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Lightning Performance and its Prevention for Quadruple-circuit Transmission Line with 220kV/110kV Voltage in a Tower

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Abstract

According to the physical process of discharge development of insulator that is struck by lightning, the lightning flashover model for quadruple-circuit transmission line with dual voltage 220kV/110kV in same tower is established basing on EMTP. The actual evaluation index of lightning protection performance is adopted with the consideration of influence of system voltage. The characteristics of multi-circuit trip-out simultaneously for mixed-voltage lines in same tower is studied, and the distinctions of lightning protection performance caused by differentiated configuration mode of lightning protection measures including phase sequence arrangement, coupling ground wire and so on. The results indicate that the lightning withstand level fluctuates approximately with the phase angle in the form of non-standard sinusoidal wave. The lightning withstand level emerges as optimum performance under the completely reversed phase sequence. The effect of coupling ground wire on top of tower is superior to that on bottom.

Keywords: *EMTP; mixed-voltage line in a tower; lightning performance; flashover simultaneously*

1. Introduction

As the acceleration of grid construction pace, the engrossment of cultivated land owing to the need of transmission corridor makes the contradiction between them becoming more acute. Thus, to construct multi-circuit transmission line on the same tower for the purpose of intensive utilization of land resources appears necessary [1]. A large number of multi-circuit transmission lines on the same tower have been completed and put into operation in China already, and in which the 220kV/110kV is taking the rising share. However appears another problem, the vertical arrangement of three-phase transmission lines of each circuit, which increases height of tower, enhance the possibility of lightning strike and, what is worse, the risk of multi-circuit flashover simultaneously [2]. Furthermore, because of the relativity low current amplitude of shielding failure generals few multi-circuit flashovers simultaneously, the faults of simultaneous flashover phenomenon basically result from counter-attack flashover [3].

To solve the problem, the transmission line model of multi-circuit on the same tower; the tower model of multi-wave impedance as well as the flashover model of insulator string are built basing on EMTP in this paper [4], [5]. And the characteristics of voltage on the insulators of quadruple-circuit transmission line with dual voltage 220/110kV on the same tower when multi-circuit flashover simultaneously are studied as well as the variation of single and double line lightning protection performance with system voltage. The influences exerted by differentiated configuration mode of protection measures on lightning protection performance are also discussed. All these research above provide scientific basis and reasonable suggestions on the operation of quadruple-circuit transmission line with dual voltage 220/110kV on the same tower.

2. Physcal Model of Simultaneously Flashover

2.1. Transmission Line Model

The most obvious characteristics of lightning phenomenon are large current and high frequency. The geometrical-size causing inductance and stray capacitance of electrical

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parameters on the condition of lightning strike, different from electrical parameters under system voltage, become prominent [6]. This paper adopts frequency-related model basing on the phase domain transformation to realize the automatic computation on circuit parameter, which varying with frequency, by inputting line structure parameters. The frequency-related model can directly solve all kinds of circuit structure, including unbalanced ones, in phase domain. Figure 1 shows the model of 220kV/110kV voltage line in a tower (220kV circuits are above 110kV ones).

2.2. Multi-Wave Impedance Tower Model

In accordance with the principle of wave impedance propagating in vertical conductor varies with height, the multi-wave impedance tower model describes the injected impulse wave propagation by means of setting sectionalized tower structure and configuring each section as lumped parameter. And in this method, the potential on tower top and injecting component of voltage applied on insulator can be figured out so that to conform the catadioptric process of current wave in tower with actual situation. The multi-wave impedance tower model shows a significant advantage in computing conspicuously complex structure and particularly high tower. And the potential distribution obtained is basically agreed with actual measurement.

This paper adopts SZG1-27 as typical tower who has quadruple-circuit transmission line with dual voltage 220kV/110kV. Tower and its wave impedance model shows in Figure 2. Given the results of measured data, a 10% reduction of wave impedance can be found in adding branch component, auxiliary wave impedances which on the behalf of tower branches are paralleled beside trunk wave impedance.

