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The reliability evaluation of an overhead transmission line based on the fault tree model

The overhead transmission line is the main part of a power system, whose state affects the reliability and stabilization of the power system. Therefore, the state of an overhead transmission line must be evaluated to protect the power system. This study analyzed the relationship between the common failure modes of transmission lines and their influencing factors, chose the influencing factors as the characteristic parameters, and built the fault tree model of an overhead transmission line. It used the improved analytic hierarchy process to evaluate the importance of the fault mode, and then calculated the corresponding weights of different fault tree models. The study also used the relative deterioration degree and membership function to calculate the probability of all kinds of faults. The correctness and validity of this model was verified by the operation data of the Guangxi grid.

Keywords: *Fault tree, overhead transmission line, reliability, improved analytic hierarchy process, membership function.*

1. Introduction

An overhead transmission line is the main part of a power system, whose running state affects the reliability and stabilization of a power system. With the rapid development of the national economy and the acceleration in power grid construction, the length of overhead transmission lines is increasing, and the difficulty of maintaining such lines is also increasing. The transmission line fault not only affects the transmission of electricity, but also leads to large-scale power cuts, causing huge economic losses. Therefore, the operational reliability of overhead transmission lines is the key to the reliability and stabilization of power systems.

Research on the reliability evaluation of overhead transmission lines has been conducted at home and abroad. According to the running time and the pollution level and ground flash density of the region of the transmission line, document [1] put forward two kinds of reliability prediction models of transmission lines based on support vector machine (SVM) and grey prediction technology. Document [2] assessed the state of extra-high-voltage (EHV) transmission lines in engineering practice and calculated the comprehensive state evaluation score of EHV transmission lines using the fuzzy comprehensive evaluation method. Moreover, document [3] divided the transmission line into five parts: tower, ground wire, hardware, insulator, foundation, and grounding device. The study put forward an upper bound algorithm of minimum cuts set about the transmission line assessment of weighted fault trees. Document [4] established a decision table of transmission lines, produced a set of decision rules using rough set theory, and calculated the degree of importance of various attributes to the running state. The weight coefficient is obtained by fixing the weight overcoming the subjectivity of traditional methods to determine the weight coefficient. Document [5] put forward a new thermal aging evaluation method for transmission lines. The study used the physical properties of a line, data of load, and weather to obtain the time series of the temperature of transmission lines. The study calculated the loss of the tensile strength of transmission lines. Furthermore, document [6] put forward a reliability assessment model of transmission lines that considers daily maintenance, and used Markov stochastic process theory to calculate the reliability index of transmission lines, which has an important reference value for power grid operation.

Given the large structure of transmission lines, the various failure modes, influencing factors, and sudden failure of one component affect the overall performance of the transmission lines. Therefore, the various situations of transmission lines must be considered to achieve state evaluation. The fault tree analysis (FTA) has a clear structure and is therefore advantageous in engineering applications. This study uses FTA to evaluate the state of transmission lines and verifies the correctness and validity against the operation data of the Guangxi grid.

2. Fault tree analysis

2.1 The principle of fault tree analysis

The FTA is used to analyze in detail the causes of the failure of systems, either as a whole or in part [7-8]. Thus, the

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FTA method is a reliability analysis tool for designing complex dynamic systems or factory tests or field failures. This method can be used to determine the basic fault, cause, impact, and probability of the failure.

In FTA, the fault state is chosen as the target of fault analysis. All the factors that directly lead to faults are searched then. All the factors of the next event are searched, until the original failure mechanism or probability distribution is found.

The events that are most unwanted to happen are usually called top events, and the events that need not be researched are called bottom events. The events between the top and bottom events are called intermediate events. Corresponding symbols are used to represent these events. Proper logic gates are used to unite the top, intermediate, and bottom events into a tree. This tree is called a fault tree, which is used to show the logical and structural relationship between the specific events of a system or equipment and the faults of various subsystems or parts. Thus, FTA is a method of evaluating the safety or reliability of a system, which uses the fault tree as a tool, analyzes the various ways of system faults, and calculates the reliability characteristics.

