Research on the Calculation of Lightning Trip Flashover Rate for 10kV Distribution Line without Grounding Line

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Abstract—**For the reason that seldom research has been studied on the lightning trip flashover rate (LTFR) of distribution line, this paper focus on studying the calculation method about LTFR. The distribution line without mounting grounding line, flashover is mainly caused by direct stroke lightning and induced stroke lightning. Then, a conclusion can be drawn that LTFR is made up of direct stroke lightning trip rate and induced stroke lightning trip rate. Based on these, a model which can consider the structure of the distribution network, the type of grounding and lighting withstand level (LWL) is established. Furthermore, ATP-EMTP and the mirror method is applied to calculate the flashover probability caused by direct stroke lightning and the induced stroke lightning respectively. Moreover, to check the accuracy of the model, a typical 10kV distribution line in high lighting stroke area of China which is called Gaotian Line is chosen and the LTFR of the line is computed as well. The result shows that the computed result is very close to the practical running result, which proves the correctness of the model.**

Index Terms—**lightning trip flashover rate, grounding line, ATP-EMTP, mirror method, lighting withstand level, distribution network**

I. Introduction

The power distribution insulation level is very low, therefore it often suffers lighting strike, which seriously threaten the reliability of power system [1]. So, it's very important to improve the LWL of distribution network for insuring power reliability. Up to now, seldom research has been studied on LTFR of 10kV distribution line, Which results in the mechanism of LTFR can't be understood rightly and clearly. solve the problem, this paper focus on the calculation method of LTFR especially for the distribution line without mounting grounding line [2]. Research shows that, for distribution system without grounding line, direct stroke lightning and induced stroke lightning may cause insulator flashover and breaker tripping. Therefore, the model of direct stroke lightning trip rate and induced stroke lightning trip rate have been established and ATP-EMTP and the mirror method is applied to calculate the flashover probability. Moreover, to check the accuracy of the model, a typical 10kV distribution line in high lighting stroke area of China which is called Gaotian Line is chosen and the LTFR of the line is computed as well. The result shows that the computed result is very close to the reality, which proves the correctness of the model.

Manuscript received November 20, 2018; revised January 12, 2019.

II. The LTFR Model's Establishment

For distribution system without grounding line, the trip out of breaker is mainly caused by direct stroke lightning and induced stroke lightning. Therefore, LTFR consists of direct stroke lightning trip rate n_1 and induced stroke lightning trip rate n_2,

$$n = n_1 + n_2 \tag{1}$$

$$n_1 = N \cdot p_1 \cdot [(P_{A,B} - P_{A,B,C}) + P_{A,B,C}(2-\eta)] \cdot \eta \tag{2}$$

$$n_2 = N \cdot p_2 \cdot [(P_{A,B}{}' - P_{A,B,C}{}') + P_{A,B,C}(2-\eta)] \cdot \eta \tag{3}$$

where, N is flash collection rate, (flashes/100km/year). p_1 is the probability of direct stroke lightning. p_2 is the probability of striking on the floor, considering the structure of distribution network, p_1=p_2=0.5. $P_{A,B}$, $P_{A,B,C}$ are the probability of two-phase flashover and three-phase flashover caused by direct stroke lightning, respectively. $P_{A,B}{}'$, $P_{A,B,C}{}'$ are the probability of two-phase flashover and three-phase flashover caused by induced stroke lightning, respectively. η is arcing rate.

III. Calculation of Key Parameters

A. Calculation of Probability of Direct Stroke Lightning Flashover

As shown in (2), the direct stroke lightning trip rate n_1 depends on the value of $P_{A,B}$, $P_{A,B,C}$. Then, to calculate these parameters, the model of 10kV distribution line suffered the direct stroke lightning is established and

doi: 10.18178/joace.7.1.46-51

ATP-EMTP is applied to calculate $P_{A,B}$ and $P_{A,B,C}$ [3], [4] (Fig. 1).