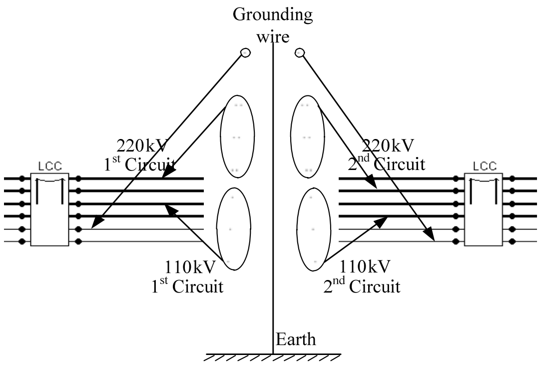

Figure 1. Model of Quadruple-circuit Transmission Line

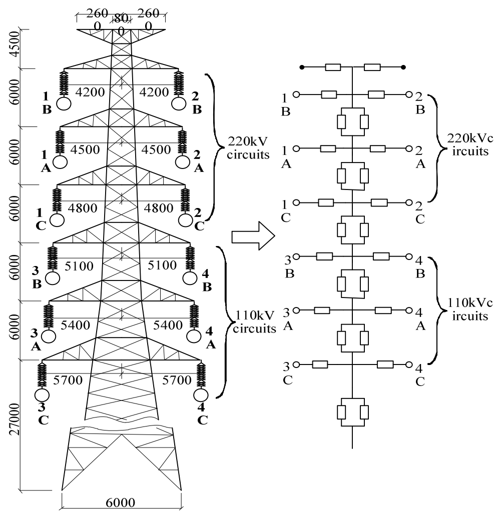

Figure 2. Tower and its wave impedance model

2.3. Insulator Flashover Model

On criterion of insulator flashover there are at present three main dissenting opinions which including definition method, intersection method and leader progression method [7]. Definition method and intersection method judge whether the flashover occurs by means of contrasting the overvoltage wave on insulator with voltage-time curve applying standard lightning impulse waveform whereas the lightning overvoltage wave applied on the insulator can hardly be regarded as standard waveform.

By comparison, leader progression method judges flashover by estimating whether the length of leader has penetrated the gap (Figure 3) even in the nonstandard wave flashover and therefore shows a great advantage. The leader progression velocity recommended by CIGRE WG33.01 is:

$$\frac{dL(t)}{dt} = ku(t)\left[\frac{u(t)}{D-L(t)} - E_0\right] \quad (1)$$

where $L(t)$ is the leader progression length and $u(t)$ is the voltage applied on insulator in time t, D is the gap length, E_0 is leader initial field strength, k is empirical factor. The voltage-time curve inverted from the curve recommended by IEC when given k=1.1, E_0=500.0kV/m is quite matched to the IEC recommended curve.

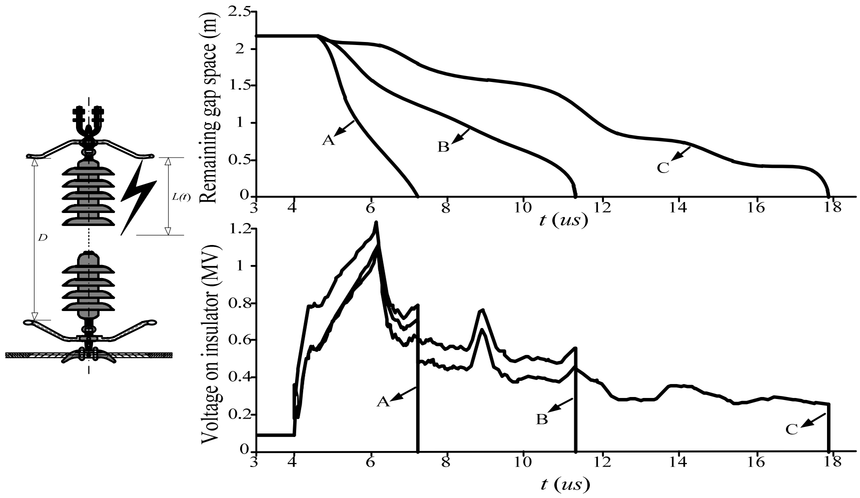

Figure 3. Principal of insulator flashover with leader progression

3. Flashover Characteristics of 220kV/110kV Voltage Lines in a Tower

Taking the 220kV/110kV voltage lines on same tower in Dongguan for example, the tower type is shown in Figure 2.Statistics collected over 2007~2011 in Dongguan district suggest that the average cloud-to-ground lightning density is 9.4 times/(km^2•a), and the accumulative probability of average lightning current is:

