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HIERARCHY EVALUATION METHOD FOR POWER TRANSFORMER CONDITION BASED ON FUZZY AND GREY CLUSTERING ANALYSIS

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Abstract. *In order to solve the problem that fixed weight (FW) cannot evaluate the transformer condition accurately and transformer condition evaluation factors have fuzzy and grey characteristics, a condition evaluation method for transformer based on fuzzy and grey clustering analysis is proposed. The method is applied to evaluate transformer condition layer by layer. Firstly, the key indicator of transformer is picked up to establish a key indicator system. Then according to grey clustering analysis (GCA) method, the grey clustering coefficient (GCC) matrix and fault layer evaluation results are obtained. Finally, the variable weight (VW) is obtained by combining variable weight synthesis mode, and then the transformer condition is evaluated by fuzzy evaluation method. The transformer test report data is carried out as case analysis and the result shows that the method we proposed can assess the transformer condition objectively and accurately.*
Keywords: Transformer, Fuzzy, Grey clustering analysis, Confidence, Variable weight

1. **Introduction.** Condition evaluation of electric power equipment is the key link in the process of condition maintenance. Power transformer as one of the most important power equipment, its condition evaluation result directly affects the implementation of maintenance work. Therefore, the transformer condition evaluation method has become a hot research topic [1].

At present, the intelligent method is used to evaluate the transformer condition at home and abroad. For example, neural network is used to evaluate transformer condition [2,3]. First, we input transformer information, and then through training this information output the transformer condition. [4-6] proposed the grey hierarchy evaluation method. This method adopts correlation analysis to get the correlation degree between different levels, so as to assess the condition. [7-9] presented the fuzzy comprehensive evaluation method which aimed at the fuzzy characteristic of transformer. And the method utilizes the fuzzy mathematics knowledge to get the membership vector, and the condition is obtained by fuzzy composite operation. Evidence theory is applied to the transformer condition assessment in [10,11]. There are some studies through the support vector machine [12,13], matter-element theory [14] and other methods to assess the condition of the transformer.

For above researches, the weight obtained by above methods is fixed weight (FW). And these authors do not consider the problem that when the transformer is abnormal, smaller weight may result in failure to accurately reflect the transformer condition. A determinate condition grade boundary is given in [5,9,11], but in the actual situation, the boundary is fuzzy, and this determinate boundary is not consistent with the actual situation. Transformer evaluation factor has the characteristics of grey and fuzziness, but [4,7,10,14] only consider the unilateral factor.

For above problems, we proposed the fuzzy and grey clustering analysis method for transformer condition evaluation. Firstly, association rules (AR) is introduced to calculate the FW for each key indicator (KI), and the GCA is used to get the fault layer condition, that is single condition. Then the variable weight (VW) coefficient is obtained by the variable weight synthesis mode, and the transformer condition is evaluated by the fuzzy evaluation method. An example analysis result shows that the evaluation method is valid and practical.

This paper is organized as follows. Section 2 introduces the single condition evaluation of transformer. The comprehensive condition evaluation method of transformer is described in Section 3. Case analysis is discussed in Section 4 and we summarize our paper in Section 5.

2. **Single Condition Evaluation of Transformer.** When faced with complex evaluation problem, the complex problem can be decomposed into several sub problems, which can simplify the complex problem and improve the accuracy of the evaluation results. The single condition evaluation of transformer is the fault layer evaluation by using GCA method. GCA method not only can avoid the clear division of state grade boundary, but also considers the grey characteristics of transformer.

2.1. **Establishment of key indicator system.** In order to accurately and comprehensively evaluate the transformer condition, it is necessary to select the indicators which can well reflect the condition of transformer. According to the actual operation of the transformer and data, the fault type of the transformer is divided into 8 categories. When the transformer is faulty, it often leads to multiple indicators state changes, so the fault types and key indicators have strong correlation. According to that the national Power Grid Corp issued the "Guide for condition evaluation of oil-immersed power transformer" [15] and the actual situation, the corresponding relationship between the failure type and the index is established. Finally, the key indicator system of the transformer is obtained as shown in Figure 1.

