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Insulation fault diagnosis based on group grey relational grade analysis method for power transformers

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Abstract: Utilising dissolved gases analysis, a new insulation fault diagnosis method for power transformers is proposed. This method is based on the group grey relational grade analysis method. First, according to the fault type and grey reference sequence structure, some typical fault samples are divided into several sets of grey reference sequences. These sets are structured as one grey reference sequence group. Secondly, according to a new calculation method of the grey relational coefficient, the individual relational coefficient and grade are computed. Then according to the given calculation method for the group grey relation grade, the group grey relational grade is computed and the group grey relational grade matrix is structured. Finally, according to the relational sequence, the insulation fault is identified for power transformers. The results of a large quantity of instant analyses show that the proposed method has higher diagnosis accuracy and reliability than the three-ratio method and the traditional grey relational method. It has good classified diagnosis ability and reliability.

Key words: dissolved gases analysis; group grey relational grade; fault diagnosis

As one of the most important and expensive equipment items in a power system, the large-scale power transformers play a key role in reliable operation of the whole power system. Dissolved gases analysis is an important method to decide the internal state of a power transformer. The conventional fault diagnosis methods such as the three-ratio method, cannot better meet the requirements of the power industry[1,2]. Power transformer in operation can be considered as a complicated grey system, and its internal insulation fault can be diagnosed with the help of grey system theory[3]. In this paper, some typical fault samples of power transformers are chosen as reference sequences and used to structure several sets of grey reference sequences. These reference sequence sets constitute one grey reference sequence group, and the group relational grade matrix is constructed to reflect the correlation of the reference and compared sequences. This increases the reliability and accuracy of the grey relational analysis. Finally, based on the group grey relational grade analysis method, the insulation fault is diagnosed for power transformers. Utilising a large quantity of instant analyses, it is shown that the proposed method has good classified diagnosis ability. It can better meet the practical requirements of the power industry.

1 Group Grey Relational Grade and Matrix

The fault diagnosis principles based on the traditional grey relational analysis are as follows:

1) The formation of the reference sequence and the compared sequence Two sequences are constructed. One is the reference sequence, and the other is the compared sequence. The reference sequence is marked as $y_1, y_2, \ldots, y_m$; the compared sequence is marked as $x_1, x_2, \ldots, x_n$. Let

$$x_i = \{x_i(1), x_i(2), \ldots, x_i(N)\} \qquad i = 1, 2, \ldots, n \tag{1}$$

$$y_j = \{y_j(1), y_j(2), \ldots, y_j(N)\} \qquad j = 1, 2, \ldots, m \tag{2}$$

where $x_i(k)$ and $y_j(k)$ are accordingly the k-th element of x_i and y_j.

2) The data generating process In the grey relational analysis, data preprocessing is first performed in order to normalize the raw data for analysis, which is also called the grey relational generating.

3) The calculation of the grey relational coefficient In traditional grey relational analysis, the grey relational coefficient between the reference sequence and compared sequence is

$$\xi_{ij}(k) = \frac{\min_i \min_k |y_j(k) - x_i(k)| + \rho \max_i \max_k |y_j(k) - x_i(k)|}{|y_j(k) - x_i(k)| + 0.5 \max_i \max_k |y_j(k) - x_i(k)|} \tag{3}$$

where $\xi_{ij}(k)$ is the grey relational coefficient between $x_i(k)$ and $y_j(k)$; $|y_j(k) - x_i(k)|$ is the absolute value be-

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tween $x_i(k)$ and $y_j(k)$, $\min_i \min_k |y_j(k) - x_i(k)|$ is the minimal distance of the two layers, $\max_i \max_k |y_j(k) - x_i(k)|$ is the maximum one; ρ is the recognition coefficient.

