Accuracy of Lightning Surge Analysis of Tower Surge Response

Naoki Itamoto, Hironao Kawamura, Kazuo Shinjo, Hideki Motoyama, Masaru Ishii

Abstract**--This paper presents a comparison between the measured and calculated results of tower surge response for verifying the accuracy of lightning surge analysis. These calculated results are obtained using the Finite Difference Time Domain (FDTD) method and the Electromagnetic Transients Program (EMTP).**

Injection current waveforms and voltage waveforms across insulator strings of the transmission tower were measured when a rectangular impulse current or a current with the rise time of 1µs were injected into the top of the tower. The measured waveforms of voltage across insulator strings are compared with the calculated voltage waveforms using the FDTD method. The calculated waveforms can reproduce the measured waveforms, and as a result, it is verified that the FDTD method is effective in a lightning surge analysis.

The influences of the geometrical arrangement of phase wires, the ground resistivity and the slope of ground on the accuracy of a surge simulation are also investigated using the FDTD method. It is clarified that these factors affect the voltages across insulator strings.

Furthermore, the calculated waveforms of voltage across insulator strings using the EMTP are compared with those calculated by using the FDTD method. A simple analysis by the EMTP cannot reproduce the calculated waveforms using the FDTD method. This is due to the difference of the initial electromagnetic field around the transmission tower struck by lightning from the TEM mode, which is the basis of the EMTP analysis.

Keywords**: Lightning surge, Transmission tower, FDTD method, EMTP, Tower surge response**

I. INTRODUCTION

TRANSMISSION line faults caused by lightning strikes give serious damages, such as a massive blackout and instant voltage drop, on electric power systems. Therefore, the rational lightning protection measures should be adopted for ensuring a stable electric power system. Several studies on surge analysis of the transmission lines have been carried out to evaluate the effect of the lightning protection measures and to estimate the lightning outrage rates [1]-[3].

Circuit transient analysis programs, such as the EMTP (Electromagnetic Transients Program), have been employed for lightning surge analyses [4]. However, those programs based on the circuit theory cannot deal with the three-dimensional geometrical structures. Recently, the FDTD (Finite Difference Time Domain) method has been developed for the lightning surge analysis of three dimensional structures [5]-[7]. The FDTD method is a numerical electromagnetic analysis method. The FDTD method can take into account a transient electromagnetic coupling between the tower and overhead wires, and also analyze the imperfect conducting medium such as the ground soil.

In this paper, the measured results of surge response on the 275kV transmission tower are analyzed using both FDTD method and EMTP, and the calculated voltage waveforms are compared with the measured waveforms. The influences of the overhead wire structure, the resistivity of the ground, and the ground inclination are also evaluated using the FDTD method.

II. ANALYSIS OF TOWER SURGE RESPONSE

In this section, comparing the calculated waveforms of the voltage across insulator strings with the measured waveforms, the authors evaluate the accuracy of the surge analysis using the FDTD method.

A. Experiment on Tower Surge Response

An experiment on the tower surge response was carried out on the Okushishiku test transmission line [8]-[11]. Fig. 1 shows the outline of the test line. This test line is designed for the 275kV double-circuit transmission line with one ground wire and six phase wires. The total length of the test line is 2.15 km, which is composed of six spans. All conductors at No. 29 tower are terminated by matching resistance of 500Ω to prevent the reflection of current waves, while all conductors at No. 34 tower are directly connected to cross arms.

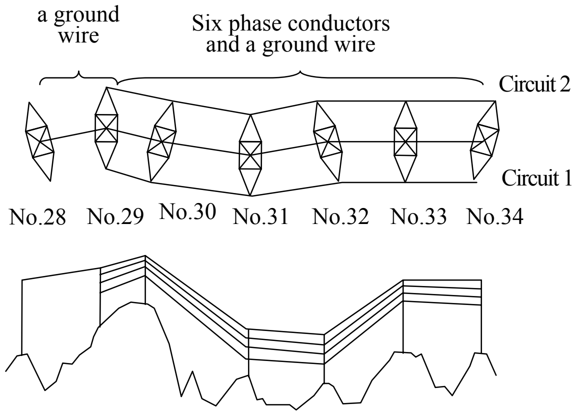
Fig. 2 shows the arrangement of the No. 30 tower for the measurement of the tower surge response. The current was injected into the No. 30 tower by the pulse generator, which was placed at the center of the tower top. The injected current waveform and the voltage waveforms across insulator strings of the tower were measured when a rectangular impulse current or a current with the rise time of 1 µs are injected into the tower top. The overhead ground wire between No. 30 tower and No. 29 tower was used as the current injection wire. The voltage waveforms across the insulator strings of the upper, middle and lower phases were measured simultaneously. The measurements were carried out in two conditions; with or without the overhead ground wire.

