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RESEARCH ARTICLE

Experimental and Analytical Studies on Lightning Surge Response of the Quadruple-Circuit Transmission Line

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ABSTRACT The compact design of a 500 kV quadruple-circuit transmission line can effectively reduce the line corridor area, but the height of the tower also increases, increasing the probability of suffering a lightning strike. The 500 kV quadruple-circuit transmission lines carry more energy, and because of this, lightning strikes that cause power line trips are more likely to result in large-scale power outages. Therefore, it is necessary to make an accurate assessment of the lightning performance of 500 kV quadruple-circuit transmission lines. First, simulated lightning-striking experiments were carried out on a scaled 500 kV quadruple-circuit transmission line in the laboratory, where transient voltages and currents were measured. Second, a numerical model was established with the Finite-Difference Time Domain (FDTD) method, which was then verified with the experimental results. Third, lightning surge responses of a 500 kV quadruple-circuit transmission line under near-real facility conditions are estimated with the verified FDTD model. In the simulations, influencing factors, such as the rise time of injecting current, the velocity of return-stroke current and the terrains, were taken into consideration, but not in previous lightning surge analysis with the Electromagnetic Transients Program (EMTP). Results show that insulator voltages on the same tower cross-arm are nearly identical, although the length of the cross-arm is large enough. Furthermore, it is found that the rise time and the lightning current velocity have great effects on the lightning surge response, and the terrains are less impactful but not negligible. Therefore, these factors should be considered carefully where higher accuracy lightning protection design is necessary.

INDEX TERMS FDTD, lightning protection, lightning surge response, quadruple-circuit tower, reduced-scale experiment.

I. INTRODUCTION

The 500 kV quadruple-circuit transmission line can significantly reduce transmission corridor width and enhance transmission capacity per unit corridor [1], [2], which has been widely used in China in recent years. However, the increased height of the tower makes it more likely to be struck by lightning, and the increased number of circuits makes it more likely that multiple circuit lines may trip together. Therefore, lightning striking a 500 kV quadruple-circuit transmission line may result in large-scale power outages. To maintain grid stability, it is necessary to make an accurate assessment of the lightning surge response of 500 kV quadruple-circuit transmission lines.

The Electromagnetic Transients Program (EMTP) [3], [4], [5], which is based on the circuit theory assuming a

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transverse electromagnetic (TEM) mode wave propagation, has been widely applied to study the lightning performance of transmission lines. In an EMTP model, the transmission tower is usually equated into multiple impedance models [6], [7], [8], [9] which can be easily interfaced with EMTP. However, when traveling downward along a transmission tower, the lightning surge is an electromagnetic (EM) wave [10], while not a TEM wave. Such equivalence may introduce a large error, especially for a 500 kV quadruple-circuit tower with more complex structures.

To address this issue, the numerical EM field simulation methods, such as the Finite-Difference Time Domain (FDTD) method and the Method of Moment (MoM) [11], [12], [13], [14], [15], [16], are preferred to fully consider the Maxwell equations and accurately estimate the fast surge response in complex structures. The FDTD method can efficiently handle complex materials especially including ground effect and is easy to be programmed [17]; while the MoM is more difficult to deal with the three-dimensional current distribution in the imperfectly conducting medium and is more difficult to be programmed [18]. Therefore, scholars [11], [12], [13], [14], [15] preferred the FDTD method to analyze the lightning surge of transmission lines. In these works, scholars have written their own code to implement the FDTD model, and no commercial software is available. For this reason, the FDTD codes were always verified with the small-scaled [12], [19], [20], [21] and full-size experiments [13], [22] before it was used to analyze the surge response of the transmission line.

In this paper, we will also write our own code to implement the FDTD model for analyzing the lightning surge response of the 500 kV quadruple-circuit transmission line. Scaled experiments are first carried out to evaluate the accuracy of the FDTD model. With the verified model, the lightning surge response of the 500 kV quadruple-circuit transmission line is calculated, considering the effect of factors such as the rise time of lightning current, the velocity of the return-stroke current, and the terrains.

