Adaptive Strategies in the Leader Propagation Model for Lightning Shielding Failure Evaluation: Implementation and Applications

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Lightning is the major cause of unexpected outage in electric transmission systems, among which lightning shielding failure accounts for the most proportion of the lightning accident for transmission systems above 500 kV. The leader propagation model (LPM) was found to be effective to the analysis of lightning shielding failure of high voltage transmission lines, especially for the ultra high voltage (UHV) transmission systems. However, it was generally slow to calculate the shielding failure rate by LPM because the progress of lightning development must be calculated repeatedly, which required large amount of computation. In this paper, adaptive strategies to accelerate the computation of LPM were proposed. The computation results were validated by the field data of the Japanese UHV transmission line and a typical 500kV AC transmission line.

***Index Terms*—adaptive strategy, leader propagation model, lightning shielding failure, lightning protection, transmission line.**

I. Introduction

As reported by State Grid Corporation of China (SGCC) and China Southern Power Grid (CSG) which totally cover about 98% area of China, lightning is the most possible reason for unexpected outage of transmission lines. In addition, for high voltage level lines especially for lines above 500 kV, shielding failure takes the most proportion of the lightning accidents. Under such a background, great attentions should be paid to the evaluation of the risk of shielding failure during the design of transmission lines.

The electrogeometric method (EGM) was widely used for lightning shielding failure evaluation in transmission lines in the past, however, as the operation voltage increase it was found the prediction error of EGM is not acceptable, especially for the UHV transmission line [1], and the leader propagation model (LPM) was introduced [2], [3]. It is widely studied and used during the latest 10 years [4], [5] and is indicated to be suitable for the lightning shielding assessment. However, in LPM, the progress of lightning development must be simulated iteratively and repeatedly, thus it requires large amount of computation, so it is much slower than EGM.

In this paper, adaptive strategies to accelerate the computation of LPM were proposed. The simulation results were validated by the field data of Japanese UHV transmission lines and a result for a typical 500kV AC transmission line was also given.

II. Leader propagation model and its adaptive strategies

The details of LPM can be found in, e.g, [2], [3], [4], [5]. When a lightning happens, a downward leader develops towards the ground. The electric field near the transmission line is intensified due to the space charges produced by the downward leader, and upward leaders may incept from the lines and develop upwards. When the head of upward leader and the downward leader become near and a specific criterion, e.g., the electric field strength in the gap exceeds the electrical breakdown strength, is satisfied, the gap breaks down and a lightning stroke happens. In real implementations, one often fixes a lateral distance between the transmission line and position of lightning (denoted by y), and simulates the lightning propagation process to determine the minimal and the maximal lightning current (i_1 and i_2, respectively) that causes shielding failure; then repeats the simulations for different y. The shielding failure rate (SFR) and the shielding failure flashover rate (SFFOR) are calculated by Eq. (1) and (2)

$$\text{SFR} = 0.1N_g \int_{y_1}^{y_2} \mathrm{d}y \int_{i_1}^{i_2} P(I)\mathrm{d}I, \tag{1}$$

$$\text{SFFOR} = 0.1N_g \int_{y_1}^{y_2} \mathrm{d}y \int_{i_c}^{i_2} P(I)\mathrm{d}I, \tag{2}$$

where N_g is the lightning density, $P(I)$ is the formula for probability of lightning current amplitude, y_1 and y_2 is minimal and maximal of y where a lightning may cause shielding failure, i_c is the lightning withstand level of the transmission line.

There are several possible ideas to accelerate the computation in LPM. 1) For each fixed y, it is required to simulate the development of the downward leader towards the ground to determine i_1 and i_2. An adaptive choice of downward propagation step (the space step the downward leader develops between two simulation steps) in the simulation may be better to balance the accuracy and efficiency . 2) The probability of lightning current amplitude has a nonuniform distribution, it's possible to accelerate the determination of i_1 and i_2 by considering this feather. 3) To integrate over y, a direct and naive method is to use the trapezoidal method with uniform sampling. An adaptive quadrature is better for a higher efficiency and accuracy.

A. Downward propagation step

In LPM, the inception of the upward leader is determined by the electric field at the conductor surface. The downward propagation step has effect on the determination of lightning propagation route and the upward leader inception time. The height of the lightning cloud, which is the root of downward leader, is assumed to be 2000 m. When the downward leader is very high, it develops vertically, and its influence to the electric field at the conductor surface is very small. On this occasion, a relative large propagation step, such as 10 m, can be used. When the downward leader is low, its influence to the electric field near the conductors is much larger, and a smaller step should be used, or the upward leader inception time cannot be exactly captured.