Fig. 3 shows the injected current waveforms. One is a

Naoki Itamoto, Hironao Kawamura and Kazuo Shinjo are with Hokuriku Electric Power Company, 2-54, Hisakata-machi, Toyama 930-0848, Japan (e-mail: n.itamoto@rikuden.co.jp). Hideki Motoyama is with Central Research Institute of Electric Power Industry, Yokosuka, Kanagawa 240-0196, Japan (e-mail: motoyama@criepi.denken.or.jp). Masaru Ishii is with Institute of Industrial Science, The University of Tokyo, 4-6-1, Komaba, Megro-ku, Tokyo 153-8505, Japan (e-mail: ishii@iis.u-tokyo.ac.jp).

Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

rectangular impulse current of 0.84A and the other is a current of 0.48A with the rise time of 1 μs.



.No	28	29	30	31	32	33	34
Span Length(m)	505	182	437	297	414	318	
Ground wire(mm^2)	HAS 150	OPGW 170		HAS 150			
Conductor (mm^2)	NONE	IACSR 610					
Tower height(m)	85.3	59.4	59.4	59.4	59.2	61.3	62.4

Fig. 1 Details of the test transmission line

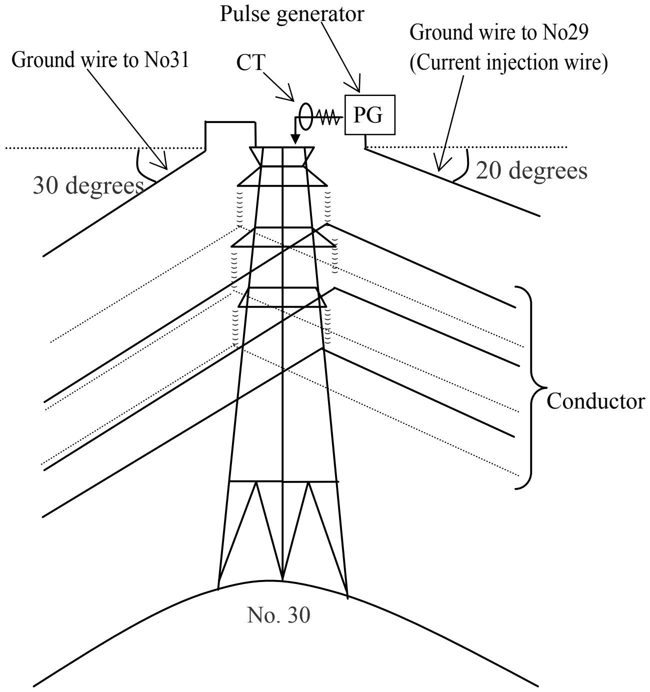


Fig. 2 Measuring set up for tower surge response

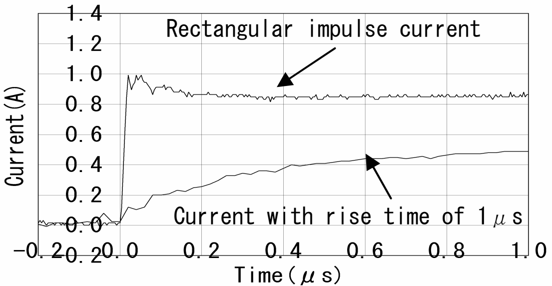


Fig. 3 Injected current waveforms

B. Analysis Using FDTD Method

1) Analysis Method

The experimental results are simulated using a numerical electromagnetic analysis program, the Virtual Surge Test Lab (VSTL) [5]-[7], which is based on the FDTD method. Fig. 4 shows the transmission tower modeled in the VSTL. The space for the analysis is 400m×400m in the horizontal and vertical directions. Space is discretized every 1 m around the tower and every 2m in other volume. The time step is determined to be 4.6 ns based on the Courant's condition. All the surfaces of the analysis space are absorbing boundaries using Liao's formulation of second order. The No. 30 tower is located at the summit of a mountain, as seen in Fig. 1. The conductors stretched from No. 30 tower to No. 29 tower and to No.31 tower are in the downward angles of 20 degrees and 30 degrees, respectively, from the horizontal plane. The steepness of the slope at the summit is from 16 degrees to 26 degrees. The resistivity of the ground soil is set to 500 Ωm.

