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Risk Analysis Method Based on FMEA for Transmission Line in Lightning Hazards

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Abstract: Failure rate of transmission line and reliability of power system are significantly affected by Lightning meteorological factor. In view of the complexity and variability of Lightning meteorological factors, this paper presents lightning trip-out rate model of transmission line in considering distribution of ground flash density and lightning day hours. Meanwhile, presents a failure rate model of transmission line in different condition, and a risk analysis method for transmission line considering multiple risk factors based on risk quantification. This method takes Lightning meteorological factor as the main evaluation standard, and establishes risk degree evaluation system for transmission line including another five evaluation standard. Put forward the risk indicators by quantify the risk factors based on experience date of transmission line in service. Based on the risk indexes comprehensive evaluation is conducted, and the evaluation result closer to practice is achieved, providing basis for transmission line risk warning and maintenance strategy. Through the risk analysis for 220 kV transmission line in a certain power supply bureau, the effectiveness of the proposed method is validated. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Transmission line, Ground flash density, Lightning day hours, Failure rate, Risk indexes, Risk analysis.

1. Introduction

The failure probability of overhead transmission lines under inclement weather conditions is much higher than under normal climatic conditions. Lightning is one of the harsh meteorological factors, which has significant impact on overhead transmission lines in service. Thus, the study of risk analysis methods on overhead transmission lines would contribute to the achievement of early risk warning under lightning weather conditions. Guarantee the safe and reliable of overhead transmission lines in service by taking security precautions in advance.

Currently, scholars have study on effects of meteorological factors on the reliability of power system. Literature [1] points out climate conditions can be divided into normal climate conditions and adverse weather conditions, the method of evaluating the reliability by simulating piecewise line under different climate conditions has being put forward. In literature [2] Monte-Carlo method is adopted to transmission line and climate area sampling, then determined the state of power transmission components and power grid reliability calculation. In [3] the reliability evaluation model of transmission lines in different weather influence monthly is established. The research in the past mainly considered the off-line reliability assessment of power grid, meanwhile, established the reliability evaluation model [4] in considering the meteorological effects. However, there is less research on risk analysis and early warning methods of transmission line on-line assessment.

Overhead transmission lines reliability is closely related to meteorological factors which are not only affected by line construction ways, but by line corridors region, such as landform and physiognomy. These factors are often determines the form [5] of a lightning striking on the transmission line. We built overhead transmission line risk assessment index system on the bases of analysis of lightning disaster main factors [6]. Based on the meteorological conditions, transmission line and the external environment factors, the level of risk analysis and weight calculation, finally make a comprehensive evaluation [7]. Proposed multifactor risk analysis method of overhead transmission lines under the thunder and lightning disasters.

2. The Determination of Transmission Line Lighting Disaster Risk Factors

Transmission line lightning trip-out fault has its unique characteristics [8]. There are two kinds of lightning overvoltage: one is the induction lightning overvoltage, the other is direct lightning overvoltage. The hazard of induction lightning overvoltage is small due to the high insulation level of transmission lines, with a focus on the direct lightning protection. From the part of the line lightning hit by we divided the direct lightning overvoltage into three kinds [9]: lightning strike on tower, namely inverse flashover; lightning strike pass the wire, namely detour lightning thunder; lightning strike to the central of ground wire. Lightning strike on the middle of ground wire span and the conductor flashover causing tripping is rare. Therefore, direct lightning protection [10] is mainly against inverse flashover overvoltage and detour lightning overvoltage.

Detour lightning thunder tripping rate and inverse flashover tripping rate which related to the influence of factors [11] such as landform, grid insulation level, the structure of the tower, the ground tilt Angle and grounding resistance. In brief, ground flash in certain conditions can cause lightning accident. According to the cause of the breakdown of the transmission line under lightning disasters, combine the experience and the actual situation to determine the related risk factors. This article selects the six risk factors such as ground lightning density, time distribution, the regional average soil resistivity of transmission line, transmission line elevation, transmission line grounding resistance and transmission line tower height.

2.1. Ground Lightning Average Density

The main damage on transmission line caused by lightning is unscheduled shutdown due to trip-out. Ground lightning density is the most important risk factor affecting lightning trip-out rate, determination of it directly affects the accuracy of the assessment. Lightning distribution is seasonal, most areas in China mainly happened in summer thunderstorm season [12]. According to the monthly statistics based on the ground lightning number per day from 2000 to 2010, we get monthly average ground lightning density. From June to September the ground lightning density was significantly higher than other months.

