Simulation Study on Transient Performance of Lightning Over-voltage of Transmission Lines

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Abstract—**As the rapid development of EHV/UHV Power System towards high capacity and long distance, lightning fault has become the chief factor that affects the safe operation of transmission lines. In-depth research on the nature of transmission lines lightning accidents and precise evaluation of the lightning overvoltage performance of transmission line are extremely significant. In this paper, the lightning strike procedure of a 500kV transmission line is simulated using PSCAD/EMTDC, the transient performance of transmission line is analyzed respectively under three situations: return-stroke, shielding failure and no fault occurs. The waveform characteristic and change rule of overvoltage at strike point and transmitting in transmission line in these three cases are analyzed.**

Keywords-transmission lines;return-stroke;shielding failure; overvoltage; transient characteristics

I. INTRODUCTION

With the rapid development of EHV/UHV Power System, the height, transmission capacity and transmission distance of transmission lines are improved continuously. As its large distribution area and length, transmission lines locate partly in area with complicated terrain and meteorology conditions, so it is stroke by lightning frequently. In recent years, operation experience of EHV/UHV transmission lines in China and abroad shows that tripping faults caused by lightning strike take a large proportion in transmission lines faults. It is lightning strike fault that has already been the first factor that affects the safe operation of transmission lines[1-4]. Therefore, it is important to assure the reliability of power system and lightning protection of transmission lines should be strengthened. In order to draw up economical and reasonable lightning protection measures, in-depth research on lightning performance of transmission line and accurate evaluation of its lightning over-voltage performance appears extremely important. In this paper, the procedure of direct lightning strike to a 500kV transmission line is simulated, lightning over-voltage transient characteristics are analyzed respectively when return stroke, shielding failure and no fault occurs.

II. ELECTROMAGNETIC TRANSIENT SIMULATION MODEL OF TRANSMISSION LINES

Lightning over-voltage of a 500kV transmission line is analyzed based on PSCAD/EMTDC under the three situations: return stroke, shielding failure and no fault occurs.Bi-exponential wave with the waveform of 2.6/50μs is used to simulate lightning current, surge impedance of lightning channel is 300Ω.

A. Model of transmission line

As the lightning current waveform is rich in high-order harmonic and parameters of transmission line are sensitive to frequency, waveform of harmonic would be weakened and distorted while it is propagating in conductor with frequency-dependent parameters[5]. Therefore, frequency-dependent model in PSCAD model library is used in this paper to simulate over-head line.

In this paper, a line model with seven towers is established. Three of them are shown in Fig.1 and the whole line model is obtained by extending it. Conductor type of the 500kV transmission line is 4×LGJ-400/35, bundle spacing d=0.45m. Double circuit over-head grounding lines with the type of JLB4-150 are installed horizontally, span of the line is 500m. Over-head grounding lines are remained in line model to introduce its influence while lightning current is propagating in conductor. In order to avoid refraction and reflection of lightning current at the ends of line, long line with length of 5km is chosen to simulate the ends of the conductor. Due to the short duration of lightning strike, impulse impedance is introduced to analyze the line terminal, over-head grounding line and conductor is grounded through it. Average soil resistivity is 100Ω·m.

