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Fuzzy comprehensive state evaluation of housing of silicone rubber insulators based on level difference maximization

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Abstract: The aging of composite insulators in outdoor operation for a long time has a direct impact on the safe and stable operation of the power grid. To solve this problem, fuzzy comprehensive evaluation of composite insulators based on level difference maximum is proposed. To verify the feasibility of this method, insulators in Xinjiang are sampled and the index evaluation system for composite insulators is established based on electrical, mechanical, hydrophobic and other properties, combined with operational years, geographical environment and other factors; Firstly, different membership functions are established according to index types. It is more likely to determine the grade of insulator by comparing measured data with the boundary value. Then, to solve the problem that weights cannot be effectively integrated in the combination weighting, level difference maximization is proposed (during the operation of insulators, the index which has a greater influence on the performance of insulators takes a higher proportion of the weight). Finally, on the basis of fully considering the clarity and ambiguity of grade division, the grade state of insulators is obtained by using the linear weighting method. The results show that compared with the traditional method, the improved method of the membership function and level difference maximum can realize the dynamic adjustment of the index based on the degree of information change. The method can better evaluate the insulator grade. The case study shows that the model can accurately and quickly judge the state of composite insulators, which can be used as a reference for manufacturing and maintenance departments.

Key words: entropy weight method silicone rubber composite insulator, fuzzy comprehensive evaluation, improved analytic hierarchy process, level difference maximization method, membership function

1. Introduction

Silicone rubber composite insulators have many advantages, such as light weight, high mechanical strength, strong hydrophobicity and transfer of hydrophobicity, pollution resistance, high lightning pressure, a simple manufacturing process and easy maintenance, etc., which can effectively curb the occurrence of pollution flashover accidents in a power grid after use, and have been widely used at home and abroad [1]. However, with the increase of its operating life, composite insulators will inevitably be affected by various environmental factors such as light, humidity, temperature difference and pollution in the long-term outdoor operation. In addition, they will be affected by a strong electric field and strong mechanical force, and composite insulators will suffer from aging to different degrees [2, 3]. The aging of insulators will directly affect the safe and stable operation of transmission lines. Therefore, the state evaluation of composite insulators is of great significance to ensure the safe and reliable operation of the power system.

After long-term outdoor operation, the composite insulator becomes a complex system, and there are many indicators that can represent its state. However, there are many uncertain factors in the evaluation process, such as the subjective arbitrariness and objective falsification of the weight value of the evaluation indicators. The state division of the evaluation index has the problem of fuzziness and randomness of grade boundaries. At present, experts at home and abroad have done a lot of research on these problems and achieved some results. In terms of a weighting algorithm, at this stage, it is mainly to study the combination of subjective and objective weighting methods. Reference [4] mainly uses the additive weighting method to simply combine the subjective and objective weights. Whether it can take into account the advantages of subjective and objective weights cannot be explained. Reference [5] introduced an intuitionistic fuzzy analytic hierarchy process (IFAHP) and fuzzy entropy theory to determine the subjective and objective weight of the index. Finally, the Bayesian correction method was used to establish the optimization model to obtain the weight value. Reference [6] uses the fuzzy set-valued statistics method and entropy weight method, and finally establishes a combined weighting model with the goal of minimizing weight deviation. These two methods are reasonable. In the aspect of an evaluation algorithm, scholars at home and abroad actively introduce system engineering theory, mainly including cloud theory, neural network and fuzzy theory. Reference [7] constructed an insulator pollution state evaluation model through cloud model processing composite insulator index detection data, but different cloud entropy determination methods may lead to conflict judgment results. References [8] and [9] built a state assessment model based on an artificial neural network. The model has strong self-learning and self-adaptation ability, but it is dependent on a large number of sample data and easy to fall into a local optimum. References [4] and [10] constructed a state evaluation model based on fuzzy theory. The model considered state influencing factors in a more comprehensive way and reduced the demand for historical data, but there was still a lack of perfect standard for determining a membership function.

In this paper, by combining the subjective and objective weighting and fuzzy comprehensive evaluation method, the basic theoretical framework of the condition evaluation of housing of the composite insulator is constructed; firstly, various parameters affecting the operation state of the composite insulator are analyzed, and the evaluation index system of a large number of factors is established. On this basis, the membership functions of different types of indicators are established to ensure the accuracy of the grade division of the calculation method of index membership, and improve the membership function in the traditional fuzzy theory. In addition, in the aspect of index weighting, the improved AHP and entropy weight method are used to determine the subjective and objective weights of the indicators respectively, and the combination weight is realized by the maximum difference method solution.

1.1. Importance of this study

The original intention of the combination weighting method is to take into account the advantages of subjective weight and objective weight. The traditional addition or multiplication weighting method cannot explain this problem. The level difference maximization method introduced in this paper determines multiple weight values of each index as the reasonable value range of the index, takes this as the constraint condition, takes the maximum discrimination of the evaluation results as the objective function, establishes the optimization model, and finally obtains the combined weight value. This method improves this problem, and the weight can be explained and has certain rationality. In the evaluation algorithm, the membership function and grade determination rules in the fuzzy evaluation method are improved. For insulators with little data difference, the traditional method may be different from the actual results. Through the improvement of the above two points, the results can be obtained more accurately. By evaluating the state of insulators, the manufacturing department can understand the variation law of various performance parameters of insulators in outdoor operation, which aspects can be improved on insulators, and design appropriate insulators according to the environmental characteristics of the region. For the power maintenance department, the insulator maintenance plan can be arranged according to the evaluation results, which reduces a lot of manpower investment and saves the cost of power operation and maintenance.