$$p(>I)=\frac{1}{1+(I/35.5)^{2.6}} \tag{2}$$

3.1. Actual Evaluation Index of Lightning Protection Performance

Affected by the system voltage, there exist diversities in lightning protection performance among lightning strikes that take place in different times and different points [8]. And because of the essence of such diversities lies in the differences of operating voltage, which aroused by the operating voltage phase angle, applied on the struck wire at moment of lightning, it is rational to introduce system operating voltage phase angle to estimate the influence of the point and time of lightning strike exerted on the lightning protection performance.

Influenced by the system voltage phase angle, voltage on the wire sequentially oscillates by the form of sinusoidal wave in operating cycles, and the voltage distributes uniformly between maximum and minimum value. Taking the randomness of lightning strike into consideration, the probability of voltage value on the wire in synchronized instant appears equally [9]. Given that, the changes of lightning protection performance in full range of phase angle are fitted by equally dividing system voltage phase angle and then calculating the lightning protection performance of each division in the same lightning strike time and point. Owing to the lightning protection performance at arbitrary phase angle can hardly presents the truth, the weighted average of lightning protection performance, which according to the probability of appearance of operating voltage phase angle when it comes the lightning strike, is taken as the actual evaluation index of lightning protection performance (equation (3) and (4)).

$$I_r=\frac{\sum_{i=1}^{n}[I_i(\varphi)\times p_i(\varphi)]}{n} \tag{3}$$

$$N_r = \frac{\sum_{i=1}^{n}[N_i(\varphi)\times p_i(\varphi)]}{n} \quad (4)$$

where I_r is the actual evaluation index of lightning protection performance, N_r is the actual evaluation index of trip-out rate, n is the number of phase angle division, $I_i(\varphi)$ is the lightning protection performance in phase angle φ, is the trip-out rate in phase angle φ, $p_i(\varphi)$ is the appearance probability of phase angle φ and there is:

$$\sum_{i=1}^{n} p_i(\varphi) = 1 \quad (5)$$

Because of the appearance probability of each phase angle division is the same, which means lightning protection performance and trip-out rate take the same weighted average, the actual evaluation index of lightning protection performance is the arithmetic mean.

3.2. Lightning Counter-Attack Performance of Quadruple-Circuit Transmission Line

Lightning protection performance and trip-out rate of single and double circuit and flashover phase distribution under different phase angle of quadruple-circuit transmission line with dual voltage 220kV/110kV in a same tower is shown in Figure 4. Numbers and letters stand for circuit and phase respectively. 1 and 2 stand for 220kV circuits, 3 and 4 stand for 110kV circuits.

It can be seen from Figure 4 that due to the voltage on wire continuously oscillates sinusoidally with system phase angle, lightning protection performance and trip-out rate of single and double circuit fluctuate approximately with the system frequency phase angle in the form of non-standard sinusoidal wave. Such nonstandard sinusoidal wave is attributing to the effects such as wave impedance of different segment.

Because of the external insulating level of 110kV circuit is inferior to 220kV circuit, while 110kV circuit is placed on the bottom of the quadruple-circuit transmission line tower that brings about a stronger coupling effect, it is still the 110kV circuit flashover firstly and double circuit occurs in the 110kV circuit. To the distribution of flashover, which may happens in all upper, middle and bottom phases, the flashover probability of bottom phase turns out to be the lowest owning to the protective effect it received. Furthermore, double circuit flashovers basically happen in the double circuits hanged on a same cross arm and, in other words, they happen in the wires with the same phase.