II. SMALL-SCALED EXPERIMENTS

Experiments were carried out on a reduced-scale 500 kV transmission line with quadruple circuits on a single tower, which is shown in Figures 1a and 1b. Note that the simulated experiments were not scaled down strictly in accordance with the actual lightning striking the transmission line. The reason is that the simulated experiments are only intended to verify the accuracy of the FDTD model, not to extrapolate the experimental results in equal proportions. This simply requires a similar structure and excitation source. More importantly, the experimental conditions limited the construction of the test platform. Limited by the size of the test site, the quadruple-circuit tower was a 1/33-scale model of the actual tower, which was constructed with carbon steel. Three such towers were placed on a 2 × 17 m^2 virtual ground made of aluminum plate. Copper wires with a diameter of 0.9 mm were used as the overhead ground lines and power lines because it was too thin to break and too thick to be stiff for placement. The virtual ground wires were connected directly to the tower corners, while the virtual power lines were hung below the cross-arms by means of epoxy insulators. All power lines at No. 1 and No. 3 towers were not terminated by matching resistance. That is due to the fact that the reflections from adjacent towers arrive at the concerned No. 2 tower with a delay of more than 50 ns and appear after the tower surge response peak, i.e., their influence is negligible in evaluating the tower surge response.

TABLE 1. Specification of measuring equipment.

Equipment	Type	Specification
Digital oscilloscope	Tektronix, DPO4104B-L	Frequency range: 1 GHz Sampling Rate: 5 GS/s
Current monitor	Pearson, 2877	Bandwidth: 300 Hz - 200 MHz Useable rise time: 2 ns
Differential probe	Tektronix, THDP0200	Bandwidth: 200 MHz Input capacity: < 2 pF

To simulate a lightning strike on a tower, a steep current wave was injected into the tower top from a remote pulse generator (PG) with a rise time of 10 ns through a coaxial cable. Observe that choosing such a fast-rising waveform was to validate the FDTD model over a wider frequency range as the minimum rising time was 100 ns for subsequent studies of the effect of rise time. A 1-kΩ resistor was inserted between the ground line at No. 2 tower and the core wire of the coaxial cable, which was used to smooth the injected current. Note that the cable sheath near the top of the tower should be open. In such a configuration, it was equivalent to a pulse source installed at the top of the tower, and positive and negative currents were injected into the tower and the cable sheath, respectively [20]. The pulse generator was at a height of 4.0 m from the virtual ground and insulated from the ground. Note that the pulse source can be also connected to the tower top with a simple conductor. In such a case, the pulse source in the simulation should be located exactly in the place where it is located in the experiment. The injected current, insulator string voltage and cross-arm voltage of No. 2 tower were measured with the equipment in Tab. 1.

III. FDTD MODEL VERIFICATION

Figure 2 shows the visualization of the established FDTD model in this paper, in which conductors were laid out to reproduce the reduced-scale experiment setup. Note that the current source in the model was placed on the top of the No. 2 tower and connected to it by a 1-kΩ resistor, which was not the same as the experimental arrangement, but could be considered equivalent to the experimental circuit. A 2-pF capacitor was inserted between the tower top and the voltage reference wire, simulating the total input capacitance of the differential probe and the lead line. The analysis space was 16 × 8 × 14 m^3 with a cell size of 0.05 m and

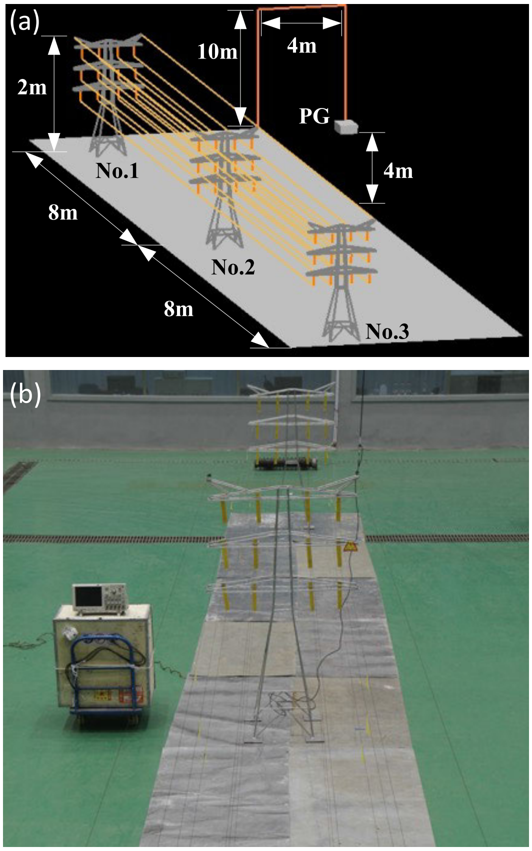

FIGURE 1. **Experimental setup of 500 kV transmission lines with quadruple-circuit on a single tower with reduced-scale model. (a) Overall view and (b) Picture of reduced-scale model.**