2.2. Lightning Day Time Distribution

The region's lightning day time distribution is double peak distribution in 24 hours, lightning mainly concentrated in 0 ~ 3 a.m, 14 ~ 23 p.m. If transmission line fault occurs in 17 ~ 23 p.m during electricity peak, that will cause great influence to power supply. Therefore, different distribution would affect the fault risk of overhead line.

2.3. Soil Resistance Rate

The soil resistivity also has bigger difference in different regions which is relevant to the probability distribution of lightning current amplitude [13]. In fact, the probability of higher lightening current amplitude will increase in the lower soil resistivity area to a great extent. Lightning current amplitude distribution directly affects the detour lightning tripping rate. Thus detour lightning tripping is much easier happened in higher soil resistivity area.

2.4. Altitude

Transmission line lightning strike is also different in different topography. Altitude is another important factor affecting the lightning current distribution which affects the transmission line detour lightning tripping rate. The height of thundercloud in mountain area is lower than in plain area, they reached critical breakdown strength of the air before a large number of charge formed, so there is less chance of the higher lightening current amplitude appearing in mountains area than in plain area [14]. In a word, lightning current amplitude decreases with increasing of altitude. Detour lightning tripping rate is more likely to happen in mountain area. Therefore, altitude should be taken into consideration in transmission line lightning risk assessment.

2.5. Transmission Line Ground Resistance

Tower grounding resistance [15] is the most important factor directly impacting on the withstandlever of inverse flashover and inverse flashover trip-out rate. When calculating a lightning withstandlever of inverse flashover, tower impulse grounding resistance is an important parameter to calculate tower impulse potential which got from measured power frequency grounding resistance multiplying by the impulse factor.

Smaller transmission line grounding resistance can effectively reduce overvoltage due to circulation through thunder lightning rod (wire) or lightning arrester which can protect the personal safety and insulation of the electrical equipment. But when the transmission environment conditions are severe and the grounding body is not buried deep enough, especially in the mountains, rock region which is high oxygen content. Thus the soil corrosion of ground would be faster which directly lead to the grounding resistance value greater than the design value. Pose a threat to transmission line operation.

In conclusion, consideration should be given to the influence of environment on ground resistance and use the actual measured value to instead the design value of ground resistance when take a risk assessment for transmission line.

2.6. Transmission Line Tower Height

The voltage level of transmission line affects the tower height, as shown in Fig. 1, shielding failure trip-out rate will increase with the increase of tower height [16]. Tower height has an impact on the lightning strike risk of transmission line.

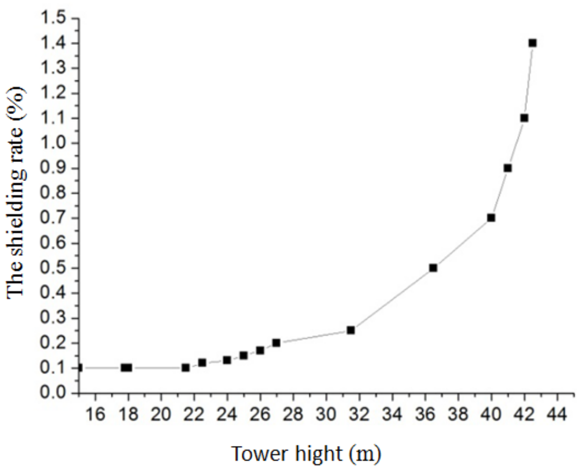

Fig. 1. The relationship between shielding failure trip-out rate and tower high degree. Example of figure.

3. Failure Mode and Effects Analysis Model of Transmission Line

From the analysis of above factors affecting the risk of transmission line, we consider that the risk factors are independent of each other as shown in Table 1. According to the theory of fault tree analysis [17], FMEA model is set up as shown in Fig. 2.

Table 1. Transmission line lightning risk factors.