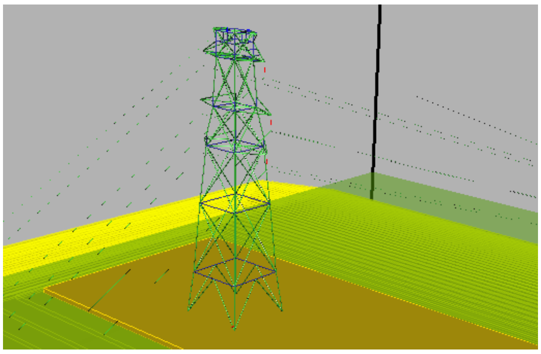
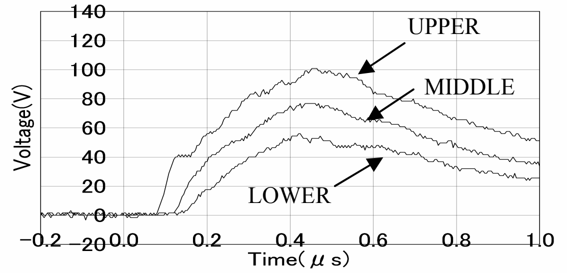


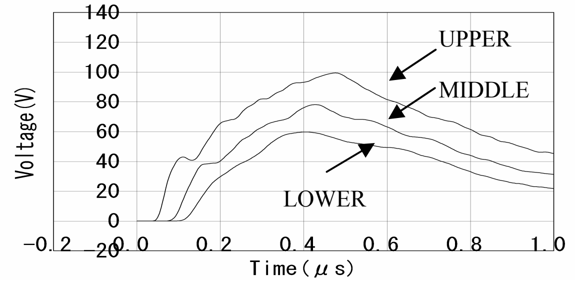
Fig. 4 Transmission tower model in VSTL

2) Analysis Result

Figs. 5 and 6 show the waveforms of the voltage across insulator strings obtained from the measurement without a ground wire. Figs. 5 (a) and (b) show the measured waveforms and the calculated waveforms using the FDTD method when a rectangular impulse current is injected into the top of the tower. The insulator voltages on upper, middle and lower phases started to rise after the current flowing into the tower reached to each arm of the tower. The peak times of the measured waveforms were observed more than 0.4 μs later. They were dominated by the round trip of the traveling wave in the tower. The calculated voltage waveforms using the FDTD method can reproduce the measured waveforms. The difference between the calculated and measured peak values is subtle. Figs. 6 (a) and (b) show the measured waveforms and the calculated waveforms using the FDTD method when a current with the rise time of 1μs injected to the tower. The voltage waveforms calculated using the FDTD method can reproduce the measured waveforms.

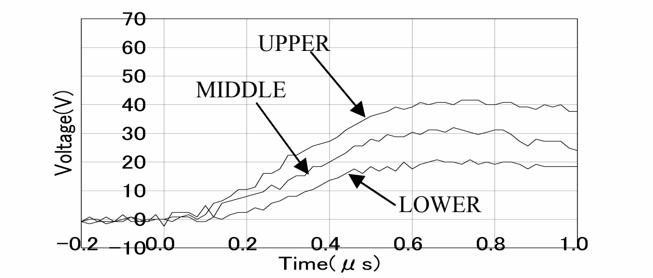


(a) Measured waveform

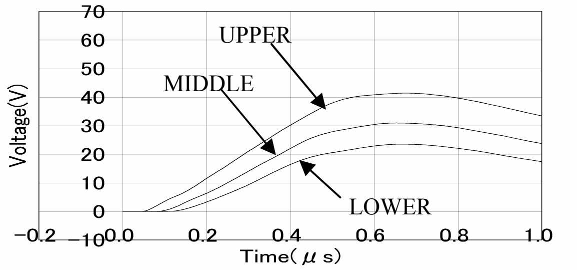


(b) Calculated waveforms

Fig. 5 Voltages across insulator strings without a ground wire (Injected current waveform: Rectangular impulse current)