The key index system is divided into two layers. The first layer is fault layer, which is divided into 8 types of faults (that is 8 single condition), i.e., $FX = \{FX_1, FX_2, \ldots, FX_8\}$. The second layer is KI layer, i.e., "Moistened insulation" $FX_1 = \{FX_{1,1}, FX_{1,2}, \ldots, FX_{1,8}\}$.

2.2. **Condition grade classification and indicator unification.** In this paper, according to the actual operation situation, the transformer condition is divided into five grades, as shown in Table 1.

In order to facilitate the comparison and calculation of the KIs, the original data will be processed, and controlled between 0∼100; the unified formula is:

$$x_{i,j} = \frac{x_z - x_{ij0}}{x_z - x_c} \times 100 \tag{1}$$

where x_z and x_c denote the warning value and initial value of transformer KI. x_{ij0} represents the measured value. When the value of $x_{i,j}$ is greater than 100, then $x_{i,j} = 100$; when the value of $x_{i,j}$ is less than 0, then $x_{i,j} = 0$.

2.3. **Calculation of fixed weight.** When calculating the weight, the expert's subjective opinion is one of the reasons that lead to the inaccurate calculation of the weight. Therefore, this paper introduces the confidence of the AR to calculate the FW which uses the objective facts to reflect the weight of KIs.

AR is used to find all subsets of items or attributes, which appear frequently in the same event [16]. According to the definition of AR, suppose $R = \{\alpha_1, \alpha_2, \ldots, \alpha_s\}$ is a