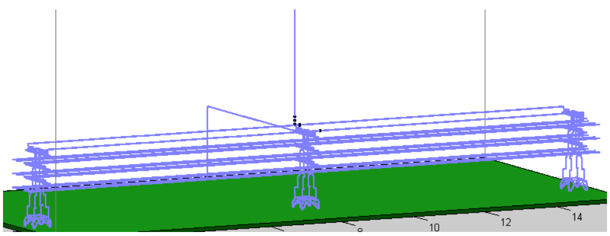

FIGURE 2. **Transmission line model used for the FDTD simulation to reproduce the experimental results.**

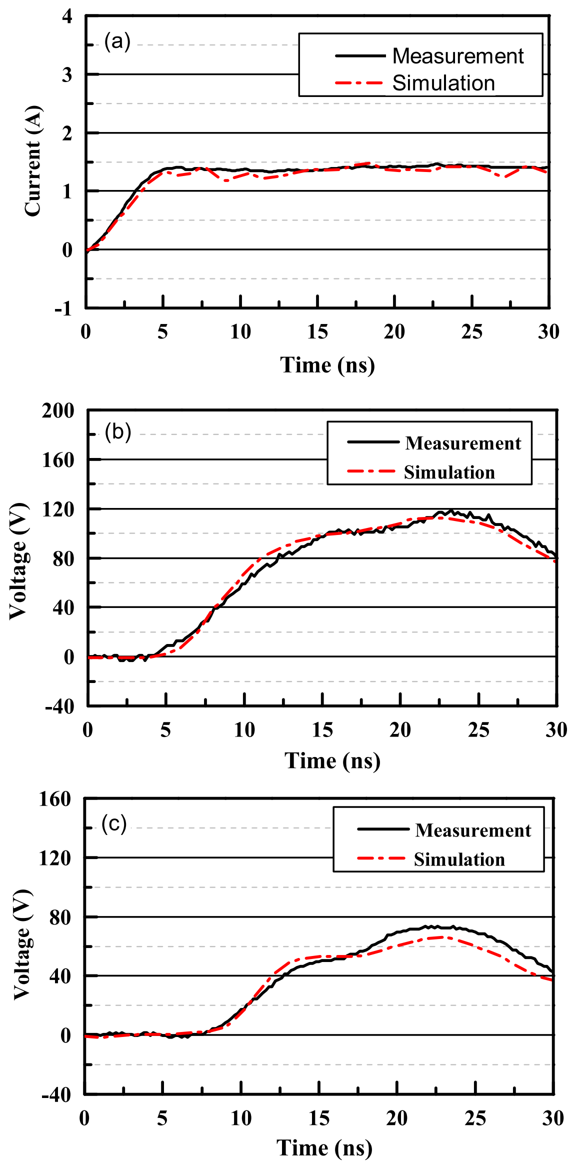

FIGURE 3. **Comparison of experimental results using reduced-scale model and the simulation results through FDTD method. (a) Injected current waveforms. (b) Voltage of the upper phase arm. (c) Voltage of the insulator strings.**

all boundary surfaces were Liao's second-order absorbing boundary conditions [23].

Figures 3 show the injected current and the voltage of the upper tower cross-arm and insulator string of No. 2 tower. The calculated results agree well with the measurements except for a small difference. The errors may be due to the measuring system used in the field test, the difference between configurations of the experimental setup and the model used for the FDTD simulation. In general, the measured waveforms have been reproduced by the FDTD method with satisfactory accuracy.

IV. ACTUAL SCALE TRANSMISSION LINE ANALYSIS

A. ANALYSIS CONDITIONS

The surge responses of a vertically suspended 500 kV quadruple-circuit line are concerned in this study, which has been used in China in the last several years. The actual quadruple-circuit tower structure is shown in Figure 4. To reduce the calculation space and thus the calculation time, only two spans on both sides of the tower are considered and are set at 360 m. However, the actual line length is much longer than this, and to simulate the actual situation, all the ground lines and power lines are extended to the absorbing boundary. The grounding system of the towers plays an important role in the surge response simulation [23], [24]. In our model, the actual grounding system is not considered, but is reduced to four conductors of 2-m length located at each tower foot.