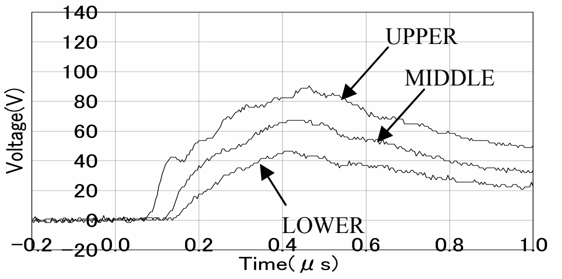
(a) Measured waveforms



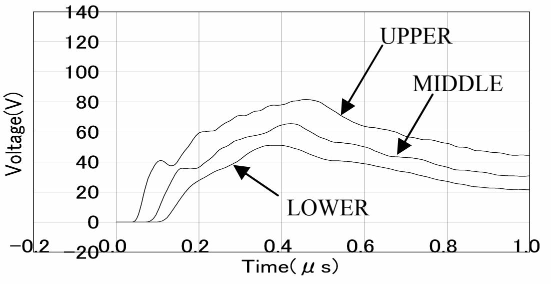
(b) Calculated waveforms

Fig. 6 Voltages across insulator strings without a ground wire (Injected current waveform: Impulse current with rise time of 1 μs)

Figs. 7 and 8 show the waveforms of the voltage across insulator strings obtained in the measurement with a ground wire. Figs. 7 (a) and (b) show the measured waveforms and the calculated waveforms using the FDTD method when a rectangular impulse current is injected into the tower. The effect of the ground wire is seen in the reduced insulator voltages in Fig. 7 (a) from those of Fig. 5 (a). Fig. 7 (b) shows that the measured waveforms are also reproduced by the calculation using the FDTD method. Fig. 8 (b) as well as shows that the calculated results using the FDTD method can reproduce the measured results of Fig 8 (a).

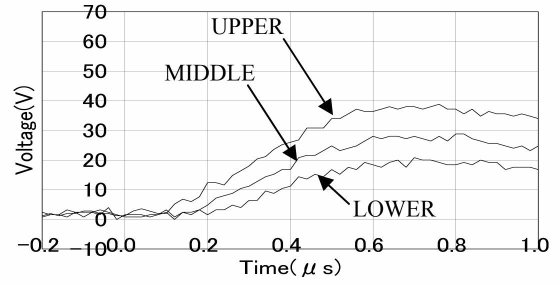


(a) Measured waveforms

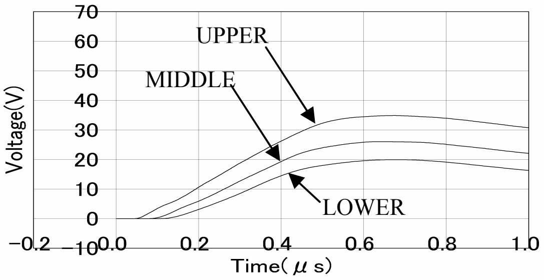


(b) Calculated waveforms

Fig. 7 Voltages across insulator strings with a ground wire (Injected current waveform: Rectangular impulse current)



(a) Measured waveforms



(b) Calculated waveforms

Fig. 8 Voltages across insulator strings with a ground wire (Injected current waveform: Impulse current with rise time of 1 μs)

C. Influence of Geometry of Phase Wires and Ground

1) Influence of Geometry of Phase Wires

The authors have evaluated the influence of the inclination of the phase wires on the voltages across insulator strings using the FDTD method. In this analysis, the ground is modeled by a perfectly conducting plane. Fig. 9 shows calculated waveforms of voltages across the upper insulator string for the case of the horizontal phase wire and for the case of the inclined phase wire, when a rectangular impulse current is injected into the tower top. The angle of the current injection wire from the horizontal plane is at 20 degrees in the case of the inclined phase wire, while that angle is at 0 degree in the case of the horizontal phase wire. The peak value of the insulator voltage is 20% larger in the case of the horizontal phase wire than in the case of the inclined phase wire. The difference is caused by the change of the transient electromagnetic coupling between the phase wire and the transmission tower. This result shows that the angle of an overhead phase wire influences the insulator voltage.