2.2 Important degree evaluation method of failure mode: improved analytic hierarchy process (IAHP)

The analytic hierarchy process (AHP) is a method of multi-objective decision analysis put forward by T. L. Saaty in the 1970s[9-10]. The judgment matrix of AHP needs consistency check. If the consistency is unmatched, the judgment matrix needs to be established again. In actual judgment, however, the judgment matrix is adjusted using rough estimates. This adjustment features randomness, which needs more than one adjustment to satisfy the consistency check. To solve this problem, the improved AHP (IAHP) is put forward, which directly calculates the relative importance (weight) using the transfer matrix, to improve AHP in satisfying the consistency check.

Fig.1 Classification and evaluation methods of fault characteristics

2.3 Method of determining the failure probability

Characteristic parameters are divided into two categories by evaluation standards of all kinds of faults in transmission lines: text description type and numeric type [11]. This study used an evaluation method based on the degree of relative deterioration to evaluate the failure probability of the fault characteristics of the text description type and an evaluation method based on the membership function to evaluate the failure probability of the fault characteristics of the numeric type.

3. Evaluating the state of transmission lines by fault tree analysis

A complete transmission line can be divided into several tower groups based on the number of towers, and these tower groups are numbered. Every numbered tower group includes a tower and foundation, insulator, metal fittings, grounding device, and affiliated facilities. A conduction ground line is set up between the two base towers. The conduction ground line belongs to the former tower in this model distinguished by the number of two towers. For example, the conduction ground line between Tower 1 and Tower 2 is used to evaluate the state of the former. A conduction ground line for the last one is especially disposed.

Based on the principle of FTA, the transmission line can be divided into seven parts – tower, foundation, insulator, metal fittings, grounding device, and affiliated facilities – which are named X1 to X7, respectively. The failure modes of each unit are also be named. For example, the corrosion leading faults of the tower, the defect of the shackles of main materials, and the crack of the concrete pole are named $X_{1.1}$, $X_{1.2}$, and $X_{1.3}$, respectively.

According to the principle of FTA, T is regarded as the top event of the fault tree, Xj (j=1,2,…,7) as the intermediate event, and X_i (i=1.1,1.2,…,7.7) as the bottom event. The kinds of faults are subdivided, and the fault tree is established through logical relationship, as shown in Fig.2

All minimum cut sets of a fault tree can be obtained. According to the logical relationship among the various events in Fig.2, the bottom events leading the top event are $\{X_{1.1}\}$, $\{X_{1.2}\}$, …, $\{X_{7.7}\}$, and the probability of faults are {P1.1}, {P1.2}, ..., {P7.7}, {P8.0}.

When no recurring events exist in the minimum cut sets of the fault tree, the minimum cut sets are mutually independent. The probability of a top event T is

$$P(T) = P(\bigcup_{i=1}^{n} K_i) \approx \sum_{i=1}^{n} P(K_i) \quad \text{... (1)}$$

Thus, the probability of a transmission line fault F(T) is

$$F(T) = P(T) = \sum_{i=1.1}^{8.3} P(X_i) \; (i = 1.1, 1.2, \ldots, 8.3) \quad \text{... (2)}$$

This study chooses the method of combining the failure probability and degree of importance (weight) to obtain the failure probability of the top events $P(T)$ because different bottom events have different degrees of importance. $P(T)$ is the unreliability of the transmission line $F(T)$.

$$P(T) = P(\bigcup_{j=1}^{8} X_j) \cong \bar{P} = \bar{P}_{X_1} W_{X_1} + \bar{P}_{X_2} W_{X_2} \cdots + \bar{P}_{X_7} W_{X_7} \quad \text{... (3)}$$