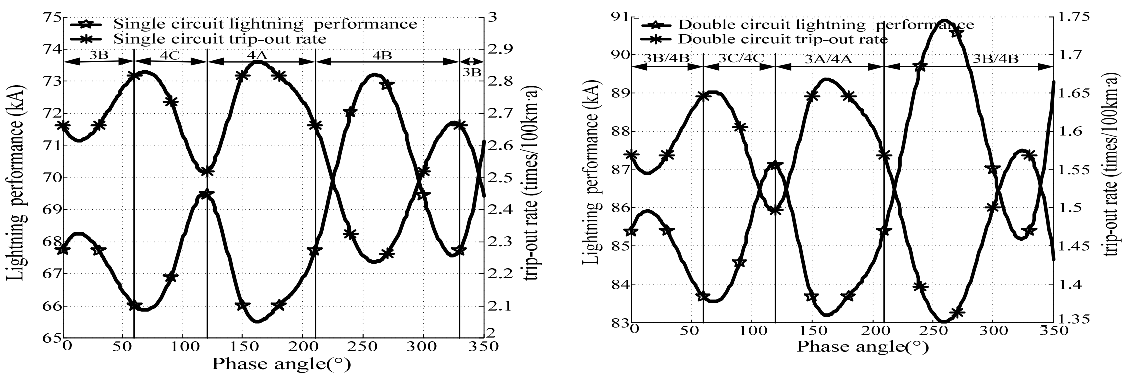

Figure 4. Lightning performance and flashover phase distribution under different phase angle

Figure 5 shows the comparison of lightning protection performance under different phase angle. It can be seen that the change of lightning protection performance is mostly identical to the phase angle. The single and double circuit lightning protection performance of negative half of system voltage is higher than the positive half of system voltage. That is because the polarity of lightning leader induced over voltage is opposite to the lightning current flowed into the tower, the positive over voltage on wire which induced by negative lightning current makes the primal voltage of wire partially counteracted, and thus drops the wire potential, decreases voltage on insulator and improves the lightning protection performance. The lightning protection performance of single and double circuit improves merely 2kA when the strike happens in negative half of system voltage wave than it happens in the positive half and that can ascribe to the negative half of system voltage is hard to neutralize.

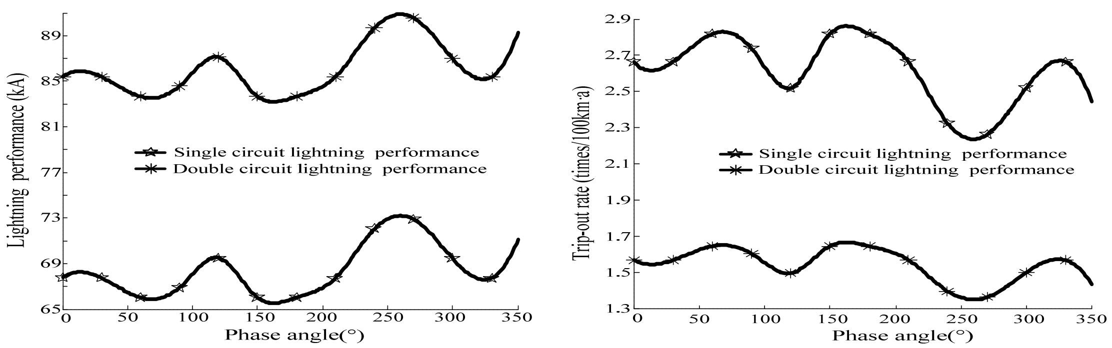

Figure 5. Comparison of Lightning performance under different phase angle

Because of 110kV circuit lies in the bottom of tower of quadruple-circuit transmission line and is protected by 220kV circuit, the lightning protection performance of 110kV circuit of quadruple-circuit transmission line with dual voltage 220kV/110kV tower is superior to that of ordinary tower under the same constraints.

3.3. Triple and Quadruple Circuit Lightning Counter-Attack Protection Performance

If the lightning current of double phase flashover is sufficiently large in quadruple-circuit transmission line with dual voltage 220kV/110kV in a same tower, the 200kV circuit on the top may flashover which leads to triple, even quadruple, circuit flashover. The changes of triple and quadruple circuit flashover are consistent with the single and double circuit. The distribution characteristics of the flashover phase in triple and quadruple circuit is the double circuit of 110kV flashover firstly and then the third and forth flashover circuits of 220kV. Moreover, the flashover probability appears higher in upper and middle phase than bottom phase. The actual evaluation index of lightning performance of single and multi-phase flashover is shown in Figure 6.

