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Research Article

A Hierarchical Fuzzy Comprehensive Evaluation Algorithm for Running State of a 6 kV (10 kV) Power Switch Cabinet

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Considering the existence of many actual influential factors of a high voltage switch cabinet in the coal mine, the paper proposes a hierarchical fuzzy comprehensive evaluation algorithm to assess the running state of the 6 kV (10 kV) power vacuum switch cabinet better and improve operational safety and reliability of the power supply system. The algorithm can realize the state evaluation of bus bars, vacuum circuit breakers, electrical cables, other components, and the switch cabinet by the bottom-up approach. The running state evaluation index system and mathematical model of the switchgear are introduced particularly. According to the different forms of data information, this algorithm comprehensively evaluates the running state of the high voltage switchgear by using the online running data, test data, equipment information, and historical data records of the distribution cabinet. The actual operation states and test data of a handcart switch cabinet are taken as examples to prove the effectiveness of the algorithm.

1. Introduction

In order to provide a basis for the further maintenance and timely repair defects, comprehensive evaluation of the 6 kV (10 kV) high voltage switch cabinet and downhole cable's health state on the ground of coal mine will be developed through continuous tracking and managing based on a comprehensive analysis of a variety of online monitoring and off-line data. In this way, equipment accidents can be prevented effectively; the safety and reliability of coal mine power supply system can be improved to some extent [1].

At present, assessments for the running state of power vacuum switch cabinet both at home and abroad, mainly concentrated on the partial discharge (PD), voltage to ground, charged detection, circuit breaker fault, and so on [2–7]. It is important to find the partial discharge in the switch cabinet to ensure the safety of electric power by monitoring the running state of the switch cabinet [8]. Research results are reported concerning the above indexes and parameters. A method uses PD to measure the endurance of wire and equipment [9, 10], while there exists real random noise in the signal processing for PD. Various mathematical methods are applied through different detecting ways such as neural networks, fuzzy theory, and catastrophe theory [11–13]. The multilevel fuzzy comprehensive evaluation model for a Gas Insulated Switchgear (GIS) running state is proposed, which provides an integrated approach for evaluating the GIS overall operating state [14, 15]. The fuzzy comprehensive evaluation method of slope stability based on GIS was researched [16]. The above methods are mainly to use the online data to evaluate the running status of the main electrical components of the high voltage switchgear, lacking various test data, equipment information, and historical data records. Therefore, the assessment results may be a little partial not to give an objective and comprehensive judgment.

Considering the actual characteristics of the high voltage switchgear influenced by many factors, the fuzzy comprehensive evaluation algorithm of the 6 kV (10 kV) distribution vacuum switchgear is established in this paper. According to the different forms of data information, combining with equipment grading method and relevant parameters, this algorithm converts the non-data information into data information to evaluate comprehensively the running state of the high voltage switch cabinet.

The paper is organized as follows. Section 2 gives the fuzzy comprehensive evaluation model. Section 3 shows

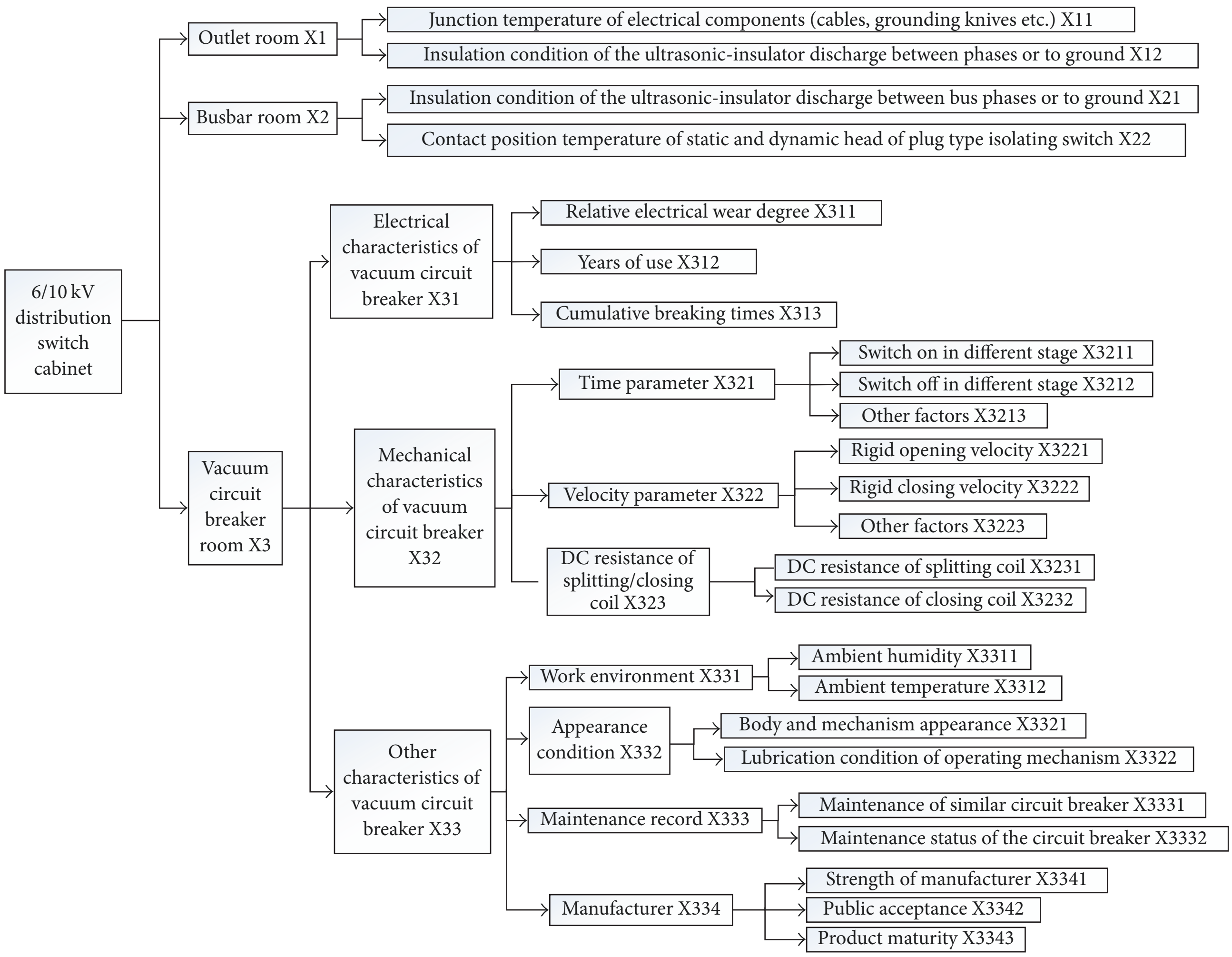

Figure 1: Evaluation index system for operation state of the 6 kV (10 kV) vacuum switchgear.

the membership functions of the various factors owing to different working states. Section 4 provides an example. Section 5 draws some conclusions.