4) The calculation of the grey relational grade The calculation of the grey relational grade is usually expressed as

$$r_{ij} = \frac{1}{n} \sum_{j=1}^{n} \xi_{ij}(k) \tag{4}$$

5) Relational sequence Assume that a row of a relational grade matrix is marked as $\boldsymbol{r} = \{r_1, r_2, \dots, r_m\}$. When processing the system fault diagnosis, this sequence is arranged in descending order, that is, $r_s > r_h > r_p > \dots$; s, h and p are certain natural numbers in $\{1, 2, \dots, m\}$. Then, because the possibility of the similarity between the compared sequence and the reference sequence s is the biggest, it is believed that this compared sequence belongs to the reference sequence s.

The correlative theory of the grey relational analysis has been discussed in many papers[4-7]. In this paper, the proposed method is the improvement of the traditional grey relational analysis.

Assume that there are $m \times b$ reference sequences listed as

$$\begin{bmatrix} y_1^1 & y_1^2 & y_1^3 & \dots & y_1^b \\ y_2^1 & y_2^2, & y_2^3 & \dots & y_2^b \\ \vdots & \vdots & \vdots & & \vdots \\ y_m^1 & y_m^2 & y_m^3 & \dots & y_m^b \end{bmatrix} \tag{5}$$

where $\{y_1^w, y_2^w, \dots, y_m^w\}$ $(w = 1, 2, \dots, b)$ is the w-th set of reference sequences, b denotes the number of reference sequence sets, m denotes the number of reference sequences in the w-th set of reference sequences. The formation of the w-th set of reference sequences is $y_i^w = \{y_i^w(1), y_i^w(2), \dots, y_i^w(N)\}(i = 1, 2, \dots, m)$ where $y_i^w(k)$ is the k-th element of y_i^w, N denotes the element number of reference sequence and $\{y_j^1, y_j^2, \dots, y_j^b\}(j = 1, 2, \dots, m)$ belongs to the same cluster of reference sequences marked as y_j. Each element of y_j is the same kind of fault reference sequence. y_j is also named as the j-th cluster of reference sequences.

The definition of compared sequences is

$$x_i = \{x_i(1), x_i(2), \dots, x_i(N)\} \qquad i = 1, 2, \dots, n \tag{6}$$

where $x_i(k)$ is the k-th element of x_i and n is the number of compared sequences.

Based on the above assumption, a relational grade solid is defined as

$$\boldsymbol{V}_r^w = \begin{bmatrix} r_{11}^w & r_{12}^w & \dots & r_{1m}^w \\ r_{21}^w & r_{22}^w & \dots & r_{2m}^w \\ \vdots & \vdots & & \vdots \\ r_{n1}^w & r_{n2}^w & \dots & r_{nm}^w \end{bmatrix} \qquad w = 1, 2, \dots, b \tag{7}$$

where r_{ij}^w is an individual grey relational grade. It indicates the individual relational extent between the individual reference sequence y_j^w and the compared sequence x_i in the w-th set of reference sequences. It can be obtained by

$$r_{ij}^w = \frac{1}{N} \sum_{k=1}^{N} \xi_{ij}^w(k) \tag{8}$$

where $\xi_{ij}^w(k)$ is the individual grey relational coefficient. The new grey relational coefficient calculation method is expressed as

$$\xi_{ij}^w(k) = \frac{\min_w \min_j \min_i \min_k |y_j^w(k) - x_i(k)| + 0.5 \max_w \max_j \max_i \max_k |y_j^w(k) - x_i(k)|}{|y_j^w(k) - x_i(k)| + 0.5 \max_w \max_j \max_i \max_k |y_j^w(k) - x_i(k)|} \tag{9}$$