2. Selection and grading of state evaluation index for composite insulator

2.1. Selection of test samples

The samples of the silicone rubber composite insulator studied in this paper are taken from Xinjiang, covering different regions (Urumqi, Turpan and Korla), different voltage grades (110 kV, 220 kV), different manufacturing dates (1999–2013), 60 pieces are divided into 18 batches. This paper selects one insulator from each batch as the research object of state evaluation. The insulator sample picture is shown in Fig. 1.

2.2. Selection of insulator condition evaluation index

With the increase of running time, the silicon rubber composite insulator becomes a very complex system when it is affected by various factors such as illumination, humidity and pollution in long-term outdoor operation. There are many state variables to characterize the aging of composite insulators, and there is no uniform measuring standard to measure the aging of composite insulators [11, 12]. The operating experience at home and abroad shows that some of the composite insulators hanging on the grid have serious appearance aging, such as dusting, whitening and craze, hydrophobicity, and mechanical strength decline, etc., which will lead to the

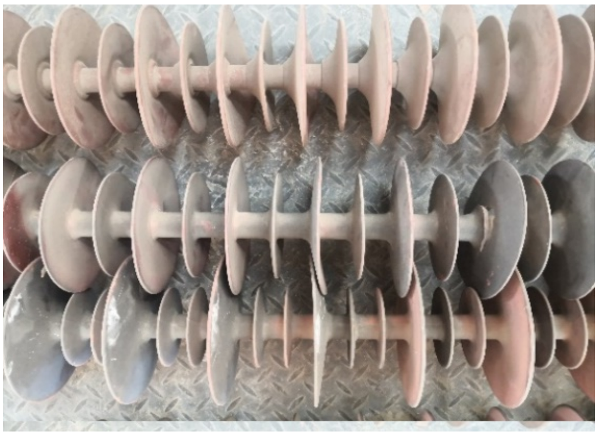

Fig. 1. Image of insulator sample

internal insulation breakdown of the insulators, string breaking and other malignant faults, posing a great threat to the safe operation of the power grid. Therefore, based on various properties of the housing structure of a silicone rubber composite insulator, this paper analyzes its aging standard and establishes a simple and efficient aging state evaluation method for silicone rubber composite insulators. The state evaluation index system of housing of a composite insulator is shown in Table 1.

Table 1. The evaluation index system of housing of composite insulators

Target layer	Criterion layer	Index layer
State evaluation index of housing of silicone rubber of composite insulators	Mechanical performance index	Appearance inspection
		Hardness
		Tear resistance
		Tensile strength
	Hydrophobicity index	Hydrophobicity
		Hydrophobicity transfer
	Electrical performance evaluation index	Volume resistivity
		Tracking and erosion resistance
		Breakdown electric field
	Pollution layer analysis	ESDD
		Leakage current
	other	Operating life
		Temperature
		Humidity

The mechanical property indexes include appearance inspection, hardness, tear strength and tensile strength. Hardness refer to GB/T 531.1-2008 "Rubber, vulcanized or thermoplastic-determination of indentation hardness-Part1: Durometer method (shore hardness)": Take three round test pieces with a diameter of 3 cm and a thickness of no less than 6mm from the umbrella skirt, test the sample with a shore A hardness tester, and take the average value as the test result after five tests on the surface of the sample. Tear strength is measured according to GB/T 529-2008 "Rubber, vulcanized or thermoplastic-determination of tear strength (trouser, angle and crescent test pieces)". Cut three rectangular test pieces with a thickness of about 2 mm, clamp the sample on the gripper of the tensile testing machine at an ambient temperature of $(27 \pm 0.2)°$, select the speed of the gripper to be (100 ± 10) mm/min, stretch the sample until it breaks, record the maximum force value, and finally divide the thickness value by the tear strength value [13–15]. The tensile strength is based on GB/T 528-2009 "Rubber, vulcanized or thermoplastic-determination of tensile stress-strain properties" take measurements: Cut three dumbbell shaped test pieces with a thickness of about 2 mm, clamp the sample on the gripper of the tensile testing machine at the ambient temperature of $(27 \pm 0.2)°$, select the speed of the gripper to run at (500 ± 50) mm/min, record the maximum shear failure force of the sample, and finally divide it by the cross-sectional area of the sample to obtain the tensile strength value [13–15].

There are two secondary indexes of hydrophobicity performance: hydrophobicity and hydrophobicity transfer. The hydrophobic transfer refers to that the surface of insulators running outdoors is polluted, and the surface of the polluted material has a hydrophobicity similar to that of silicone rubber. There are three methods for hydrophobicity measurement: the static contact angle method, spray grading method, and surface tension method [16]. This article uses the water spray classification method, namely the HC method, which refers to the water droplet shape and the percentage of the wetted surface on the surface of the insulator after the insulator is exposed to the fine water mist for a period of time. The hydrophobicity of the composite insulators can be divided into 7 grades, namely HC1–HC7. Among them, HC1 represents strong hydrophobicity, the water droplets are in a discrete state, and the shape of the water droplets is roughly circular; HC7 represents complete hydrophilicity, and a water film is formed on the surface of the insulator. The method is simple and fast, and is very suitable for rapid detection of the hydrophobicity of composite insulators at the operating site.