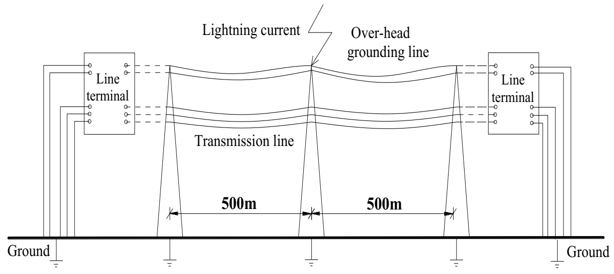
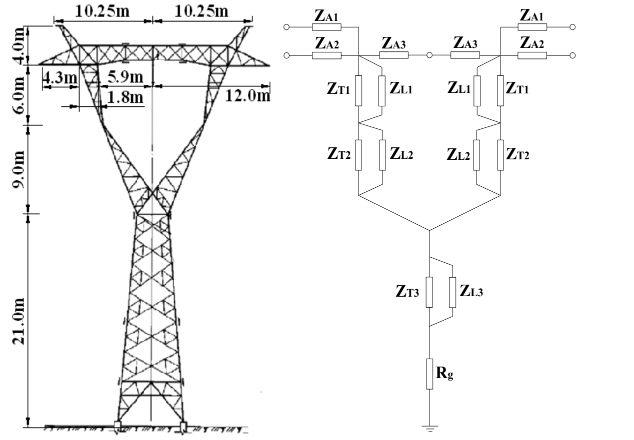


Figure 1. Simulation model of transmission lines

B. Model of tower

In current study, lumped inductance model, single surge impedance model and multiple impedance model are often used as tower model[6]. To simulate the refraction and reflection influence of lightning current while it is propagating in tower, multiple surge impedance proposed by T.Hara[7-8] is applied to the tower of 500kV transmission line. The model of the 500kV glass tower with type of ZB1 is shown in Fig. 2(b).Z_{AK} is the surge impedance of cross arm, Z_{TK} is the surge impedance of pillar, Z_{LK} is the surge impedance of bracket, R_g is the grounding resistance of tower. According to parameters of ZB1 cup-type tower of Fig.2(a), tower surge impedance of different part are calculated as shown in Table Ⅰ.All towers are grounded respectively, each R_g=7Ω.



(a) (b)

Figure 2. Parameters of glass tower with the type of ZB1（a） and its multiple surge impedance model（b）

TABLE I. SURGE IMPEDANCE OF DIFFERENT PART OF ZB1 CUP-TYPE TOWER

Surge impedance of Cross arm	Z_{A1}	Z_{A2}	Z_{A3}
Impedance Value（Ω）	257.89	231.28	233.28
Surge impedance of Pillar	Z_{T1}	Z_{T2}	Z_{T3}
Impedance Value（Ω）	139.50	124.90	79.66
Surge impedance of Bracket	Z_{L1}	Z_{L2}	Z_{L3}
Impedance Value（Ω）	1255.45	1124.30	716.96

C. *Criterion of insulator flashover*

In this paper, comparison method is adopt as criterion of insulator flashover in simulation study, in the model, insulator is instead by voltage-controlled switch. The control voltage of this switch is set as the U50% impulse discharge voltage of 500kV line insulator suggested in regulation and it is 2138kV[9]. If the voltage across the insulator is lower than control voltage, the switch would open and current can't enter the conductor.

III. TRANSIENT CHARACTERISTICS ANALYSIS OF THE LIGHTNING OVERVOLTAGE OF TRANSMISSION LINES

In this paper, overvoltage characteristics are analyzed respectively under these situations: return-stroke or no fault occurs while lightning strikes the top of the tower, shielding failure or no fault occurs while lightning strikes the conductor. Simulation results show that the return-stroke lightning withstand level is 171.23kA and that of shielding failure is 20.63kA. Therefore, lightning current of return-stroke fault can be set as 175kA and that of no fault set as 120kA; lightning current of shielding failure fault can be set as 25kA and that of no fault set as 15kA.

A. *Varying characteristic of lightning overvoltage while return-stroke occurs to transmission line*

1) Varying characteristic of overvoltage at lightning strike point.

Set the amplitude of lightning current as 175kA, ignore the operating voltage of line, while lightning strikes the tower at conductor side of phase A, return-stroke fault occurs to line(phase A). Waveform of the overvoltage across insulator while return-stroke occurs is shown in Fig.3. From Fig.3, while return-stroke occurs, potential of tower top rises rapidly due to the injection of lightning current. Once the voltage across the insulator installed between tower top and conductor of fault phase(phase A) surpasses the U50%, flashover occurs and grounding fault emerges. Due to the short-term interface from fault phase, high-frequency oscillation appears in non-fault phase until oscillations ends.