In the w-th set of reference sequences, $\xi_{ij}^w(k)$ is the grey relational coefficient between $x_i(k)$ and $y_j^w(k)$, $|y_j^w(k) - x_i(k)|$ is the absolute difference between $x_i(k)$ and $y_j^w(k)$, $\min_w \min_j \min_i \min_k |y_j^w(k) - x_i(k)|$ is the minimal distance of the four layers and $\max_w \max_j \max_i \max_k |y_j^w(k) - x_i(k)|$ is the maximum distance of the four layers. Thus, the group grey relational grade matrix is defined as

$$\boldsymbol{R}_{\text{group}} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \dots & \tilde{r}_{1m} \\ \tilde{r}_{21} & \tilde{r}_{22} & \dots & \tilde{r}_{2m} \\ \vdots & \vdots & & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \dots & \tilde{r}_{nm} \end{bmatrix} \tag{10}$$

where $\tilde{r}_{ij}$ is called the group grey relational grade and is defined as

$$\tilde{r}_{ij} = \frac{1}{b}\left[\sum_{w=1}^{b}(r_{ij}^{w})^{p}\right]^{\frac{1}{p}} \qquad p = 1, 2, \ldots, \infty \tag{11}$$

It means the whole relational extent between the i-th compared sequence and the j-th cluster of reference sequences. While the group relational grade matrix $\boldsymbol{R}_{\text{group}}$ represents the collectivity relational relationship between the compared sequences and reference sequence group.

Compared with the traditional method, the proposed method can increase the accuracy and reliability of the grey relational analysis and reduce the requirements on data accuracy of the reference signal.

2 Basic Principle of Fault Diagnosis

The basic principle of fault diagnosis using the proposed method for power transformers can be divided into the following steps[7,8]:

2.1 Fuzzy method of data preprocessing for power transformers

The gas content of H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and G_{sum} (the sum of the gas content of CH_4, C_2H_6, C_2H_4 and C_2H_2) are chosen for analysis[9,10]. In this paper, the data are expressed in the range between 0 and 1. The fuzzy method is expressed as[2]

$$\left.\begin{aligned}
&P(1,j) = 1 - \exp\left(-4\times\frac{G_{\text{H}_2}(j)}{300}\right)^2 \qquad j = 1, 2, \ldots, M\\
&P(i,j) = 0.05 + \frac{0.95[G(i,j) - G_{\min}(j)]}{G_{\max}(j) - G_{\min}(j)} \qquad i = 2,3,4,5; j = 1, 2, \ldots, M\\
&G_{\text{sum}} = G(2,j) + G(3,j) + G(4,j) + G(5,j)\\
&P(6,j) = 1 - \exp\left(-4\times\frac{G_{\text{sum}}}{700}\right)^2 \qquad j = 1, 2, \ldots, M
\end{aligned}\right\} \tag{12}$$

where $P(i,j)$ $(i = 1, 2, \ldots, 6; j = 1, 2, \ldots, M)$ denotes the fuzzy value of raw gas content of H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and G_{sum}, j denotes the j-th sample and M is the number of samples. In the j-th sample, $G_{\text{H}_2}(j)$ denotes the raw content of H_2. $G(i,j)$ $(i = 2, 3, 4, 5)$ accordingly denotes the raw gas content of CH_4, C_2H_6, C_2H_4 and C_2H_2. $G_{\min}(j)$ and $G_{\max}(j)$ denote the minimal and maximal raw gas content of CH_4, C_2H_6, C_2H_4 and C_2H_2.

2.2 Construction of reference sequence and compared sequence

In this paper, 36 typical historical samples of power transformers are chosen to structure the reference sequences. These samples include the normal state, the low temperature overheating fault, the middle temperature overheating fault, the high temperature overheating fault, the low energy discharge fault and the high energy discharge fault sample. Each sample includes six elements which are the raw gas content of H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and G_{sum}. After these samples are preprocessed with Eq. (12), six sets of reference sequences are structured for this study. These six sets of reference sequences constitute one grey reference sequence group and each set of reference sequences includes six kinds of reference sequence expressed as

$$\begin{bmatrix} y_1^1 & y_1^2 & y_1^3 & \cdots & y_1^6 \\ y_2^1 & y_2^2 & y_2^3 & \cdots & y_2^6 \\ \vdots & \vdots & \vdots & & \vdots \\ y_6^1 & y_6^2 & y_6^3 & \cdots & y_6^6 \end{bmatrix} \tag{13}$$

where $\{y_1^w, y_2^w, \ldots, y_6^w\}$ $(w = 1, 2, \ldots, 6)$ is the w-th set of reference sequences. In the w-th set of reference sequences, y_1^w denotes the normal state reference sequence, y_2^w denotes the low temperature overheating fault reference sequence, y_3^w denotes the middle temperature overheating fault reference sequence, y_4^w denotes the high temperature overheating fault reference sequence, y_5^w denotes the low energy discharge fault reference sequence and y_6^w denotes the high energy discharge fault reference sequence.