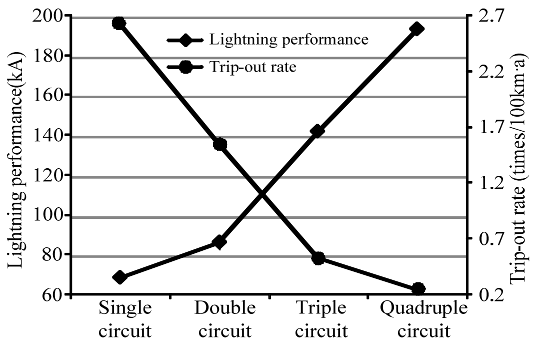

Figure 6. Lightning performance of single-phase and multi-phase flashover

The coupling effect on phase that has not flashover is enhanced owning to the fault phase grounding and the corresponding wire becomes earthed wire when the multi-circuit flashover. Meanwhile, due to the shunting effect of flashover phase, it is possible to improve multi-circuit lightning protection performance by decreasing voltage on insulator. It can be seen from Figure 6 that the actual evaluation index of lightning protection performance are 141kA and 192kA respectively corresponding to the triple and quadruple circuit flashover which are superior to the 220kV multi-circuit tower with ordinary configuration. That is mainly because of the coupling and shunting effect the broken-down 110kV circuit applied on the 220kV. Particularly, the increase of quadruple-circuit flashover protection performance is dramatic.

3.4. The Phase Angle Characteristics of Quadruple-Circuit Transmission Line

Phase characteristics of single and double circuit flashover voltage are shown in Figure 7 when the system voltage phase angle of quadruple-circuit is 0°. The voltage applied on insulator string of two circuits of 110kV and A phase of one 220kV circuit and B phase of another. It can be seen that although the placement and parameters of circuits on both sides of the tower, as well as the phase of wires hanging on the cross arms, are symmetrical, because of the asymmetry lies in the point of lightning strike, there still are nuances of the voltage applied on insulator strings of which hang on the identical phase and the same cross arms. B phase wire firstly flashover owning to the maximally positive potential when lightning strike and the system voltage phase is 0°. The voltage on insulator can hardly fluctuates with time after flashover and given the wave impedance and stray capacitance of the flashover channel, there remains residual voltage on the insulator string.

When the lightning current exceeds 85kA, B phase of the first 110kV circuit and B phase of the second breakdowns in succession, and the interval between both flashovers is some 5us. Because of the placement and parameters of insulators and flashover phase wires are symmetrical, which equalizes the insulator voltages of the both flashover circuits, voltage difference between the insulator strings which haven't been flashed-over is increased due to double circuit flashover.