In the implementation, the electric field at the surface of the conductor surface, denoted by E, is calculated and we define $r = \frac{E}{E_c}$, where E_c is the critical inception electric field and is a constant. When r exceeds 1.0, the upward leader incepts. The downward propagation step is adjusted according to r, the closer r is to 1.0, the smaller the simulation step is. The minimal step used is chosen to be 1 m.

B. The distribution of lightning current

When determining i_1 and i_2, we have to simulate the cases where lightning current value is with large probability more accurate, while the cases where the lightning current is with small probability can be coarser. We omit more details due to space limitation.

C. Adaptive lightning position sampling

Assuming $\int_{i_1}^{i_2} P(I)\mathrm{d}I$ is a smooth non-periodic function of y, Eq.(1) and Eq.(2) can be computed by high order quadrature rather than trapezoidal integration. Due to the difficulty to determine the lateral region where a lightning may lead to a shielding failure, a sufficient large region $[y_1, y_2]$ is chosen, resulting in heavy computation if uniform trapezoidal method is used. We instead use a reliable adaptive recursive algorithm which is a combination of three-point Simpson's rule, five-point Simpson's rule and Romberg extrapolation. Its tolerance error can be freely controlled.

III. Validation and Results

A. Validation by the Japanese UHV transmission line

The Japanese UHV transmission line is chosen to verify the validity of the model. The conceptual diagram of the transmission line configuration is shown in [1]. The operating data shows that the lightning shielding failure rate is 3.33 stroke/(100 km·year), and the result calculated by the analysis model is 3.20 stroke/(100 km·year), which satisfies the operating data well.

B. Comparisons for algorithms with and without adaptivity

A typical 500 kV transmission line is chosen to show the efficiency of the adaptive strategy. In all algorithms, the downward propagation step is adaptive ranging from 10 m to 1 m. It is assumed the phase angle of the operating voltage is 90 degree and the line is in mountain areas. The results are computed by a PC with Intel Xeon E5-2430 CPU and 40 G RAM, under the following conditions:

1) Algorithm 1: the Δy is uniformly 0.1 m.
2) Algorithm 2: the Δy is uniformly 0.5 m.
3) Algorithm 3: the Δy is uniformly 1 m.
4) Algorithm 4: the minimal Δy is 1 m and using fully adaptive algorithm.

Algorithm 1 uses a very fine simulation condition and the associated result is assumed to be the exact result. Results shown in Tab. I indicate that the adaptive strategies greatly accelerate the simulation while retaining high accuracy.

TABLE I
SIMULATION RESULTS AND CPU TIMES

Algorithm	SFR (stroke/(100 km·year))	CPU time (s)	relative error with Algorithm 1
1	0.5614	14292	-
2	0.5592	2858	0.39%
3	0.5729	1413	2.05%
4	0.5640	431	0.46%

IV. Conclusion

In this paper, adaptive strategies for the implementation of LPM to evaluate the shielding failure were proposed, in which the propagation step, the lightning current distribution and the lightning position sampling were considered. The computing speed is greatly improved while the accuracy is retained.

1) The propagation step is adjusted according to electric field at the conductor surface. When upward leader is about to incept, the propagation step adaptively become smaller.
2) The error tolerance of lightning current i_1 and i_2 are adjusted according to the probability distribution of lightning current.
3) By using adaptive recursive Simpson's rule to account for the lightning position, the lightning position is sampled adaptively.

Examples of the Japanese UHV line and a typical 500 kV transmission line in China were used to validate the model and the adaptive strategies. Results show the LPM with adaptive strategies computes the SFR/SFROR accurately and efficiently.

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References

[1] Sakae Taniguchi, Toshihiro Tsuboi and Shigemitsu Okabe. Observation results of lightning shielding for large-scale transmission lines. IEEE Transactions on Dielectrics and Electrical Insulation, 2009, 16(2):552-559.

[2] L. Dellera and E. Garbagnati. Lightning stroke simulation by means of the leader progression model PART II: Exposure and shielding failure evaluation of overhead lines with assessment of application graphs. IEEE Transactions on Power Delivery, 1990, 5(4), 2023-2029.

[3] IEEE Guide for Direct Lightning Stroke Shielding of Substations, IEEE Std-998, 2012.

[4] Bengang Wei, Zhengcai Fu, and Haiyan Yuan. Analysis of Lightning Shielding Failure for 500-kV Overhead Transmission Lines Based on an Improved Leader Progression Model. IEEE Transactions on Power Delivery, 2009, 24(3), 1433-1440.

[5] Behrooz Vahidi, Mostafa Yahyaabadi, Mohammad Reza Bank Tavakoli and S. M. Ahadi. Leader Progression Analysis Model for Shielding Failure Computation by Using the Charge Simulation Method. IEEE Transactions on Power Delivery, 2008, 23(4), 2201-2206.