The electrical performance indicators have three secondary indicators: volume resistivity, tracking and erosion resistance, and a breakdown electric field. The volume resistivity is determined according to GB/T 1692-2008 "Vulcanized rubber-determination of the insulation resistivity". Cut three square test pieces with a thickness of about 1 mm and a side length of 150 mm. After the test pieces are cleaned and dried for 24 hours, the sample is connected to the measuring end of the high resistance meter, and the instrument is adjusted. After a test voltage of 1000 V is passed on for one minute, the indicated value of resistance is read. Tracking and erosion resistance is determined according to GB/T 6553-2014 "Electrical insulating materials used under severe ambient conditions-test methods for evaluating resistance to tracking and erosion". The details are as follows: the test environment temperature is 23°, the sample is at a 45° angle with the horizontal plane, the polluted liquid flows down at a uniform speed, and the voltage is increased to 2.5 kV, 3.5 kV, 4.5 kV for 6 hours, and the sample is observed to be damaged under that voltage. A breakdown electric field is measured according to GB 1408.1-2006 "Electrical Strength of insulating Material-Test methods – Part 1: Texts at Power frequencies". Cut three rectangular test pieces with a thickness of about 2 mm, test voltage from zero according to a voltage boost speed of 2 kV/s continuous and uniform voltage boost until the sample is broken down, read the breakdown voltage value [14, 15].

The pollution layer analysis includes two secondary indexes: equivalent salt deposit density (ESDD) and leakage current. Among them, the ESDD measurement method: firstly, clean the clean rag in ionic water for several times, then clean the insulator surface with the rag, and then clean the rag in the cleaning solution to obtain the cleaning solution. Measure the conductivity and temperature of the cleaning solution with a conductivity meter, and then convert it to the conductivity value at the standard temperature (20°). ESDD can be calculated according to the change of conductivity, an insulator area and cleaning water volume [17]. The leakage current measurement method: the test converts the current into voltage signals by measuring the voltage at both ends of the non-inductive resistance in the string circuit, and the maximum value of the leakage current pulse amplitude in each cycle (20 ms) is recorded by an oscilloscope to obtain the leakage current of the insulator [18].

Other factors include three secondary indicators: operating life, temperature and humidity. When the composite insulator is running outdoors for a long time, the running time and the surrounding environment also have a certain impact on the aging of the insulator. Due to the differences in temperature and humidity in various regions, composite insulators in different regions will also show different aging characteristics, which will have a certain impact on the aging of insulators. Therefore, these three secondary indicators are selected to evaluate the state of composite insulators.

2.3. Insulator status classification

By referring to relevant standards and literature [12–19], this paper proposes a classification method of insulation status based on the management and operation experience of composite insulators, that is, grade 1–4 corresponds to four insulation states: good, normal, early warning and abnormal. The relationship between insulation status and corresponding maintenance strategies is shown in Table 2. This method is beneficial to the inspection personnel to accurately judge the

Table 2. Insulation grade description and maintenance strategy

Insulation grade	State description	Maintenance strategy
Good	Insulator has good performance and keeps long-term safe and stable operation	The maintenance shall be extended for one year according to the normal cycle
General	Some index of insulator fluctuates abnormally, but it does not affect normal operation	Maintenance is carried out in accordance with the normal cycle
Early warning	There is a slight malfunction that will not affect the equipment in the short term	Track the development trend of indicators and arrange maintenance as soon as possible in normal cycle
Abnormal	There has been a serious malfunction and the stable operation of the equipment has been affected	Strengthen the observation and inspection of the equipment, and arrange the maintenance immediately

health condition of the equipment, so as to make a reasonable test and maintenance plan, and avoid the occurrence of excessive maintenance.

3. Establishment of state evaluation model for composite insulator

Fuzzy comprehensive evaluation adopts mathematics to provide a reasonable quality or grade evaluation for many problems in life [20, 21]. Its basic idea is to use the concept of membership in fuzzy mathematics to quantify qualitative indicators, which is to determine the fuzzy things, so as to use traditional mathematical methods to process them.

3.1. Establish fuzzy evaluation state variable set

When evaluating silicone rubber composite insulators, the first step is to establish a state variable set for the selected characteristic quantities. Let U be the set of first-level indicators of silicone rubber composite insulators. $U = u_i(1, 2, 3, 4, 5)$, where u_i $(i = 1, 2, 3, 4, 5)$ is the mechanical performance index, hydrophobicity index, electrical performance index, pollution layer analysis and other factors, and each of the first-level index is composed of multiple secondary indicators. For example, the secondary index corresponding to mechanical performance index is defined as u_{1j} $(j = 1, 2, 3, 4)$.

3.2. Create comment set

To comprehensively evaluate silicone rubber composite insulators, it is also necessary to determine the comment set. The comment set is the evaluation level, which divides the overall performance of the evaluation object. In this article, the comment set of silicone rubber composite insulators consists of four states. Use $V = \{V_1, V_2, V_3, V_4\}$ to represent; V_1, V_2, V_3, V_4, respectively, indicate that the state of the silicone rubber composite insulator is good, normal, early warning, and abnormal.

3.3. Build evaluation matrix

After determining the comment set, determine the membership function of each index to the above four states. The membership function refers to the proportion of the established indicators belonging to each evaluation level using mathematical methods. Since orders of magnitude and dimension of each index are different, the index data must first be normalized [21].

3.3.1. Normalization of indicators

For qualitative data, the quantization of quantitative data is considered, and the number between 0 and 1 is also used as the quantization score. The smaller the value is, the worse the performance of the index is. The higher the value, the better the performance of the index.

For the larger the better the numerical index, the normalized formula is:

$$x'_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}. \tag{1}$$

For the smaller the better the numerical index, the normalized formula is:

$$x'_{ij} = 1 - \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}, \tag{2}$$

where: x_{ij} is the measurement data of the index; $x_j^{\max}$, $x_j^{\min}$ are the maximum and minimum values of the j-th index; x'_{ij} is the normalized value of x_{ij}.

Based on the literature and reference to the statistical data of authoritative departments and institutions as well as the corresponding guidelines, this paper determines the fuzzy boundary value of the evaluation index of housing of silicone rubber composite insulators [12–19]. The boundary values are shown in Table 3.

