The Evaluation Method of the Lightning Strike on Transmission Lines Aiming at Power Grid Reliability

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Abstract. Lightning protection of power system focuses on reducing the flashover rate, only distinguishing by the voltage level, without considering the functional differences between the transmission lines, and being lack of analysis the effect on the reliability of power grid. This will lead lightning protection design of general transmission lines is surplus but insufficient for key lines. In order to solve this problem, the analysis method of lightning striking on transmission lines for power grid reliability is given. Full wave process theory is used to analyze the lightning back striking; the leader propagation model is used to describe the process of shielding failure of transmission lines. The index of power grid reliability is introduced and the effect of transmission line fault on the reliability of power system is discussed in detail.

1. Introduction
Lightning stroke is the main cause of transmission line trip-out[1-2]. More than 50% power system faults are caused by lightning stroke in China according to statistics. Transmission line lightning stroke failure causes damage to transmission equipment on the one hand, line successive failures caused by lightning stroke also threaten safe and reliable operation of power grid, which affects the development of social economy seriously. Lighting protection of transmission lines is emphasized in power system, and relevant scholars conducted a lot of research. However, there are still following disadvantages in power transmission and transformation system lightning protection. Firstly, reduction of lightning trip-out rate is regarded as the objective, the electric network reliability problem caused by lightning stroke trip-out is rarely designed and studied directly. Secondly, the index of electric trip-out rate is distinguished according to voltage grade. The function difference of the lines is not considered. The same lightning trip-out rate index is adopted aiming at lines with the same voltage level and different capacity and importance. The protection level of key lines is relatively weak due to the above disadvantages, and general lines have relatively excessive protection design. Therefore, it is necessary to study the power transmission and transformation system lightning protection method for guaranteeing the electric network reliability, and study the influence of lightning stroke failure on the security reliability of power grid.

Jiangmen is located in southern China, and it is one of regions with the strongest and most frequent lightning activities in China [3]. It is important to develop lightning protection in Jiangmen power grid, which can be used for reference in power grid construction and operation in other multi-thunder regions in China.

In the paper, Jiangmen power grid is adopted as the research object for studying the transmission line lightning stroke analysis method for electric network reliability. A transmission line lightning
stroke trip-out rate evaluation method is proposed based on full-wave process theory lightning back-striking calculation method and leader progression theory lightning shielding failure calculation method, wherein tower models, dielectric strength, ground resistance, terrain and lightning activity along the line, etc. are considered comprehensively. Electric network reliability index is introduced for fully discussing the influence of transmission line lightning stroke failure on electric network reliability. The lightning stroke failure rate of 500kV, 220kV and 110kV typical transmission lines are evaluated, and differentiated lightning stroke trip-out rate indexes are proposed.

2. Transmission Line Lightning Stroke Analysis Method

2.1. Analysis Method of Transmission Line Back-Striking

Wherever Times is specified, Times Roman or Times New Roman may be used. If neither is available to you, please use the font closest in appearance to Times. Avoid using bit-mapped fonts if possible. True-Type 1 or Open Type fonts are preferred. Please embed symbol fonts, as well, for math, etc. The lightning stroke process is transiently analyzed based on the theory of full wave process. Meanwhile, the actual wave process of ground power transmission and transformation system as well as underground grounding device and grounding system is considered. The line back-striking performance when lighting direct stroke on the tower top. Matrix eigenvalue and characteristic vector principles are used. Matrix similarity transformation is adopted for simplifying wave process on multi-conductor lines with mutual electromagnetic contact into n mutually independent modulus, which is equivalent to single conductor wave process. A multi-wave impedance model is adopted for the tower in simulation [4,5]. The tower is divided into a main support and branch supports. It is assumed that each part is evenly distributed. The wave impedance is calculated through their own dimension and geometry function [6], current source model is adopted for lightning current model, and the impedance size is 300 Ω, and bi-exponent pulse is adopted for lightning current [7]:

\[
i(t) = \frac{I_0}{\lambda} \left( e^{-\alpha t} - e^{-\beta t} \right) = \frac{I_0}{\lambda} \left( e^{-\alpha' t} - e^{-\beta' t} \right)
\]

\[
\lambda = \exp \left[ -\frac{\alpha}{\beta} \right]^{\alpha/\beta}
\]

In the formula: I0 refers to lightning current maximum value, \(\lambda\) refers to current correction factor \(\tau_1\) and \(\tau_2\) are time constants determining current rise time and delay time, \(\tau_1<\tau_2\), and \(\alpha=1/\tau_1, \beta=1/\tau_2\). It is concluded through calculation that \(\lambda=0.966159, \alpha=14623, \beta=1883107\) aiming at 2.6/50 μs lightning current, and \(n\) is 3.