Similarly,

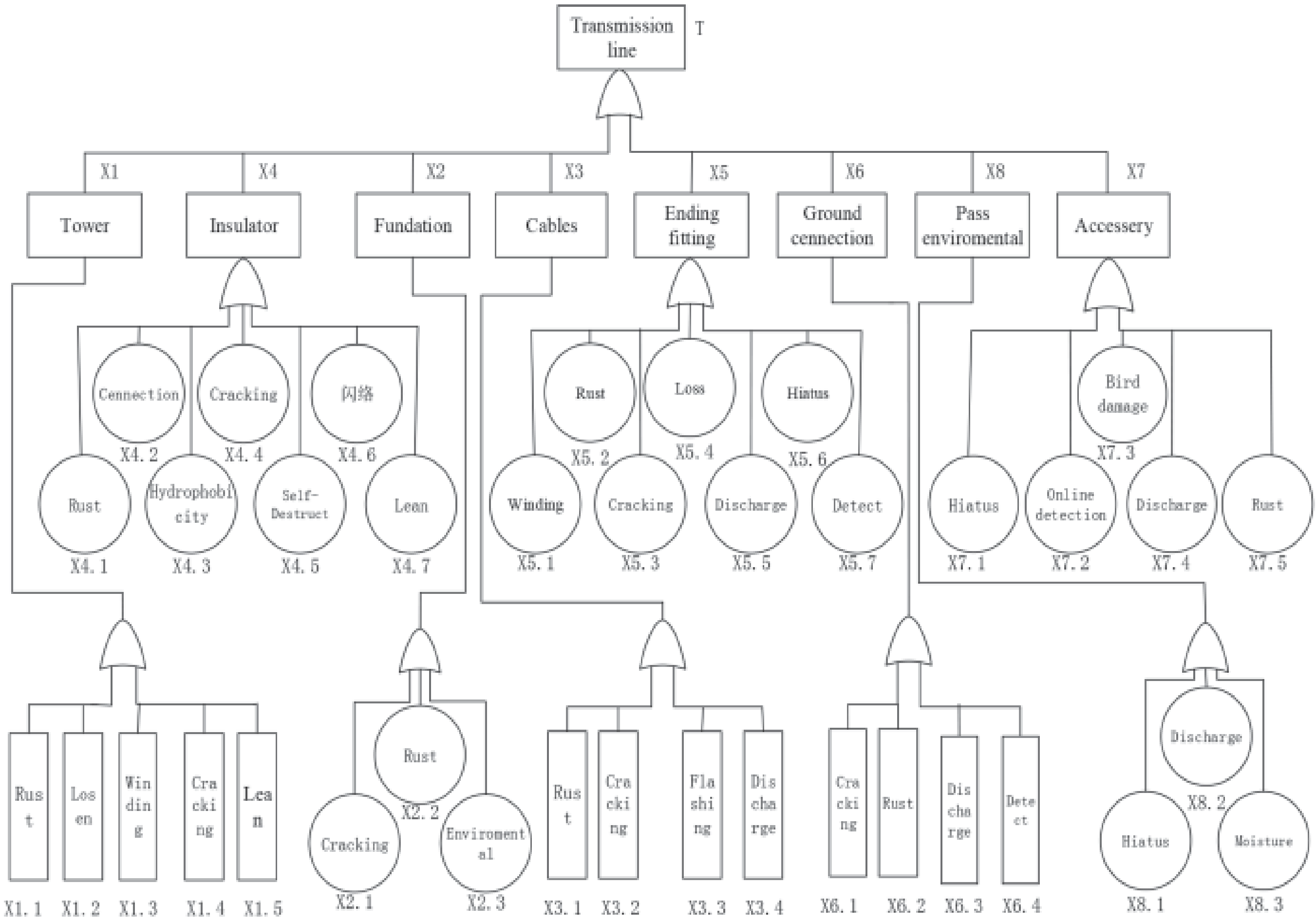

Fig.2 Fault tree model of an overhead transmission line

$$\bar{P}_{X_1} = \sum_{i=1.1}^{1.5} P_{X_i} W_{X_i},$$

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$$\bar{P}_{X_4} = \bar{P}_{X_{4.1}} W_{X_{4.1}} + \bar{P}_{X_{4.2}} W_{X_{4.2}} + \bar{P}_{X_{4.3}} W_{X_{4.3}} + \bar{P}_{X_{4.4}} W_{X_{4.4}} + \bar{P}_{X_{4.5}} W_{X_{4.5}} + \bar{P}_{X_{4.6}} W_{X_{4.6}} + \bar{P}_{X_{4.7}} W_{X_{4.7}} \quad \text{... (4)}$$

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$$\bar{P}_{X_7} = \sum_{i=7.1}^{7.3} P_{X_i} W_{X_i}$$

The unreliability of the faults of every tower group can be obtained: $P_1(T)$, $P_2(T)$, …, $P_n(T)$.