2. Fuzzy Comprehensive Evaluation Model

The operating state evaluation index system of the 6 kV (10 kV) distribution vacuum switchgear is shown in Figure 1 [17, 18]. The distribution vacuum switch cabinet is mainly composed of a cable outlet chamber, a bus room, and a vacuum circuit breaker room. Therefore, the corresponding operation state evaluation index system is composed of three parts: the cable outlet chamber ($X1$), the bus room ($X2$), and the vacuum circuit breaker room ($X3$).

2.1. Factors of Judging Objects. Considering the fuzziness of various evaluation factors of the distribution vacuum switchgear, a multilevel fuzzy comprehensive evaluation method is employed to establish the state evaluation model of the distribution vacuum switchgear. According to the evaluation index of Figure 1, the project layer of the comprehensive state of is defined as $U_X = (U_{X1}, U_{X2}, U_{X3})$, which expresses the top project layer including three judging objects ($X1, X2, X3$). Then the overall project layer is divided into several subprojects of the next level, which are decomposed to the lower level indexes again. If there is no subproject, the higher-level project is decomposed directly to the indexes. For example, the mechanical test project of vacuum circuit breaker is decomposed into 3 subitems: time parameter, velocity parameter, and DC resistance of splitting/closing coil, $U_{X32} = (U_{X321}, U_{X322}, U_{X323})$. Namely, the project layer for mechanical characteristics consists of three judging objects: $X321$, $X322$, and $X323$.

2.2. Comment Collection. The comments of a switch cabinet are divided into four grades. Namely, each item is divided into four grades: {good ($V1$), better ($V2$), general ($V3$), and careful ($V4$)}. The comment collection is $V = \{V1, V2, V3, V4\}$, which means great, good, general, and careful, respectively. In fact, the comment collection is suitable for any layer. Namely, the running state of the relative upper layer including influential factors can be evaluated into four grades. For instance, time parameter can be evaluated according to {good ($V1$), better ($V2$), general ($V3$), and careful ($V4$)}. Certainly, the results of time parameter can influence the evaluation of the upper layers $X32$ and $X3$. Table 1 only describes

Table 1: Comments collection of the switch cabinet.

	Working state	Components aging degree	Failure possibility	Examination and reparation
Great ($V1$)	stable	very low	very low	no
Good ($V2$)	good for a long time	a certain degree	low	no
General ($V3$)	normal	no serious damage	increasing	no
Careful ($V4$)	abnormal	high or abnormal	high	yes

Great: the switch cabinet's working state is stable; each component works good; the failure possibility is very low; *Good*: the switch cabinet has been running for a period, some electrical components have a certain degree of aging, and vacuum circuit breaker has a certain degree of electrical wear. But the test data of power off and on is normal; the working performance is generally stable; the possibility of fault occurrence is low; the maintenance is not necessary; *General*: electrical components in the switch cabinet have no serious damage; the possibility of failure increases somewhat, yet it will not pose a threat to the safe operation temporarily; it is necessary to analyze and judge the specific abnormal types of electrical components; *Careful*: running or testing data from the main electrical components is abnormal dramatically; faults may occur; it is advisable to cut off the power supply and overhaul the power switch cabinet, finding the cause of abnormal conditions or abnormal components; the engineers consider replacing the specific equipment if necessary.

the conditions of the entire switch cabinet. The comment collection of each subproject is similar.

2.3. Weight Collection A of Evaluation Factors. The weight collection can be regarded as the fuzzy relationship between the evaluation object and the evaluation factor, which reflects the proportion of each evaluation factor in the process of comprehensive evaluation and decision. According to the judgment matrix of analytic hierarchy process (AHP), this paper adopts AHP to determine the calculated maximum eigenvalue of the comparison judgment matrix. By solving the characteristic equation and obtaining the eigenvectors corresponding to the largest eigenvalue, the paper finally gets the weight vector of each index [19]. In accordance with the above method, AHP is employed to assign weights to each index of the switch cabinet, and the calculation results are shown in Table 2. The number of evaluation factors which each layer contains decides the one of weight values. The sum of all the weight values of each layer is 1. For instance, the cable outlet chamber ($X1$) contains two indexes with weight value $(0.5, 0.5)$. Then, A_{X1} can be employed to represent layer $X1$'s weight set, $A_{X1} = (0.5, 0.5)$. In the same way, $X31$'s weight set is $A_{X31} = (0.758, 0.091, 0.151)$.

Table 2: Weight value of evaluation index.

index	Weight value of the subindex of the lower layer ($A_{X\cdots}$)
$X1$	$(0.5, 0.5)$
$X2$	$(0.5, 0.5)$
$X3$	$(0.648, 0.230, 0.122)$
$X31$	$(0.758, 0.091, 0.151)$
$X32$	$(0.539, 0.298, 0.163)$
$X33$	$(0.125, 0.355, 0.326, 0.194)$
$X321$	$(0.309, 0.582, 0.109)$
$X322$	$(0.297, 0.540, 0.163)$
$X323$	$(0.5, 0.5)$
$X331$	$(0.267, 0.495, 0.065, 0.163)$
$X332$	$(0.178, 0.273, 0.462, 0.087)$
$X333$	$(0.4, 0.6)$
$X334$	$(0.297, 0.538, 0.165)$

2.4. Each Hierarchy Fuzzy Relation Matrix [19, 20]. In view to the hierarchy thought of AHP, the paper needs to decompose the whole project into various subprojects. While we must calculate the lowest evaluation indexes from the opposite direction. As illustrated in Figure 1, the maximum layer number of the fuzzy comprehensive evaluations is four. Hence, there are four-layer subindexes to evaluate running state of each subproject layer. More importantly, we can obtain a local comprehensive evaluation from the lower level indexes and acquire the whole comprehensive evaluation matrix step by step.