The leader progression method is regarded as insulator flashover criterion [8,9], air discharge physical mechanism is utilized for calculating the leader discharge in air gaps, when the leader length in the gap reaches the gap length, insulation flashover occurs. Gap breakdown time \(T_b\) can be regarded as the sum of injection starting time \(t_p\), injection development time \(T_s\), ionization front propagation time \(T_l\) leader progression time \(T_i\) and gas heating time \(T_g\), namely breakdown time can be written into follows:

\[
T_b = t_p + T_s + T_l + T_i + T_g
\]

In the formula, ionization front propagation time \(T_i\) is very short compared with other time duration. It is generally included into leader progression time \(T_l\); gas heating time \(T_g\) experimental value should be shorter than 0.1 μs, therefore \(T_g\) also can be ignored in calculation. In addition, injection starting time \(t_p\) also can be ignored generally in actual calculation, or can be directly included into injection development time \(T_s\). The leader progression method is regarded as insulation flashover criterion for judging whether the insulation is flashed over or not under the effect of non-standard shock wave, and its flashover voltage and flashover time should be determined.

The calculation formula of the line back-striking trip-out rate is shown as follows:
\[ n = N_l \eta P g \]  

In the formula: \( N_l \) refers to the line ground flash frequency per 100 km year, \( \eta \) refers to arc over rate, \( P \) refers to line statistic lightning withstand level probability, and \( g \) refers to lightning striking rate against poles.

### 2.2. Analysis Method of Transmission Line Shielding Failure

Basic thought of leader progression model: the field intensity of the ground and ground objects are gradually increased during downward development process of lightning. When the field intensity is increased to a certain value, upward head-on leaders are produced on the ground objects. When the upward and downward leaders meet the breakdown condition during relative development, lightning strike occurs. When a lightning leader model is used for analyzing the line shielding failure characteristics, the model parameters and criterion with higher influence on the calculation result can be divided into the following four aspects: lightning leader model, head-on leader starting criterion, upward leader model and final breakdown criterion, etc.\[10]\.

In the paper, it is believed in the model that the electric charge is evenly distributed in the lightning leader, total electric charge in the lightning channel \( Q \) is related with lightning current amplitude \( I \), which can be calculated according to formula (5)\[11-12]\.

\[ Q = 76 \times 10^{-3} \cdot I^{6.68} \]  

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In the paper, it is believed that the lightning leader is always developed along the direction with the maximum electric field strength.

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The above-mentioned lightning leader model is utilized for calculating the ground lightning position of the lightning leader which is located in one place with certain lightning leader (hit conductor, ground wire or earth). The method of calculating line shielding failure trip out rate refers that the area along the line is divided into square areas then the lightning current amplitude scope of possible shielding failure of the lightning leader in the area can be calculated. The shielding failure frequency in the area within one year can be expressed as follows:

\[ a = 0.1N_l \int_0^H \int_0^L p(I) dIdy \]  

\[ (6) \]
In the formula $a$ refers to shielding failure rate, time/ (100km year), $N_g$ refers to ground flash density, times/ (km$^2$ year), $p$ (I) refers to lightning current amplitude probability density function, $y_1$ and $y_2$ represent upper and lower bounds of the lateral range from ground lightning position to the transmission line, $I_1$ and $I_2$ represent the minimum and maximum currents during shielding failure.

2.3. Calculation Method of Lightning Stroke Trip-out Rate

Line lightning stroke trip-out rate is related to line tower models, dielectric strength, ground resistance as well as terrain and lightning activity along the line etc., they respectively affect line back-striking trip-out rate and shielding failure trip-out rate, thereby determining line lightning protection performance. Tower model, dimension, dielectric strength, terrain and grounding conditions of each base tower are different in the actual line, and the lightning protection performance is also different. However, since there are many towers in the actual line, each base tower respectively undergoes trip-out rate analysis one by one with huge workload. Therefore, it is necessary to analyze overall lightning protection performance of lines according to the following feasible method: the lines are divided into several categories according to the statistic rules of all parameters affecting line lightning protection performance. Line lightning stroke trip-out rate in reach category is calculated. On the basis, the overall lightning protection performance of the line is obtained through the weighted sum method.

3. Power Grid Reliability

Power grid reliability refers that power system can continuously meet system operation restraints and measurement of power user load demands for short term under real-time operation mode and external working environment. Power generation and transmission system reliability is measured through quantitative reliability index. The indexes generally include PLC (Probability of Load Curtailments), EFLC (Expected Frequency of Load Curtailments), EDLC (Expected Duration of Load Curtailments), ADLC ADLC (A Average Duration of Load Curtailments), ELC (Expected Load Curtailments), EENS (Expected Energy Not Supplied), BPII (Bulk Power Interruption Index), BPECI (Bulk Power Energy Curtailment Index) and SI (Severity Index), etc.