Table 3. Fuzzy boundary value of each evaluation index

Evaluation grade	**Evaluation index**	V_4 **(abnormal)**	V_3 **(early warning)**	V_2 **(general)**	V_1 **(good)**
Mechanical performance index	Appearance inspection	0.20	0.40	0.60	0.80
	Hardness	0.14	0.38	0.62	0.86
	Tear resistance	0.12	0.33	0.56	0.78
	Tensile strength	0.20	0.34	0.55	0.79
Hydrophobicity index	Hydrophobicity	0.17	0.33	0.67	0.83
	Hydrophobicity transfer	0.20	0.40	0.60	0.80
Electrical performance index	Volume resistivity	0.26	0.46	0.59	0.90
	Tracking and erosion resistance	0.20	0.40	0.60	0.80
	Breakdown electric field	0.15	0.38	0.62	0.83
Pollution layer analysis	ESDD	0.25	0.50	0.75	0.90
	Leakage current	0.20	0.50	0.80	0.95
other	Operating life	0.21	0.42	0.63	0.83
	Temperature	0.20	0.40	0.60	0.80
	Humidity	0.60	0.65	0.75	0.80

3.3.2. Normalization of indicators

1. Benefit evaluation index grade membership function

If the actual value y_{tij} of profit quantitative evaluation index U_{ij} $(j = 1, 2, \ldots)$ of the composite insulators A_t $(t = 1, 2, 3, \ldots, n)$ on grade V_k $(k = 1, 2, 3, 4)$ is no less than z_{ijk}, that is,

$y_{tij} \geq z_{ijk}$, where z_{ijk} represents the reference value of profit quantitative evaluation index U_{ij} under grade V_k, then its grade membership function is as in Eqs. (3)–(5), and the image is shown in Fig. 2.

$$\mu_{tij1} = \begin{cases} 1 & (y_{tij} \geq z_{ij1}) \\ \dfrac{y_{tij} - z_{ij2}}{z_{ij1} - z_{ij2}} & (z_{ij2} \leq y_{tij} < z_{ij1}) \\ 0 & (0 \leq y_{tij} < z_{ij2}) \end{cases}, \tag{3}$$

$$\mu_{tijk} = \begin{cases} \dfrac{z_{ij,k-1}}{y_{tij}} & \left(y_{tij} \geq z_{ij,k-1}\right) \\ 1 & \left(z_{ijk} \leq y_{tij} < z_{ij,k-1}\right) \\ \dfrac{y_{tij} - z_{ij,k+1}}{z_{ijk} - z_{ij,k+1}} & \left(z_{ij,k+1} \leq y_{tij} < z_{ij,k}\right) \\ 0 & \left(0 \leq y_{tij} < z_{ij,k+1}\right) \end{cases} \quad (k = 2,\ 3), \tag{4}$$

$$\mu_{tij4} = \begin{cases} \dfrac{z_{ij3}}{y_{tij}} & (y_{tij} \geq z_{ij3}) \\ 1 & (z_{ij4} \leq y_{tij} < z_{ij3}) \\ \dfrac{y_{tij}}{z_{ij4}} & \left(0 \leq y_{tij} < z_{ij4}\right) \end{cases}. \tag{5}$$

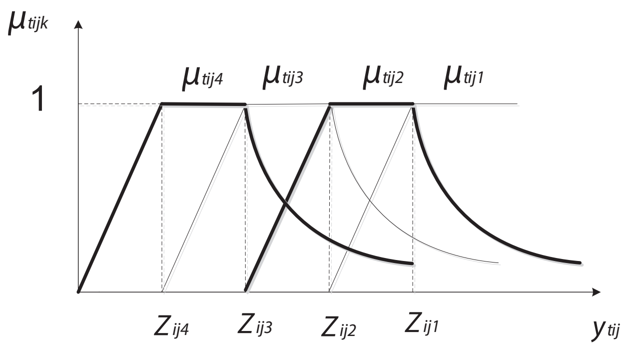

Fig. 2. Grade membership function of profit evaluation index

2. Cost-based evaluation index grade membership function

If the actual value y_{tij} of cost quantitative evaluation index U_{ij} $(j = 1, 2, 3, 4)$ of the composite insulators A_t $(t = 1, 2, 3, \ldots, n)$ on grade V_k $(k = 1, 2, 3, 4)$ is no greater than z_{ijk}, that is, $y_{tij} \leq z_{ijk}$, then its grade membership function is as in Eqs. (6)–(8), the image is shown in Fig. 3.

$$\mu_{tij1} = \begin{cases} 1 & (0 \leq y_{tij} \leq z_{ij1}) \\ \dfrac{z_{tij2} - y_{tij}}{z_{tij2} - z_{tij1}} & (z_{ij1} < y_{tij} \leq z_{tij2}) \\ 0 & (y_{tij} > z_{ij2}) \end{cases}, \tag{6}$$

$$\mu_{tijk} = \begin{cases} \dfrac{y_{tij}}{z_{ij,k-1}} & \left(0 \le y_{tij} \le z_{ij,k-1}\right) \\ 1 & \left(z_{ij,k-1} < y_{tij} \le z_{ijk}\right) \\ \dfrac{z_{ij,k+1} - y_{tij}}{z_{ij,k+1} - z_{ijk}} & \left(z_{ij,k+1} \le y_{tij} < z_{ij,k}\right) \\ 0 & \left(y_{tij} > z_{ij,k+1}\right) \end{cases} \quad (k = 2,\ 3), \tag{7}$$

$$\mu_{tij4} = \begin{cases} \dfrac{y_{tij}}{z_{ij3}} & (0 \le y_{tij} \le z_{ij3}) \\ 1 & (z_{ij3} < y_{tij} \le z_{ij4}) \\ \dfrac{z_{ij4}}{y_{tij}} & (y_{tij} > z_{ij4}) \end{cases} . \tag{8}$$

