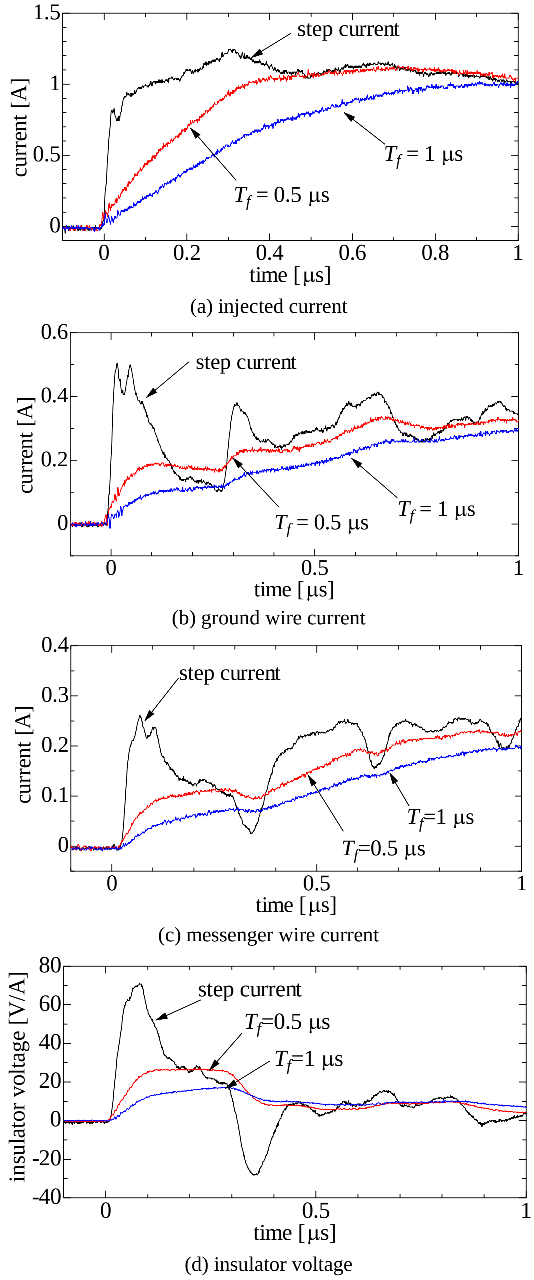


Fig. 8. Measured waveforms obtained by the field test.

B. Calculated Results by the Proposed Model

Fig. 9 shows the simulation circuit around pole No. 5, to which a lightning stroke is assumed (although the circuit diagram shows the distribution line on the right-hand side only, the line also exists on the left-hand side). In the same way, the rest of the circuit, from pole No. 1 to 4 and from No. 6 to 9, is represented as shown in Fig. 1. The internal circuit of the PG is represented as it is shown in Fig. 6. The concrete poles are represented by the simulation model proposed in [2] and [3]. Ref. [2] describes the method for determining the parameters of the model. The voltage sources e_1, e_2 and e_3, representing the time variation of the coupling between the overhead ground wire and the phase wires, are part of the

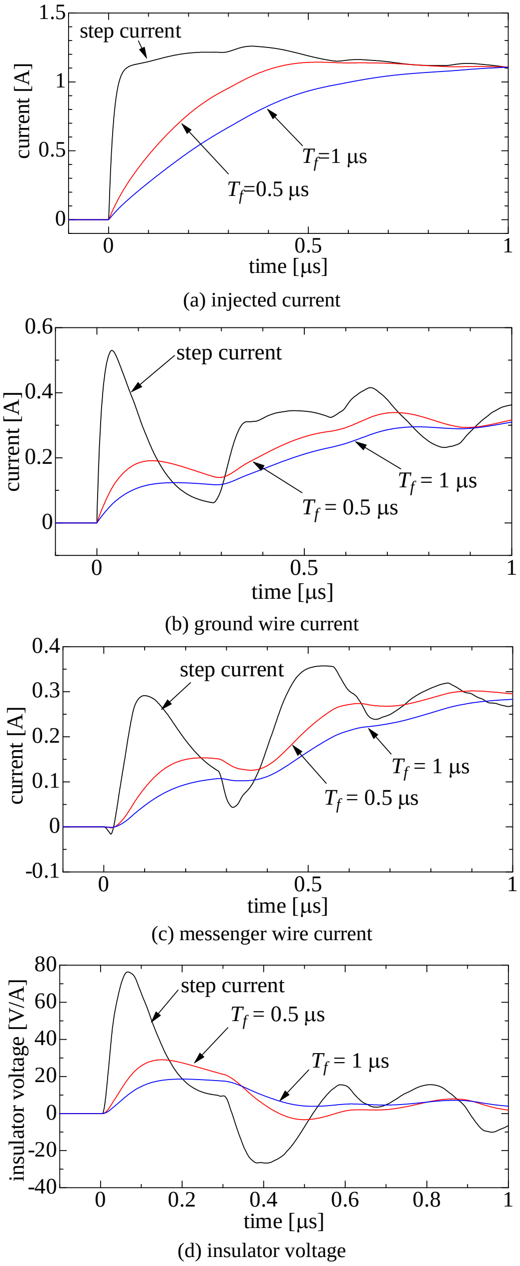


Fig. 10. Calculated waveforms obtained by the proposed model.