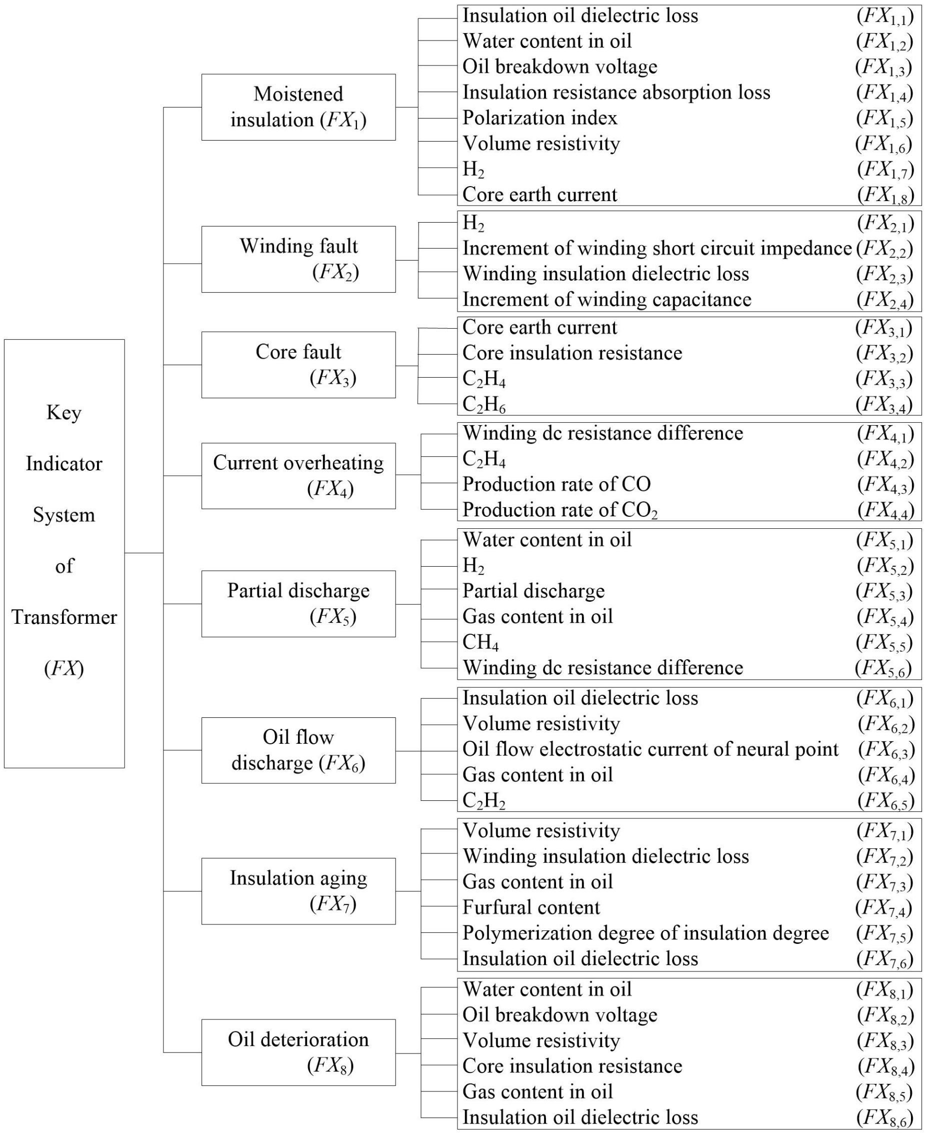

FIGURE 1. Key indicator system of transformer

TABLE 1. Condition grade classification of transformer

Condition grade	Transformer condition description.
Good	All monitoring data are close to the initial value.
Normal	Monitoring data are far from the attention value.
Attention	Part monitoring data are close to the attention value.
Abnormal	Part monitoring data are close to the warning value.
Fault	Monitoring data exceed the prescribed warning value.

finite item set which is composed by S items. Given the transaction database (TDB) $M = \{\beta_1, \beta_2, \ldots, \beta_N\}$, where $\beta_i = \{\alpha_1, \alpha_2, \ldots, \alpha_t\} \subset R$, known as the t-item set. AR reflects the dependence or correlation between the different items, like $X \to Y[support, confidence]$, where $X \subseteq M$, $Y \subseteq M$ and $X \cap Y \neq \emptyset$.

Support and confidence are two important concepts in AR. Support degree is the probability that transaction X and Y appear simultaneously in the TDB, that is: $S(X \to Y) = P(X \cup Y)$. Confidence is the probability of both X and Y contained in TDB, namely, $C(X \to Y) = P(X, Y)|P(X) = P(X \cup Y)/P(X)$. The greater value of C indicates the higher relationship between transaction X and Y.

It is known that KIs and faults have strong correlation, which meets the definition of confidence. Therefore, we use the confidence to calculate the FW; the steps are as follows.

1) Determine the transaction database $M = \{\text{transformer appears any fault}\}$.

2) Determine the item set $X_{i,j} = \{j\text{-th key indicator abnormal in } i\text{-th fault}\}$.

3) Determine the item set $Y_i = \{i\text{-th fault occurs}\} = M_i$.

4) Calculate confidence C: $C(X_{i,j} \to Y_i) = \frac{P(X \cup Y)}{P(X)} = \frac{\sigma(X_{i,j} \cup Y_i)}{\sigma(X_{i,j})} \times 100\%$, where, $\sigma(A)$ denotes the number of transaction which contains A in M.

5) Determine the FW: $\omega_{i,j}^0 = C_{i,j} / \sum_{k=1}^{n} C_{i,k}$, where, $C_{i,j}$ represents the confidence of the j-th KI in the i-th fault, and n is the number of the i-th fault.

Each type fault of transformer is equally important to the transformer condition, so the FW of single condition is $\omega_i^0 = 1/n$, in this paper $n = 8$, that is $\omega_i^0 = 0.125$.

2.4. **Single condition evaluation.** The key of GCA evaluation model is to establish an effective whitening function (WF). The evaluation model based on triangle whiten function (TWF) is suitable for solving the clustering problem of less information [17]. Each grade boundary point of transformer is not clear, but easier to determine the condition of transformer mostly belongs to which grey. Therefore, this paper selects the center point TWF (CP-TWF), and the TWF of the first grey class and final grey class is changed to the WF of lower measure and upper measure respectively. The WF of each grey class is fault f_j^1, abnormal f_j^2, attention f_j^3, normal f_j^4, good f_j^5, the specific form is as follows:

$$f_j^1 = \begin{cases} 0, & x \notin [0, 20] \\ 1, & x \in [0, 10] \\ \frac{20-x}{10}, & x \in [10, 20] \end{cases}$$

$$f_j^2 = \begin{cases} 0, & x \notin [15, 45] \\ \frac{x-15}{15}, & x \in [15, 30] \\ \frac{45-x}{15}, & x \in [30, 45] \end{cases}$$