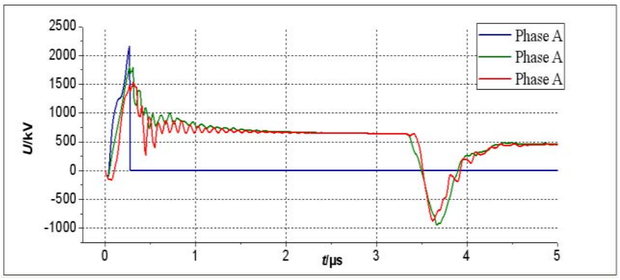


Figure 3. Waveforms of overvoltage across insulator while return-stroke fault occurs

Overvoltage waveforms of tower top and three phase conductors at lightning strike point are shown in Fig.4.From Fig.4 and Table Ⅱ, while return-stroke occurs, voltage at tower top is highest, whose peak value is 3.5 times of that of the non-fault phases. Due to the flashover on phase A, its overvoltage is higher than that of non-fault phases and the peak value is 2.3 times of that of non-fault phases. As the influence of operating voltage is ignored, waveforms of non-fault phases are almost overlapping.

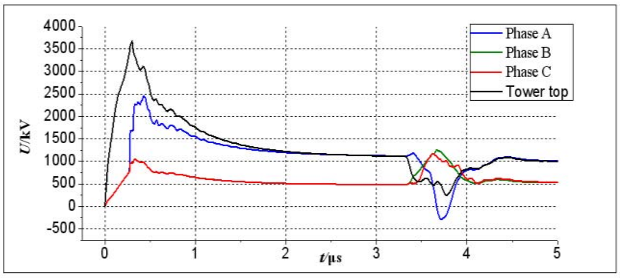


Figure 4. Waveforms of overvoltage of tower top and three phase conductors while return-stroke fault occurs

TABLE II. AMPLITUDE OF OVERVOLTAGE AT DIFFERENT POINT WHILE RETURN-STROKE FAULT OCCURS

Position	Phase A	Phase B	Phase C	Tower Top
Umax(kV)	2456	1050	1050	3678

2) Varying characteristic of lightning overvoltage at different position away from strike point while return-stroke fault occurs.

As a result of the influence of impulse corona and the frequency-dependent characteristic of line parameters, lightning overvoltage wave would be weakened and distorted while propagating in transmission line[5,10]. Fig.5 and Fig.6 show the waveforms of overvoltage while lightning with a current amplitude of 175kA strikes the tower top directly and return-stroke fault occurs on phase A. Fig. 5 shows the overvoltage at different position from strike point and Fig. 6 shows that at tower top at different position.

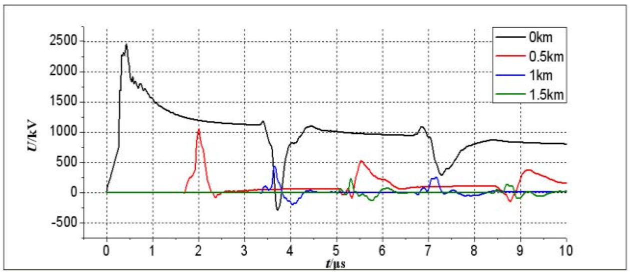


Figure 5. Waveform of overvoltage at different position from strike point on phase A while return-stroke occurs

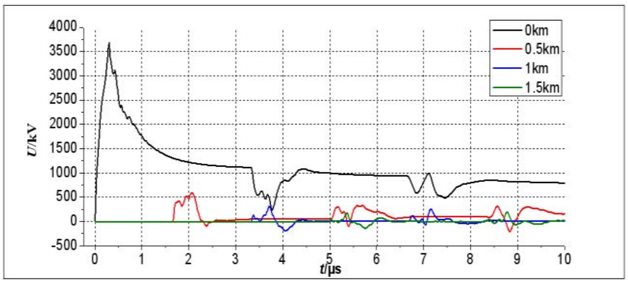


Figure 6. Waveform of overvoltage at tower top at different position from strike point while return-stroke occurs

