

# Optimal Design of Transmission Line Tower Grounding Resistance Control Values Using Particle Swarm Optimization

**Authors:** Tao Yafeng, Chen Xinmeng, Wan Wencheng, Xinmeng Chen

**Date:** 2025-04-20T12:43:58+00:00

## Abstract

To enhance the lightning protection performance and scientific rigor of transmission line grounding device design, an optimization model for transmission line grounding resistance is established by analyzing the mathematical relationship between grounding resistance and backflashover trip rate, and an optimal design method for tower grounding resistance control values based on the particle swarm optimization algorithm is proposed. The optimal design method analyzes the influencing factors of backflashover trip rate, taking tower structural parameters, terrain parameters along the line, lightning parameters, and soil resistivity as model data inputs. The objective function of the model is designed by weighting the difference in total line backflashover trip rate and the proportion of backflashover trip rate exceeding limits. The particle swarm optimization algorithm is then employed to achieve soil resistivity zone division and selection of grounding resistance control values, which serve as the optimal design scheme for tower grounding resistance. The computational steps of the particle swarm optimization algorithm and a typical example are presented, with design results meeting preset requirements.

## Full Text

### Optimization Design of Tower Grounding Resistance Control Values for Transmission Lines Based on Particle Swarm Optimization Algorithm

**Yafeng Tao<sup>1</sup>, Xinmeng Chen<sup>2</sup>, Wencheng Wan<sup>3</sup>**

<sup>1</sup>. Huanggang Power Supply Company, State Grid Hubei Electric Power Co., Ltd., Huanggang 435400, China

<sup>2</sup>. CSSC Jiujiang Marine Equipment (Group) Co., Ltd., Jiujiang 332000, China

<sup>3</sup>. Wuhan Power Supply Design Institute Co., Ltd., Wuhan 430074, China

---

## Abstract

To enhance the lightning protection performance and scientific design of transmission line grounding devices, this paper analyzes the mathematical relationship between grounding resistance and back-flashover rate, establishes an optimization model for transmission line grounding resistance, and proposes an optimization design method for tower grounding resistance control values based on the Particle Swarm Optimization (PSO) algorithm. The method analyzes influencing factors of the back-flashover rate, using tower structural parameters, terrain parameters along the line, lightning parameters, and soil resistivity as model inputs. The objective function is formulated by weighting the difference between the total line back-flashover rate and the target value, along with the proportion of sections exceeding the back-flashover rate limit. The PSO algorithm is then employed to achieve soil resistivity segmentation and selection of grounding resistance control values as the optimal design scheme. The calculation steps of the PSO algorithm and a typical example are provided, demonstrating that the design results meet predetermined requirements.

**Keywords:** tower grounding resistance; back-flashover rate; optimization design; section division; Particle Swarm Optimization algorithm

---

## Introduction

With socioeconomic prosperity and progress, electricity demand continues to grow, leading to rapid development in the scale and density of high-voltage transmission line construction. Transmission lines inevitably traverse diverse regions including mountainous areas, plains, farmland, and urban zones, making their safe and reliable operation increasingly critical. Statistics indicate that lightning-induced accidents account for approximately 40%-70% of high-voltage transmission line faults [1-5], with this proportion exceeding 80% in thunderstorm-prone regions, causing substantial economic losses to grid operations. As a crucial channel for lightning discharge current, the grounding system constitutes a fundamental measure for maintaining grid safety and stability, with effective lightning protection grounding serving as an important prerequisite for secure grid operation.

Tower grounding resistance directly determines the tower top potential, thereby affecting the voltage withstand capability of line insulator strings and the probability of back-flashover, which directly influences line lightning protection performance [4]. Consequently, transmission line grounding design primarily focuses on lightning protection, with grounding resistance as the main control indicator.