The surge responses at various tower parts are concerned in this study, especially, the voltage of each tower cross-arm,

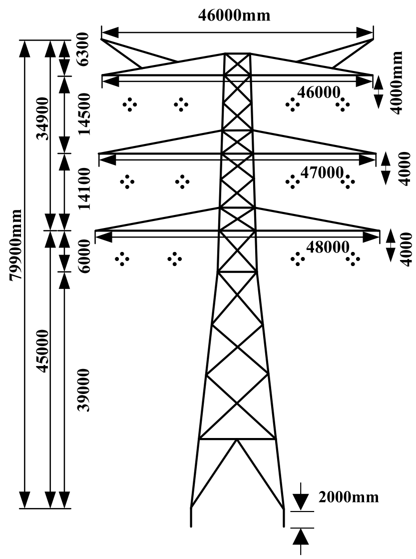

FIGURE 4. Actual scale model of quadruple-circuit tower.

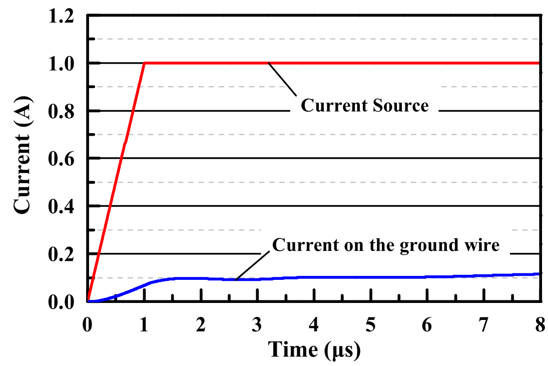

FIGURE 5. Waveform of current source simulating a lightning and flowing through ground wire.

the voltage of the outer power line and the voltage of insulator strings (or power line to tower cross-arm voltage). In our model, these voltages are calculated by the following methods. First, the tower cross-arm voltage is defined as the horizontal integration of the electrical field vertical to the tower and line directions from the absorbing boundary to the cross-arm. Second, the power line voltage is defined as the horizontal integration of the electrical field from the absorbing boundary to the power line. Third, the V type of the insulator string is always used in an actual 500 kV quadruple-circuit transmission line. Considering that the flashover always occurred along the air gap between the power line and the cross-arm above, the voltage of the insulator string is defined as the vertical integration of the electrical field from the power line to the cross-arm above.

The base case started with a calculation as follows. The analysis space was 800 × 100 × 200 m^3. In the pre-simulations, spatial cells of 2 m, 1 m and 0.5 m were used separately. The results showed that the cell size had an effect, while the maximum difference in amplitude did not exceed 5%. However, with a cell size of 1 m, the calculation took over 8 times longer than that with a cell size of 2 m, i.e., several hours to calculate a single case. By trade-off between efficiency and accuracy, a cell size of 2 m was used for all following simulations in this paper. Liao's second-order absorbing boundary was used in the model [25]. To simulate a lightning path, the current source was laid out in a vertical perfectly conducting wire, which was embedded in an 8 × 8 m^2 dielectric parallelepiped of $\varepsilon_r = 9$ surrounded by air. In this way, the return stroke current could propagate at a speed of 0.67c [26]. It is recommended to insert a several-hundred-ohm lumped resistor between the lightning channel and the tower to simulate a more realistic current reflection coefficient at the top of the tower [27]. An 800-Ω lumped resistor was applied in our model as it is the typical equivalent impedance of the lightning channel. The ground resistivity was set to 1000 Ω · m. The simulations were run on a desktop PC (Intel(R) i7-9750H@2.60 GHz, 16 GB RAM) and took around 30 minutes for a single case.

A trapezoidal waveform current with a rise time of 1.0 μs and an amplitude of 1 A was applied in all simulations. Observe that the trapezoidal waveform is different from the actual lightning, but such a waveform is better for understanding the surge response characteristics, i.e., the refraction and reflection of the lightning waves. Figure 5 shows the waveform of the current source, together with the calculated current waveforms flowing through the overhead ground wire.

In our simulations, the overvoltage was calculated without considering the effect of the AC voltage. Note that the AC voltage cannot be ignored when analyzing the lightning performance of transmission lines as it affects crucially the phase insulators that will flashover [24], [28], especially for lines of high AC voltage as the investigated one.