From the above, the lowest fuzzy relationship matrix can be defined as follows:

$$R_{Xij\cdots k} == \begin{bmatrix} \mu_{k_{1\cdots 1}} & \cdots & \mu_{k_{1\cdots 4}} \\ & \ddots & \\ \vdots & \mu_{k_{i\cdots j}} & \vdots \\ & \ddots & \\ \mu_{k_{n_{ij}\cdots k\cdots 1}} & \cdots & \mu_{k_{n_{ij}\cdots k\cdots 4}} \end{bmatrix}, \quad (1)$$

where $\mu_{k_{i\cdots j}}$ expresses the membership degree of the item k, $k = 1, 2, \ldots, n_{ij}$; $n_{ij\cdots k}$ expresses the number of influential factors with the item k. For example, R_{X31} is the fuzzy relation matrix of the electrical characteristics of the vacuum circuit breaker, whose influential factors are three (illustrated in Figure 1). Therefore, the dimension of the matrix is 3×4. The first row represents the degree of the relative electric wear belonging to $V1$ (great), $V2$ (good), $V3$ (general), and $V4$ (careful), respectively.

By the weigh value shown in Table 1, the lower level fuzzy relationship matrix R_{Xij} can be calculated.

The local comprehensive evaluation model is

$$B_{Xij} = A_{Xij} \cdot R_{Xij} = A_{Xij} \begin{bmatrix} A_{Xij1} \cdot R_{Xij1} \\ \vdots \\ A_{Xijk} \cdot R_{Xijk} \\ \vdots \\ A_{Xijn_{ij}} \cdot R_{Xijn_{ij}} \end{bmatrix} = \cdots, \quad (2)$$

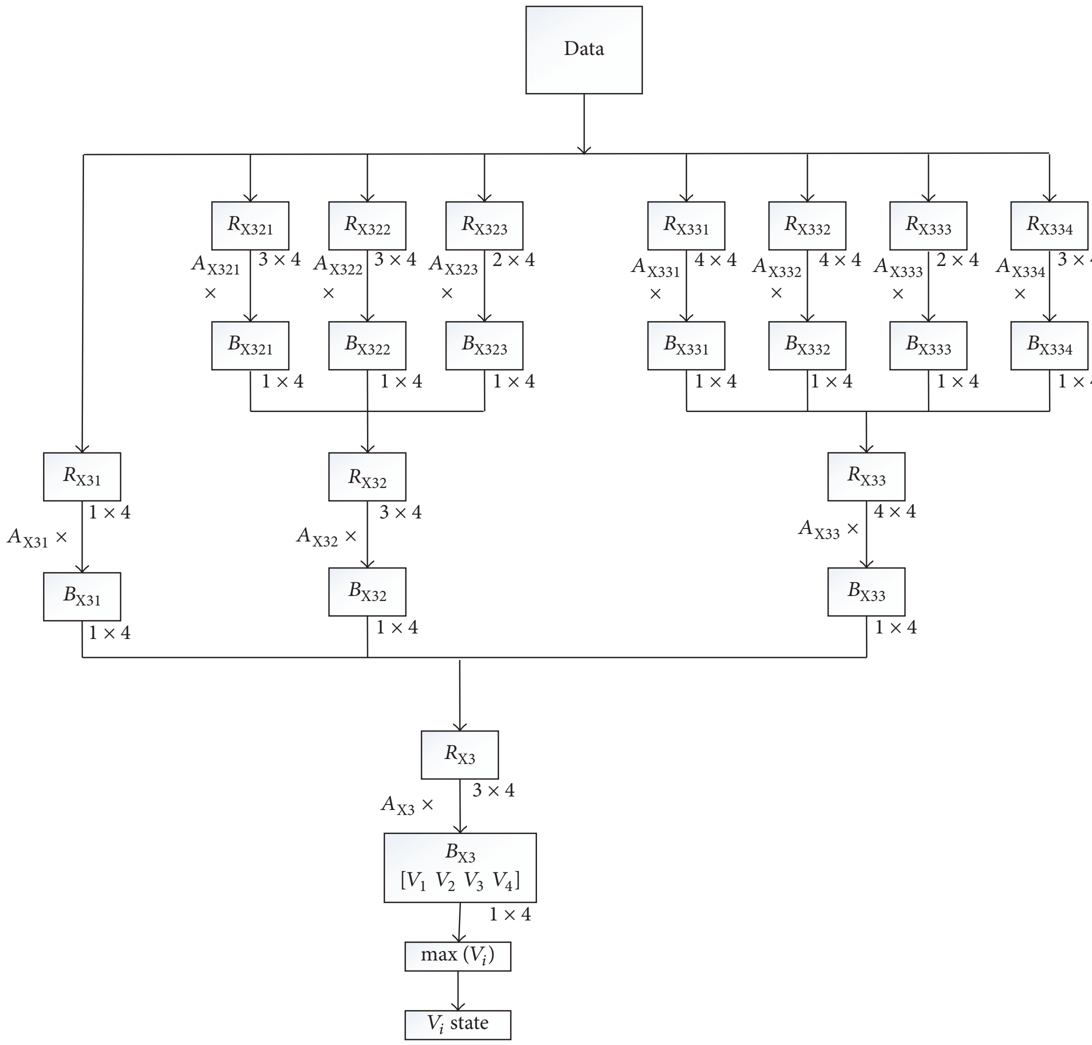

FIGURE 2: Flow chart of the comprehensive hierarchical evaluation algorithm.

where A_{Xij} is the weight value the subproject layer X_{ij} attached to the higher project. n_{ij} expresses the number of influential factors with the item X_{ij}. R_{Xijk} is the next lower fuzzy relationship matrix. If the fuzzy relation matrix of some layer R_{Xijk} is with the corresponding weight values A_{Xijk} in Table 2, we can obtain the comprehensive evaluation matrix of item X_{ijk}, $B_{Xijk} = A_{Xijk} \cdot R_{Xijk}$. Figure 2 illustrates the algorithm's process. The higher fuzzy relationship matrix R_{Xij} is composed of the lower evaluation matrix B_{Xijk}.

$$R_{Xij} = \left[B_{Xij1} \ \cdots \ B_{Xijk} \ \cdots \ B_{Xijn_{ij}}\right]^T \tag{3}$$

From (2), $B_{Xij} = A_{Xij} \cdot R_{Xij}$ can establish the higher fuzzy relationship matrix.

$$R_{Xi} = \left[B_{Xi1} \ \cdots \ B_{Xik} \ \cdots \ B_{Xin_i}\right]^T \tag{4}$$