$$f_j^3 = \begin{cases} 0, & x \notin [35, 65] \\ \frac{x-35}{15}, & x \in [35, 50] \\ \frac{65-x}{15}, & x \in [50, 65] \end{cases}$$

$$f_j^4 = \begin{cases} 0, & x \notin [55, 85] \\ \frac{x-55}{15}, & x \in [55, 70] \\ \frac{85-x}{15}, & x \in [70, 85] \end{cases}$$

$$f_j^5 = \begin{cases} 0, & x \notin [80, 100] \\ \frac{x-80}{10}, & x \in [80, 90] \\ 1, & x \in [90, 100] \end{cases}$$

The grey clustering coefficient (GCC) of each fault is obtained by using the GCA formula

$$\delta_i^k = \sum_{j=1}^{m} f_j^k(x_{i,j}) \omega_{i,j}^0 \tag{2}$$

Among them δ_i^k is GCC, $f_j^k(\,)$ denotes CP-TWF, and $\omega_{i,j}^0$ is FW. The single condition is determined by the maximum principle method.

3. **Comprehensive Condition Evaluation of Transformer.** In the comprehensive condition evaluation of transformer stage, if a single condition is abnormal, and its weight coefficient is not great, it will lead to inaccurate evaluation result and cannot accurately reflect the actual operating condition. Therefore, this paper uses the variable weight theory and fuzzy evaluation method to assess the transformer condition which can avoid the occurrence of such problems.

3.1. **Determination of variable weight.** The core idea of the VW is that the FW changes with the change of state. The VW formula that introduced into the balance function is as follows:

$$\omega_i(x_1, \ldots, x_m) = \omega_i^0 x_i^{(\alpha-1)} \Big/ \sum_{k=1}^{m} \omega_k^0 x_i^{(\alpha-1)} \tag{3}$$

where, ω_i and ω_i^0 are the VW and FW of the i-th fault, m denotes the number of fault, x_i is the score of i-th fault, and $x_i = \omega_{i,j}^0 x_{ij}$, α denotes the balance factor. $\alpha > 0.5$ indicates that the balance consideration of fault is not so important. When the serious flaw of fault is ruled out, then $\alpha < 0.5$. $\alpha = 1$ means equaling FW mode. In this paper $\alpha = 0$.

3.2. **Comprehensive condition evaluation.** The comprehensive condition of transformer is obtained by using fuzzy evaluation method, the formula is $B = J \circ \omega$, where $\circ$ represents the fuzzy operator, the weighted mean model is used in this paper. J is the matrix of GCC, ω is VW. Finally, the maximum principle method is used to determine the transformer overall condition.

4. Case Analysis.

4.1. **Application of condition evaluation method.** Taking a transformer in a certain area as an example, the measured values x_{ij0}, warning values x_z and initial values x_c of KIs are shown in Table 2.

In Figure 1, the "Winding fault" FX_2 is taken as an example to calculate the FW. We collect the data of KI which are measured in Table 2. The total TDB contains 880

Table 2. Test data of key indicator

Key indicator	Measured values x_{ij0}	Warning values x_z	Initial values x_c
Oil breakdown voltage/kV	56.7	27	58
Water content in oil/(mg/L)	4.5	32.5	3.5
H_2/(uL/L)	160	195	7.0
Increment of winding capacitance/%	5.0	6.5	1
Furfural content/(mg/L)	0.008	0.26	0.0
C_2H_6/(uL/L)	19.7	84.5	2.5
C_2H_4/(uL/L)	16.3	60	4.6
Gas content in oil/%	1.6	4	1.0
Increment of winding short circuit impedance/%	3.2	4	1.0
Volume resistivity/($10^9\Omega \cdot$ m)	48	2.3	60
Winding insulation dielectric loss/(tg·δ)%	0.79	1.04	0.17
Winding dc resistance difference/%	3.7	5.2	1
C_2H_2/(uL/L)	0	6.5	0.0
Insulation oil dielectric loss/(tg·δ)%	1.46	5.2	0.55
CH_4/(uL/L)	27.3	130	8.5
Insulation resistance absorption loss/%	1.75	1	2
Polarization index	2.16	1.2	2.4
Core earth current/A	0.06	0.13	0.01
Core insulation resistance/MΩ	800	77	1000
Production rate of CO/(%/month)	20	130	0
Production rate of CO_2/(%/month)	51	260	0
Partial discharge/pC	67	650	30
Polymerization degree of insulation paper	850	192	1000
Oil flow electrostatic current of neural point/uA	0.08	1.3	0.02