B. SURGE RESPONSES CHARACTERISTICS

Figure 6 shows the simulation results under the above basic conditions. In Figure 6a, the maximum value of the tower cross-arm voltage is nearly 3 times larger than that of the outer power lines. It means that the insulator string voltage depends more on the tower cross-arm voltage, although the time reaching the peak is different between the cross-arm voltage and power line voltage.

Figure 6b plots the insulator string voltages, which are the difference between the cross-arm voltages and the corresponding power line voltages. Note that the insulator string voltage is affected by the electric field due to the current flowing through the tower. In this case, the electrical field in a vertical direction between the power line and cross-arm has also been integrated; however, its magnitude proves to be small [10]. The insulator string voltages at the same tower cross-arm are almost identical, especially for the upper phase. Therefore, multi-circuit flashover simultaneously may occur when lightning strikes the tower.

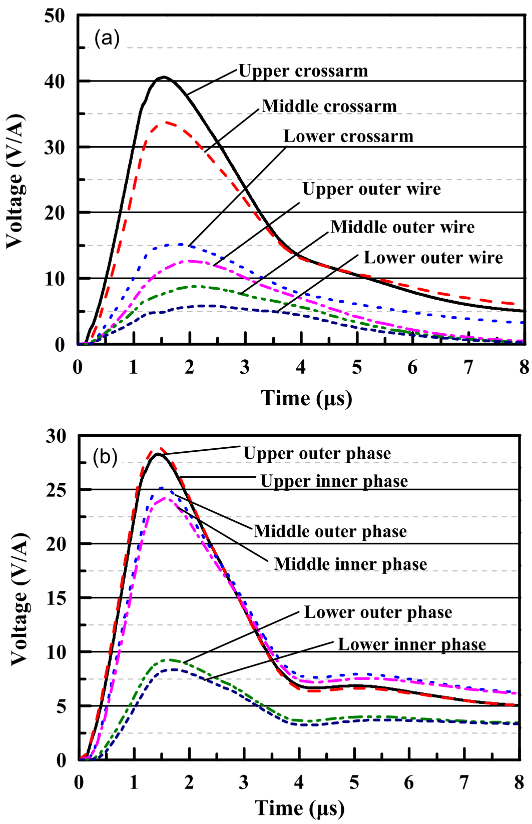

FIGURE 6. Voltage waveforms in the basic case. (a) Voltage of the tower cross-arms and outer power lines and (b) Voltage of the insulator strings.

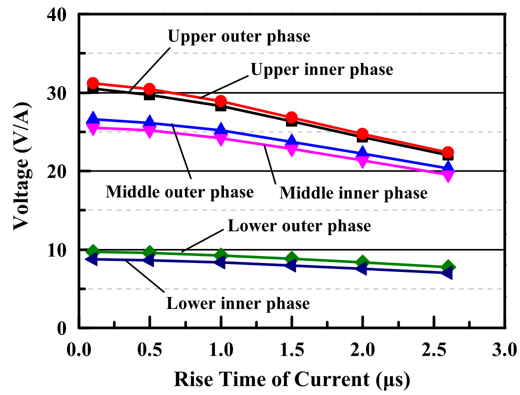

FIGURE 7. The maximum voltage of insulator strings as a function of the rise time of current.

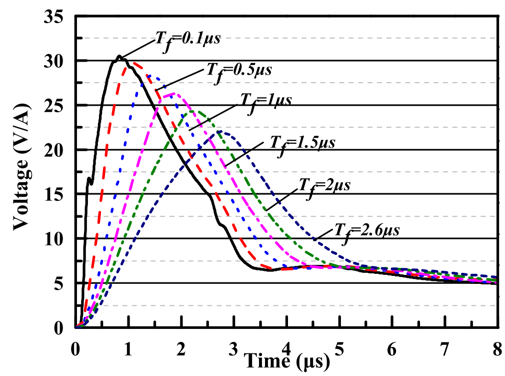

FIGURE 8. Upper outer insulator string voltage over different front time.

C. INFLUENCE OF CURRENT RISE TIME

The rise time of the current source is an important factor in determining the surge response of a transmission tower in practice. In this section, current waveforms with rise times of 0.1, 0.5, 1, 1.5, 2 and 2.6 μs are employed. Figure 7 shows the relationship between the maximum value of insulator string voltage with the rise time of the current source. The peak value of insulator string voltage decreases in inverse proportion to the rise time, namely by about 28%, 24% and 20% for the upper, middle, and lower phases respectively when the rise time is from 0.1 μs to 2.6 μs.