The w-th set of reference sequences is marked as

$$y_i^w = \{y_i^w(1), y_i^w(2), \ldots, y_i^w(6)\} \qquad i = 1, 2, \ldots, 6$$

where $y_i(k)$ is the k-th element of y_i^w. Different sets are not related.

The compared sequence is marked as

$$x_j = \{x_j(1), x_j(2), \ldots, x_j(6)\} \qquad j = 1, 2, \ldots, n$$

where n is the number of awaiting-checked samples, $x_j(k)$ is the k-th element of x_j.

2.3 Computing individual grey relational grade and relational coefficient

The individual relational grade is computed by Eq. (8) and the individual relational coefficient is computed by Eq. (9).

2.4 Computing group grey relational grade and forming group grey relational grade matrix

The calculation of the group grey relational grade usually uses Eq. (11). In this paper, choosing $p=1$ for a diagnosis case study, the calculation method for group grey relational grade is

$$\tilde{r}_{ij} = \frac{1}{b}\sum_{w=1}^{b} r_{ij}^{w} \tag{14}$$

Thus, a group grey relational grade matrix is defined according to Eq. (10).

2.5 Identifying the fault according to relational sequence

A row of a group relational grade matrix marked as $\tilde{\boldsymbol{r}} = \{\tilde{r}_1, \tilde{r}_2, \ldots, \tilde{r}_m\}$ is assumed. When processing system fault diagnosis, this sequence is arranged in descending order, that is, $\tilde{r}_s > \tilde{r}_h > \tilde{r}_p > \ldots$; s, h and p are certain natural numbers in $\{1, 2, \ldots, m\}$. Then, because the possibility of the similarity between the compared sequence and the reference sequence s is the biggest, it is believed that this compared sequence belongs to the reference sequence s.

3 Fault Case Test and Analysis

The following is the fault case test and analysis based on group grey relational analysis. First, six fault samples have been chosen as awaiting-identified fault samples. Each sample includes six elements which are the raw gas content of H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 and G_{sum}. After the six samples are preprocessed with Eq. (12), a set of compared sequences is formed. It is marked as

$$x_i = \{x_i(1), x_i(2), \ldots, x_i(6)\} \qquad i = 1, 2, \ldots, 6$$

where $x_i(k)$ is the k-th characteristic element of the fault sample x_i, x_1 is the compared sequence of the normal state sample, x_2 is the compared sequence of the low temperature overheating fault sample, x_3 is the compared sequence of the middle temperature overheating fault sample, x_4 is the compared sequence of the high temperature overheating fault sample, x_5 is the compared sequence of the low energy discharge fault sample and x_6 is the compared sequence of the high energy discharge fault sample.

According to the basic principle of fault identification based on the group grey rational grade analysis method for power transformers, the corresponding group grey relational matrix $\boldsymbol{R}_{group}$ is obtained. There are six elements in each row. In turn, from the first to the sixth elements it denotes the relational intensity between the testing sample and the normal state, the low temperature overheating fault, the middle temperature overheating fault, the high temperature overheating fault, the low energy discharge fault and the high energy discharge fault. The bigger the relational grade, the closer the relational extent. Its maximum denotes the fault type of the awaiting-identified fault sample. The result based on group grey relational analysis is expressed as

$$\boldsymbol{R}_{group} = \begin{bmatrix} 0.71748 & 0.63599 & 0.62822 & 0.61304 & 0.67934 & 0.51342 \\ 0.61308 & 0.74460 & 0.64550 & 0.59866 & 0.61232 & 0.50521 \\ 0.56746 & 0.74809 & 0.80475 & 0.75685 & 0.60155 & 0.56189 \\ 0.66702 & 0.65440 & 0.74905 & 0.81021 & 0.61443 & 0.67719 \\ 0.66778 & 0.72808 & 0.63745 & 0.65213 & 0.76713 & 0.62764 \\ 0.57135 & 0.61362 & 0.60766 & 0.67111 & 0.61801 & 0.79207 \end{bmatrix} \tag{15}$$

