

Article

Lightning Failure Risk Assessment of Overhead Transmission Lines Based on Modified Dempster–Shafer Theory

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Abstract: Lightning has a certain degree of potential threat to the safe operation of overhead transmission lines. In order to make targeted lightning protection arrangements and reduce the impact of lightning on overhead transmission lines, it is necessary to conduct lightning risk assessments on overhead transmission lines. This paper proposes a lightning failure risk assessment method for overhead transmission lines based on a modified Dempster–Shafer theory. First, analyze the historical lightning failure data of the line, determine the lightning failure impact factors, and use confidence to express the relationship between the lightning failure and the impact factor; then, use entropy weight theory and gray relational theory to calculate the value of mass function, and modify it on this basis; finally, use Dempster–Shafer theory to determine the trust degree and fit this with the calculated lightning trip rate to produce the risk assessment. This paper analyzes the lightning failure data of overhead transmission lines in some areas of Hebei Province. The results show that, compared with the evaluation method of the Dempster–Shafer theory, the accuracy of the evaluation is improved to a certain extent after correcting the mass function value. It can be seen that this method can integrate and comprehensively consider different data and can provide a reference for preventing damage to transmission lines by lightning strike weather.

Keywords: lightning failure; mass function correction; Dempster–Shafer theory; risk assessment



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1. Introduction

According to statistics from the Power Reliability Management Center, 40–70% of overhead transmission line failures are line trips caused by lightning [1–3]. In line design and operation inspection, accurate lightning risk assessment can effectively identify the risk of line failure caused by lightning strikes, further guide the arrangement of lightning protection measures for lines, and reduce the impact of lightning strikes on line operation, which has certain research significance.

To date, some achievements have been made in the lightning failure risk assessment for overhead transmission lines. In the literature [4], a lightning model for overhead transmission lines was established using EMTP-ATP to evaluate the effect of the equivalent impedance of the lightning channel on the lightning protection performance of overhead lines. In the literature [5], the transmission line Tucurui–Oriximina–Manaus was used as the research object, and the lightning protection level was evaluated using the electrical geometric model (EGM). In the literature [6], the ground inclination angle, lightning incidence angle, and other impact factors were comprehensively considered, an improved EGM was used to evaluate and calculate the overhead transmission line, and relevant lightning protection transformation measures were proposed. In the literature [7], a 2D analysis model based on the leader propagation concept was established to analyze the lightning shielding performance of a double circuit UHV transmission line in Japan. In the above literature, the lightning failure for overhead transmission lines was analyzed by

establishing a physical model or a mathematical model. During the modeling, weather conditions, altitude, and other impact factors would have been simplified or ignored, so the assessment results were not targeted.

With the development of big data technology in power systems, based on historical lightning failure data of overhead transmission lines, there is a method of risk assessment of lightning failure in overhead transmission lines using various data mining algorithms. For a system with complex mechanisms and uncertainty, data analysis shows its advantages. In the literature [8], a statistical analysis of lightning failure data of transmission lines was carried out, the connection between the lightning trip rate and data was studied, and differentiated lightning protection and assessment was proposed. In the literature [9], the lightning trip prediction model based on a GA-BP neural network and transmission line data was established for transmission lines, and the lightning trip warning for the whole line was achieved. In the literature [10], the analytic hierarchy process was improved, and a full level assessment system was established, which could comprehensively analyze various impact factors of lightning risk. In the literature [11], meteorological monitoring data were collected using multi-sensors, and a meteorological risk assessment model was established based on an analytic hierarchy process using expert scores.

With regard to the above literature, [8] performed a statistical analysis only, without considering the links between the data; [11] considered only the weather conditions around the lightning overhead transmission lines, without considering the effects of transmission line data, and expert experience evaluation has certain subjective factors that may adversely affect the accuracy of the results.