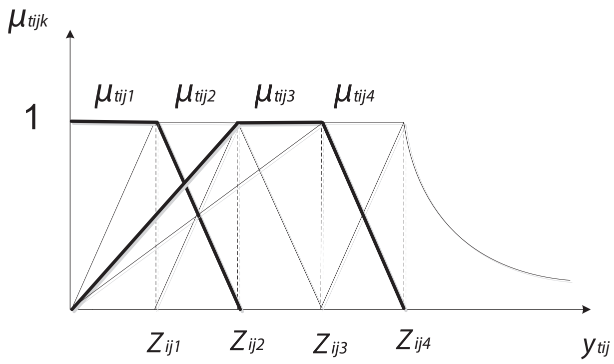

Fig. 3. Grade membership function of cost evaluation index

3.4. Create a weight set

The determination of the weight is an extremely important part of the evaluation. The first-level indicator weight set is expressed as $W = \{w_1,\ w_2,\ w_3,\ w_4,\ w_5\}$, and weights satisfy non-negativity and normalization, that is, $w_i \ge 0$ ($i = 1, 2, 3, 4, 5$) and $\sum_{i=1}^{5} w_i = 1$. The weights of second-level indicators are represented by k_j ($j = 1, 2, 3, \ldots, 14$). There are three methods to determine weights: the subjective weighting method, objective weighting method, and subjective and objective weighting method [20, 21]. The combination weighting method can effectively combine the advantages of subjective and objective weighting methods. Among them, the commonly used additive synthesis method depends on the weight coefficient distribution of the subjective and objective weight, but this method is too rigid, which is not conducive to distinguishing the superior and inferior information in the subjective and objective weight information. In this paper, the grade difference maximization method adopted takes the maximum differentiation of evaluation results as the objective function, takes the reasonable value range of index weight as the constraint condition to establish the optimization model, and solves the maximum and minimum value of the combination weight of evaluation indexes obtained by the subjective and objective weighting method as the upper and lower limits of the combination weight constraints. The specific methods are as follows:

3.4.1. Addition combination weighting method

Let w_j be the weight after the combination of the two methods, where A_j is the weight obtained by the improved AHP, B_j is the weight obtained by the entropy weight method, θ is the preference coefficient, generally $\theta = 0.5$.

$$w_j = \theta A_j + (1 - \theta) B_j \,. \tag{9}$$

3.4.2. Difference maximization combination weighting method

1. Calculate the weight of a single method

Suppose there are m weighting methods to weight k indexes, the weight matrix $A_{k\times m}$ can be obtained by

$$A_{k\times m} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k1} & a_{k2} & \dots & a_{km} \end{bmatrix} = (a_{ij})_{k\times m} \,,$$

where: a_{ij} is the weight of the j method to the i index, $i = 1, 2, \dots, k$; $j = 1, 2, \dots, m$.

2. Calculate the range of combination weights

The interval range $a_i \in [a_i^-, a_i^+]$ of combined weights $\alpha = (a_1, a_2, \dots, a_k)$ can be determined by the weight matrix $A_{k\times m}$. Among them:

$$a_i^+ = \max\{a_{i1}, a_{i2}, \dots, a_{im}\}, \qquad a_i^- = \min\{a_{i1}, a_{i2}, \dots, a_{im}\}.$$

3. Difference maximization combined weight optimization model calculation

$$\max s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (a_i (x_i - \overline{x}))^2 \,, \qquad \text{s.t.} \begin{cases} \sum\limits_{i=1}^{n} a_i = 1 \\ a_i^- \le a_i \le a_i^+ \end{cases} , \tag{10}$$

where: s_2 serves for the comprehensive evaluation value of variance; x_i as the evaluation indexes; average $\overline{x}$ as the evaluation indexes.

4. Comprehensive evaluation calculation results

$$R = \sum_{i=1}^{n} a_i x_i \,, \tag{11}$$

where: R is the comprehensive evaluation value; a_i serves for combination evaluation index weight; x_i is the evaluation index; n is the number of evaluation units.

The weight value of each index in this paper is obtained by using the combination weight method above, among which weight 1 is the weight value obtained by the improved AHP. Weight 2 is the weight obtained by the entropy weight method. The specific weight values are shown in Table 4.

Table 4. Evaluation index weight value of composite insulator

First-level index	Weight	Second-level index	Weight 1	Weight 2	Addition combination	Level difference maximization
Mechanical performance	0.17	Appearance inspection	0.10	0.07	0.09	0.10
		Hardness	0.46	0.36	0.41	0.46
		Tear resistance	0.22	0.20	0.21	0.20
		Tensile strength	0.22	0.36	0.29	0.24
Hydrophobicity	0.38	Hydrophobicity	0.62	0.77	0.70	0.72
		Hydrophobicity transfer	0.38	0.23	0.30	0.28
Electrical performance	0.26	Volume resistivity	0.20	0.17	0.19	0.17
		Tracking and erosion resistance	0.60	0.63	0.62	0.63
		Breakdown electric field	0.20	0.20	0.20	0.20
Pollution layer analysis	0.11	ESDD	0.38	0.43	0.41	0.38
		Leakage current	0.62	0.57	0.59	0.62
Other	0.08	Operating years	0.55	0.84	0.70	0.58
		Temperature	0.17	0.06	0.12	0.17
		Humidity	0.28	0.10	0.19	0.25