2.5. Comprehensive Evaluation Vector. From the forward direction, we define the highest level comprehensive evaluation matrix:

$$B_{Xi} = A_{Xi} \cdot R_{Xi} = A_{Xi} \cdot \begin{bmatrix} A_{Xi1} \cdot R_{Xi1} \\ \vdots \\ A_{Xij} \cdot R_{Xij} \\ \vdots \\ A_{Xin_i} \cdot R_{Xin_i} \end{bmatrix}, \tag{5}$$

where $B_{Xi} = (b_{i1}, \ldots, b_{i4})$ indicates fuzzy comprehensive evaluation collection on the objective layer with the item Xi. A_{Xi} and R_{Xi} are weight collection and higher fuzzy relationship matrix respectively, whose values are listed in Table 1. As Figure 2 shows, according to the above equations, the fuzzy relationship matrix can be derived from the bottom to the top. With the evaluation result of each factor for the subproject obtained, the final evaluation result is acquired based on each level result. Therefore, (1)–(5) can be regarded as the fuzzy hierarchical comprehensive evaluation model.

According to the comprehensive evaluation vector, the result set is obtained B_{Xi} ($i = 1, \ldots, n_i$). The maximum membership degree method is adopted, taking the biggest indicator max (bj) whose corresponding evaluation element V_i is the judgment result [21]. That is,

$$V = \{V \mid V_i \longrightarrow \max(bj)\}. \quad (6)$$

The above fuzzy comprehensive hierarchical evaluation algorithm can be illustrated by the flowchart Figure 2. The bottom-up approach is adopted to evaluate the fuzzy relation matrix at the bottom. For evaluation index system as shown in Figure 1, with the operating data, historical data records, various test data, and equipment information of the 6 kV (10 kV) vacuum switchgear, the fuzzy relationship matrixes of the bottom layer can be calculated. Then by the corresponding weights given by Table 2 we can employ (5) to calculate the comprehensive evaluation matrix of the layer. The evaluation matrixes of this layer constitute the fuzzy relation matrix of the upper layer as each row, and the upper layer's weight value is used to calculate the comprehensive evaluation matrix of the upper layer until the top layer.

Finally, the authors obtain a fourth-order row vector. The numerical order corresponding to the largest value represents the level of the running state of the vacuum switchgear. For instance, the third number is largest, which expresses the running state is $V3$ (general).

3. Membership Functions and Membership Degree

Membership function is the fuzzy relationship between the evaluation factors and the evaluation state. When the membership degree of each parameter is determined, the corresponding original data should be preprocessed firstly, which is converted to the number between 0 and 1. In this paper, the concept of relative degradation degree [20] is introduced, which reflects the degree of deterioration of the index state reflected by different values. It is a quantitative index with the range of value $[0, 1]$. After preprocessing the original data, the membership degree can be calculated via the membership function. For the temperature, insulation, electrical characteristics, and other quantifiable indicators, the use of semitrapezoidal and triangular membership distribution function is shown in Figure 3. The comment collection is $V = \{V1, V2, V3, V4\}$; quantization domain is $X = \{a1, a2, a3, a4, a5, a6, a7, a8, a9, a10\}$.

It is difficult to quantitatively describe indicators of working environment, appearance, maintenance records, and manufacturers, as these kinds of data are relatively static. Therefore, the fuzzy statistical test method is used to determine their membership degree. The method is as follows: according to the evaluation object and the evaluation index, the questionnaire is made and distributed to each expert to

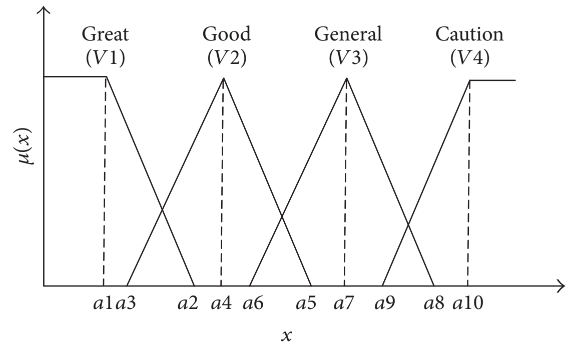

Figure 3: Semitrapezoid and triangle membership functions.

determine the membership degree of each factor, to obtain the single factor judgment matrix:

$$\mu_{ij} = \frac{L_i}{L}, \quad (7)$$

where μ_{ij} is membership degree; L_i is the number of people considering i belonging to the j comment; L is the total number of evaluation experts.

3.1. Membership Functions of the Temperature of the Electrical Components in the Bus and Outlet Chambers. The temperatures at the breaker cable joint, at grounding connection in the outlet chamber, and at the static contact area of the plug type isolating switch in the busbar chamber are gradually increasing with time. The junction temperature cannot exceed 60 degrees centigrade according to regulations. So, the relative deterioration degree function at the joint of cable connectors, grounding knife switches, and so on is

$$x = f(\theta) = \exp\left(\frac{\theta - 60}{60}\right), \quad (8)$$

where θ is temperature in Celsius at the cable joint, grounding connection, and so forth. The membership function is as follows:

Great Comments (V1)

$$\mu(x) = \begin{cases} 1 & x \le 0.5 \\ \dfrac{13 - 20x}{3} & 0.5 \le x < 0.65 \\ 0 & x \ge 0.65 \end{cases} \quad (9)$$

Good Comments (V2)

$$\mu(x) = \begin{cases} 10x - 5 & 0.5 \le x < 0.6 \\ \dfrac{15 - 20x}{3} & 0.6 \le x < 0.75 \\ 0 & x < 0.5 \text{ or } x \ge 0.75 \end{cases} \quad (10)$$

General Comments (V3)

$$\mu(x)=\begin{cases}\dfrac{20x-12}{3} & 0.6\le x<0.75\\ \dfrac{18-20x}{3} & 0.75\le x<0.9\\ 0 & x<0.6 \text{ or } x\ge 0.9\end{cases} \quad (11)$$

Careful Comments (V4)

$$\mu(x)=\begin{cases}1 & x\ge 0.9\\ \dfrac{10x-7}{2} & 0.7\le x<0.9\\ 0 & x<0.7\end{cases} \quad (12)$$

3.2. Membership Functions of the Ultrasonic Discharge between Phases or to Ground in Bus Bar Room and Outlet Room. According to experiments, the values of the ultrasonic testing data mainly concentrate on 6~20 dB. If the data is lower than 10 dB, the state is great; if it is higher than 20 dB, it means that there is a serious discharge inside the switch cabinet. The relative deterioration function can be set as

$$x=f(u)=\exp\left(\frac{u-20}{20}\right), \quad (13)$$

where u is the ultrasonic data, expressed in decibels.