Risk factor	Sign
The ground lightning average density	U_1
Lightning day time distribution	U_2
Landscape (vegetation)	U_3
Altitude	U_4
Ground resistance	U_5
Tower height	U_6

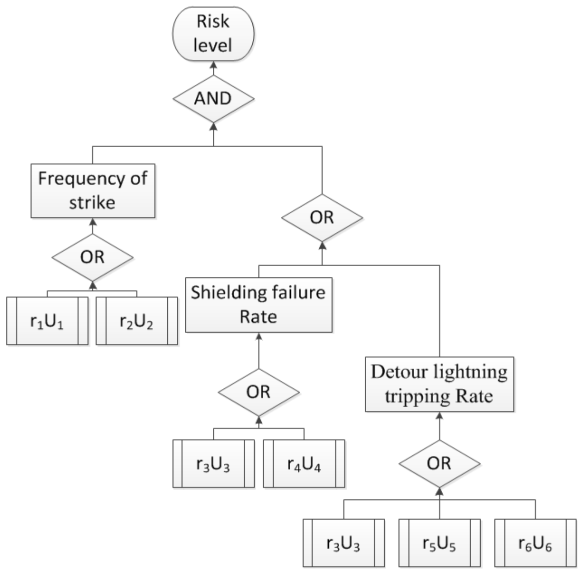

Fig. 2. Failure mode and effects analysis model.

3.1. Risk Factors Quantify

Determining the probability of each risk events U_i is the key to build FMEA model. Transmission lines have different failure rate under different environmental conditions. The failure rate even varied with different levels of risk under the same condition. For example, transmission line failure rate is obviously higher under red level of the lightning weather than general lightning weather. Therefore, we should select targeted indexes when assess the risk of transmission lines.

Risk assessment indicators can be obtained from building failure rate model of single external risk factors under different risk level based on transmission lines operating experience statistics [18].

Suppose a_i the risk index transformed into risk level is each of the six quantitative applied risk factors such as ground flash density, lightning day time distribution, landform, altitude, ground resistance and tower height, which can be calculated by equation (1):

$$\lambda_{ia_i} = \frac{N_{a_i}}{N_{ia_i}}, i = 1,2,3,\ldots,n, \quad (1)$$

where λ_{ia_i} is the transmission line failure rate of risk factor i under risk level a_i, λ_{ia_i} is the function of the risk level a_i, N_{a_i} is the failure number of risk factor i under the risk level a_i, N_{ia_i} is the total failure number of risk level a_i under risk factor i.

3.2. The Determination of Weights

Due to the incidence of various factors on the transmission line fault rate is different, this paper used improved analytic hierarchy process (IAHP) [19] to deal with the weight of each risk factor, that is to divide the problem to into two stages: first, use familiar three scale method (0,1,2) to do a comparison between any two elements, then establish a comparison matrix and calculate sorting index for each element; second, transform comparison matrix into judgment matrix and prove that it can completely satisfy the consistency. Suppose r_i is the weight of six risk factors weight sets.

3.2.1 Establish Comparative Matrix

$$A = (b_{ij}) \quad (2)$$

where b_{ij} can now be written as follows:

$$b_{ij} = \begin{bmatrix} 2 & b_i \text{ is important than } b_j \\ 1 & b_i \text{ is as important as } b_j \\ 0 & b_j \text{ is important than } b_i \end{bmatrix}, \quad (3)$$

$$r_i = \sum_{j=1}^{6} b_{ij} \quad (4)$$

3.2.2. Construct Judgment Matrix

$$B(b_{ij}) = \begin{bmatrix} b & b_1 & b_2 & b_3 & b_4 & b_5 & b_6 & M_i & W_i & w_i \\ b_1 & 1 & & & & & & & & \\ b_2 & & 1 & & & & & & & \\ b_3 & & & 1 & & & & & & \\ b_4 & & & & 1 & & & & & \\ b_5 & & & & & 1 & & & & \\ b_6 & & & & & & 1 & & & \end{bmatrix} \quad (5)$$

$$M_i = \prod_{j=1}^{6} b_{ij} \quad (6)$$

$$w_i = \frac{W_i}{\sum_{j=1}^{6} W_i} \quad (7)$$

$$W_i = \sqrt[6]{M_i} \quad (8)$$

$$\sum_{j=1}^{6} w_i = 1 \quad (9)$$

3.2.3. Consistency Check

$$B = (b_{ij}), C = (c_i) = B \bullet [w_i]^T \quad (10)$$

The biggest characteristic value:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{6} \frac{c_i}{w_i} \quad (11)$$

$$P_{B.I.} = \frac{\lambda_{\max} - n}{n - 1} \leq 0.001 = \varepsilon \quad (12)$$