3.5. Multi-index comprehensive evaluation

According to the actual situation and characteristics of housing of silicone rubber composite insulators, using Formulas (3)–(8), the grade membership μ_{tijk} of composite insulators A_t with respect to the grade evaluation index u_{ij} can be calculated, which is usually expressed by the grade membership matrix. Similarly, the weights of the primary and secondary indicators can be expressed in the form of vectors: $\boldsymbol{\omega} = (\omega_1, \omega_2, \cdots, \omega_5)^T$, $\boldsymbol{\omega}_i = (\omega_{i1}, \omega_{i2}, \cdots, \omega_{in})^T$. In this paper, the fuzzy linear weighted comprehensive evaluation method is selected to establish the state evaluation level of silicone rubber composite insulators [22]. The specific method is as follows:

1. Calculate the comprehensive membership of composite insulators A_t with respect to the first-level index u_{ij} to the evaluation level V_k

$$\mu_{tik} = \frac{\boldsymbol{\omega}_i^T \boldsymbol{\mu}_{tijk}}{\sum\limits_{k=1}^{h} \boldsymbol{\omega}_i^T \boldsymbol{\mu}_{tijk}}, \tag{12}$$

where $\boldsymbol{\mu}_{tijk} = (\mu_{tij_{1k}}, \mu_{tij_{2k}}, \ldots, \mu_{tijnk})$ is the k-th column vector of the grade membership matrix μ_{tij}. Thus, the comprehensive membership vector $\boldsymbol{\mu}_{ti} = (\mu_{tiik})_{1\times 4}$ of A_t about u_i to all levels V_k can be obtained. Therefore, the grade membership matrix $\boldsymbol{\mu}_{ti} = (\mu_{tik})_{4\times 4}$ of A_t to the 5 first-level evaluation indexes can be obtained.

2. Calculate the comprehensive membership of composite insulators A_t to the evaluation grade V_k

$$\mu_{tk} = \frac{\boldsymbol{\omega}^T \boldsymbol{\mu}_{tik}}{\sum\limits_{k=1}^{h} \boldsymbol{\omega}^T \boldsymbol{\mu}_{tik}}, \tag{13}$$

where $\boldsymbol{\mu}_{tik} = (\mu_{ti1k}, \mu_{ti2k}, \ldots, \mu_{tink})$ is the k-th column vector of the grade membership matrix μ_{ti}. Then, we can get the comprehensive membership matrix $\boldsymbol{\mu}_t = (\mu_{tk})_{1\times 4}$ of A_t about u_i to all levels V_k.

3. Determination of composite insulator grade

In general grade evaluation problems, the principle of maximum membership is a simple and more commonly used method, that is, the state evaluation of composite insulators A_t is made according to the value of μ_{tk}. However, the principle of maximum membership is sometimes unreasonable due to the small gap between the various data and other reasons. Therefore, this paper uses the weighted average method to judge the grade status of composite insulators. The specific steps are as follows: quantify the four evaluation levels, and use V_k to represent the four evaluation levels of abnormal, early warning, normal and good, with values of 4, 3, 2 and 1, and use the weighted average formula to obtain the final evaluation result [23].

$$v = \frac{\sum\limits_{k=1}^{n} v_k \times \mu_{tk}}{\sum\limits_{k=1}^{n} \mu_{tk}}, \tag{14}$$

where μ_{tk} represents the k–th element in the final evaluation matrix $\boldsymbol{\mu}_t$.

4. Case study

In order to verify the feasibility of this theory, two groups of operating composite insulators in Xinjiang are selected. The first group is selected from composite insulators that have been in good operation for 6 years in the Korla area of Xinjiang; the second group is selected from the composite insulators that have been in operation for 15 years in Turpan, Xinjiang, and have a long operating time and are about to be returned. According to the index evaluation system of silicone rubber composite insulators established in this paper, the evaluation index values of the two groups of composite insulators are shown in Table 5.

1. For the first group of composite insulators (A_1), from Eqs. (3) to (8), the membership matrix for the four evaluation grades under the second-level index can be obtained. Due to space

Table 5. Value table of various indexes of composite insulator

First-level indicators	Second-level indicators	First group		Second group	
		Measured value	Normalized value	Measured value	Normalized value
Mechanical properties	Appearance inspection	0.5	0.500	0.3	0.300
	Hardness	73	0.476	80	0.143
	Tear resistance (kN/m)	6.32	0.591	3.28	0.253
	Tensile strength (Mpa)	5.37	0.665	3.54	0.199
Hydrophobicity	Hydrophobicity	HC3	0.667	HC6	0.167
	Hydrophobicity transfer	0.6	0.600	0.3	0.300
Electrical properties	Volume resistivity (Ω·m)	7.21×10^{13}	0.585	4.63×10^{13}	0.339
	Tracking and erosion resistance	0.6	0.600	0.2	0.200
	Breakdown electric field (kV/mm)	18.95	0.703	16.46	0.387
Pollution layer analysis	ESDD (mg/cm^2)	0.03	0.850	0.12	0.400
	Leakage current (mA)	5.08	0.975	76.54	0.617
Other	Operating years(n)	6	0.792	15	0.417
	Temperature	0.6	0.600	0.5	0.500
	Humidity	0.6	0.600	0.75	0.750

Note: Some indicators are qualitative indicators without definite units. Among them, temperature and humidity are the overall changes of local air temperature and humidity, which are defined as qualitative indicators in this paper.

reasons, this paper gives the membership matrix for the first two indexes, which are as follows:

$$\boldsymbol{\mu}_{11j} = \begin{bmatrix} \mu_{11} \\ \mu_{12} \\ \mu_{13} \\ \mu_{14} \end{bmatrix} = \begin{bmatrix} 0 & 0.500 & 1 & 0.800 \\ 0 & 0.400 & 1 & 0.798 \\ 0.141 & 1 & 0.948 & 0.558 \\ 0.479 & 1 & 0.827 & 0.511 \end{bmatrix},$$

$$\boldsymbol{\mu}_{12j} = \begin{bmatrix} \mu_{21} \\ \mu_{22} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 & 0.493 \\ 0 & 1 & 1 & 0.667 \end{bmatrix}.$$