The function ultrasonic discharge between phases or to ground in bus bar room and outlet room is as follows.

Great Comments (V1)

$$\mu(x)=\begin{cases}1 & x\le 0.47\\ \dfrac{61-100x}{14} & 0.47\le x<0.61\\ 0 & x\ge 0.61\end{cases} \quad (14)$$

Good Comments (V2)

$$\mu(x)=\begin{cases}\dfrac{100x-47}{14} & 0.47\le x<0.61\\ \dfrac{78-100x}{17} & 0.61\le x\le 0.78\\ 0 & x<0.47 \text{ or } x\ge 0.78\end{cases} \quad (15)$$

General Comments (V3)

$$\mu(x)=\begin{cases}\dfrac{100x-61}{17} & 0.61\le x<0.78\\ \dfrac{100-100x}{22} & 0.78\le x\le 1\\ 0 & x<0.61 \text{ or } x\ge 1\end{cases} \quad (16)$$

Careful Comments (V4)

$$\mu(x)=\begin{cases}0 & x<0.78\\ \dfrac{100x-78}{22} & 0.78\le x\le 1\\ 1 & x\ge 1\end{cases} \quad (17)$$

3.3. Membership Functions of Electrical Characteristics of Vacuum Circuit Breaker. (1) Relative deterioration degree function of electrical wear degree is as follows. Through the measurement of an actual breaking current I_{ci}, the paper got the corresponding specified breaking times N_{mi} according to the N-I_c curve of circuit breaker factory test. Then, the relative wear was calculated: $Q_{mi}=1/N_{mi}$, and the cumulative sum $\sum Q_m$ was also obtained, by which the relative electrical life of circuit breaker was acquired. It is assumed that the relative deterioration function of electrical wear degree is

$$x=f(Q_{mi})=\sum Q_m. \quad (18)$$

(2) Relative deterioration degree function of cumulative breaking times is as follows:

$$x=f(n)=\frac{n}{N}, \quad (19)$$

where, n is breaking times of the vacuum circuit breakers: N is the maximal breaking times of the vacuum circuit breakers.

(3) Relative deterioration function of using years is as follows, years of use function being

$$x=f(m)=\left(\frac{m}{M}\right)^2, \quad (20)$$

where m is the years that vacuum circuit breaker has been used. M is the total years that vacuum circuit breakers can be used.

According to the membership function method, the membership functions of the electrical characteristics of the vacuum circuit breaker is shown in Table 3.

3.4. Membership Functions of Mechanical Characteristics of Vacuum Circuit Breaker

3.4.1. Membership Function of Time Parameter. According to the relevant provisions of *Preventive Test Procedure for Electric Power Equipment*: "If the switching on time in different stage in the interphase is no more than 5 ms & the switching off time is no more than 3 ms, the switching synchronization is contented except for other provisions." The membership functions are shown in Table 4. Other factors were treated by fuzzy statistical method via (7).

3.4.2. Membership Function of Velocity Parameter. The speed characteristics include the parameters of rigid opening velocity, rigid closing velocity, and other factors (containing the average switching on and off speed, etc.). As for the opening velocity and closing velocity, the fuzzy distribution of state

Table 3: Membership functions of electrical characteristic evaluation.

comment	Factor: Relative electric wear degree	Factor: Cumulative break times	Factor: Years of use
Great ($V1$)	$\mu(x)=\begin{cases}1 & x<0.1\\ \dfrac{4-10x}{3} & 0.1\le x<0.4\\ 0 & x\ge 0.4\end{cases}$	$\mu(x)=\begin{cases}1 & x<0.2\\ -5x+2 & 0.2\le x<0.4\\ 0 & x\ge 0.4\end{cases}$	$\mu(x)=\begin{cases}1 & x<0.16\\ \dfrac{-100x+25}{9} & 0.16\le x<0.25\\ 0 & x\ge 0.25\end{cases}$
Good ($V2$)	$\mu(x)=\begin{cases}5x-0.5 & 0.1\le x<0.3\\ -5x+2.5 & 0.3\le x<0.5\\ 0 & x\ge 0.5 \text{ or } x<0.1\end{cases}$	$\mu(x)=\begin{cases}5x-1 & 0.2\le x<0.4\\ -10x+5 & 0.4\le x<0.5\\ 0 & x\ge 0.5 \text{ or } x<0.2\end{cases}$	$\mu(x)=\begin{cases}\dfrac{100x-16}{9} & 0.16\le x<0.25\\ \dfrac{-100x+36}{11} & 0.25\le x<0.36\\ 0 & x\ge 0.36 \text{ or } x<0.16\end{cases}$
General ($V3$)	$\mu(x)=\begin{cases}5x-1.5 & 0.3\le x<0.5\\ \dfrac{8-10x}{3} & 0.5\le x<0.8\\ 0 & x\ge 0.8 \text{ or } x<0.3\end{cases}$	$\mu(x)=\begin{cases}\dfrac{20x-8}{3} & 0.4\le x<0.55\\ \dfrac{11-20x}{3} & 0.55\le x<0.7\\ 0 & x\ge 0.7 \text{ or } x<0.4\end{cases}$	$\mu(x)=\begin{cases}\dfrac{100x-25}{11} & 0.25\le x<0.36\\ \dfrac{16-25x}{7} & 0.36\le x<0.64\\ 0 & x\ge 0.64 \text{ or } x<0.25\end{cases}$
Careful ($V4$)	$\mu(x)=\begin{cases}\dfrac{10x-6}{3} & 0.6\le x<0.9\\ 1 & 0.9\le x<1.0\\ 0 & x<0.6\end{cases}$	$\mu(x)=\begin{cases}\dfrac{20x-11}{3} & 0.55\le x<0.7\\ 1 & 0.7\le x<1.0\\ 0 & x<0.55\end{cases}$	$\mu(x)=\begin{cases}\dfrac{25x-9}{3} & 0.36\le x<0.64\\ 1 & 0.64\le x<1.0\\ 0 & x<0.36\end{cases}$

Table 4: Membership functions of switching on and switching off.