From Fig.5, while return-stroke occurs, amplitude of voltage wave at strike point on conductor of phase A is 2456kV, it changes to 1049kV, 434kV, 229kV respectively 0.5km, 1km, 1.5km away. That is lightning over-voltage wave is weakened rapidly while propagating in transmission line, from strike point to 1.5km away, the amplitude reduces by 91%.

From Fig.6, amplitude of over-voltage at tower top stroke by lightning is 3678kV, it changes to 591kV, 312kV, 192kV respectively at the tower top 0.5km, 1km, 1.5km away. Amplitude of lightning overvoltage weakens seriously and oscillation appears at wave front.

B. Varying characteristic of lightning overvoltage while shielding failure occurs to transmission line

1) Varying characteristic of lightning overvoltage at strike point on conductor：

While amplitude of lightning current is 25kA, ignore the operating voltage, shielding failure occurs on conductor of phase A, fault emerges. Fig. 7 shows the wave of overvoltage across the insulator while shielding failure occurs, because the lightning current injects into conductor of phase A at strike point and propagating toward both direction of line, voltage to ground of phase A rises rapidly. Once the voltage across insulator surpasses its U50%, flashover occurs on this line and grounding fault appears. High-frequency oscillation emerges in over-voltage of non-fault phase and lasts for a while (phase B and phase C) because of the short-term interface from fault phase. Compared Fig3 with Fig.7, we know that the polarity of overvoltage of fault phase is contrary, this is due to the induction component of the return-stroke overvoltage caused by lightning striking on tower top.

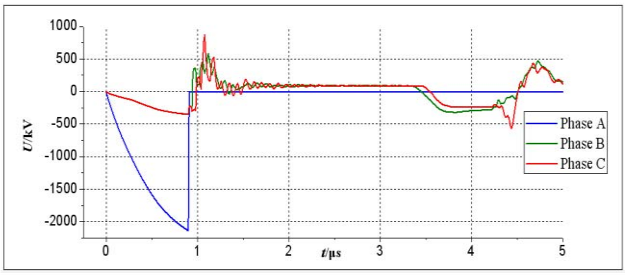


Figure 7. Waveform of overvoltage across the insulator while shielding failure occurs

Waveforms of lightning overvoltage at strike point of three phase conductors and tower top are shown in Fig.8 while shielding failure occurs. From Fig.8 and Table Ⅲ, amplitude of overvoltage of fault phase(phase A) is highest, its peak value is 5.5 times of that of non-fault phases(phase B and phase C). Because the operating voltage is ignored, waveforms of non-fault phases are almost overlapping, whose amplitude is only 396kV. While shielding failure occurs on conductor of phase A, amplitude of induced overvoltage at tower top is low, it is only 37% of that of fault phase and two humped appears at the wave front. Compared Table Ⅱ with Table Ⅲ, it can be found that overvoltage caused by shielding failure is lower than that caused by return-stroke as a result of the amplitude of lightning current is lower while shielding failure occurs.

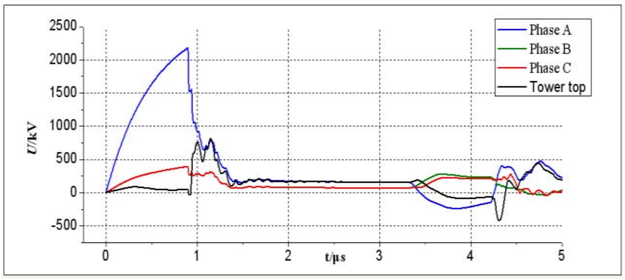


Figure 8. Waveform of overvoltage of three phase conductors and tower top while shielding failure occurs

TABLE III. PEAK VALUE OF OVERVOLTAGE AT DIFFERENT POINT WHILE SHIELDING FAILURE OCCURS

Position	Phase A	Phase B	Phase C	Tower Top
Umax(kV)	2183	396	396	816

2) Varying characteristic of lightning overvoltage at different position away from strike point while shielding failure occurs.