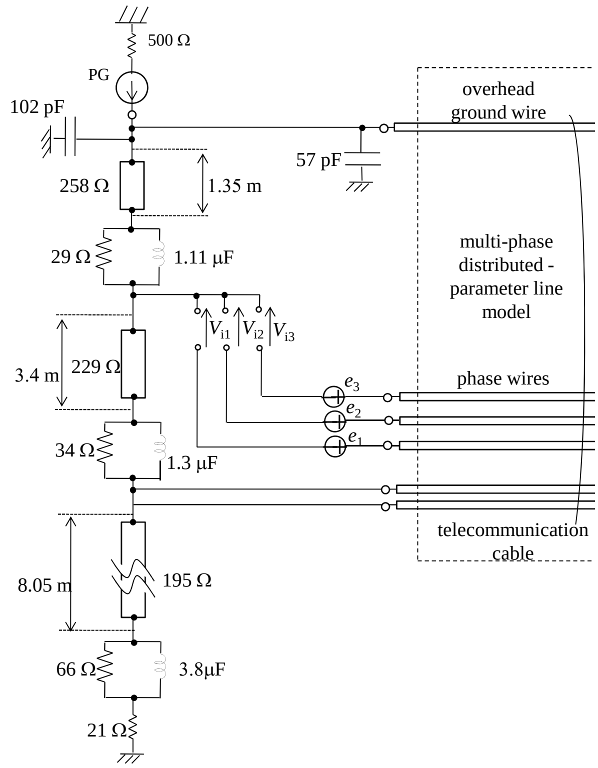


Fig. 9. Simulation model of pole No. 6.

concrete pole model. The overhead ground wire, the phase wires, and the telecommunication cable are modeled together by one multiphase distributed-parameter line model with the line constants obtained in Section III. The line constants were calculated at 100 kHz with a ground resistivity of 1,000 Ωm.

Fig. 10 shows the calculated waveforms. It is clear that the calculated results agree well with the measured ones shown in Fig. 9, in terms of maximum values and transient waveshapes. For the simulation, XTAP, a transient analysis program developed at CRIEPI, was used.

V. Conclusion

This paper has presented the measured surge-impedance matrix of an actual-size test distribution line equipped with a telecommunication cable. Based on the measured data, a method for modeling a distribution line with a telecommunication cable has been proposed. The accuracy of the proposed model has been verified by comparing with field test results. Since the proposed model is sufficiently accurate, it can be used for lightning overvoltage studies of a distribution line equipped with a telecommunication cable.

VI. References

[1] Subcommittee for Power Distribution Systems, Lightning Protection Design Committee: “Guide of Lightning Protection Design for Power Distribution Lines”, CRIEPI Report, No. T69 (2002)

[2] S. Matsuura, T. Noda, A. Asakawa, and S. Yokoyama: “A Distribution Line Model for Lightning Overvoltages Studies”, *IEEJ Trans. PE*, Vol. 128, No. 9, pp. 1139-1149 (2008-9)

[3] S. Matsuura, T. Noda, A. Asakawa, and S. Yokoyama: "Lightning Surge Characteristics of an Actual Distribution Line and Validation of a Distribution Line Model for Lightning Overvoltage Studies", *IEEJ Trans. PE*, Vol. 128, No.9, pp. 1150-1158 (2008)

[4] T. Miyazaki, S. Okabe, K. Aiba, and T. Hirai: “A Study on Observation Results of Lightning Phenomena on Distribution Lines Based on a Lightning-Surge Analysis Model for Direct Lightning Strokes”, *IEEJ Trans. PE*, Vol. 126-B, No. 12, pp. 1295-1303 (2006)

[5] A. Takahashi, S. Furukawa, K. Ishimoto, A. Asakawa, and T. Hidaka, “Influence Of Grounding Resistance On Effectiveness Of Lightning Protection For Power Distribution Lines With Surge Arresters”, *Proc.* of the 30th *Int. Conf. on Lightning Protection (ICLP)*, No. 1057 (2010)

[6] The Institute of Electrical Installation Engineers of Japan: Lightning Protection for Information-oriented and Computerized Society (1999)

[7] H. Sugimoto: “Effect of Overhead Ground Wire Installing under Distribution Lines on Surge Arrester Failures”", *IEEJ Trans. PE*, Vol. 130, No. 5, pp. 529-535 (2010)

[8] Investigation R&D Committee on Lightning Parameters for Insulation and Protection Designs of Power Systems: "Lightning Parameters for

Insulation and Protection Designs of Power Systems", IEEJ Technical Report, No. 1033 (2005)

[9] H. Goshima, H. Motoyama, A. Asakawa, A. Wada, T.Shindo, S. Yokoyama, ”Characteristics of Electromagnetic Field due to Winter Lightning Stroke Current to a High Stack”, Trans. *IEEJ Trans. PE*, Vol. 120, pp44-49 (2000)