By using Eq. (12) and combining with the weight values in Table 4, the comprehensive membership matrix of the first-level index of composite insulators to the evaluation grade V_k can be obtained as follows:

$$\boldsymbol{\mu}_{1i} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \end{bmatrix} = \begin{bmatrix} 0.058 & 0.276 & 0.388 & 0.278 \\ 0 & 0.393 & 0.393 & 0.213 \\ 0.029 & 0.367 & 0.360 & 0.244 \\ 0.279 & 0.304 & 0.252 & 0.165 \\ 0.200 & 0.247 & 0.269 & 0.285 \end{bmatrix}.$$

Similarly, Eq. (13) can be used to obtain the comprehensive membership matrix of the first group of composite insulators for the evaluation grade V_k:

$$\boldsymbol{\mu}_1 = \begin{bmatrix} 0.064 & 0.345 & 0.358 & 0.233 \end{bmatrix}.$$

According to Eq. (14), $v = 2.760$. At this time, the value of v is within the range of 2–3, so the grade is defined as general, that is, the overall condition of composite insulators is normal, but it needs to be checked from time to time during operation.

2. For the second group of composite insulators (A_2), from Eqs. (3) to (8), the membership matrix of the four evaluation grades under the second-level index can be obtained. Due to space reasons, this paper gives the membership matrix of the last two indexes, which are as follows:

$$\boldsymbol{\mu}_{23j} = \begin{bmatrix} \mu_{31} \\ \mu_{32} \\ \mu_{33} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.395 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0.029 & 1 & 0.982 \end{bmatrix},$$

$$\boldsymbol{\mu}_{24j} = \begin{bmatrix} \mu_{41} \\ \mu_{42} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.600 & 1 \\ 0 & 0.234 & 1 & 0.810 \end{bmatrix},$$

$$\boldsymbol{\mu}_{25j} = \begin{bmatrix} \mu_{51} \\ \mu_{52} \\ \mu_{53} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0.500 & 1 & 0.800 \\ 0 & 1 & 1 & 0.867 \end{bmatrix}.$$

By using Eq. (12) and combining with the weight of evaluation indexes in Table 4, the comprehensive membership matrix of first-level indexes to the evaluation grade V_k can be calculated as follows:

$$\boldsymbol{\mu}_{2i} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \\ \mu_5 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0.160 & 0.840 \\ 0 & 0 & 0.123 & 0.877 \\ 0 & 0.004 & 0.210 & 0.785 \\ 0 & 0.077 & 0.452 & 0.470 \\ 0 & 0.148 & 0.441 & 0.411 \end{bmatrix}.$$

Similarly, Eq. (13) can be used to obtain the comprehensive membership matrix of the second group of composite insulators for the evaluation grade V_k:

$$\boldsymbol{\mu}_2 = \begin{bmatrix} 0 & 0.021 & 0.214 & 0.765 \end{bmatrix}.$$

According to Eq. (14), $v = 3.744$. At this time, the value of v is in the range of 3–4 and the level is early warning. It can be considered that this group of composite insulators is developing from early warning to abnormal, and there is a high probability of failure, so it is necessary to shorten the maintenance cycle and conduct regular detection during operation.

These two examples show that the calculated results are consistent with the on-site operating state of composite insulators. Therefore, the housing of the model of silicone rubber composite insulators established in this paper can reliably judge the state of the insulator.

5. Conclusion

In view of the aging problem of composite insulators in outdoor operation for a long time, the insulators in Xinjiang are sampled, the state of insulators in this area is analyzed, and the fuzzy comprehensive evaluation method of composite insulators based on the level difference maximization is proposed. The following conclusions are drawn:

1. The index evaluation system and fuzzy comprehensive evaluation model of composite insulators are established. Through the analysis of samples, based on the technical evaluation items such as electrical performance, mechanical performance and hydrophobicity, comprehensively considering the factors such as operation life and geographical environment, as well as referring to industry standards, a two-level and four grade index system is established, and the comprehensive analysis of multiple factors is realized by the fuzzy evaluation method.
2. Compared with the additive weighting method, it cannot explain its rationality. Level difference maximization determines the reasonable value interval of the combination weight according to the subjective and objective weight, takes this interval as the constraint, and takes the maximum discrimination of the evaluated object as the objective function to establish the optimization model and solve the combination weight. Therefore, the combination mode of the combination weight is reasonable, and the combination weight can be explained.
3. The example analysis shows that by improving the membership function, subjective and objective weighting method and the application of the linear weighting method, the model is more perfect and reasonable, and the model algorithm is simple, adaptable and easy to program. The evaluation conclusion is also closer to the real operation state of composite insulators in this area. For the manufacturing department, understanding the changes of its performance parameters can not only reduce unnecessary losses in the subsequent insulator improvement and design, but also save energy. For the power maintenance department, it reduces a lot of manpower investment and saves the cost of power operation and maintenance.

References

[1] Liang X.D., Gao Y.F., Wang J.F. *et al.*, *Rapid development of silicone rubber composite insulators in China*, High Voltage Engineering, vol. 42, no. 9, pp. 2888–2896 (2016), DOI: 10.13336/j.1003-6520.hve.20160907025.

[2] Yuan Z.K., *Degradation characteristics and mechanism of materials in composite insulator under high humidity*, PhD Thesis, North China Electric Power University, Beijing (2019).