The modified Dempster–Shafer theory method comprehensively considers the external environmental factors and the factors of the transmission tower itself, calculates the mass function value using entropy weight theory and the grey relational analysis method, and integrates it with the Dempster–Shafer theory to assess the lightning failure risk of the transmission line. Moreover, this method relies on regional data, and the evaluation results are more regionally specific. Based on this method, this article adds correction parameters to the mass function to improve the accuracy of the evaluation.

2. Modified Dempster–Shafer Theory

This paper proposes a lightning failure risk assessment method for overhead transmission lines based on the modified Dempster–Shafer theory. Using the historical lightning failure data of overhead transmission lines in a certain area, the influence factors of lightning failures are determined, and confidence is used to express the correlation between lightning failures and impact factors; then, correction parameters are introduced to correct it; finally, the trust degree is determined using the Dempster–Shafer theory and fitted to the lightning trip rate to produce the risk assessment.

2.1. Determination of Impact Factor

The collected historical lightning failure data of overhead transmission lines were sorted and filtered. By consulting related literature and line operation experience, this article divides the impact factors into two categories: environmental factors and line factors. Environmental factors include weather conditions, altitude, topography, and landforms as impact factors; line factors include tower height, voltage level, and the tower model as impact factors. Among these factors, there are no direct data for altitude. This article uses the latitude and longitude in the fault data to query it in Google Earth software.

2.2. Calculation of Mass Function Value

The association rule in the data mining method can be used to determine the relationship between the impact factor and lightning failure. Define p_{ij} as the confidence of the j th impact factor of the i th tower. The specific calculation formula is as follows:

$$p_{ij} = \frac{n_{jx_i}^*}{n_{jx_i} \cdot f} \quad (1)$$

In the formula, $n_{jx_i}^*$ is the number of towers in the data where the i th tower is at the x index of the impact factor j ; n_{jx_i} is the number of the tower i in the data at the x index of the impact factor j ; f is the number of years in which data are collected. For example, the No. 5 pole tower is under the 220 kV indicator of the impact factor of voltage level.

A small value of p_{ij} indicates that the risk of lightning failure is small, and the formula for normalizing p_{ij} is as follows:

$$p'_{ij} = \frac{\max(p_{ij}) - p_{ij}}{\max(p_{ij}) - \min(p_{ij})} \quad (2)$$

The confidence matrix P is formed after normalization. Define p_{ij}^* as the proportion of the i th tower under the j th impact factor. The specific calculation formula is as follows:

$$p_{ij}^* = \frac{p'_{ij}}{\sum_{i=1}^m p'_{ij}} \quad (3)$$

The entropy value of the j th impact factor e_j is as follows:

$$e_j = -\frac{1}{\ln(m) \sum_{i=1}^m [p_{ij}^* \cdot \ln(p_{ij}^*)]} \quad (4)$$

The calculation formula of the weighted transmission line lightning failure correlation matrix X is as follows [12]:

$$X = (x_{ij})_{m \times n} = \left[\frac{p_{ij}^* (1 - e_j)}{\sum_{j=1}^n (1 - e_j)} \right]_{m \times n} \quad (5)$$

In Equations (3)–(5), m is the number of towers; n is the number of impact factors.

ζ_{ij} is the optimal correlation coefficient, and the specific calculation formula is as follows:

$$\zeta_{ij} = \frac{\min_i \min_j |x_{0j} - x_{ij}| + 0.5 \max_i \max_j |x_{0j} - x_{ij}|}{|x_{0j} - x_{ij}| + 0.5 \max_i \max_j |x_{0j} - x_{ij}|} \quad (6)$$

In Equation (6), x_{0j} is the maximum x value of the j th column.

The mass function value $m_j(K_i)$ can be calculated using the optimal correlation coefficient ζ_{ij} , and the specific calculation formula is as follows:

$$m_j(K_i) = \left(1 - \frac{\sum_{j=1}^n \zeta_{ij}}{n} \right) \cdot x_{ij} \quad (7)$$

2.3. Correction of Mass Function Value and Calculation of Trust Degree

The Dempster–Shafer theory belongs to the category of artificial intelligence, which was first applied in the expert system. Dempster proposed it, and Shafer perfected and developed the theory. The Dempster–Shafer theory can fuse multiple kinds of information to improve the accuracy of assessment. In this paper, we fuse the mass function with Dempster–Shafer theory to calculate the trust degree.