The current power industry standard “*Design Code for Grounding of AC Electrical Installations*” (GB/T 50065-2011) [5] simply determines the design limit

of tower grounding impedance for high-voltage transmission lines with ground wires based solely on soil resistivity. The standard divides soil resistivity into five levels using  $100 \Omega \cdot \text{m}$  intervals and specifies corresponding power-frequency grounding impedance limits of  $15 \Omega$  for each level. However, when line voltage levels, tower types, and terrain conditions vary, the insulation levels differ significantly. Even under the same grounding impedance level, the lightning withstand capability can vary substantially. Therefore, using uniform grounding impedance control based solely on identical soil resistivity results in large variations in line lightning protection levels. Some lines may have inadequate lightning protection affecting operational reliability, while others may be over-designed, compromising economic efficiency [6-10]. Particularly in areas with relatively high soil resistivity, blind expansion of grounding conductors or implementation of auxiliary resistance reduction measures are often adopted to meet regulatory requirements, significantly increasing overall project investment. Moreover, these auxiliary measures not only increase operation and maintenance workload but also lack unified standards and supervision, preventing accurate assessment of their effectiveness and leaving hidden dangers for safe line operation.

Currently, domestic research on transmission line tower grounding optimization design primarily focuses on the optimization of grounding devices themselves and resistance reduction measures [11-20], with limited studies on optimizing grounding resistance control values. In 2016, Li Zhenqi et al. [21] proposed different grounding resistance designs for towers. In 2021, Lin Baixi et al. [22] suggested reasonable grounding resistance values, but these were still determined according to design specifications. In 2023, Tong Xuefang et al. [23] proposed a differential design study for tower grounding resistance control values, employing the Monte Carlo method to reasonably select optimal grounding resistance control values with good results in practical cases. However, this algorithm requires pre-setting the number of soil resistivity classification levels before optimization, necessitating multiple trials for different lines.

Based on this context, this paper establishes an optimization design model for transmission line grounding resistance values starting from the influencing factors of back-flashover rate, and solves it using the Particle Swarm Optimization algorithm from intelligent algorithms. Without requiring pre-set soil resistivity classification, the method is tested on a 500 kV transmission line system to provide a set of optimal grounding resistance values that ensure both lightning protection effectiveness and economic efficiency.

---

### 1.1 Mathematical Model for Grounding Resistance Optimization Design

The grounding resistance optimization design is a nonlinear integer multi-objective programming problem. Given the control target for transmission

line back-flashover rate, the objective is to design a set of soil resistivity classifications and corresponding grounding resistance values that satisfy constraints. The constraints include: (1) the total line back-flashover rate must not exceed the control target; (2) the difference between adjacent soil resistivity levels must be greater than or equal to  $500 \Omega \cdot \text{m}$ ; (3) the difference between adjacent grounding resistance values must be greater than or equal to  $5 \Omega$ ; and (4) to ensure engineering feasibility, grounding resistance values must exceed a minimum critical value when soil resistivity exceeds a certain range. The objective functions aim to: make the total back-flashover rate as close as possible to the design control target, and maximize the proportion of each classification's local back-flashover rate.

Through weighted averaging, the multi-objective problem can be transformed into a single-objective optimization problem. Based on the above objective functions and constraints, the nonlinear integer multi-objective optimization mathematical model can be summarized as follows:

Let  $R$  denote the objective function;  $\omega_1$  and  $\omega_2$  are weighting coefficients for the two sub-objectives;  $N_k$  represents the back-flashover rate of the  $k$ -th section, a nonlinear function of grounding resistance and soil resistivity;  $p_k$  is the proportion of the  $k$ -th soil resistivity level;  $R_k$  is the grounding resistance value;  $N$  is the total line back-flashover rate;  $K$  is the total number of classifications;  $\rho_k^{\max}$  and  $\rho_k^{\min}$  are the upper and lower limits of soil resistivity for the  $k$ -th level; and  $R_{\min}$  is the lower limit of grounding resistance. The coefficients  $a_2, a_1, a_0$  are constants of the fitting function.

Since the back-flashover rate  $N_k$  in the constraints is a nonlinear function of grounding resistance  $R$  and soil resistivity  $\rho$ , and both grounding resistance  $R$  and soil resistivity classification only take integer values, with the objective function containing two sub-objectives, problem (1) constitutes a nonlinear integer multi-objective programming problem with four constraints.

---

## 1.2 Back-Flashover Rate Fitting Function

The most critical step in problem (1) is calculating the total transmission line back-flashover rate  $N$ , which appears in both the objective function and constraints and is key to ensuring lightning protection effectiveness. Currently, various methods exist for calculating total back-flashover rate, including the standard method, Monte Carlo method, and ATP software modeling method. The standard method considers relatively few influencing factors and has limitations, particularly producing large errors when applied to high-voltage transmission line analysis. The Monte Carlo method lacks unified criteria for lightning strike location determination and flashover judgment. The most conventional and universal calculation method for studying lightning back-flashover performance of overhead transmission lines is simulation modeling based on the ATP program.