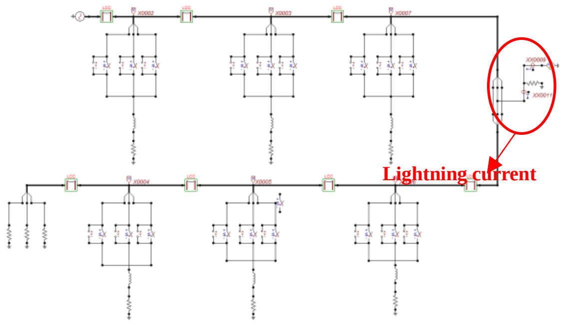

Figure 1. The model of 10kV distribution line suffered direct stroke lightning in ATP-EMTP.

It is very difficult and complicated to find out the value of LWL when the ATP-EMTP software is running. So, trial-and-error method is used to search the LWL. If the voltage of insulator becomes zero, flashover is occurring, the lighting current under this condition is just the LWL. And then, $P_{A,B}$ and $P_{A,B,C}$ can be obtained by using the probability statistics equation of lighting current excessing LWL (Fig. 2-4).

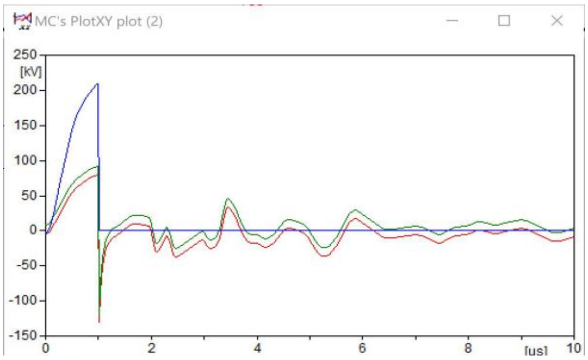

Figure 2. Simulation waveform of single-phase flashover under direct stroke lightning.

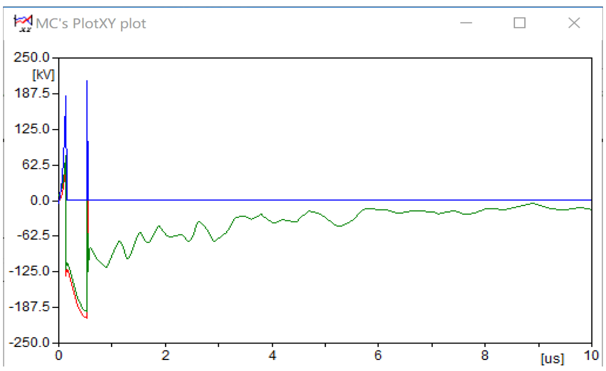

Figure 3. Simulation waveform of two-phase flashover under direct stroke lightning.

The flashover probability of direct stroke lighting in the mountainous areas of China can be expressed as,

$$\lg P = -\frac{I}{44} \tag{4}$$

Then, the flashover probability of two-phase or three-phase under the condition of direct stroke lightning can be written as,

$$P_{A,B} = 10^{(\frac{-I_d}{44})} \tag{5}$$

$$P_{A,B,C} = 10^{(\frac{-I_t}{44})} \tag{6}$$

where, I_d, I_t are the LWL of two-phase flashover and three-phase flashover under direct stroke lightning, respectively.

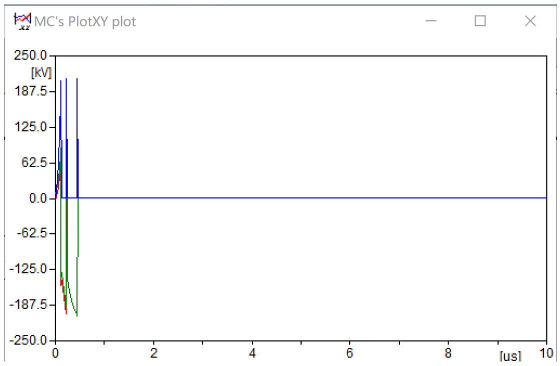

Figure 4. Simulation waveform of three-phase flashover under direct stroke lightning.