comment	Factor: Switching on in different stage (ms)	Factor: Switching off in different stage (ms)
Great ($V1$)	$\mu(x)=\begin{cases}1 & x<1.0\\ 2-x & 1.0\le x<2.0\\ 0 & x\ge 2.0\end{cases}$	$\mu(x)=\begin{cases}1 & x<1.0\\ 1.5-x & 1.0\le x<1.5\\ 0 & x\ge 1.5\end{cases}$
Good ($V2$)	$\mu(x)=\begin{cases}\dfrac{x}{2} & 0\le x<2.0\\ 3-x & 2.0\le x<3.0\\ 0 & x\ge 3.0\end{cases}$	$\mu(x)=\begin{cases}x-0.5 & 0.5\le x<1.5\\ 2.5-x & 1.5\le x<2.5\\ 0 & x<0.5 \text{ or } x\ge 2.5\end{cases}$
General ($V3$)	$\mu(x)=\begin{cases}\dfrac{x-1}{2} & 1.0\le x<3.0\\ 4-x & 3.0\le x<4.0\\ 0 & x<5.0 \text{ or } x<1.0\end{cases}$	$\mu(x)=\begin{cases}x-1 & 1.0\le x<2.0\\ 3-x & 2.0\le x<3.0\\ 0 & x<1.0\end{cases}$
Caution ($V4$)	$\mu(x)=\begin{cases}\dfrac{x-1}{3} & 1.0\le x<4.0\\ 1 & 4.0\le x\\ 0 & x<1.0\end{cases}$	$\mu(x)=\begin{cases}x-1.5 & 1.5\le x<2.5\\ 1 & 2.5\le x\\ 0 & x<1.5\end{cases}$

Table 5: Membership functions ofopening velocity and closing velocity.

comment	Factor: Rigid opening velocity (m/s)	Factor: Rigid closing velocity (m/s)
Great ($V1$)	$\mu(x)=\begin{cases}1 & x\geq 0.8\\ \dfrac{5x-2}{2} & 0.4\leq x<0.8\\ 0 & x<0.4\end{cases}$	$\mu(x)=\begin{cases}1 & x\geq 0.8\\ \dfrac{5x-2}{2} & 0.4\leq x<0.8\\ 0 & x<0.4\end{cases}$
Good ($V2$)	$\mu(x)=\begin{cases}4-5x & 0.6\leq x<0.8\\ 5x-1 & 0.4\leq x<0.6\\ 0 & x<0.4 \text{ or } x\geq 0.6\end{cases}$	$\mu(x)=\begin{cases}4-5x & 0.6\leq x<0.8\\ 5x-1 & 0.4\leq x<0.6\\ 0 & x<0.4 \text{ or } x\geq 0.6\end{cases}$
General ($V3$)	$\mu(x)=\begin{cases}3-5x & 0.4\leq x<0.6\\ \dfrac{10x-1}{3} & 0.1\leq x<0.4\\ 0 & x<0.1 \text{ or } x\geq 0.6\end{cases}$	$\mu(x)=\begin{cases}3-5x & 0.4\leq x<0.6\\ \dfrac{10x-1}{3} & 0.1\leq x<0.4\\ 0 & x<0.1 \text{ or } x\geq 0.6\end{cases}$
Careful ($V4$)	$\mu(x)=\begin{cases}\dfrac{4-10x}{3} & 0.1\leq x<0.4\\ 1 & x<0.1\\ 0 & x\geq 0.4\end{cases}$	$\mu(x)=\begin{cases}\dfrac{4-10x}{3} & 0.1\leq x<0.4\\ 1 & x<0.1\\ 0 & x\geq 0.4\end{cases}$

influence to vacuum circuit breaker can be expressed as the Gaussian distribution function:

$$f(x)=\exp\left[-\left(\frac{x-a}{b}\right)^2\right], \tag{21}$$

where the unit of x is m/s; a is the center of the membership function, which is the optimal speed required by the breaker manufacturer; and b is the width of the membership function, which is determined by the requirements of the opening velocity and closing velocity of the manufacturer.

For example, the required opening velocity of a circuit breaker manufacturer is 3.4 ± 0.8 m/s, which can be defined as

$$f(x)=\exp\left[-\left(\frac{x-3.4}{0.8}\right)^2\right]. \tag{22}$$

The requirements of the closing velocity are 3.2 ± 0.2 m/s, which can be defined as

$$f(x)=\exp\left[-\left(\frac{x-3.2}{0.2}\right)^2\right]. \tag{23}$$

The membership functions about the opening velocity and closing velocity are shown in Table 5. Other factors are treated by fuzzy statistical method, as is shown by (7).

3.4.3. DC Resistance of the Splitting/Closing Coil. The DC resistance of the splitting/closing coil should be in accordance with the manufacturer's regulations, usually within the range of the factory specified value of ±5%. For example, a circuit breaker manufacturer has a specified value of 110 Ω. It can be assumed that the function form is

$$f(x)=\exp\left[-\left(\frac{x-110}{11}\right)^2\right]. \tag{24}$$

The membership functions of the DC resistance of the splitting/closing coil are established as shown in Table 6.

4. Example Verifications

In order to verify the feasibility and effectiveness of the fuzzy comprehensive evaluation method in the circuit breaker, a central handcart switch cabinet with a model number of KYN28 is taken as the experimental object. The switch cabinet uses the vacuum circuit breaker with a model number of ZN28 (A)-12 10 kV, which is a split type, whose vacuum degrees are all within the range of 1.333×10^{-4} to 1.333×10^{-5} Pa. The main technical parameters of the electrical and mechanical characteristics are shown in Table 7. The environmental conditions required by the switch cabinet are shown in Table 8. The 6 kV (10 kV) power vacuum switch cabinet in the paper is particularly referred to a kind of high voltage

Table 6: Membership functions of DC resistance of splitting/closing coil.