Therefore, this paper employs ATP modeling combined with polynomial fitting to obtain the quantitative relationship between grounding resistance and back-flashover rate. Through ATP/EMTP simulation modeling, the line back-flashover rate can be directly simulated given a set of initial grounding resistance values and other tower parameters. The total line back-flashover rate  $N$  is then obtained through weighted averaging based on section length proportions, calculated as follows:

$$N = \sum_{k=1}^K p_k \cdot N_k$$

where  $N_k$  is the back-flashover rate of the  $k$ -th section.

Taking a 500 kV tower as an example, when other tower parameters are fixed, ATP/EMTP simulation modeling can obtain data on grounding resistance versus back-flashover rate for different tower structures, as shown in [Figure 1: see original paper].

Analysis of the standard calculation method reveals that grounding resistance primarily affects the lightning withstand level, which in turn influences the back-flashover rate. The relationship between lightning withstand level and back-flashover rate is expressed as:

$$\log_{10}(N) = -\frac{I}{88}$$

where  $I$  is the lightning withstand level. The relationship between grounding resistance  $R$  and back-flashover rate in [Figure 1: see original paper] exhibits a parabolic quadratic distribution. This paper adopts a quadratic fitting function to determine the quantitative relationship between grounding resistance  $R$  and back-flashover rate  $N$ . In the numerical fitting, only tower grounding resistance  $R$  ( $\Omega$ ) is considered as the independent variable, with the fitting function between back-flashover rate  $N$  and grounding resistance  $R$  defined as:

$$\hat{N} = a_2 R^2 + a_1 R + a_0$$

where  $\hat{N}$  is the fitted back-flashover rate, and  $\mathbf{a} = [a_2, a_1, a_0]$  is the vector of fitting coefficients. Using MATLAB's `polyfit` function enables quadratic fitting:  $\mathbf{a} = \text{polyfit}(R, N, 2)$ . To evaluate fitting accuracy, the Global Relative Error (GRE) is introduced, defined as the ratio of absolute error to exact value:

$$\text{GRE} = \frac{1}{m} \sum_{i=1}^m \left| \frac{\hat{N}_i - N_i}{N_i} \right|$$

where  $m$  is the total number of samples. A smaller GRE value indicates better precision of the predictive model.

Fitting the data for the four tower types in [Figure 1: see original paper] yields the quadratic fitting coefficients and GRE values shown in . The GRE values for all four tower type fitting curves are less than 3.5%, indicating good accuracy of the quadratic fitting.

---

## 2.1 Basic Principles of Particle Swarm Optimization Algorithm

Problem (1) belongs to the class of multi-objective nonlinear integer programming problems. Current algorithms for solving such problems include enumeration methods, Monte Carlo methods, and intelligent algorithms such as Particle Swarm Optimization (PSO). Enumeration and Monte Carlo methods suffer from exponential time complexity when handling multi-dimensional problems. Problem (1) is a two-dimensional optimization problem where computation time grows dramatically with increasing classification levels. In contrast, the PSO algorithm considers information exchange among particles, enabling faster convergence toward optimal solutions and significantly reducing optimization computation time. Therefore, this paper selects the PSO algorithm to solve problem (1).

As a population-based evolutionary intelligent algorithm, each particle in PSO possesses two attributes: position and velocity. The particle position represents a feasible solution to the problem. For problem (1), the position is a 2K-dimensional vector corresponding to K soil resistivity classifications and their associated grounding resistance values, expressed as  $\mathbf{x} = [\rho_1, \rho_2, \dots, \rho_K, R_1, R_2, \dots, R_K]$ . Particle velocity is a vector representing the search direction. Initially, PSO randomly generates a particle swarm within the feasible domain. During iteration, particle positions and velocities are updated based on individual historical optimal values and swarm historical optimal positions, progressively approaching the optimal solution.

---

## 2.2 Particle Swarm Optimization Algorithm Flow

The PSO algorithm flowchart is shown in [Figure 4: see original paper].

### Figure 4. PSO Algorithm Flowchart

The specific procedure is as follows:

1. **Import preparatory data:** The preparatory dataset includes soil resistivity data along the transmission line, tower grounding resistance versus back-flashover rate data from ATP/EMTP simulation modeling, and minimum critical grounding resistance values satisfying engineering requirements. These datasets are imported into the MATLAB workspace.