The largest unreliability of the fault is usually chosen as the final unreliability of the transmission line for security, that is, $P(T) = P_1(T) \vee P_2(T) \vee \ ... P_n(n)$. The "$\vee$" indicates the undertaking of a large operation. Thus, the final unreliability of the transmission line $R(T)$ is

$$R(T) = 1 - P(T) \quad \text{... (5)}$$

The failure probability of the failure mode of the transmission line can be evaluated through an evaluation method based on the membership function and degree of relative deterioration. The degree of importance of every failure mode in the fault tree can be obtained through IAHP.

4. Actual example

A 500 kV overhead transmission line in the Guangxi province is used in this study. The relevant data of the fault characteristics are shown in Table 1, according to the operating data in May 2012.

The evaluation process of the overhead transmission line of Tower #26 is as follows:

(1) The evaluation process of the failure probability

The evaluation of the failure probability of the fault characteristics are of the text description type. The insulator explosive (C8) in #26 is evaluated by experts using certain techniques.

The failure probability determined by this characteristic can be obtained:

$$\mu = \frac{1}{4}(0.11 + 0.09 + 0.13 + 0.08) = 0.11 \quad \text{... (6)}$$

The evaluation of the failure probability are of the fault characteristics of the numeric type.

According to the calculation results in Table 3, the

TABLE 1: RELEVANT DATA OF THE FAULT CHARACTERISTICS

Number of tower	Code	Fault characteristic	Result
01	C1	Arrester setting fault	Lead breakage of phase A arrester
08	C2	Metal parts produce heat	Temperature anomaly of phase A wire connector over 63
	C3	Grounding device break down	Earth screen is dragged out 3 meters
9	C4	Case of missing and losing	Leg B lacks 2 complementary materials, leg C lacks 7, leg D lacks 1 in the first platform
10	C5	Bracing wire rusting	8 bracing wires are 12% rusted
	C6	Protection facilities damaged	Protecting fall line is loosened
26	C7	Metal abrasion	Mechanical strength is 86% of original
	C8	Insulator explosive	4th piece of latter insulator, and the 1st, 5th, 6th of the former insulator string explosive in phase B
	C5	Bracing wire rusting	4 bracing wires rusting in the upper part
	C9	Sectional area of damaged wire	Percentage of sectional area is 7%
	C10	Tortuosity	Tortuosity of main material is 27%
33	C7	Metal abrasion	Mechanical strength is 86% of the original
	C11	Protect the metal falling	Back shock hammer falling in phase A and phase B
54	C4	Cases of missing and losing	Lack of tower material for the front left leg of the tower
	C1	Arrester setting fault	Counter damaged of phase A arrester
	C12	Flapper of tower damaged	Flapper of the tower damaged
	C9	Tortuosity	Tortuosity of the main material is 23%
71	C13	Ground wires divided	3 meters ahead of the left overhead ground wire divided
	C8	Insulator explosive	6th of the insulator string explosive in the straight tower
155	C14	UT clip rust and damaged	Back of the 2 UT clips and the yoke plate under are stolen
	C15	Online monitoring device damaged	Power of the online monitoring device battery is low

TABLE 2: EXPERT EVALUATION SCORE

	Expert 1	Expert 2	Expert 3	Expert 4
C8	0.11	0.09	0.13	0.1

TABLE 3: RELATED FAILURE PROBABILITY OF THE CHARACTERISTICS

Fault characteristic	Membership function	Failure probability
C7	$\mu = \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{30}(86-75) = 0.0432$	0.04323
C5	$\mu = \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{14}(4-7) = 0.1883$	0.1883
C9	$\mu = \frac{7-5}{20} = 0.1$	0.1
C10	$\mu = \frac{1}{2} + \frac{1}{2}\sin\pi(0.27-0.5) = 0.1693$	0.1693