However, when using Dempster–Shafer theory for multi-information fusion, weather conditions, altitudes, topography, and landforms are geographical impact factors, whereas tower height, voltage level, and tower model are line impact factors, and the two types of multiple impact factors may, due to their own complexity, cause information conflicts. This information conflict means that when conducting evidence combination, distribution for

the basic trust degree of two focal elements that have no intersection is incorrect, and thus causes a mismatch between the results and general perception.

The weighted transmission line lightning failure correlation matrix X reflects the degree to which lightning failures are related to various impact factors and the tower. To address the information conflict that may exist between the geographic impact factor and the line impact factor, the correction parameter α is introduced to modify the mass function value and thereby reduce the possible impact of the information conflict on the result. For the weighted transmission line lightning failure correlation matrix X , $x_{\max}(x_{\max} = \max\{x_1, x_2, \dots, x_n\})$ was determined, and the relative weight x'_j using Equation (8) was calculated to obtain the relative weight matrix X' .

$$X' = X/x_{\max} = (x_1, x_2, \dots, x_n)/x_{\max} \quad (8)$$

The defined correction parameter α is calculated using the following formula:

$$\alpha_j = 1 - x'_j \quad (9)$$

According to correction parameter α_j , correct the mass function value to obtain the corrected mass function value $m'_j(K_i)$, with the calculation formula as follows:

$$m'_j(K_i) = (1 - \alpha_j)m_j(K_i) \quad (10)$$

The value of the revised mass function is used for fusion to calculate the trust degree $Bel(K_i)$. The calculation formula is as follows:

$$Bel(K_i) = (m'_1 \oplus \dots \oplus m'_j)m_j(K_i) = \frac{\prod_{x=1}^j m'_x(K_i)}{\sum_{i=1}^m \prod_{x=1}^j m'_x(K_i)} \quad (11)$$

In the formula, j is the number of impact factors; m is the number of towers.

2.4. Risk Assessment

In order to make the lightning risk result of the entire transmission line more intuitive, the transmission line is divided into sections. Because transmission lines of 110 kV and above are long, in this article, we decided to divide the sections according to altitude.

P_i is used to indicate the lightning trip rate of the i th tower, and P_i meets the following formula:

$$P_i = N/L \cdot f \quad (12)$$

where f is the number of years; N is the number of lightning failure trips in a section of the overhead transmission line in f year(s); and L is the total length of this section of the transmission.

Divide sections for data according to altitude, and, respectively, find the $\sum P_i$ and $\sum Bel(K_i)$ under each section. Conduct the fitting to obtain the fitting equation for P_i and $Bel(K_i)$.

P_{av} is the average value of lightning trip rate in all overhead transmission lines in the data, and the calculation formula is as follows:

$$P_{av} = N_{all}/L_{all} \cdot f \quad (13)$$

where N_{all} is the number of trips for lightning failure of all overhead transmission lines in f year(s); f is the number of years; and L_{all} is the total length of all overhead transmission lines in the data.