Figure 8 presents the insulator string voltages for the upper outer phase corresponding to different rise times. It can be included that as the current rise time increases, the peak insulator string voltage gradually decreases, specifically, the rise time increases from 0.1 to 2.6 and the peak voltage decreases by about 26.7%. Furthermore, as the current rise time increases, the time for the insulator string voltage to reach its peak gradually increases. Observe that a flashover model should be considered when discussing the effect of current waveshape on the lightning performance of an overhead line.

D. INFLUENCE OF RETURN-STROKE CURRENT VELOCITY

In the conventional simulations, the return-stroke current speed is always set to c. However, the typical return-stroke current speed is ranging from $c/3$ to $2c/3$ [26]. In this section, the effect of the return-stroke current velocity on the lightning surge response is examined with the FDTD model. Different speeds ($0.59c$ to c) are simulated by assuming the relative permittivity of the 8×8 m^2 dielectric parallelepiped in the range from 50 to 1. Figure 9 shows the maximum insulator string voltage as a function of the return-stroke current velocity. The peak value of insulator strings voltage decreases rapidly in proportion to the value of return-stroke current speed, namely by about 48%, 47% and 46% for the upper, middle, and lower phases respectively when the speed is ranging from c to $0.59c$. The reason may be that the space horizontal electric field drops rapidly with the increase of current velocity in the lightning channel [29], accordingly, resulting in a sharp reduction in the induced voltage of the phase conductor and an increase in the insulator string voltage.

Figure 10 plots insulator string voltage waveforms for upper outer phases corresponding to different speeds of the return-stroke current. It can be seen that the return-stroke current velocity has a great effect on the tower lightning surge response, specifically, the front time, the tail time and the amplitude, which are important for the flashover process of the insulator string. Therefore, the return-stroke current speed should be considered properly for the lightning performance estimation and the lightning protection design.

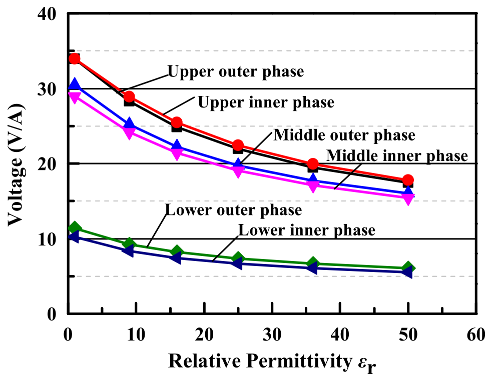

FIGURE 9. The maximum value of the insulator string voltage as a function of the return-stroke current velocity.

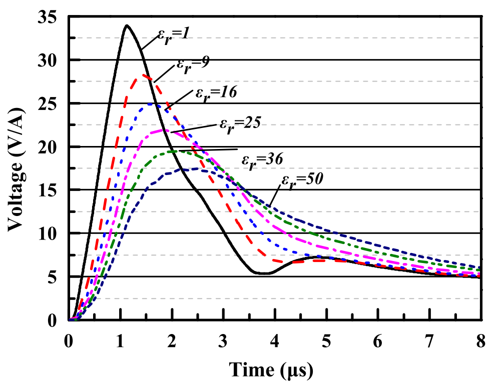

FIGURE 10. Upper outer insulator string voltage over different return-stroke current velocity.

E. INFLUENCE OF ANGLE OF TRANSMISSION LINE

In the actual project, configurations of transmission lines are not the same in different terrains, which may also affect the lightning surge response. Three different terrains are considered, i.e., plain, mountaintop and mountain slope.

On the plain, horizontal angles are formed when the direction of the transmission line should be changed. The horizontal angle is defined as α in the top right corner of Figure 11a, which is set to be 0° to 25° at 5° intervals in the simulations. Figure 11a shows the relationship between horizontal angle and insulator strings voltage. It can be concluded that the maximum value of insulator string voltage decreases with an increase of the horizontal angle, namely by about 15%, 15% and 24% for the upper, middle, and lower phases respectively when the horizontal angle is from 0° to 25°.

While on the mountains, there are two kinds of configurations of transmission lines shown in the top right corners of Figures 11b and 11c, and their corresponding vertical angles are defined as β and θ respectively. Both angles, i.e., β and θ, are set to be 0° to 8° at 2° intervals in the simulations. Simulation results show that the maximum value of insulator string voltage decreases when the vertical angles become larger, namely by about 7.2%, 7.4% and 12% for the upper, middle, and lower phases respectively in Figure 11b, and 4.8%, 4.9% and 6.2% in Figure 11c.