comment	Factor	
	DC resistance of splitting coil (Ω)	DC resistance of closing coil (Ω)
Great ($V1$)	$\mu(x)=\begin{cases}1 & x\geq 0.8\\ \frac{5x-2}{2} & 0.4\leq x<0.8\\ 0 & x<0.4\end{cases}$	$\mu(x)=\begin{cases}1 & x\geq 0.8\\ \frac{5x-2}{2} & 0.4\leq x<0.8\\ 0 & x<0.4\end{cases}$
Good ($V2$)	$\mu(x)=\begin{cases}4-5x & 0.6\leq x<0.8\\ 5x-2 & 0.4\leq x<0.6\\ 0 & x<0.4 \text{ or } x\geq 0.6\end{cases}$	$\mu(x)=\begin{cases}4-5x & 0.6\leq x<0.8\\ 5x-2 & 0.4\leq x<0.6\\ 0 & x<0.4 \text{ or } x\geq 0.8\end{cases}$
General ($V3$)	$\mu(x)=\begin{cases}3-5x & 0.4\leq x<0.6\\ \frac{10x-1}{3} & 0.1\leq x<0.4\\ 0 & x<0.1 \text{ or } x\geq 0.6\end{cases}$	$\mu(x)=\begin{cases}3-5x & 0.4\leq x<0.6\\ \frac{10x-1}{3} & 0.1\leq x<0.4\\ 0 & x<0.1 \text{ or } x\geq 0.6\end{cases}$
Careful (V4)	$\mu(x)=\begin{cases}\frac{4-10x}{3} & 0.1\leq x<0.4\\ 1 & x<0.1\\ 0 & x\geq 0.4\end{cases}$	$\mu(x)=\begin{cases}\frac{4-10x}{3} & 0.1\leq x<0.4\\ 1 & x<0.1\\ 0 & x\geq 0.4\end{cases}$

Table 7: Technical parameters of vacuum circuit breaker.

Circuit breaker type	ZN28(A)-12	Rated voltage	10 kV
Rated short circuit breaking current (kA)	20	Rated short circuit peak withstand current	20~50
Mechanical life (times)	10000	Spring mechanism type	CT19
Three phase switch in different periods (ms)	≤2.0	Switching time	20~50
Bounce time of closing contact (ms)	≤2.0	Closing time	50~70

switch cabinet used in the coal mine, whose environmental conditions are bad. Therefore, it must have the ability of shock-resistance and antipollution. Because of the limitation of the space, the circuit breaker room is taken as an example to verify.

4.1. Evaluation Algorithm for Electrical Characteristics. According to short-circuit and open-circuit current values of 10 kV vacuum circuit breaker KYN28 running from the operation record, the number of using years, and the times of switching on and off, we can get the relative wear amount $Qm = 0.47$, years of using circuit breakers $f(m) = (12/25)2 = 0.23$, and the cumulative break times $f(n) = 370/3000 = 0.123$ from (18)–(20). By the membership functions of electrical characteristics of 10 kV vacuum circuit breaker shown in Table 3, the fuzzy relation matrix R_{X31} can be obtained.

The influential factors R_{X31} are three (illustrated in Figure 1). Therefore, the dimension of the fuzzy relation matrix is 3×4. The first row represents the degree of the relative electric wear belonging to $V1$ (great), $V2$ (good), $V3$ (general), and $V4$ (careful), respectively.

From Figure 1, $X31$ has three subitems (factors): $X311$, $X312$, and $X313$. The factors' membership functions are listed in Table 3. By $Q_m = 0.47$ and the first column's functions of Table 1, we can obtain the elements of the matrix as 0, $(x = 0.47 \geq 0)$, $-5x + 2.5$ $(0.3 \leq x = Q_m = 0.47 < 0.5)$, $5x - 1.5$ $(0.3 \leq x = Q_m = 0.47 < 0.5)$, 0 $(x = 0.47 < 0.6)$ Hence, the first row's values are 0, 0.15, 0.85, 0.

Table 8: Environmental conditions of switch cabinet.

Ambient air temperature	−10°C~+40°C	Indoor humidity (relative humidity)	Daily average is not greater than 95%
Altitude	No more than 1000 m	Earthquake intensity	8
Maximum wind speed	35 m/s	Environmental pollution grade	II

In the same way, replacing $x = f(m) = (12/25)2 = 0.23$ into the four functions in the 2nd column, we can get the values of the second values:

$$R_{X31} = \begin{bmatrix} 0 & 0.15 & 0.85 & 0 \\ 0.22 & 0.78 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}. \quad (25)$$

The weight value of relative electrical wear, the number of years used, and the number of cumulative breaking times are shown in Table 2, $A_{X31} = (0.758, 0.091, 0.151)$. Then lower evaluation matrix B_{X31} is obtained.

$$\begin{aligned} B_{X31} &= A_{X31} \cdot R_{X31} \\ &= (0.758, 0.091, 0.151) \cdot \begin{bmatrix} 0 & 0.15 & 0.85 & 0 \\ 0.22 & 0.78 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \\ &= (0.171, 0.185, 0.644, 0). \end{aligned} \quad (26)$$

The four values of B_{X31} represent the membership degree $(V1, V2, V3, V4)$ of the electrical characteristics of the vacuum circuit breaker. The first number 0.171 indicates the membership degree of $V1$ (great). The third number 0.644 expresses the member degree of $V3$ (general). From (6), the maximum is the item of $V3$, which means the running state is $V3$ (general).

4.2. Evaluation Algorithm for Mechanical Characteristics. According to the preventive test, the switching on time in different stage of the 10 kV vacuum circuit breaker is 0.7 ms; the switching off time is 1.2 ms; and the DC resistance of the splitting coil closing coil is 104 Ω and 117 Ω, respectively. The membership degrees of rigid opening and closing velocities of circuit breaker are 3.6 m/s and 3.1 m/s. Other factors of time parameter and velocity parameter are calculated by fuzzy statistics method as (7). For the above data, the fuzzy relation matrixes R_{X321}, R_{X322}, and R_{X323} can be obtained by substituting them into Tables 4–6. For instance, the rigid closing velocity 3.1 m/s is preprocessed by (23), which becomes 0.78. Then, set $x = 0.78$, from the 2nd column's functions in Table 5, and we can obtain the 2nd row's elements: $(5x-2)/2$ $(x = 0.78)$, $4-5x$ $(x = 0.78)$, 0, 0. Namely, they are 0.95, 0.1, 0, 0. The fuzzy relation matrixes of the time parameter, speed parameter, and the DC resistance of the splitting/closing coil of the 10 kV vacuum circuit breaker are listed.

$$\begin{aligned} R_{X321} &= \begin{bmatrix} 1 & 0.35 & 0 & 0 \\ 0.3 & 0.7 & 0.2 & 0 \\ 0.3 & 0.5 & 0.2 & 0 \end{bmatrix}, \\ R_{X322} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0.95 & 0.1 & 0 & 0 \\ 0.5 & 0.3 & 0.2 & 0 \end{bmatrix}, \\ R_{X323} &= \begin{bmatrix} 0.857 & 0.285 & 0 & 0 \\ 0.668 & 0.665 & 0 & 0 \end{bmatrix}. \end{aligned} \quad (27)$$