4. Evaluation of Typical Transmission Line

4.1. Typical Line Basic Parameters

In the paper, respectively one 500 kV, 220 kV and 110 kV line with more frequent lightning stroke trip-out accidents in Jiangmen is selected to analyzing and studying the lightning protection performance of the three typical lines. Three typical phase conductor line and ground wire parameters are shown in table I. The sag should be selected according to the typical value of standard DL/T 620-1997 ‘Over-voltage protection and insulation coordination of AC electrical apparatus’. The insulator parameters are selected according to the typical value of the line, and $U_{50p}$ is converted according to standard DL/T 620-1997. Tower models in each line with the highest proportion or the most representative tower models in the aspect of tower characteristics are calculated. Single-circuit erection is adopted for 500 kV line, the adopted towers mainly include straight line cup type towers and angled towers, as shown in Fig.1. Two typical tower structures and dimensions selected in the paper are shown in Fig 2. 110 kV lines include double-circuit, three-circuit and four-circuit erection modes. The adopted towers include double-circuit straight line tower, double-circuit angled tower, three-circuit straight line tower (1 base), four-circuit straight line tower (1 base), etc. The structure and model of two typical towers selected in the paper is shown in Fig.3.

4.2. Typical Line Calculation Result

Lightning stroke trip-out rate calculation results of of the 500 kV typical line is 1.03time/ (100km year), the back-striking trip-out rate is 0.053time/ (100km year), and total trip-out rate is 1.08time/ (100km year); for 220 kV typical line, shielding failure trip-out rate is 0.83 times/ (100km year), back-striking trip-out rate is 1.45 times/ (100km year), and total trip-out rate is 2.28 times/ (100km year); for 110 kV typical line, shielding failure trip-out rate is 1.40time/ (100km year), back-striking trip-out rate is 2.36time/ (100km year), and total trip-out rate is 3.76 times/100 km year.
### Table 1. Parameters of phase conductor and ground wire

| Line  | diameter (mm) | bundle No | Insulator length (m) | $U_{50\%}$ (kV) |
|-------|---------------|-----------|----------------------|-----------------|
| 500 kV Conductor | 23.94 | 4 | 4.3 | 2385 |
| 220 kV Ground wire | 16 | 1 | - | - |
| 220 kV Conductor | 33.6 | 2 | 2.2 | 1292 |
| 110 kV Ground wire | 16 | 1 | - | - |
| 110 kV Conductor | 23.94 | 1 | 1.2 | 700 |
| kV ground wire | 9.6 | 1 | - | - |

### Figure 1 Typical tower parameters of 500 kV lines

- (a) ZB1
- (b) JT

### Figure 2 Typical tower parameters of 220 kV lines

- (a) ZJ001
- (b) SZ

### Figure 3 Typical tower parameters of 110 kV lines

- (a) ZGU1
- (b) JGU3
4.3. Reliability Evaluation with Consideration of Lightning Stroke Risks

Lightning occurs in summer mostly, and electric network reliability is evaluated under lightning stroke failure rate for Jiangmen power grid during summer in the project. Time sequential simulation method is obtained to obtain the electric network reliability evaluation results of Jiangmen power grid power generation and transmission system under lightning stroke failure rate as shown in the table. Calculation results in the table show that the reliability level in summer mode under lightning operation mode is reduced, wherein the PLC of Guangzhou power grid under the operation mode is 0.002404, PLC is reduced by 0.000207 under lighting operation mode; ELC and EENS are respectively 89.86MW/year and 4820.05MWh/year, and the system SI is 17.55 system score/year; The SI of ELC, EENS and system is respectively increased by 23MW/year, 459MWh/year and 1.67 system scores/year.

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| Table.2. Electric network reliability evaluation result under lightning stroke failure rate |
|---------------------------------------------------------------|
| **Index** | **Regular summer mode** | **Summer mode under lightning stroke** |
| PLC PLC | 0.002197 | 0.002404 |
| EFLC (time/year) | 10.91 | 11.75 |
| EDLC (hour/year) | 19.25 | 21.06 |
| ADLC (hour/time) | 1.77 | 1.79 |
| ELC (MW/year) | 66.70 | 89.86 |
| EENS (MWh/year) | 4360.62 | 4820.05 |
| BPII (MW/MW.yr) | 0.00 | 0.01 |
| BPECI (MWh/MW.year) | 0.26 | 0.29 |
| SI (system branch/year) | 15.88 | 17.55 |

5. Conclusion

Lightning stroke characteristics of transmission lines with frequent lightning strokes in Jiangmen are analyzed. The line corridor ground lightning density is higher than 10time/(km2•year). The evaluation result shows that the 500 kV line shielding failure trip-out rate is far higher than the back-striking trip-out rate, which is consistent with the operation result; 220 kV transmission line shielding failure trip-out rate is similar to back-striking trip-out rate. The relation thereof is related to tower ship, terrain and other factors. 110 kV transmission line back-striking trip-out rate is high relatively, and the back-striking trip-out rate in some terrains is prominently higher than shielding failure.

Power grid reliability analysis is introduced. The influence of transmission line lightning stroke failure on electric network reliability is considered. Quantitative reliability index is used for evaluating the changes of electric network reliability index before and after lightning stroke failure. The result shows that lightning stroke risks lead to higher influence on electric network reliability, transmission line lightning risk evaluation should be developed from pure lightning stroke trip-out rate to consideration of electric network reliability.
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