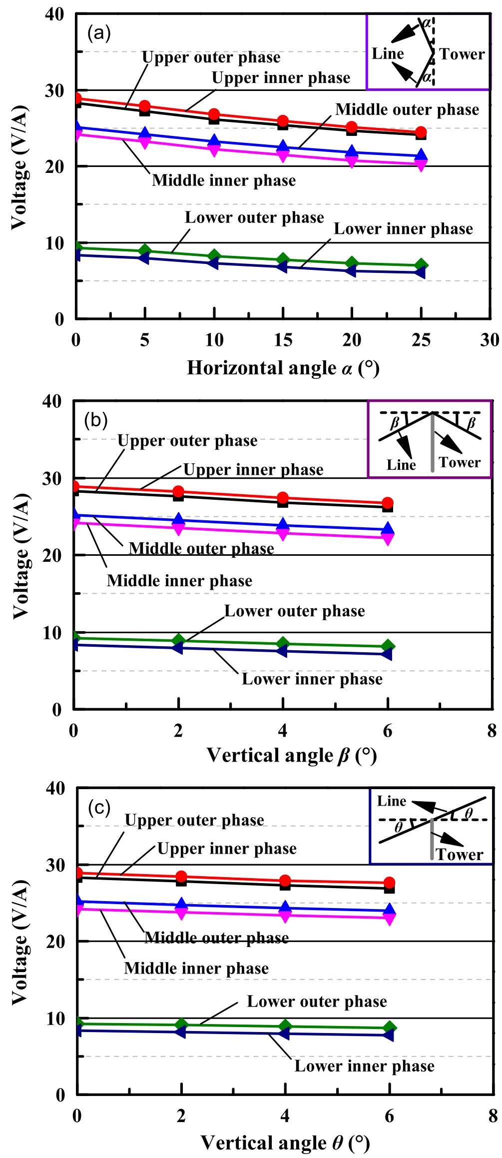

FIGURE 11. Influence of the transmission line angle on the maximum value of insulator strings voltage. (a) On the plain. (b) On the mountain top. (c) On the mountain slope.

The effect of terrain on overvoltage is mainly attributable to the variation in direction and inclination of the transmission line, which changes the way the phase conductors are coupled to the lightning channel and increases the mutual inductance between the phase conductors. This has an effect on the induced voltage of the phase conductors and thus causes a change in the insulator string voltage.

V. CONCLUSION

In this paper, surge response experiments were carried out on the reduced quadruple-circuit transmission line to verify the accuracy of the established FDTD model. After that, the verified FDTD model was applied to study the lightning surge responses of an actual 500 kV quadruple-circuit tower, considering factors such as the rise time of the lightning current, the velocity of the return-stroke current, and the terrains. The following key conclusions are drawn.

(1) The induced voltage of the lines is approximately 30% of the voltage of corresponding cross-arms when lightning strikes the 500 kV quadruple-circuit tower, and the former should not be ignored to assess the insulator string flashover.

(2) The long cross-arm length (e.g., 46 m in this paper) has little effect on the voltage waveforms of the insulator strings hung on it. This may lead to a multi-circuit flashover when the phases on the same cross-arm layer have similar instantaneous values at the instant of a lightning strike.

(3) The rise time of current injected into the tower has a great effect on the surge response of transmission lines. For the 500 kV quadruple-circuit tower concerned in this paper, the voltage amplitude of the insulator string decreases by about 28%, 24% and 20% for the upper, middle, and lower phases respectively when the rise time is from 0.1 μs to 2.6 μs.

(4) The velocity of lightning current cannot be ignored in terms of the surge response of transmission lines. For the tower considered in this paper, the voltage amplitude of the insulator string is reduced by approximately 50% when the velocity is from c to $0.59 \cdot c$.

(5) The effect of terrain on the transmission line surge response should be also considered in the simulations, especially when the transmission line direction changes on the plain. In this case, the voltage amplitude of insulator strings can be reduced by up to 24% when the line is turned at an angle of 25°. In comparison, mountainous terrain has less influence on the lightning surge response.

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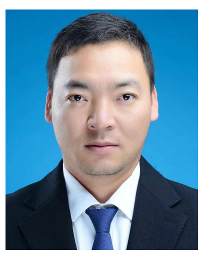

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