The weights of the lower subindex of time parameter and speed parameter of the circuit breaker and and DC resistance of the splitting/closing coil are shown in Table 2. Consequently, the lower evaluation matrix B_{X32} is obtained based on the following calculations:

$$\begin{aligned} B_{X32} &= A_{X32} \cdot R_{X32} = A_{X32} \times \begin{bmatrix} A_{X321} \cdot R_{X321} \\ A_{X322} \cdot R_{X322} \\ A_{X323} \cdot R_{X323} \end{bmatrix} \\ &= (0.539, 0.298, 0.163) \\ &\quad \times \begin{bmatrix} 0.516 & 0.57 & 0.138 & 0 \\ 0.892 & 0.103 & 0.033 & 0 \\ 0.763 & 0.475 & 0 & 0 \end{bmatrix} \\ &= (0.668, 0.416, 0.084, 0). \end{aligned} \quad (28)$$

4.3. Evaluation Algorithm for Other Factors. According to the daily inspection record of 10 kV vacuum circuit breaker, the fuzzy statistical method shown in (7) is adopted to obtain the fuzzy relation matrixes of other factors (working environment $X331$, appearance condition $X332$, maintenance record $X333$, and manufacturer $X334$) of 10 kV vacuum breaker:

$$R_{X331} = \begin{bmatrix} 0.6 & 0.3 & 0.1 & 0 \\ 0.2 & 0.6 & 0.2 & 0 \\ 0.4 & 0.4 & 0.2 & 0 \\ 0.4 & 0.5 & 0.1 & 0 \end{bmatrix},$$

$$R_{X332} = \begin{bmatrix} 0.4 & 0.5 & 0.1 & 0 \\ 0.2 & 0.3 & 0.4 & 0.1 \\ 0.2 & 0.4 & 0.4 & 0 \\ 0 & 0.2 & 0.2 & 0.6 \end{bmatrix},$$

$$R_{X333} = \begin{bmatrix} 0.2 & 0.2 & 0.5 & 0.1 \\ 0.1 & 0.3 & 0.6 & 0 \end{bmatrix},$$

$$R_{X334} = \begin{bmatrix} 0.2 & 0.4 & 0.4 & 0 \\ 0.1 & 0.4 & 0.4 & 0.1 \\ 0.5 & 0.4 & 0.1 & 0 \end{bmatrix}. \quad (29)$$

The weights of other factors can be obtained by Table 2. The calculation process is similar to (1)-(2).

$$\begin{aligned} B_{X33} &= A_{X33} \cdot R_{X33} = A_{X33} \cdot \begin{bmatrix} A_{X331} \cdot R_{X331} \\ A_{X332} \cdot R_{X332} \\ A_{X333} \cdot R_{X333} \\ A_{X334} \cdot R_{X334} \end{bmatrix} \\ &= (0.125, 0.355, 0.326, 0.194) \\ &\times \begin{bmatrix} 0.350 & 0.485 & 0.155 & 0 \\ 0.218 & 0.371 & 0.329 & 0.080 \\ 0.140 & 0.260 & 0.560 & 0.040 \\ 0.196 & 0.400 & 0.351 & 0.054 \end{bmatrix} \\ &= (0.205, 0.355, 0.387, 0.052). \end{aligned} \quad (30)$$

4.4. Comprehensive Evaluation Algorithm. The fuzzy relation matrix of judgment set of 10 kV vacuum circuit breaker can be obtained by using all kinds of judging results obtained before and taking them as the judging factors and then carrying on the comprehensive evaluation of the highest level. Namely, from the above evaluation matrixes, the upper fuzzy relation matrix is

$$\begin{aligned} R_{X3} &= \begin{bmatrix} B_{X31} \\ B_{X32} \\ B_{X33} \end{bmatrix} = \begin{bmatrix} 0.171 & 0.185 & 0.644 & 0 \\ 0.668 & 0.416 & 0.084 & 0 \\ 0.205 & 0.355 & 0.387 & 0.052 \end{bmatrix}, \\ B_{X3} &= A_{X3} \cdot R_{X3} \\ &= (0.648, 0.230, 0.122) \\ &\times \begin{bmatrix} 0.171 & 0.185 & 0.644 & 0 \\ 0.668 & 0.416 & 0.084 & 0 \\ 0.205 & 0.355 & 0.387 & 0.052 \end{bmatrix} \\ &= (0.290, 0.259, 0.484, 0.006). \end{aligned} \quad (31)$$

According to the division of 10 kV vacuum switch cabinet comments collection, the maximum indicator 0.484 shows that the whole working status of 10 kV vacuum circuit breaker is in the general stage. It is indicated that the vacuum circuit breaker has been working for a long time; its elements are in a certain degree of damage; the probability of failure of the occasional vacuum breaker is relatively large; it needs timely checking and repairing. Actual operation records show that the vacuum circuit breaker during this time often indicates device performance's degradation, failure rate rising than before. Although the test data shows no serious abnormal phenomenon, the work performance is not stable. Therefore, it is necessary to maintaining and repairing for the power switch cabinet.

5. Conclusion

This paper proposes a method for evaluating the running states of switch cabinet based on fuzzy comprehensive evaluation algorithm. Using the analytic hierarchy method to determine weight judgment matrixes, based on the fuzzy statistics method to determine the membership functions and to generate the fuzzy relationship matrix, vacuum switchgear running condition assessment model is established via the algorithm. Compared to the algorithms mentioned in the literatures, the algorithm uses a hierarchical fuzzy theory, online operation data, comprehensive application of distribution cabinet test data, historical maintenance records, switch cabinet environment, and some other information. Since the amount of information involved is hierarchical, rich, and more comprehensive, the running state of each subproject and the whole switch cabinet can be effectively reflected and judged. Especially combining equipment information and historical maintenance records with the testing can directly reflect the results of the assessment of the credibility. The feasibility and effectiveness of the algorithm are verified by a practical example. The model implements the evaluation for electrical properties and running states of the cable outlet chamber and busbar chamber, vacuum circuit breaker, and mechanical properties of the cable insulation, obtaining the whole evaluation of running conditions of the switchgear. It will provide strong basis for vacuum switchgear's maintenance and overhaul.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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