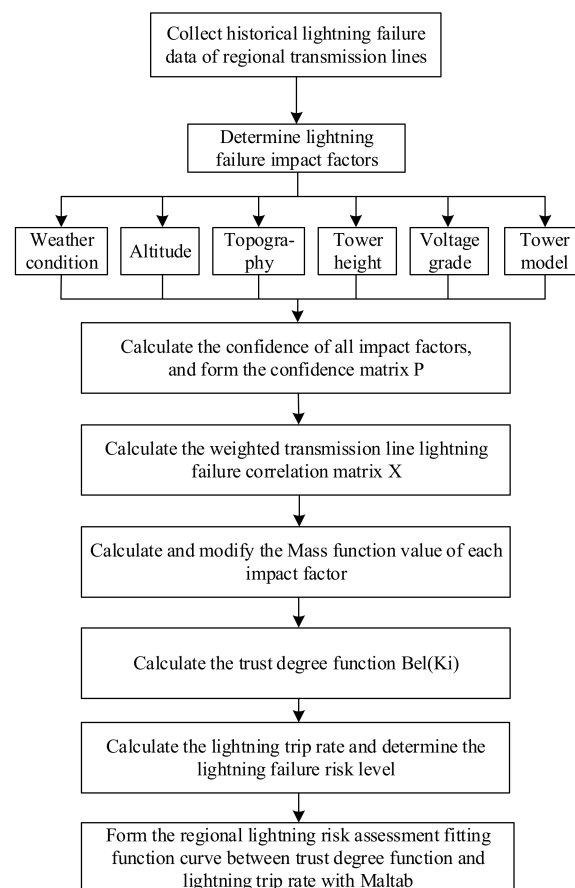
Divide the risk level of lightning failure of overhead transmission lines by P_{av} , with specific division of risk level as shown in Table 1.

Table 1. Lightning Failure Risk Level Table for Overhead Transmission Lines.

Judgment Method	Risk Level
$P_l \leq 0.25P_{av}$	I (low risk)
$0.25P_{av} < P_l \leq 0.75P_{av}$	II (medium to low risk)
$0.75P_{av} < P_l \leq P_{av}$	III (medium risk)
$P_{av} < P_l \leq 1.25P_{av}$	IV (medium to high risk)
$P_l > 1.25P_{av}$	V (high risk)

As for a specific transmission line, calculate the trust degree $Bel(K_i)$ of each tower in the line using its historical data of lightning failure, and obtain the lightning trip rate P_i of each tower using curve fitting. Then, determine the risk level of lightning failure for each tower in comparison with Table 1 to obtain the transmission line risk assessment, with tower-related accuracy, so that relevant staff can make targeted lightning protection arrangements.

The overall process for lightning failure risk assessment in overhead transmission lines set out in this paper is shown in Figure 1.

**Figure 1.** Lightning failure risk assessment flowchart.

3. Case Study

3.1. Calculation of Lightning Failure Risk

We sorted out and analyzed lightning failure data of overhead transmission lines in some areas of Hebei Province from 2011 to 2019. We assessed the lightning failure risk in overhead transmission lines using the method in this paper. First, we determined the weather conditions, altitude, topography, tower height, voltage grade, and tower model as impact factors of lightning failure in overhead transmission lines. We queried the altitude using Google Earth software with the longitude and latitude in the lightning failure data.

We calculated the confidence of all impact factors according to Equation (1):

- (1) Weather conditions: this was divided by region, and the confidence calculation results are shown in Table 2:

Table 2. Weather condition factor confidence table.

Areas	Confidence
Baoding	5.93×10^{-3}
Cangzhou	7.04×10^{-3}
Handan	1.70×10^{-2}
Hengshui	2.46×10^{-3}
Shijiazhuang	6.72×10^{-3}
Xingtai	6.35×10^{-3}

- (2) Altitude: this could be divided into four grades, and the confidence calculation results are shown in Table 3:

Table 3. Altitude factor confidence table.

Altitude (m)	Confidence
(0, 300)	1.31×10^{-2}
(300, 600)	4.70×10^{-3}
(600, 900)	4.74×10^{-3}
(900, 1200)	3.28×10^{-3}

- (3) Topography: this could be divided into three grades, and the confidence calculation results are shown in Table 4:

Table 4. Topographic factors confidence table.

Topography	Confidence
Plain	1.11×10^{-2}
Mountainous area	8.24×10^{-3}
Hill	1.06×10^{-3}

- (4) Tower height: this could be divided into four grades, and the confidence calculation results are shown in Table 5:

Table 5. Tower height factor confidence table.

Tower Height (m)	Confidence
(15, 35)	1.25×10^{-2}
(35, 55)	1.37×10^{-2}
(55, 75)	2.27×10^{-3}
(75, 80)	5.76×10^{-4}

- (5) Voltage grade: this could be divided into three grades, and the confidence calculation results are shown in Table 6:

Table 6. Confidence table of voltage grade factor.