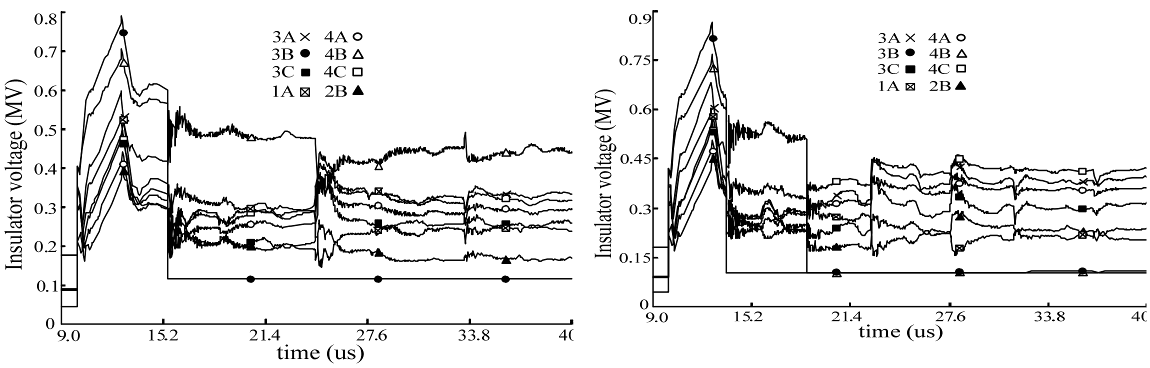

Figure 7. Phase characteristics of single and double circuit flashover voltage

4. Configrations of Lightning Protection Measures

4.1. Effect of Phase Sequence Arrangement on Counter-Attack Performance

There are 1296 kinds of phase sequence arrangement for quadruple-circuit transmission line in a tower theoretically. 666 kinds still remain when wipes off the reduplicate ones emerge from the symmetry in phase sequence arrangement of multi-circuit. 6 kinds of single circuit phase arrangement including ABC, ACB, BAC, BCA, CAB, and CBA are used to encode the circuit order of quadruple-circuit transmission line.

In the actual transmission line construction, electromagnetic environment, natural power transportation and unbalanced degree of circuit are the preoccupations of phase sequence arrangement [10]. According to the relevant reference material, the phase sequence arrangement 5335 has a optimal magnetic field, 1342 has a optimal electric field, 1616 has a optimal natural power and unbalanced degree, 1246 has a minimum radio disturbance and 1166 has a minimum noise. The actual evaluation index of lightning protection performance and trip-out rate of the phase sequence arrangement mentioned above is shown in Figure 9.

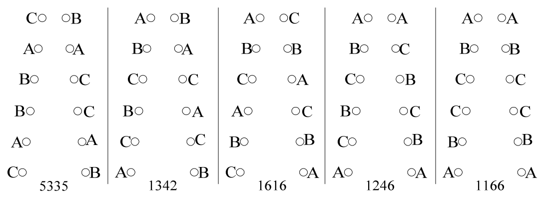

Figure 8. Phase sequence arrangement

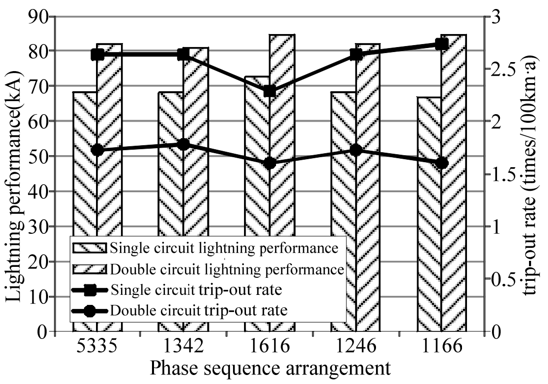

Figure 9. Lightning performance of different phase sequence arrangement

Phase sequence arrangement of circuit carries distinct weight on lightning protection performance of quadruple-circuit transmission line with dual voltage 220kV/110kV in a same tower. As can be seen from the Figure 9 that phase sequence arrangements 5335, 1342 and 1246 show few differences in lightning protection performance of single circuit flashover which mainly because the single circuit flashover distributes intensively in low voltage circuit and the middle phase together with upper phase suffers a higher probability of flashover. Moreover, the distance between middle phase and upper phase is relatively small which makes lightning protection performance basically consensus. Therefore the completely reverse phase sequence it seemed, by and large, possesses an optimum single and double circuit lightning protection performance.

4.2. Effect of Tower Grounding Resistance on Counter-Attack Performance

Grounding resistance has an evident influence on lightning counter-attack protection performance, and the reduction of such resistance will be of use in lightning-proof. When the tower is stroke by the lightning and lightning current flow into the earth, the grounding device presents resistance state which is generally described as impulse grounding resistance. However, due to the impulse grounding resistance, which is typically less than power frequency grounding resistance, is liable to be affected by soil properties, peak of impact current, geometrical shape of the grounding devices, the power frequency grounding resistance is still served as considerable basis in actual practices. Figure 10 shows the effect on lightning protection performance caused by grounding resistance. It can be seen that the lightning performance dramatically decreases with the increase of tower grounding resistance and the protection performance could be significantly enhanced by reducing the grounding resistance below 23Ω. Yet such reduction in some high soil resistivity districts is difficult to accomplish, it seems sensible to adopt other comprehensive measurements from the view of economy and technique.