According to Eq. (15), the group relational analysis can effectively and accurately identify the six test samples. By means of the traditional grey relational analysis method, the diagnosis result with a set of reference sequences, whose diagnosis accuracy is the best in the six sets of reference sequences, is as follows:

$$\boldsymbol{R}_{group} = \begin{bmatrix} 0.66864 & 0.48653 & 0.60956 & 0.62676 & 0.58872 & 0.65922 \\ 0.75525 & 0.81580 & 0.67385 & 0.50466 & 0.37275 & 0.49234 \\ 0.56379 & 0.78120 & 0.85168 & 0.65321 & 0.39982 & 0.43961 \\ 0.69972 & 0.60830 & 0.75414 & 0.85313 & 0.55268 & 0.57905 \\ 0.67773 & 0.58678 & 0.63425 & 0.62483 & 0.55836 & 0.60071 \\ 0.51211 & 0.59264 & 0.58686 & 0.69489 & 0.64463 & 0.60594 \end{bmatrix} \tag{16}$$

According to Eq. (16), the fifth and sixth sample diagnosis results are errors. By means of the three-ratio diagnosis method, the first and second sample diagnosis results are errors. In contrast, the group relational analysis diagnosis result is the best.

In addition, 110 samples have been tested. The diagnosis results based on the group grey relational analysis, the traditional grey relational analysis with a set of reference sequences whose diagnosis accuracy is the best in the six sets of reference sequences and the three-ratio method are shown in Tab. 1.

Tab. 1 The diagnosis results of 110 samples %

Diagnosis method	Diagnosis accuracy
Three-ratio method	67. 27
Traditional grey relational analysis method with a set of reference sequences (the best diagnosis result)	80. 91
Group relational analysis	88. 18

According to diagnosis effectiveness and reliability, the group relational analysis is the best.

4 Conclusion

This paper presents a new insulation fault diagnosis method based on the group relational grade analysis method for power transformers. The new method improves the grey relational analysis and reduces the dependency on any single reference signal. Through the fault case test and analysis on 110 samples of power transformers, the diagnosis accuracy based on group relational analysis is 88. 18%. By means of the traditional grey relational analysis method, with a set of reference sequences, whose diagnosis accuracy is the best in the six sets of reference sequences, the diagnosis accuracy is 80. 91%. By means of the three-ratio method, the diagnosis accuracy is 67. 27%. By contrast and analysis, the proposed method gains good results and shows its viability. It can also be widely used in other fields of fault analysis and signal identification, and has sound prospects for practical application.

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基于群灰色关联度分析方法的电力变压器绝缘故障诊断

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摘要: 基于变压器油中溶解气体分析, 提出了一种基于群灰色关联度分析的变压器绝缘故障诊断新方法. 首先根据故障类型与灰色参考序列构造, 选择变压器典型故障样本构造多组参考序列, 这些参考序列组构成一个灰色参考序列群. 其次根据给出的新的关联系数计算方法, 计算个体关联系数和关联度. 然后根据给出的群灰色关联度计算方法, 计算群灰色关联度和构造群灰色关联度矩阵. 最后根据关联序识别变压器绝缘故障诊断. 通过大量变压器绝缘故障诊断实例分析, 所提方法诊断准确性与可靠性优于三比值法和传统的灰色关联分析方法, 具有较好的分类诊断能力和可靠性.

关键词: 溶解气体分析; 群灰色关联度; 故障诊断

中图分类号: TM41; TM855