B. *Calculation of Flashover Probability of Induced Stroke Lightning*

To calculate the probability of two-phase and three-phase flashover caused by induced stroke lightning. To get P'_{AB}, the induced overvoltage of insulators under induced stroke lightning condition must be calculated at first [5]-[7].

The flashover overvoltage of conductor caused by induced stroke lightning can be calculated by the following equations,

$$U'_{A,B} = \frac{U_{A,B}}{0.1h_{gt}} \tag{7}$$

$$U_{A,B} = \frac{U_{50\%}(Z_{AA}+2R_i)}{Z_{AA}(1-k_{AB})} \tag{8}$$

$$Z_{AA} = 60\ln\frac{2h_A}{r_A} \tag{9}$$

where, h_{gt} is the height of the tower, (m). $U_{50\%}$ is the flashover voltage of insulator, (kV). Z_{AA} is the surge impedance of phase A. R_i is the grounded resistance, (Ω). k_{AB} is the dimension coupling coefficient. r_A is the radius of conductor A,(cm). h_A is the height of the conductor A, (m).

Taking the height of the tower into consideration, the three-phase flashover overvoltage caused by induced stroke lightning can be calculated by function (10),

$$U'_{A,B,C} = \frac{U_{A,B,C}}{0.1h_{gt}} \tag{10}$$

where, $U_{A,B,C}$ can be gotten using the following expression,

$$U_{A,B,C} = \frac{U_{50\%}(Z_{eq} + 2R_i)}{Z_{eq}(1 - k_{ABC})} \tag{11}$$

where, k_{ABC} is dimension coupling coefficient among three phase A. B and C. Z_{eq} is equivalent surge impedance. Z_{AB} is the mutual surge impedance between phase A and B.

The relationship between Z_{eq} and Z_{AA}, Z_{AB} is shown as following,

$$Z_{eq} = (Z_{AA} + Z_{AB})/2 \tag{12}$$

Generally, for multi-conductor transmission line, mirror method is used to solve the surge impedance, such as the calculation of Z_{AB}, which is shown in Fig. 5.

$$Z_{AB} = \ln \frac{d'_{AB}}{d_{AB}} \tag{13}$$

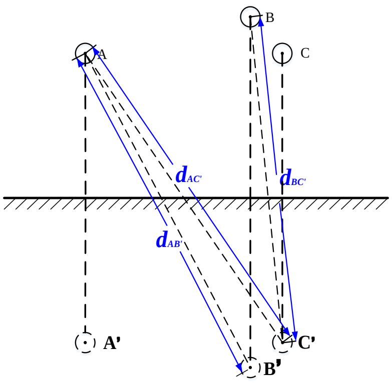

Figure 5. The mirror point of three phase distribution line.

As shown in Fig. 5, point A, B, C represents phase A, B and C of 10kV distribution line, respectively. And A', B' and C' are the corresponding mirror point of A, B, C. d_{XY} is the distance between point X and point Y.

$$k_{ABC} = \frac{Z_{AC} + Z_{BC}}{Z_{AA} + Z_{AB}} = \frac{\ln \frac{d_{AC'}}{d_{AC}} + \ln \frac{d_{BC'}}{d_{BC}}}{\ln \frac{2h_A}{r_A} + \ln \frac{d_{AB'}}{d_{AB}}} \tag{14}$$

According to the mirror method, $d_{AC'}$, $d_{BC'}$, $d_{AB'}$ can be expressed as,

$$d_{AC'} = \sqrt{(2h_A)^2 + (d_{AC})^2} \tag{15}$$

$$d_{BC'} = \sqrt{(h_B + h_C)^2 + (d_{BC})^2} \tag{16}$$

$$d_{AB'} = \sqrt{(h_A + h_B)^2 + (d_{AB})^2} \tag{17}$$

where, h_A, h_B, h_C are the height of the conductor A, B, C, respectively, (m). The value of $P'_{A,B}$ and $P'_{A,B,C}$ can be easily obtained when the $U'_{A,B}$ and $U'_{A,B,C}$ is calculated [8].