2) Influence of Ground Resistivity

The authors have evaluated the influence of ground resistivity on the voltage across insulator strings using the FDTD method. In this evaluation, the phase wire is stretched horizontally and the surface of ground is a horizontal plane. Fig. 10 shows the calculated waveforms of voltages across the upper insulator string for the two types of ground resistivity, 0 and 500 Ωm, when a rectangular impulse current is injected into the tower top. Both voltage waveforms are the same until the reflection from the tower foot reaches the upper arm of the tower (t=0.45μs). After the reflection reaches the upper arm, the insulator voltage for the case of 500-Ωm soil decays slower than the case of 0-Ωm soil. This clearly shows the influence of the ground resistivity on the waveform of insulator voltages.

3) Influence of Inclination of Ground

The authors have evaluated the influence of inclination of ground on the voltage across insulator strings using the FDTD method. In this evaluation, the phase wire is stretched horizontally and the ground resistivity is set to 0 Ωm. Fig. 11 shows the calculated waveforms of voltages across the upper insulator string for the two conditions of ground, namely the horizontal ground and the sloped ground, when a rectangular impulse current is injected into the tower top. After the reflection from the tower foot reached the upper arm of the tower, the voltage calculated for the case of the sloped ground decays slower than that for the case of the horizontal ground. The ground inclination affects the voltage across insulator strings as well as the ground resistivity.

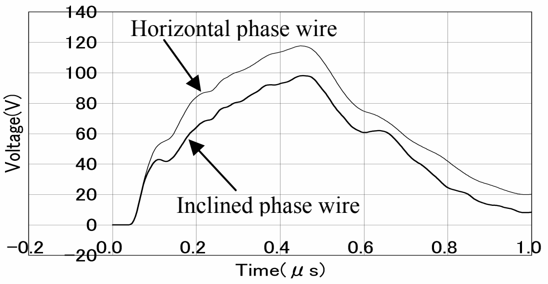


Fig. 9 Calculated waveforms of voltages across the upper insulator string without a ground wire for the cases of the horizontal phase wire and the inclined phase wire

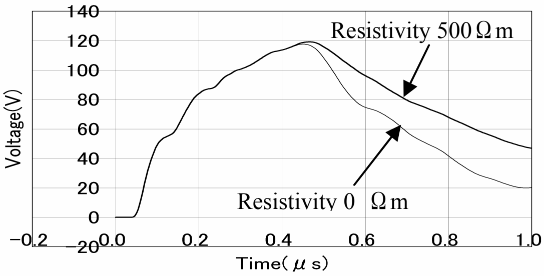


Fig. 10 Calculated waveforms of voltages across upper insulator string without a ground wire for the cases of ground resistivity 0 and 500 Ωm.

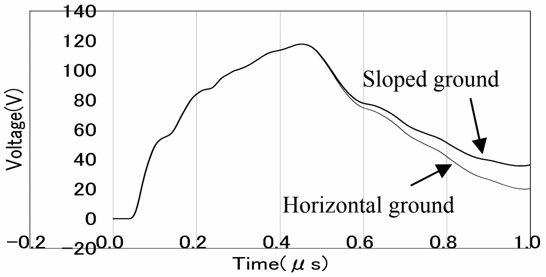


Fig. 11 Calculated waveforms of voltages across upper insulator string without a ground wire for the cases of horizontal ground and sloped ground

III. ANALYSIS USING EMTP

In this section, the accuracy of the surge analysis using EMTP is evaluated through comparison with the calculated results using the FDTD method. In this evaluation, phase wires are stretched horizontally and ground is regarded as a perfectly conducting plane.

A. Analysis Method

J. Marti model of 7 phases is employed in the EMTP analysis to simulate the frequency-dependent characteristics of a multi-phase transmission line. The transmission tower is modeled by the multistory tower model [12] as shown in Fig. 12. The parameters of the tower model are shown in Table1. The surge impedance of the tower is set to 80Ω in order to produce the same current value flowing into the ground wire in the calculations using the FDTD method.