sets of data, including 116 sets of winding fault. In the 116 sets, the exceeding standard times of $FX_{2,1}$, $FX_{2,2}$, $FX_{2,3}$ and $FX_{2,4}$ are 102, 112, 108 and 110. In the 880 sets of TDB, the exceeding standard times of four KIs are 396, 115, 237 and 112. That is $\sigma(FX_{2,1}) = 396$, $\sigma(FX_{2,2}) = 115$, $\sigma(FX_{2,3}) = 237$, $\sigma(FX_{2,4}) = 112$, $\sigma(FX_{2,1} \cup FX_2) = 102$, $\sigma(FX_{2,2} \cup FX_2) = 112$, $\sigma(FX_{2,3} \cup FX_2) = 108$, $\sigma(FX_{2,4} \cup FX_2) = 110$. According to Step 4 the confidence of H_2 is calculated, $C_{2,1} = \frac{\sigma(FX_{2,1} \cup FX_2)}{\sigma(FX_{2,1})} \times 100\% = 25.76\%$, similarly $C_{2,2} = 97.39\%$, $C_{2,3} = 45.57\%$, $C_{2,4} = 98.21\%$. According to Step 5 the FW is computed, $\omega^0_{2,1} = 0.0965$, $\omega^0_{2,2} = 0.3649$, $\omega^0_{2,3} = 0.1707$, $\omega^0_{2,4} = 0.3679$. In the same way, the FW of each KI is obtained and the matrix A is shown as the following:

$$A = \begin{bmatrix} 0.0654 & 0.0937 & 0.1358 & 0.2632 & 0.2513 & 0.0543 & 0.0601 & 0.0762 \\ 0.0965 & 0.3649 & 0.1707 & 0.3679 & - & - & - & - \\ 0.3857 & 0.1574 & 0.3018 & 0.1533 & - & - & - & - \\ 0.1426 & 0.1475 & 0.3513 & 0.3586 & - & - & - & - \\ 0.1402 & 0.0857 & 0.2004 & 0.0859 & 0.3756 & 0.1122 & - & - \\ 0.1216 & 0.1257 & 0.4413 & 0.1354 & 0.1760 & - & - & - \\ 0.0917 & 0.1508 & 0.0923 & 0.2904 & 0.2980 & 0.0768 & - & - \\ 0.1682 & 0.2514 & 0.1401 & 0.1805 & 0.1293 & 0.1305 & - & - \end{bmatrix}$$

where, A_{ij} represents the FW of the j-th KI in the i-th fault.

Similarly, the "Winding fault" FX_2 is taken as an example to calculate the GCC. First, according to Equation (1), $x_{2,1} = 18.53$, $x_{2,2} = 26.67$, $x_{2,3} = 28.74$, $x_{2,4} = 27.27$. Then, according to Formula (2) calculate the GCC. $\delta^1_2 = \sum_{j=1}^{4} f^1_j(x_{2,j})\omega^0_{2,j} = f^1_1(x_{2,1})\omega^0_{2,1} + f^1_2(x_{2,2})\omega^0_{2,2} + f^1_3(x_{2,3})\omega^0_{2,3} + f^1_4(x_{2,4})\omega^0_{2,4} = f^1_1(18.53)*0.0965 + f^1_2(26.67)*0.3649 + f^1_3(28.74)*0.1707 + f^1_4(27.27)*0.3649 = 0.0142$. In the same way, $\delta^2_2 = 0.7639$, $\delta^3_2 = 0$, $\delta^4_2 = 0$, $\delta^5_2 = 0$. Then, according to maximum principle method, $\max\limits_{1 \le m \le 5} = \{\delta^k_2\} = 0.7693 = \delta^2_2$, "Winding fault" condition evaluation is second grey, namely "Abnormal". In the same way, the GCC of each KI is obtained and the matrix J is shown as the following:

$$J = \begin{bmatrix} 0.0088 & 0.0141 & 0.0339 & 0.3171 & 0.2323 \\ 0.0142 & 0.7639 & 0 & 0 & 0 \\ 0 & 0 & 0.1723 & 0.3059 & 0.0083 \\ 0 & 0.0878 & 0.0067 & 0.1713 & 0.1797 \\ 0.0126 & 0.0893 & 0.0053 & 0.0286 & 0.5096 \\ 0 & 0 & 0 & 0.1308 & 0.6225 \\ 0 & 0.1381 & 0 & 0.1603 & 0.3366 \\ 0 & 0 & 0 & 0.2173 & 0.4252 \end{bmatrix}$$

The clustering results are shown in Table 3.

According to Equation (3), the VW vector is $\omega = \{0.1029, 0.2995, 0.1110, 0.1020, 0.1033, 0.0876, 0.1021, 0.0916\}$. The transformer comprehensive condition is obtained by fuzzy

Table 3. GCC and clustering results of single condition

Single condition	Fault	Abnormal	Attention	Normal	Good	Clustering results
Moistened insulation	0.0088	0.0141	0.0339	0.3171	0.2323	Normal
Winding fault	0.142	0.7639	0	0	0	Abnormal
Core fault	0	0	0.1723	0.3059	0.0083	Normal
Current overheating	0	0.0878	0.0067	0.1713	0.1797	Good
Partial discharge	0.0126	0.0893	0.0053	0.0286	0.5096	Good
Oil flow discharge	0	0	0	0.1308	0.6225	Good
Insulation aging	0	0.1381	0	0.1603	0.3366	Good
Oil deterioration	0	0	0	0.2173	0.4252	Good

Table 4. Comparison of FW and VW fuzzy comprehensive evaluation results

Weight mode	Fault	Abnormal	Attention	Normal	Good	Results
FW	0.0045	0.1367	0.0273	0.1644	0.2893	Good
VW	0.0065	0.3384	0.0238	0.1347	0.2236	Abnormal

evaluation method, and the comparison of fuzzy comprehensive evaluation results of FW and VW is shown in Table 4.

It can be seen from Table 4, there are significant differences between FW and VW evaluation results, and their results are "Good" and "Abnormal" respectively. However, the clustering results in Table 3 show that the "Winding fault" is abnormal. When power-cut detection, it was discovered that the short circuit has occurred. This leads to the winding fault. Therefore, the transformer condition is "Abnormal". This shows that the VW fuzzy evaluation result is consistent with the actual situation. It is proved that the evaluation method proposed in this paper can accurately and objectively evaluate the transformer condition.

4.2. **Discussion.** It can be seen from Table 3, the method proposed in this paper can accurately assess the transformer single condition. This is because we use the confidence to get the weight, and then combine with the GCA to evaluate the transformer single condition. The method avoids the problems of over-reliance on expert opinion or subjective experience and the difficulty of condition grade boundary division. The method not only gives full play to the advantage that confidence can reflect the FW of each single condition based on objective facts, but also makes full use of the advantage that GCA can get each single condition, so as to evaluate the transformer single condition accurately and objectively. In the transformer comprehensive evaluation stage, it can be known that the VW can accurately reflect the condition of transformer through the comparison results of fixed weight and variable weight evaluation. It is because the VW can automatically adjust the weight according to the evaluation results of single condition. From the variable weight vector, it can be seen that the single condition weight of non-normal is lager, which highlights the advantages of VW. In summary, the condition method based on fuzzy grey clustering and variable weight can accurately assess the transformer comprehensive condition. And it shows that the method has the theoretical and practical application value.

5. **Conclusion.** 1) The confidence of association rules is used to calculate the fixed weight of the key indicator. It gives full play to the advantage of using the objective facts to reflect the weight, and avoids over-reliance on subjective experience.

2) The application of VW is helpful to solve the problem that it may not reflect the true condition of the transformer under the FW.

3) The combination of fuzzy grey clustering not only takes account of the fuzziness of the transformer system, but also considers the characteristics of its grey. The evaluation method of layer by layer makes the evaluation be logicality, accuracy and practicality.

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