C. Calculation of Lightning Strike Probability

Lightning strike probability can be expressed as,

$$N = 0.1 \cdot N_g (b + 4h_{gt}) \tag{18}$$

where, N_g is ground flash density, ($times/km^2 \cdot a$), b is the distance between two grounding lines, (m). For the distribution line without grounding line, b equals zero, b=0.

D. Calculation of Ground Flash Density

According to *IEEE guide for improving the lightning* performance *of electric power overhead distribution lines* (IEEE Std 1410™-2010), ground flash density N_g can be gotten using the following equation,

$$N_g = 0.04 T_d^{1.25} \tag{19}$$

where, T_d is the number of days with thunder per year.

E. Calculation of Arcing Rate

For Chinese distribution system belonging to undergrounded system, arcing rate depends on the ionization degree of arc channel, the length of arc channel and system voltage, which can be written as,

$$\eta = (1.6 \cdot \frac{U_N}{l_{dis}}) \cdot 10^{-2} = (1.6 \cdot \frac{U_N}{2(D+l)}) \cdot 10^{-2} \tag{20}$$

where, η is the probability of stable arc after two-phase flashover, the arcing rate. U_N is the voltage of system, (kV). l_{dis} is the length of discharge path when two-phase flashover, (m). D is the length of insulator, (m). l is the diameter of insulator, (m).

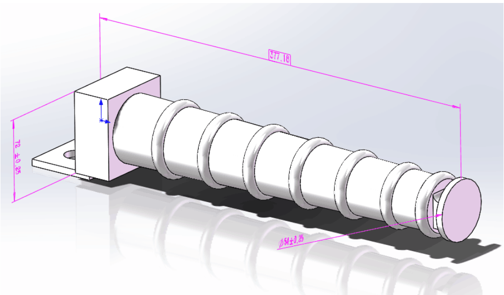

Figure 6. The insulator used in 10kV distribution line.

Fig. 6 is the schematic diagram of the insulator which is often used in 10kV distribution line, and the creep age distance of the insulator is obtained,

$$l_{dis} = 2(D + l) \tag{21}$$

IV. Calculation of LTFR of Distribution Line in a High Thunderstorm Region

A. Parameter of 10kV Distribution Network of A High Thunderstorm Region

To check the correctness of model, Gaotian Line in Qingyuan is chosen to calculate the LTFR (Table I).

TABLE I. PARAMETERS OF 10KV DISTRIBUTION LINE OF GAOTIAN LINE

P	h_A	h_B	h_C	r_A	D	l	$U_{50\%}$	R_i	U_N
V	9.2	10	9.2	0.0075	0.377	0.06	210	20	10

Note, P denotes parameters, V denotes the value of parameters. The unite of the parameters are m, except $U_{50\%}$, U_N, R_i which the unites are kV and Ω, respectively.

B. Calculation of LTFR

Based on the above working, the parameters of (2) and (3) can be obtained which are listed in Table II.

TABLE II. THE PARAMETERS OF TRIP OUT MODEL

P	$P_{A,B}$	$P_{A,B,C}$	$P'_{A,B}$	$P'_{A,B,C}$	η
V	0.452	0.297	0.7	0.3	0.183

Using the date of Table II, the LTFR can be easily get,

$$\begin{aligned} n_1 &= N\cdot p_1\cdot[(P_{A,B}-P_{A,B,C})+P_{A,B,C}(2-\eta)]\cdot\eta \\ &= 0.1\cdot 0.04\cdot T_d^{1.25}\cdot 40\cdot 0.5\cdot \\ &[(0.452-0.297)+0.297(2-0.183)]\cdot 0.183 \\ &= 1.02\times10^{-2}T_d^{1.25} \end{aligned} \tag{22}$$

$$\begin{aligned} n_2 &= N\cdot p_2\cdot[(P_{A,B}'-P_{A,B,C}')+P_{A,B,C}'(2-\eta)]\cdot\eta \\ &= 0.1\cdot 0.04\cdot 120^{1.25}\cdot 40\cdot 0.5 \\ &[(0.7-0.3)+0.3(2-0.183)]\cdot 0.183 \\ &= 1.38\times10^{-2}T_d^{1.25} \end{aligned} \tag{23}$$

Consequently, the total LTFR is,

$$n = n_1 + n_2 = 2.4\times10^{-2}T_d^{1.25} \tag{24}$$

After a series computing process, we get the mathematical expression between the thunder days and the trip out, as shown in (22), (23), (24), respectively.