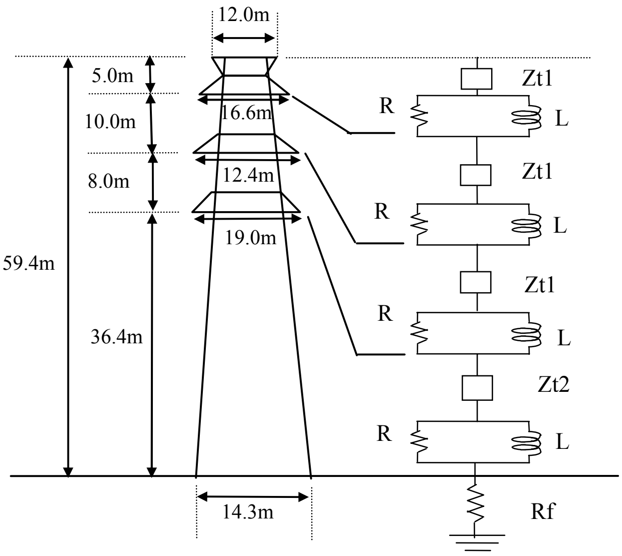


Fig. 12 Multistory tower model in EMTP analysis

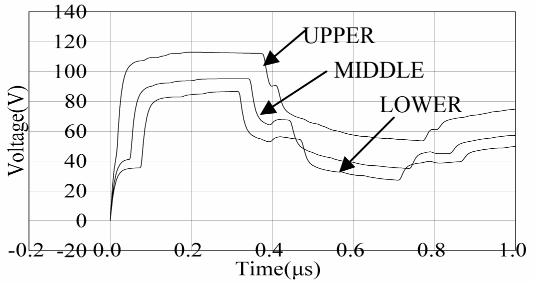
TABLE 1
TOWER MODEL CONSTANTS OF THE TRANSMISSION LINE.

Tower surge impedance	Zt1	80Ω
	Zt2	80Ω
Surge propagation velocity	Vt	300m/μs
Time constant	L/R	2H/Vt
Attenuation coefficient	Γ	0.8
Tower footing resistance	Rf	0Ω

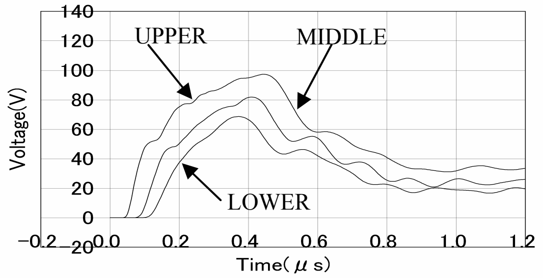
B. Analysis Results

Fig. 13 (a) shows the calculated waveforms of the voltage across insulator strings using the EMTP and Fig. 13 (b) shows that using the FDTD method when a rectangular current is injected into the tower top. The calculated waveforms using the EMTP are step-like waveforms and cannot reproduce the calculated waveforms with slow rise and decay using the FDTD method. These results show that the initial electromagnetic field around the tower is quite different from the TEM (Transverse Electromagnetic) mode, which is the basis of the EMTP analysis.

Fig. 14 (a) and 14 (b) are the calculated voltage waveforms when a current with the rise time of 1 μs is injected into the tower top. Fig. 14 (a) shows that the rise time of the calculated waveforms using EMTP is approximately 0.4μs, which is shorter than that using the FDTD method shown in Fig. 14 (b). The difference of the peak voltage is due to the smaller coupling coefficient between the ground wire and a phase wire in the non-TEM mode than in the TEM mode [13]. The multistory tower model compensates this effect by assuming higher tower surge impedance [12].

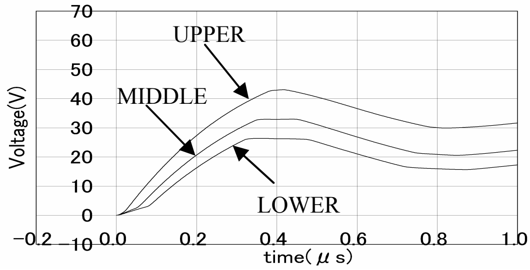


(a) Calculated waveform using EMTP

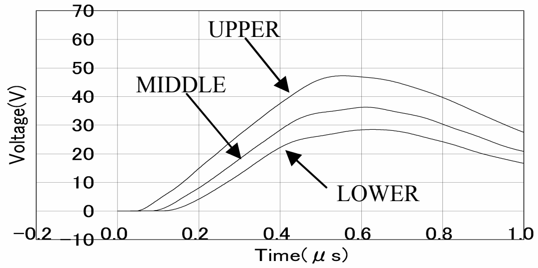


(b) Calculated waveform using FDTD method

Fig. 13 Voltages across insulator strings with a ground wire for rectangular current injection



(a) Calculated waveform using EMTP



(b) Calculated waveform using FDTD method

Fig. 14 Voltages across insulator strings with a ground wire for injection of current having rise time of 1 μs

IV. CONCLUSIONS

This paper discusses the accuracy of lightning surge analyses of tower surge response using the FDTD method and EMTP. The conclusions are as follows.