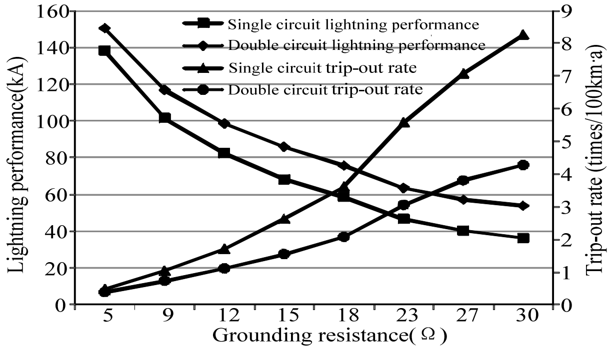

Figure 10. Lightning performance impacted by grounding resistance

4.3. Effect of Coupling Earthed Wires on Counter-Attack Performance

Overhead coupling wires have a coupling and shunting effect on reducing the voltage on insulator and improving the lightning protection performance when lightning occurs.

Figure 11 and Figure 12 illustrate the lightning protection performance of single and double circuit when not installing coupling earthed wires and installing on the top or the button of tower. The results show that lightning protection performance of the circuit erected coupling earthed wires appears superior to the circuit that fail to installed such wires, And the configuration of erecting on the top, especially in terms of high grounding resistance, seems like working best. Consequently, when the grounding resistance can hardly reduce due to unfavorable geological conditions or fail to retrofit the grounding device, the lightning protection performance is better if erecting coupling earthed wire on the top of the tower.

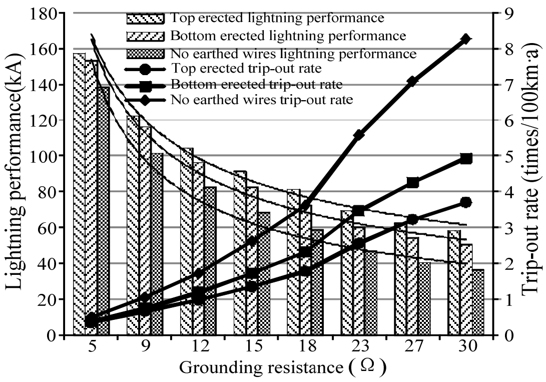

Figure 11. Lightning performance of single circuit flashover under different coupling earthed wires erecting modes

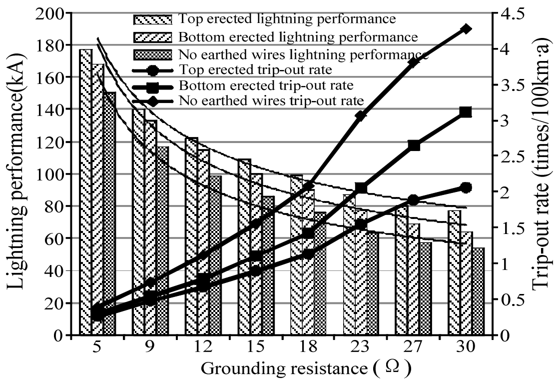

Figure 12. Lightning performance of double circuit flashover under different coupling earthed wires erecting modes

5. Conclusion

1) The single and double circuit flashover of quadruple-circuit transmission line with dual voltage 220kV/110kV in same tower both occur in low voltage circuit. Lightning withstand level and trip-out rate fluctuate approximately with the system voltage phase angle in the form of non-standard sinusoidal wave.

2) The protection performance of multi-circuit flashover is improved as a result of coupling and shunting effects the flashover phase exerts on the none-flashover ones and reduces the voltage applied on them.

3) The constant variance of voltage applied on the insulators of each phase is caused by the wire working voltage. Such variance will increase due to the nonsymmetrical lightning strike point and acquire further enhancement because of the coupling effect flashover phase exerts on the none-flashover ones.

4) The completely reverse phase sequence possesses an optimum single and double line lightning protection performance of quadruple-circuit transmission line with dual voltage 220kV/110kV in same tower.

5) Flashover protection performance dramatically decreases with the increase in tower grounding resistance and the protection performance could be significantly enhanced by reducing the grounding resistance below 23Ω.

6) Lightning protection performance of the circuit erected coupling earthed wire appears superior to the circuit that have no such wire. And the configuration of erecting on the top, especially in terms of high grounding resistance, seems like working best.

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