2. **Establish functions:** Based on the soil resistivity dataset along the transmission line, establish the soil resistivity proportion function as follows:

$$p_k = \frac{\text{Number of data points with } \rho \leq \rho_k}{\text{Total number of data points}}$$

The back-flashover rate fitting function can be calculated using equation (3) from Section 1.2.

3. **Initialize particle swarm and parameters:** Initialization includes determining swarm size and dimension, randomly generating initial positions (grounding resistance values and soil resistivity classifications) and velocities within the feasible domain, and setting parameters: iteration count  $GEN$ , inertia factor  $\omega$ , acceleration factors  $c_1$  and  $c_2$ , and value ranges for soil resistivity and grounding resistance.

Since the inertia factor significantly influences global search capability and convergence speed, this paper adaptively adjusts the inertia factor using equation (7) to decrease it with increasing iterations:

$$\omega(t) = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \cdot \frac{t}{GEN}$$

where  $\omega_{\max}$  and  $\omega_{\min}$  are the maximum and minimum inertia factors, and  $t$  is the current iteration number.

4. **Check convergence conditions:** The convergence conditions are set as: (a) reaching maximum iteration count  $T_{\max}$ ; or (b) the optimal objective function value remaining unchanged for multiple iterations. If either condition is satisfied, output the optimal grounding resistance values, soil resistivity classifications, and optimal objective function value, then terminate; otherwise proceed to step 5.
5. **Update particle velocity and position:** Particle velocity and position are updated according to equations (8) and (9):

$$\mathbf{v}_i(t+1) = \omega \mathbf{v}_i(t) + c_1 r_1 (\mathbf{p}_i^{\text{best}} - \mathbf{x}_i(t)) + c_2 r_2 (\mathbf{g}^{\text{best}} - \mathbf{x}_i(t))$$

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t+1)$$

where  $\mathbf{v}_i$  is the velocity of the  $i$ -th particle;  $c_1$  and  $c_2$  are acceleration factors;  $\mathbf{p}_i^{\text{best}}$  and  $\mathbf{g}^{\text{best}}$  are individual and global best positions;  $t$  is the current iteration number. To prevent excessive velocity from overshooting the optimum or insufficient velocity from approaching it, velocity boundary handling is applied as in equation (10):

$$\mathbf{v}_i = \max(\min(\mathbf{v}_i, \mathbf{v}_{\max}), \mathbf{v}_{\min})$$

6. **Adaptive mutation:** Randomly select mutation nodes in particle positions and mutate them to other random values within the feasible domain.
7. **Check four constraints:** Verify satisfaction of all four constraints:  $|\rho_k - \rho_{k-1}| \geq 500$ ,  $|R_k - R_{k-1}| \geq 5$ ,  $N \leq N_{\text{target}}$ , and  $R_k \geq R_{\min}(\rho_k)$ . If all constraints are satisfied, calculate the particle's objective function value; otherwise, set the objective function value to a large penalty value.
8. **Update individual and global optima:** Calculate current individual and population objective function optimal values, update historical optimal values, and update corresponding positions and velocities. Return to step 4.

### 3.1.1 Line Overview

Soil resistivity data collected along a 500 kV transmission line is shown in [Figure 5: see original paper]. The soil resistivity along the line is mainly distributed in the range of 500–4000  $\Omega \cdot \text{m}$ , accounting for 89.9% of the data. Low soil resistivity sections below 500  $\Omega \cdot \text{m}$  constitute 7.12%, while ultra-high soil resistivity sections above 4000  $\Omega \cdot \text{m}$  account for 2.98%.

### 3.1.2 Line Back-Flashover Rate Target

Referring to the “*Guide for Lightning Protection of Overhead Transmission Lines*” (DL/T 2209-2021), the lightning trip-out rate for 500 kV lines should not exceed 0.14 times/(100 km · year). Based on operational statistics from commissioned 500 kV transmission lines in China, most lightning trip-out events are caused by shielding failures. According to references [24, 25], the shielding failure proportion is approximately 85% for 500 kV lines. Taking the shielding failure proportion as 85%, the back-flashover proportion is set at 20%, establishing the back-flashover rate target at 0.028 times/(100 km · year).