3.3. Risk Level Rating

From six risk factors above, we can determine the risk probability index and weight index based on the possibility of harm transform into risk and weight analysis. The probability of basic risk event U_i is as follows:

$$U_i = r_i \lambda_i \quad (13)$$

$$\begin{aligned} V_1 &= U_1 + U_2 \\ V_2 &= U_3 + U_4 + U_5 + U_6 \end{aligned} \quad (14)$$

The risk level of transmission lines under the lightning disasters are for:

$$R = CV_1 \bullet V_2 \; U_i = r_i \lambda_i \quad (15)$$

In equation (15), C is a constant which is the magnification times for more expediently judging the risk level of transmission line, usually take 10.

Comprehensively analysis the effects and weights of the six risk factors on transmission lines, we can take the risk level as shown in Table 2.

Table 2. Risk analysis table of Transmission lines under the thunder and lightning disasters.

Comprehensive index R	Risk level
>1	Highest
>0.8	Higher
>0.5	Medium
>0.3	Low

High risk index greater than 1 indicates the highest risk level. That is transmission lines malfunction easily under lightning disasters, the security of power system face great risks. We need to strengthen and improve the existing lightning protection measures. Risk index greater than 0.8 shows that risk level is higher which may lead to transmission line tripping, conductor wire breakdown and Insulator damage etc. The risk index is less than or equal to 0.5 shows the low risk level, indicates that the existing lightning protection measures can effectively ensure the safety of the transmission line and the stability of power grid. We do not need to take additional measures.

Therefore, we need to focus on the situation of larger risk index. Analysis and calculation the relevant parameters of risk factors which may cause transmission line failure, there by select suitable protection measures.

4. Actual Example

To verify the validity of the model, this paper selected three sections of transmission lines in a given area for calculation and analysis.

1) Select lines surrounding lush vegetation signed line 1, where the average altitude is 2250 m, sample of grounding resistance measured average value is 15.2 Ω, tower height is 40 m;

2) Select lines surrounding scarce vegetation signed line 2, where the average altitude is 1800 m, sample of grounding resistance measured average value is 13.8 Ω, tower height is 30 m;

3) Select lines surrounding scarce vegetation signed line 3, where the average altitude is 1800 m, sample of grounding resistance measured average value is 13.8 Ω, tower height is 20 m;

The above three lines are evaluating the risk in this period of time 16 ~19 p.m and 21 ~ 23 p.m.

4.1. Risk Indexes Evaluation

Comprehensive considering the line information, operational experience data and failure rate statistics combined with equation (1), we can get the risk quantification m indicators shown in the Table 3, Table 4 and Table 5 below.

Table 3. Transmission line 1 risk indexes.

Risk indexes	Value	Risk level	Fault rate
The ground lightning average density	0.4	3	0.28
Lightning daytime distribution	16 ~19 p.m and 21 ~ 23 p.m	3	0.7
Landscape	Lush	3	0.6
Altitude	2250	3	0.584
Ground resistance	>15 Ω	3	0.81
Tower height	40 m	3	0.7

Table 4. Transmission line 2 Risk indexes.

Risk indexes	Value	Risk level	Fault rate
The ground lightning average density	0.2	2	0.28
Lightning daytime distribution	16 ~19 p.m and 21 ~ 23 p.m	3	0.7
Landscape	Lush	1	0.1
Altitude	2250	2	0.342
Ground resistance	>15 Ω	2	0.27
Tower height	40 m	2	0.2

Table 5. Transmission line 3 Risk indexes.