Using the mathematical equation, the LTFR of Qingyuan under different thunder days is calculated, which is shown in Table III.

TABLE III. THE RELATIONSHIP BETWEEN THE LTFR AND THE THUNDER DAYS

T_d	80	120	160	200	240
n_1	2.440	4.051	5.804	7.672	9.635
n_2	3.302	5.481	7.853	10.379	13.036
n	5.742	9.532	13.657	18.051	22.671
n_1/n	42.494%	42.499%	42.498%	42.502%	42.499%
n_2/n	57.506%	57.501%	57.502%	57.498%	57.501%

C. Analysis of Influence Factors

The fitting relationship between the thunder days and the LTFR from-Table III, is shown in Fig. 7-9.

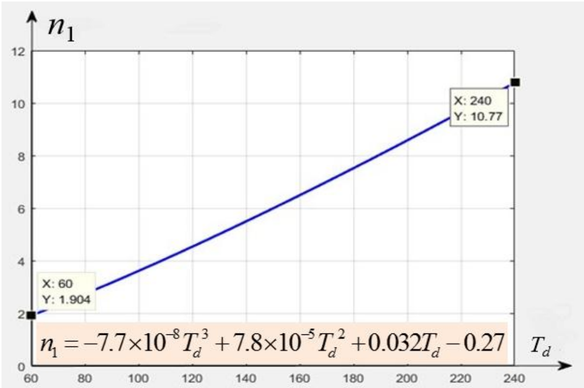

Figure 7. Relationship between thunder days and the direct stroke lightning trip rate.

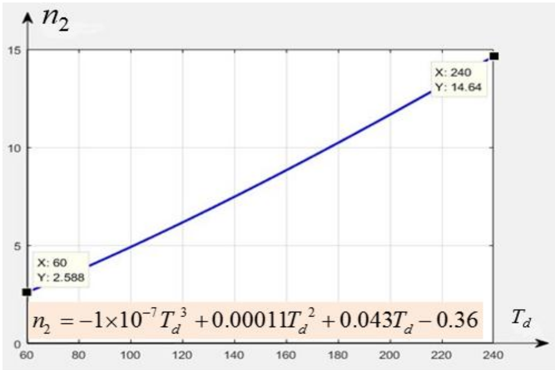

Figure 8. Relationship between thunder days and the induced stroke lightning trip rate.

Figure 9. Relationship between thunder days and the total LTFR.

Under the condition of direct stroke lightning, the function between direct stroke lightning rate n_1 and the thunder days T_d can be written as,

$$n_1 = -7.7\times10^{-8}T_d^{\,3} + 7.8\times10^{-5}T_d^{\,2} + 0.032T_d - 0.27 \tag{25}$$

Under the condition of induced stroke lightning, we can get the fitting curve expression between induced stroke lightning rate n_2 and the thunder days T_d expresses as function (26),

$$n_2 = -1\times10^{-7}T_d^{\,3} + 7.8\times0.00011T_d^{\,2} + 0.043T_d - 0.36 \tag{26}$$

According to the relationship curve in Fig. 9, the expression between stroke lightning rate n and thunder days $T_{\rm d}$ can be written as,

$$n = -1.8\times10^{-7}T_d^{\ 3} + 0.00018T_d^{\ 2} + 0.075T_d - 0.63 \quad (27)$$

From the curves and the equations above, a conclusion can be drawn that, the LTFR is in direct proportion to the thunder days, that is, the more days of thunder, the higher the LTFR.

In addition, changing the value of LWL, the relationship curve between the LWL and the LTFR can be drawn as Fig. 10-13.