[3] Xoa Y.F., Song X.M., He J.Z. *et al.*, *Evaluation method of aging for silicone rubber of composite insulator*, Transactions of China Electrotechnical Society, vol. 34, no. S1, pp. 440–448 (2019), DOI: 10.19595/j.cnki.10006753.tces.L80647.

[4] Tang J., Liu Q.S., Liu J.W. *et al.*, *Evaluation of composite insulators based on fuzzy comprehensive evaluation*, Engineering Journal of Wuhan University, vol. 52, no. 5, pp. 451–456 (2019), DOI: 10.14188/j.1671-8844.2019-05-012.

[5] Huang X., Wang L.Y., Wang Q. *et al.*, *Grey fuzzy comprehensive evaluation model of contamination state for insulators based on IFAHP with bayesian modified method*, Science Technology and Engineering, vol. 20, no. 13, pp. 5135–5141 (2020), DOI: CNKI:SUN:KXJS.0.2020-13-018.

[6] Liu Y.P., Xu Z.Q., Fu H.C. *et al.*, *Insulation Condition Assessment Method of Power Transformer Based on Improved Extension Cloud Theory With Optimal Cloud Entropy*, High Voltage Engineering, vol. 46, no. 2, pp. 397–405 (2020), DOI: 10.13336/j.1003-6520.hve.20190215004.

[7] Fan L., Xia F., Su H.Y. *et al.*, *Risk assessment of high voltage insulator contamination condition by cloud theory*, Power System Protection and Control, vol. 40, no. 15, pp. 57–62 (2012), DOI: CNKI:SUN:JDQW.0.2012-15-014.

[8] Wang S.H., Jing H., *Study on method for predicting pollution Flashover insulators in contact network*, Journal of the China Railway Society, vol. 40, no. 3, pp. 58–67 (2018), DOI: CNKI:SUN:TDXB.0.2018-03-011.

[9] Huai M.Q., *Research on prediction of contamination state of insulator on catenary based on fuzzy neural network*, Master Thesis, Lanzhou Jiaotong University, Gansu (2018).

[10] Yang Z.C., Zhang C.L., Ge L. *et al.*, *Comprehensive fuzzy evaluation based on entropy weight method for insulator flashover pollution*, Electric Power Automation Equipment, vol. 34, no. 4, pp. 90–94 (2014), DOI: CNKI:SUN:DLZS.0.2014-04-016.

[11] Zhou Y.M., *Studies on the degradation depth of silicon composite insulator in service*, Master Thesis, Wuhan University, Wuhan (2018).

[12] Chen X.C., Li L.Q., Wu Z.G. *et al.*, *Research on shed properties of network operating composite insulators*, Guangdong Electric Power, vol. 29, no. 6, pp. 104–108 (2016), DOI: 10.3969/j.issn.1007-290X.2016.06.019.

[13] Yang L.G., Florian Pauli, Kay Hameyer, *Influence of thermal-mechanical stress on the insulation system of a low voltage electrical machine*, Archives of Electrical Engineering, vol. 70, no. 1, pp. 233–244 (2021), DOI: 10.24425/aee.2021.136064.

[14] Liu Y., Wang J.G., Han F. *et al.*, *Electrical and mechanical properties of composite insulators after different operation periods*, High Voltage Engineering, vol. 34, no. 5, pp. 1017–1021 (2008), DOI: 10.13336/j.1003-6520.hve.2008.05.027.

[15] Yao L.N., Wu Y.H., Wang S.H. *et al.*, *Electrical and mechanical properties of on-line composite insulators*, Insulating Materials, vol. 48, no. 8, pp. 23–27 (2015), DOI: 10.16790/j.cnki.1009-9239.im.2015.08.005.

[16] Jia Z.D., Yang C.X., Wang X.L. *et al.*, *Aging characteristics of composite insulators based on hydrophobicity transfer test*, High Voltage Engineering, vol. 41, no. 6, pp. 1907–1914 (2015), DOI: 10.13336/j.1003-6520.hve.2015.06.019.

[17] Zhang M.M., *Research on evaluation Method of Insulator pollution Status Assessment Based on UV Pulse Parameters*, Master Thesis, Southwest Jiaotong University, Sichuan (2019).

[18] Mao Y.K., Guan Z.C., Wang L.M. *et al.*, *Evaluation of contamination levels of outdoor insulators based on the principal components analysis of leakage current Pulse*, Transactions of China Electrotechnical Society, vol. 24, no. 8, pp. 39–45 (2009), DOI: 10.19595/j.cnki.10006753.tces.2009.08.007.

[19] Ning G.T., Fang B., Qin D. *et al.*, *Design and application of comprehensive evaluation index system of smart grid based on coordinated planning of major network and power distribution network*, Archives of Electrical Engineering, vol. 70, no. 1, pp. 103–113 (2021), DOI: 10.24425/aee.2021.136055.

[20] Zhou L.L., *Research of methods and their application of determining the weights of attributes in fuzzy comprehensive evaluation*, Master Thesis, Northeastern University, Liaoning (2014).

[21] Li G., Li J.P., Sun X.L. *et al.*, *Research on a combined methods of subjective-objective weighting and its rationality*, Management Review, vol. 29, no. 12, pp. 17–26+61 (2017), DOI: 10.14120/j.cnki.cn115057/f.2017.12.002.

[22] Chen Y.C., Dai J.Y., Xie D., *Comprehensive evaluation of mine ventilation system based on combination weighting cloud model*, Systems Engineering, vol. 38, no. 6, pp. 35–42 (2020), DOI: 1001-4098(2020)06-0035-08.

[23] Wang L.L., *Research on cleaner production evaluation index system and grade comprehensive evaluation methodologies of wastewater treatment plants in cities and towns*, PhD Thesis, Dalian University of Technology, Dalian (2015).