Risk indexes	Value	Risk level	Fault rate
The ground lightning average density	0.5	4	0.28
Lightning daytime distribution	16 ~19 p.m and 21 ~ 23 p.m	3	0.7
Landscape	Lush	1	0.1
Altitude	2250	2	0.342
Ground resistance	>15 Ω	2	0.27
Tower height	40 m	1	0.2

4.2. Weight Calculation

According to the practical experience data combining experts scoring, use the three scale method (0, 1, 2) for comparison between any two elements. Then establish a comparison matrix and calculate the ranking indexes of each element as follows:

Establish comparative matrix as follows:

$$A(b_{ij}) = \begin{bmatrix} b & b_1 & b_2 & b_3 & b_4 & b_5 & b_6 & r \\ b_1 & 1 & 2 & 2 & 2 & 2 & 2 & 11 \\ b_2 & 0 & 1 & 2 & 0 & 2 & 2 & 7 \\ b_3 & 0 & 0 & 1 & 0 & 1 & 1 & 3 \\ b_4 & 0 & 2 & 2 & 1 & 2 & 2 & 9 \\ b_5 & 0 & 0 & 1 & 0 & 1 & 1 & 3 \\ b_6 & 0 & 0 & 1 & 0 & 1 & 1 & 3 \end{bmatrix} \quad (16)$$

Construct judgment matrix as follows:

$$B(b_{ij}) = \begin{bmatrix} b & b_1 & b_2 & b_3 & b_4 & b_5 & b_6 & M_i & W_i & w_i \\ b_1 & 1 & 3 & 9 & 2.28 & 9 & 9 & 4986.38 & 4.13 & 0.458 \\ b_2 & 1/3 & 1 & 3 & 0.58 & 3 & 3 & 5.22 & 1.32 & 0.145 \\ b_3 & 1/9 & 1/3 & 1 & 0.19 & 1 & 1 & 0.007 & 0.44 & 0.049 \\ b_4 & 0.58 & 1.73 & 5.2 & 1 & 5.2 & 5.2 & 141.09 & 2.28 & 0.252 \\ b_5 & 1/9 & 1/3 & 1 & 0.19 & 1 & 1 & 0.007 & 0.44 & 0.049 \\ b_6 & 1/9 & 1/3 & 1 & 0.19 & 1 & 1 & 0.007 & 0.44 & 0.049 \end{bmatrix} \quad (17)$$

Consistency check:

$$B = (b_{ij}), C = (c_i) = B \bullet [w_i]^T$$
$$= (2.788, 0.884, 0.294, 1.532, 0.294, 0.294) \quad (18)$$

The biggest characteristic value:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{6} \frac{c_i}{w_i} = 6.048 \quad (19)$$

$$P_{B.I.} = \frac{\lambda_{\max} - n}{n-1} = \frac{6.048 = 6}{6-1} \leq 0.001 = \varepsilon \quad (20)$$

We can get the weight of various risk indexes in Table 6.

Table 6. Weights of risk indexes.

Risk index weight	Weight
The ground lightningaverage density r_1	0.456
Lightning day time distribution r_2	0.145
Landscape (vegetation) r_3	0.049
Altitude r_4	0.049
Ground resistance r_5	0.252
Tower height r_6	0.049

4.4. The Calculation of Risk Level

According to the proposed equation (13), (14), (15), the risk level comprehensive indexes of the three lines are shown in Table 7.

Table 7. Risk level comprehensive index.

Comprehensive index R	Risk level
1.025	Highest
0.72	Medium
0.3	Low

According to the actual circuit operating experience data of Line 1 which faults often happened, lightning activity lead to circuit disconnection or insulation accident such as insulator explosive for many times. The result calculated in this paper is high risk level consistent with the actual, so we need to modify or strengthen the lightning protection measures of transmission lines; Line 2 failure more ordinary, more for tripping or failure such as fault automatic reclosing, this paper get the risk level of the calculation results as the medium, can strengthen the lightning protection measures; Line 3 low incidence of accidents, this paper calculated risk ratings are the lowest. Above all, it is the result of the proposed risk assessment model was consistent with actual situation, and it can evaluate different transmission lines in the risk level of the same type of weather conditions, can also assess the same transmission line in different circumstances outside risk level. That has a certain flexibility and wide practicability.

5. Conclusion

Transmission line risk early warning is one of the main contents of the power grid security early warning. A Gordian knot lies in how to build early warning methods and model. In this paper, the key is to build a fault model considered the thunder day distribution, ground lightning density and other risk factors affecting the safety of transmission line, the actual lightning activity impact on transmission line is described more accurately. Thus get more data of risk factors which is more in line with actual situation, and then get more accurate risk rating criteria of transmission lines under lightning disasters which can provide evidence for security plans and accident treatment measures.

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