## 3.2 Typical Tower Back-Flashover Rate

Based on ATP program transient analysis of lightning striking a 500 kV line, the relationship between grounding resistance  $R$  and back-flashover rate  $N$  for tower type 5B1-ZB3 is obtained. The fitting function is:

$$N = 10^{-1.0415 \times 10^{-4} R^2 + 0.0307 R - 2.3320}$$

with a global relative error of 1.3677%.

### 3.3 PSO Iteration and Optimization Results

The particle swarm size is set to 500. For this case, the classification number  $K$  is cycled between [3, 8], resulting in particle dimensions cycling between [6, 16]. The PSO initialization parameters are: iteration count  $GEN = 500$ , inertia factor  $\omega$  defined by equation (7), acceleration factors  $c_1 = c_2 = 1.5$ , maximum velocity  $v_{\max} = 5$ , and minimum velocity  $v_{\min} = -5$ . In this case, soil resistivity ranges in [500, 10383]  $\Omega \cdot \text{m}$ , and grounding resistance ranges in [5, 50]  $\Omega$ .

When initializing the particle swarm, MATLAB commands `randi([v_{min}, v_{max}])` can initialize particle velocities, and `randi([_{min}, _{max}])` can initialize particle positions. Other parameters are: maximum iterations = 100, adaptive mutation rate = 0.5, and weighting coefficients  $\omega_1 = \omega_2 = 0.5$  in the objective function.

The optimal grounding resistance design scheme recommended by the PSO algorithm is shown in .

**Table 6. Soil Resistivity Classification and Grounding Resistance Values**

Soil Resistivity ( $\Omega \cdot \text{m}$ )	Grounding Resistance ( $\Omega$ )	Proportion (%)	Local Back-Flashover Rate (times/(100 km $\cdot$ year))	Total Back-Flashover Rate (times/(100 km $\cdot$ year))
300	15	7.12	0.012	
300-1100	20	28.45	0.028	
1100-2600	25	35.67	0.028	0.028
2600-6100	30	18.76	0.028	
> 6100	35	10.00	0.028	

The results show that the PSO algorithm recommends 5 classification levels. The optimal grounding resistance design values and soil resistivity classifications achieve a total line back-flashover rate of 0.028 times/(100 km  $\cdot$  year), exactly equal to the maximum design control value. The proportion of soil resistivity classifications exceeding the maximum back-flashover rate is 4.76%, which is lower than the 6.3% achieved by the Monte Carlo method [23], ensuring line safety and reliability. The total computation time for the PSO algorithm configuration is 3.1945 seconds, representing a significant improvement over the 65.5 seconds required by the Monte Carlo method in reference [23]. Compared

with the grounding resistance control values specified in regulations, the PSO algorithm' s scheme offers notable improvements in both implementability and economy while ensuring the total line lightning trip-out rate remains within requirements, satisfying predetermined construction criteria.

---

## Conclusion

This paper addresses the transmission line grounding resistance optimization design problem by establishing a nonlinear integer multi-objective optimization model and solving it using the Particle Swarm Optimization algorithm from intelligent algorithms. Testing on a 500 kV transmission line system demonstrates that the PSO algorithm can provide a set of optimal grounding resistance values that guarantee both lightning protection effectiveness and economic efficiency. The algorithm also offers advantages of simple operation, rapid convergence, and short computation time, making it suitable for grounding resistance design optimization of ultra-long transmission lines.

---

## References

- [1] LIU Junbo, WANG Zhigang, JIN Peng, et al. Lightning protection operation analysis of 220 kV overhead transmission lines in Jilin province[J]. Jilin Electric Power, 2018, 46(3): 17-19.
- [2] HU Jindian, WANG Hengkang, ZHAO Yuxin, et al. Study on influence of grounding resistance of transmission line tower on counterattack trip-out rate[J]. Sichuan Electric Power Technology, 2019, 42(6): 14-18.
- [3] CAO Pulin, SHU Hongchun, MA Yi, et al. The correlation degree of lightning location system and measured field traveling wave data for lightning induced fault distinguishing[J]. Proceedings of the CSEE, 2015, 35(20): 5220-5227.
- [4] HE Jinliang, ZENG Rong. Power system grounding technology[M]. Beijing: Science Press, 2007.
- [5] Ministry of Housing and Urban-Rural Development of the People' s Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People' s Republic of China. Design code for grounding of AC electrical installations: GB/T 50065-2011[S]. Beijing: China Planning Press, 2012.
- [6] LI Ming. Research on counterattack lightning performance and information processing technology for 110-220 kV transmission lines[D]. Beijing: North China Electric Power University, 2014.
- [7] LIU Xiao. Research on counterattack lightning performance of transmission lines[D]. Beijing: North China Electric Power University, 2016.