Voltage Grade (kV)	Confidence
110	5.53×10^{-3}
220	1.33×10^{-2}
500	3.92×10^{-3}

- (6) Tower model: this could be divided into six grades, and the confidence calculation result is shown in Table 7:

Table 7. Tower model factor confidence table.

Tower Model	Confidence
Cat-head type	1.40×10^{-2}
Umbrella type	1.23×10^{-2}
Drum type	1.97×10^{-2}
JG type	4.03×10^{-3}
Wishbone type	1.18×10^{-3}
Cup type	3.09×10^{-3}

The total number of overhead transmission line towers in the data was 15,847, and the number of impact factors was six. The mass function value was calculated using the entropy method and gray correlation analysis, then the modified Mass function value of each influence factor was obtained using Equations (8)–(10), and finally, the trust degree function $Bel(K_i)$ of 15,847 towers was calculated according to Equation (11).

3.2. Assessment of Lightning Failure Risk

Using historical lightning failure data in this case, we calculated the average value P_{av} of lightning trip rate in overhead transmission lines according to Equation (13), giving the P_{av} as 0.03367 (times/100 km per year) after calculation. Therefore, the lightning failure risk level of this area can be divided as shown in Table 8:

Table 8. Lightning Failure Risk Level Table of Regional Overhead Transmission Lines.

Judgment Method	Risk Level
$P_l \leq 0.00842$	I (low risk)
$0.00842 < P_l \leq 0.02525$	II (medium to low risk)
$0.02525 < P_l \leq 0.03367$	III (medium risk)
$0.03367 < P_l \leq 0.04209$	IV (medium to high risk)
$P_l > 0.04209$	V (high risk)

We calculated the corresponding P_i based on Equation (12) and conducted fitting for the corresponding trust degree function $Bel(K_i)$ to obtain the function shown in Figure 2:

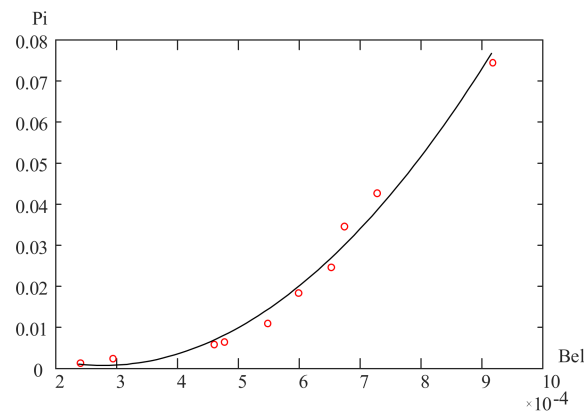


Figure 2. Fitting function of trust degree and lightning trip rate.

3.3. Comparison of Evaluation Results

To further validate the accuracy of assessment results, we calculated the lightning failure data of the company in 2020 using the above algorithm and compared it with the fitting function in Figure 2, with the results shown in Figure 3.

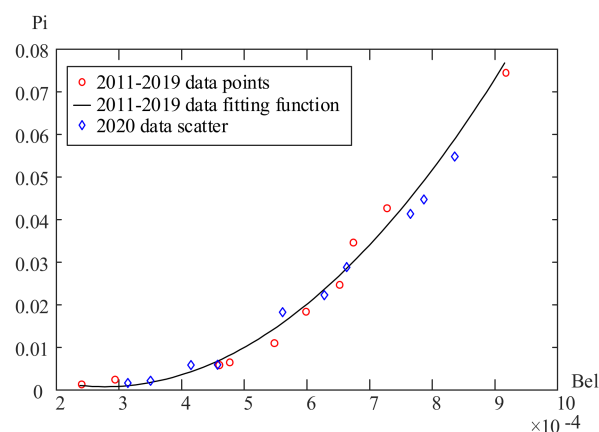


Figure 3. 2020 data scatter and fitting function.