1) The calculated waveforms of voltages across insulator strings using the FDTD method can reproduce well the measured waveforms when a rectangular impulse current or a current with the rise time of 1 μs are injected into the tower top. It is verified that the FDTD method is effective in

the lightning surge analysis.

2) Inclination of a phase wire, ground resistivity, and slope of ground influence the voltage across an insulator string. Therefore, the geometrical arrangement of a transmission tower and phase wires should be taken into account carefully for the accurate analysis of lightning surges on transmission lines.

3) The calculated waveforms of voltages across insulator strings by a simple EMTP analysis differ from the calculated waveforms using the FDTD. This is due to the difference of the initial electromagnetic field from the TEM mode, which is the basis of the EMTP analysis. A more sophisticated model is necessary for an accurate surge analysis by EMTP.

V. ACKNOWLEDGMENT

The authors would thank the help and advice received from Drs. Taku Noda and Akiyoshi Tatematsu of CRIEPI.

VI. REFERENCES

[1] Y. Aihara, et al., “Development of a New Calculation Program for the Lightning Outage Rate of Transmission Lines,” CRIEPI Report T01006, 2001

[2] T. Wakai, N. Itamoto, T .Sakai, M. Ishii, “Evaluation of Transmission Line Arresters against Winter Lightning, “IEEE Trans. Power Delivery, vol. 15, no. 2, pp.684-690, April 2000

[3] H. Kawamura, K. Shinjo, T. Araya, ”Evaluation of Lightning Outage Rate Considering Line Surge Arrester Failure,” Trans. IEE Japan, vol. 125-B, no. 7, pp.723-727, 2005 (in Japanese)

[4] http://www.emtp.com

[5] T. Noda. S. Yokoyama, "Development of a General Surge Analysis Program Based on the FDTD Method," Trans. IEE Japan, vol. 121-B, no. 5, pp.625-632, 2001 (in Japanese)

[6] T. Noda, S. Yokoyama, "Thin Wire Representation in Finite Difference Time Domain Surge Simulation", IEEE Trans, Power Delivery, Vol. 17. no. 3, pp.840-847, July 2002

[7] T. Noda, A. Tatematsu, S. Yokoyama, "Improvements of an FDTD-Based Surge Simulation Code and its Application to the Lightning Overvoltage Calculation of a Transmission Tower," Proc. IPST (Int. Conf. on Power Syst. Transients) 2005, Paper # IPST05-138

[8] K. Shinjo, “Characteristics of Transients Response of Okushishiku Test Transmission Line Struck by Natural and Triggered Lightning,” Trans. IEE Japan, vol. 117-B, no. 4, pp.478-487, 1997 (in Japanese)

[9] H. Motoyama, K. Shinjo, Y. Matsumoto, N. Itamoto, “Observation and Analysis of Multiphase Back Flashover on the Okushishiku Test Transmission Line caused by Winter Lightning,” IEEE Trans. Power Delivery, vol. 13, no. 4, pp.1391-1398, October 1998

[10] Y. Matsumoto, O. Sakuma, K. Shinjo, M. Saiki, T. Wakai, T. Sakai, H. Nagasaka, "Measurement of Lightning Surges on Test Transmission Line Equipped with Arresters Struck by Natural and Triggered Lightning," IEEE Trans. Power Delivery, vol. 11, no. 2, pp.996-1002, April 1996

[11] N. Itamoto, K. Shinjo, T. Wakai, T. Sakai, H. Motoyama, M. Ishii, "Observation of Winter Lightning at the 275kV Okushishiku Test Transmission Line," Proc. ISH’97, Montreal, vol. 5, pp.59-62, 1997

[12] M. Ishii, T. Kawamura, T. Kouno, E. Ohsaki, K. Murotani, T. Higuchi, "Multistory Transmission Tower Model for Lightning Surge Analysis," IEEE Trans. Power Delivery, vol. 6, no. 3, pp.1327-1335, July 1991

[13] Y. Baba, M. Ishii, "Numerical Electromagnetic Field Analysis on Lightning Surge Response of Tower with Shield Wire," IEEE Trans. Power Delivery, vol. 15. no. 3, pp.1010-1015, July 2000