While conductor of phase A is stroke directly by lightning with amplitude of 25kA, changing characteristic of overvoltage at different position away from strike point is shown in Fig.9. It can be found that the amplitude of overvoltage wave at strike point on phase A is 2183kV and it changes to 259kV,57kV, 26kV after it propagating 0.5km, 1km, 1.5km. It is weakened rapidly, after propagating from strike point to a span, the amplitude is reduced by 88%, after three spans, it becomes 1.2% only. Compared with return-stroke fault, overvoltage caused by shielding failure is weakened obviously while propagating in transmission line.

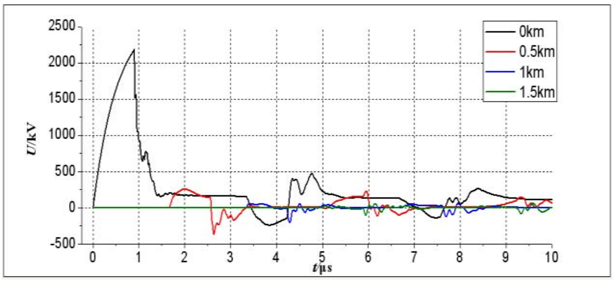


Figure 9. Waveform of overvoltage at different position away from strike point on phase A while shielding failure occurs

C. Varying characteristic of overvoltage while transmission line is stroke without any fault

1) Varying characteristic of overvoltage while tower top is stroke without any fault.

As the return-stroke lightning withstand level of line is 171.23kA, while tower top is stroke by lightning with amplitude of 120kA, return-stroke fault wouldn't occur. At this moment, waveform of overvoltage across the insulator is shown in Fig.10, waveforms of overvoltage to ground of tower top and three phase conductors are shown in Fig.11. From Fig.10, it can be found that the overvoltage across the line insulator almost agree with each other. Amplitude of overvoltage of phase A is a bit higher than that of other two phases and that of phase B is a bit higher than that of C. It is because that the strike point is located at the tower top at conductor side of phase A, the distance between three phase conductors and strike point is different, it makes the space distribution different thus the inductive voltage is distinct. Fig.11 shows that waveform of voltage to ground of three phase is overlapping due to the neglect of the operating voltage, the voltage to ground is 570kV, however voltage to ground at tower top is 2513kV, that is 4.4 times of that of conductor.

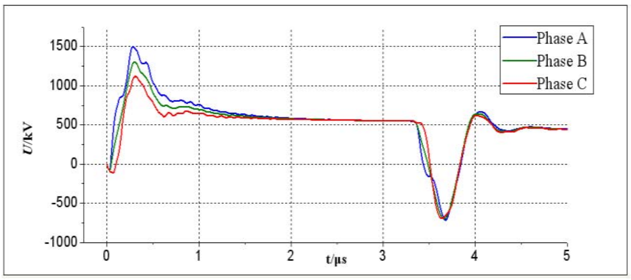


Figure 10. Waveform of overvoltage across insulator while tower top is stroke without any fault

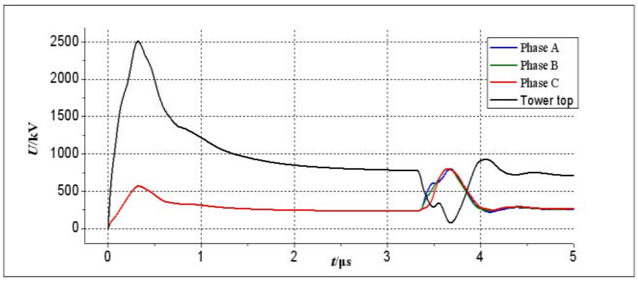


Figure 11. Waveform of overvoltage of tower and three phase conductors while tower top is stroke without any fault

2) Changing characteristic of overvoltage while conductor is stroke without any fault.

