Accuracy of Lightning Surge Analysis of Tower Surge Response

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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 1 µs 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 method 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 were 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 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 tower surge response were directly connected to cross arms.

Fig. 3 shows the injected current waveforms. One is a
Developing 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.
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 1 µs injected to the tower. The voltage waveforms calculated using the FDTD method can reproduce the measured waveforms.

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).
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.

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 Table 1. 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.

<table>
<thead>
<tr>
<th></th>
<th>Zt1</th>
<th>Zt2</th>
</tr>
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<tbody>
<tr>
<td>Tower surge impedance</td>
<td>80Ω</td>
<td>80Ω</td>
</tr>
<tr>
<td>Surge propagation velocity</td>
<td>Vt</td>
<td>300m/µs</td>
</tr>
<tr>
<td>Time constant</td>
<td>L/R</td>
<td>2H/Vt</td>
</tr>
<tr>
<td>Attenuation coefficient</td>
<td>Γ</td>
<td>0.8</td>
</tr>
<tr>
<td>Tower footing resistance</td>
<td>Rf</td>
<td>0Ω</td>
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</tbody>
</table>

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].

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.

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VI. REFERENCES