TABLE 4: PROBABILITY OF THE FAILURE MODE

Unit	Failure mode	Corresponding characteristic	Corresponding failure probability	Probability of failure mode
X1	X1.3	C10	0.1693	0.1693
X3	X3.1X3.2	C5C9	0.18830.1	0.2883
X4	X4.5	C8	0.11	0.11
X5	X5.4	C7	0.0432	0.0432

probability of the failure mode can be calculated by the corresponding relations between the failure modes and failure characteristics.

(2) The reliability evaluation of the overhead transmission line of tower #26

The calculation of the degree of importance is of the failure mode.

According to Table 6, the failure probability of the overhead transmission line of Tower #26 can be calculated, that is, the unreliability degree:

$$P(T) = \sum_{j=1}^{5} P(Xj) \times Wj \approx 0.1134 \qquad \text{... (7)}$$

The reliability degree of the overhead transmission line of Tower #26 is as follows:

$$R(T) = 1 - P(T) = 0.8866 \qquad \text{... 8}$$

The others can be calculated via the same way, as shown in Table 7.

The reliability degree of every tower should be operated using the fuzzy operator "∧" because the whole transmission line is cascaded by every tower unit.

$$R = \mathop{\wedge}_{i}^{n} R_i(T) = \wedge(0.9791, 0.9403, \ldots, 0.8987) = 0.8866 \qquad \text{... (9)}$$

Table 5: Degree of importance of every failure mode

	X1.1	X1.2	X1.3	X1.4	X1.5	X2.1	X2.2	X2.3	X3.1	X3.2
W	0.1614	0.1793	0.2942	0	0.3651	0.2855	0.3014	0.4131	0.2914	0.3035
	X3.3	X3.4	X4.1	X4.2	X4.3	X4.4	X4.5	X4.6	X4.7	X5.1
W	0.2013	0.2038	0.1927	0	0	0	0.3224	0.2915	0.1934	0.1245
	X5.2	X5.3	X5.4	X5.5	X5.6	X5.7	X6.1	X6.2	X6.3	X6.4
W	0.0913	0.1125	0.1034	0.1324	0.2714	0.1645	0.2014	0.3125	0.2513	0.2348
	X7.1	X7.2	X7.3	X7.4	X7.5	X8.1	X8.2	X8.3		
W	0.2425	0.2013	0.1847	0.2116	0.1599	0.4113	0.3335	0.2552		

Table 6: Degree of importance and failure probability of every unit

	X1	X2	X3	X4	X5	X6	X7	X8
W P	0.2014	0.1305	0.2125	0.1234	0.1034	0.0915	0.0734	0.0639
	0.1693	0	0.2883	0.11	0.0432	0	0	0

Table 7: Reliability degree of every tower

	#1	#8	#9	#10	#26	#33	#54	#71	#155
R(T)	0.9791	0.9403	0.8903	0.9104	0.8866	0.8723	0.9323	0.9027	0.8987

Here, *i* is the label of the tower, and *n* is the number of the tower.

Evaluation result: The reliability degree of the overhead transmission line is 0.8866 < 0.9. Thus, few risks of total reliability and some faults may exist.

Actual situation: A few insulator explosive and wire damage can be seen. Urgent repairs on Tower #26 must be made. Moreover, repairs on lines and insulators of the other towers for normal operations must be done. This evaluation is similar to the evaluation results of the model in this study.

5. Conclusion

This study introduced the principle of FTA, set up the fault tree model of an overhead transmission line, and put forward a method of calculating the weight of the failure mode using IAHP. The failure mode can be divided into text description type and numeric type by the evaluation standards of different transmission line faults. The failure probability can be calculated using two evaluation methods, which are based on the degree of relative deterioration and membership function. The correctness and validity of this model were verified using the operation data of the Guangxi grid.

6. Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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