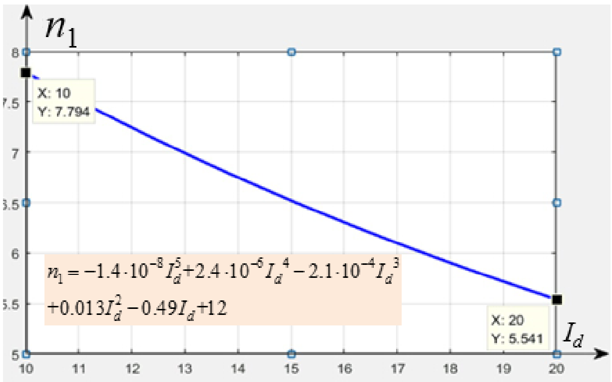

Figure 10. Relationship between the direct stroke lightning trip rate and the LWL of two-phase flashover.

The expression between the direct stroke lightning rate n_1 and the LWL of two-phase flashover $I_{\rm d}$ can be written as,

$$n_1 = -1.4\times10^{-8}I_d^{\ 5} + 2.4\times10^{-6}I_d^{\ 4} - 2.1\times10^{-4}I_d^3 + 0.013I_d^2 - 0.49I_d + 12 \quad (28)$$

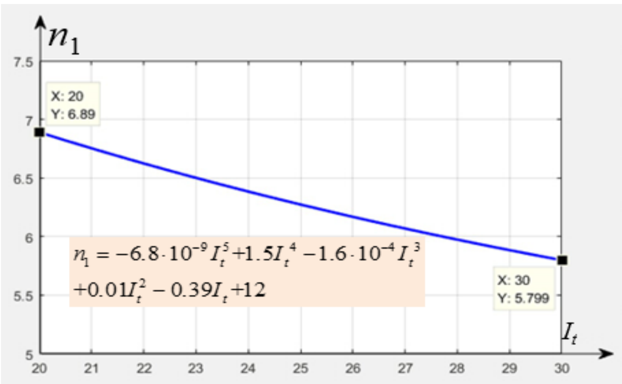

Figure 11. Relationship between the direct stroke lightning trip rate and the LWL of three-phase flashover.

The value of the direct stroke lightning rate n_1 decreases with the increasing of the LWL of three-phase flashover $I_{\rm t}$,

$$n_1 = -6.8\times10^{-9}I_t^{\ 5} + 1.5I_t^{\ 4} - 1.6.\times 10^{-4}I_t^3 + 0.01I_t^2 - 0.39I_t + 12 \quad (29)$$

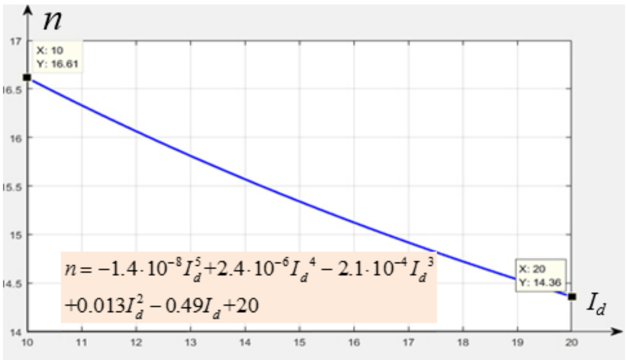

Figure 12. Relationship between the total LTFR and the LWL of two-phase flashover.

According to the relationship curve in Fig. 12, the stroke lightning rate n can be expressed by the LWL of two-phase flashover $I_{\rm d}$ as (30),

$$n = -1.4\times10^{-8}I_d^{\ 5} + 2.4\times10^{-6}I_d^{\ 4} - 2.1\times 10^{-4}I_d^3 + 0.013I_d^2 - 0.49I_d + 20 \quad (30)$$