From the comparison in Figure 3, the result of the assessment shows that the lightning failure data from 2020 and from 2011 to 2019 relatively fits. The lightning failure assessment result considering six impact factors has good applicability in this area, and it provides a better indication of the relation rule between the lightning failure in this area and the six impact factors.

In addition, we did not conduct mass function correction on historical data, but instead compared the fitting function curve obtained with the corrected fitting function curve, with the results shown in Figure 4.

In Figure 4, the corrected fitting function curve better fits the 2020 lightning failure data; the predicted lightning trip rate of the corrected curve is slightly higher than of that without correction, and this can help avoid putting lightning protection measures in place to address a low risk value indicated by the cure without correction. There were 16 lightning trips in the area in 2020. Lightning failure prediction curve fitting with and without correction and the actual data for 2020 was subjected to statistical comparison to calculate the goodness of fit. It can be seen from Table 9 that the uncorrected lightning failure prediction fitting curve R^2 is 0.8759, and the corrected lightning failure prediction fitting curve R^2 is 0.9382. It can be seen that the correction of the mass function can improve the accuracy of the evaluation result to a certain extent.

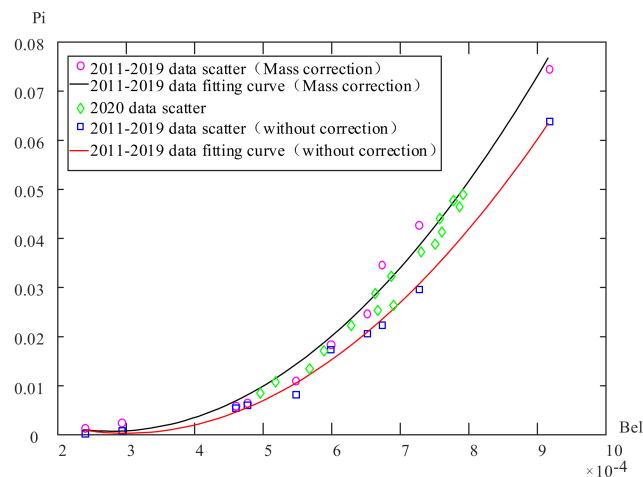


Figure 4. Comparison of fitted function curves with and without correction.

Table 9. Goodness of fit test.

Fit Function	R-Square Comparison
Mass function correction	0.9382
Mass function without correction	0.8759

The risk assessment in this paper took historical data of transmission line lightning failure in a certain area as a sample, calculated the trust degree Bel using a modified Dempster–Shafer theory, and established the relationship between this and the lightning strike trip rate through function fitting. The risk level division of the lightning trip rate made the presentation of the results more intuitive. The predicted risk level can be obtained by inputting the relevant data calculation, which can produce a risk assessment for the transmission line.

4. Conclusions

In this paper, based on the historical lightning failure of overhead transmission lines, we assessed the risk in the lightning failure of overhead transmission lines using a modified Dempster–Shafer theory and reached the following conclusions using data analysis:

- (1) In the case study, the Dempster–Shafer theory and the Dempster–Shafer theory with modified mass function values were used for fitting, and the R-square values of the goodness of fit were 0.8759 and 0.9382, respectively. Thus, modified Dempster–Shafer Theory can improve the accuracy of the evaluation results to a certain extent.
- (2) Through the information fusion calculation using multiple impact factors, we can clearly see the strong or weak relationship between lightning failure and various impact factors in the area to be assessed, which has a certain reference value for the differentiated lightning protection of lines.
- (3) As for the transmission lines within the sample data, we can determine the lightning risk level of each tower in the whole transmission line, enabling the lightning risk degree of each section to be visually displayed, and this has a reference value for lightning protection arrangements of the whole transmission line.
- (4) Regarding the limitations of the method in this paper: the data sample should not be too small, as this will lead to low assessment accuracy or even an inability to complete the assessment; other collected impact factor data can also be added to this method in follow-up work; and the algorithm structure of this paper can be further optimized, and research can be continued on this basis.

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