The shielding failure lightning withstand level of line obtained by simulating is 20.63kA, so no tripping fault would occur while lightning with a amplitude of 15kA striking conductor of phase A. At this moment, waveform of overvoltage across the line insulator is shown in Fig.12 and that of tower top and three phase conductor is shown in Fig.13. From Fig.12, waveform of overvoltage across the line insulator without lightning strike almost agree with each other. Waveform of line insulator of phase A has a sharp front compared with another tow phases. From Fig.13, amplitude of voltage to ground of phase A while ignoring the influence of operating voltage is 1574kV, however waveform of overvoltage of another two phases without lightning strike agree well. The amplitude of conductor voltage to ground of phase B is 378kV and that of C is 340kV. Because the amplitude of lightning current is lower, the amplitude of inductive voltage at tower top is only 99kV.

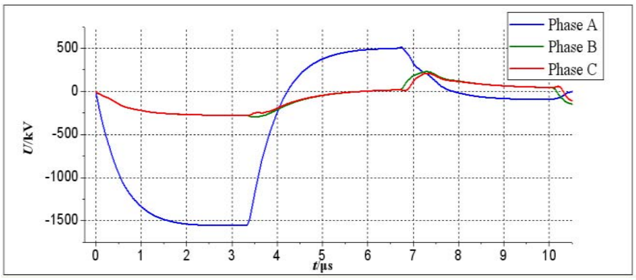


Figure 12. Waveform of overvoltage across the insulator while conductor is stroke without any fault

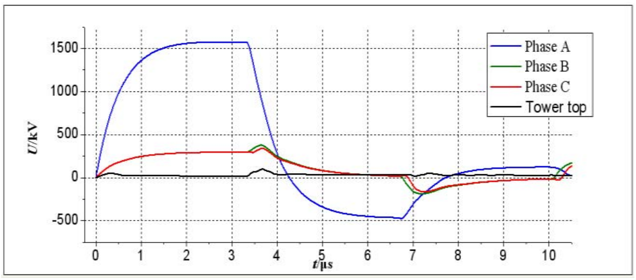


Figure 13. Waveform of overvoltage of tower top and three phase conductors while conductor is stroke without any fault

IV. CONCLUSIONS

In this paper, electromagnetic transient simulation program PSCAD/EMTDC is used to modelling the procedure of lightning striking on 500kV transmission line, transient changing characteristic of lightning overvoltage is analyzed under the three situations: return-stroke, shielding failure and no fault occurs, the following conclusions can be obtained:

- While return-stroke or shielding failure occurs, the overvoltage across the fault phase insulator appears as the form of grounding fault, high-frequency oscillations emerges in the waveform of non-fault phase and last for a moment before disappear. When tower top is stroke without any fault, the waveforms of overvoltage across the insulator almost agree with each other while ignoring the operating voltage. However, when the ends of the conductor are stroke and fault occurs, ignore the operating voltage, waveforms of overvoltage of non-fault phase insulator are nearly overlapping, overvoltage of fault-phase insulator is higher and wave front is more steep. Due to its higher lightning current amplitude, overvoltage of return-stroke is higher than that of shielding failure.

- Both the overvoltage waves of return-stroke and shielding failure would be weakened and distorted while propagating in transmission line. Amplitude of overvoltage is weakened rapidly, it reduces to less than 10% while propagating from strike point to 1.5km away. The reduction of amplitude of shielding failure overvoltage is more obvious than that of return-stroke overvoltage. The wave front of overvoltage distorts during the procedure of propagating. Oscillation or two humped appears.

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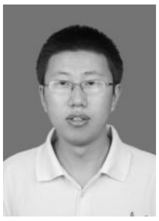

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