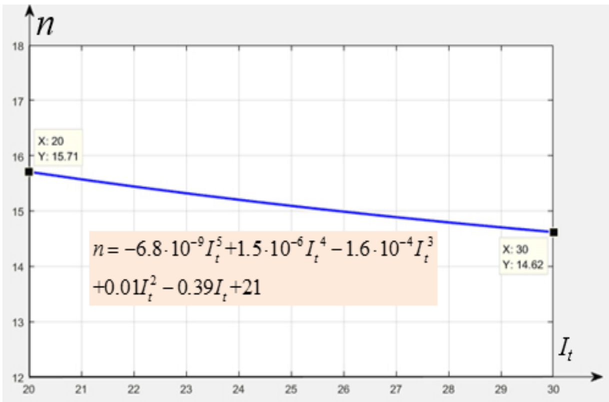

Figure 13. Relationship between the total LTFR and the LWL of three-phase flashover

The mathematic function (31) is used to express the relationship between the stroke lightning rate n and the LWL of three-phase flashover $I_{\rm t}$,

$$n = -6.8\times10^{-9}I_t^{\ 5} + 1.5\times10^{-6}I_t^{\ 4} - 1.6.\times 10^{-4}I_t^3 + 0.01I_t^2 - 0.39I_t + 21 \quad (31)$$

From Fig. 10-13, a conclusion can be drawn from the relationship curves that the LTFR is in negative correlation with the LWL. Especially, compared with the LWL of three-phase flashover, the LWL of two-phase flashover has a greater influence on the LTFR.

V. Conclusion

For 10kV power distribution line without mounting grounding line, the LTFR caused by induced stroke lightning is higher than that of direct stroke lightning.

The model reveals that the LTFR cause by direct stroke lightning depending on the LWL. While for the induced stroke lightning, the LWL has no influence on the LTFR which mainly relies on the flashover voltage.

Many factors have significant influence on the LTFR. Among them, the thunder days has the greatest effect on LTFR. The LTFR increases abruptly with the increasing of thunder days.

The LWL has great influence on n_1, while it almost has no influence on n_2.

The LTFR decrease with increasing of LWL under the condition of direct stroke lightning. Compared with the LWL of three-phase flashover, the LWL of two-phase flashover has a greater influence on the LTFR.

REFERENCES

[1] A. Jiang, P. Nie, J. Yang, et al. "Design and evaluation of differentiated lightning protection countermeasures for Pu Dong 10 kV distribution lines," in *Proc. 2016 China International Conference on Electricity Distribution (CICED 2016)*, Xi'an, 2016, pp. 1-5.

[2] W. Jin, W. Wang, "Differentiated lighting protection method for 10 kV distribution grid," in *Proc. 2012 China Interational Conference on Electricity Distribution (CICED 2012)*, Shanghai, 2012, pp. 1-4.

[3] J. A. Martinez-Velazco F C. "Lightning performance analysis of overhead transmission lines using the EMTP," *IEEE Transactions on Power Delivery*, vol. 3, no. 20, 2005, pp. 2200-2210.

[4] M. S. Rahimian, A. M. Hussein, "ATP modelling of the lightning current within a tall structure and the attached channel," in *Proc. 2012 International Conference on Lightning Protection (ICLP)*, Vienna, Austria, 2012, pp. 1-5.

[5] Z. Lu, S. Gu, C. Zhao, "Calculation of lightning trip-out rates for 10 kV overhead distribution line," in *Proc. 2014 International Conference on Lightning Protection (ICLP)*, Shanghai, China, 2014, pp. 667-670.

[6] T. Sun, H. Liu, Y. L. Qi, H. Li, W. J. Zhou, J. H. Yu, "Lightning trip-out risk evaluation of a 220kV transmission line in Shiyan," in *Proc. 2014 International Conference on Lightning Protection (ICLP)*, Shanghai, China, 2014, pp. 1508-1511.

[7] G. D. Gao, H. F. Wang, L. T. Huang, S. F. Zhao, "The calculation model of the shielding failure trip-out rate of double-circuit *transmission* line on the same tower," in *Proc. 2012 Power Engineering and Automation Conference*, Wuhan, China, 2012, pp. 1-5.

[8] Transmission and Distribution Committee, *IEEE Guide Improving the Lightning Performance of Electric Power Overhead Distribution Lines*, USA: New York, 2011.

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