- [8] CHEN Zhilin, CHEN Yao, JIANG Chengyuan, et al. The analysis of lightning counterattack withstand level of 500 kV transmission line[J]. *Journal of Electric Power*, 2014, 29(6): 498-504.
- [9] LI Fuming, ZENG Jian, ZHANG Qinglei, et al. Analysis of factors affecting the lightning back flashover performance[J]. *Insulators and Surge Arresters*, 2015(4): 55-58.
- [10] XIAO Annan, ZHANG Weixiang, JIAO Yuping, et al. Multi-factor comparative analysis of lightning trip out rate in transmission line based on ATP-EMTP simulation software[J]. *Insulators and Surge Arresters*, 2019(4): 146-150.
- [11] LIAO Zhihua. Research on optimization measures for transmission line tower grounding systems[D]. Changsha: Changsha University of Science & Technology, 2013.
- [12] DING Zushan. Optimization design and application of transmission line tower grounding electrodes[D]. Xuzhou: China University of Mining and Technology, 2021.
- [13] LI Teng, HU Yuanchao, GAO Xiaojing, et al. Research on resistance reduction efficiency and influencing factors of transmission lines auxiliary grounding grid[J]. *Water Resources and Power*, 2021, 39(4): 165-169.
- [14] SUN Hongbo, YU Deshui. Design and resistance computation of ring-shaped grounding device of transmission line[J]. *Inner Mongolia Electric Power*, 2021, 39(6): 91-93.
- [15] YANG Xin, YI Junhua, LIU Yubin, et al. Grounding safety check and improved design of 110 kV steel pipe tower in a city[J]. *Insulators and Surge Arresters*, 2022(5): 92-100.
- [16] NI Renxin. Design and analysis of lightning protection and grounding for overhead transmission lines[J]. *Electric Power Equipment Management*, 2022(17): 56-58.
- [17] YUAN Weisen. Research and analysis of lightning protection and grounding system for transmission line[J]. *Mechanical and Electronic Control Engineering*, 2022, 4(2): 211-213.
- [18] KUANG Yulai, TANG Bo, XIE Huanghai, et al. Design scheme of shared tower grounding network based on uniform ground potential distribution[J]. *Insulators and Surge Arresters*, 2022(2): 115-124.
- [19] QI Siyi, ZHAO Hongfeng. Optimization and design of lightning protection characteristics of radial grounding conductors of line towers[J]. *Advances of Power System & Hydroelectric Engineering*, 2022, 38(1): 1-6.
- [20] WANG Xuming, LOU Jianyong, LI Wei, et al. Resistance reduction scheme design of tower grounding body by CDEGS[J]. *Insulators and Surge Arresters*, 2022(6): 117-122.

- [21] LI Zhenqi, CAI Xiang, YI Hao, et al. Study on difference tower grounding considering the characteristics of the grounding resistance[J]. Journal of Electric Power Science and Technology, 2016, 31(4): 168-174.
- [22] LIN Baixi. Design and analysis of lightning protection and grounding resistance of 110 kV transmission line[J]. The Journal of New Industrialization, 2021, 11(2): 32-33.
- [23] TONG Xuefang, FAN Mian, WANG Fusheng, et al. Differential design of tower grounding resistance control values for transmission line[J]. Insulators and Surge Arresters, 2023(5): 106-119.
- [24] LI Huiqi, TIAN Dongge, WANG Ping, et al. Study on the relationship between the microtopography and shielding failure of transmission lines[J]. Insulators and Surge Arresters, 2014(3): 73-83.
- [25] LIU Qian, CAO Wen, MIAO Haoming, et al. Research on protective effect of ground copper bars on secondary cables in substations[J]. Power System and Clean Energy, 2021, 37(7): 58-64.

---

**Author Biography:** Tao Yafeng (1994-), male, bachelor' s degree, primarily engaged in research on lightning protection and grounding technology. E-mail: cxm15061887237@163.com.

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv –Machine translation. Verify with original.*