Research on Fault Diagnosis Method of High Voltage Circuit Breaker Based on gray Relational Analysis and D-S Evidence Theory

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Abstract. In this paper, a high-voltage circuit breaker diagnosis method based on gray correlation analysis and DS evidence theory is proposed for the fault diagnosis of high-voltage circuit breakers. The fault diagnosis calculation results of a high voltage circuit breaks using this method are compared with those using only gray correlation analysis. The comparison result shows that the proposed method has higher accuracy and reliability, and can accurately determine the type of faults occurring in the high-voltage circuit breaker through the monitored characteristic parameters, avoiding more subjective judgments and improving the reliability of the results.

1. Introduction
As a key electrical equipment that is indispensable in the power system, the high-voltage circuit breaker plays a decisive role in the commissioning and resection of different lines when the power system operates normal and stable, and it’s also a key device capable of quickly and accurately removing faults in the event of a power system failure to ensure the stability of the power system[1,2]. Therefore, the good or bad state of the high-voltage circuit breaker will directly determine whether the entire power system can operate safely and stably, and the state of the high-voltage circuit breaker needs to be obtained through maintenance. With the continuous development of modern computer technology and automation application technology, the overhaul technology applied to the fault diagnosis of high-voltage circuit breakers has gradually matured, being capable of judging the type of fault or predicting the type of fault that may occur through monitoring the state of the high voltage circuit breaker when it is in operation and combing with various signals extracted from sensors. Therefore, the state of high voltage circuit breakers can be diagnosed. This type of maintenance diagnosis is also called state maintenance[3-5].

There are many related researches on the diagnosis methods of high voltage circuit breakers at home and abroad. The advanced big data processing technology is adopted, which establishes an auto regressive mathematical model, uses neural network mining technology to extract the characteristic value variables of the circuit breaker state, and adopts mathematical method of cluster analysis to comprehensively judge the data of different dimensions, so as to diagnose the the state of the circuit breaker[6]. The Bayesian theory, which is widely used in the field of circuit breaker diagnosis, is the basic structure, and a diagnostic method with more accurate prediction function is obtained by using vector-machine correlation method[7]. Based on the cuckoo search algorithm, the optimal solutions for the parameters of support vector machine are obtained[8]. The results are compared with those...
using the particle swarm algorithm and show more accuracy. The neural network algorithm is used to continuously train the sensors on the circuit breaker to detect eigenvalue signals, so as to obtain a more accurate basic model of fault diagnosis[9]. Then, various faults that may occur in the circuit breaker are sorted and classified. In the end, the various faults of the circuit breaker can be predicted and diagnosed, being prevented from happening. A series of functions are obtained by decomposing the vibration signals of circuit breakers with the mathematical method of modal decomposition, and the obtained energy entropy is inputted into the vector machine, and then various mechanical faults of the high-voltage circuit breaker can be accurately diagnosed[10].

In this paper, a high-voltage circuit breaker diagnosis method based on gray correlation analysis and DS evidence theory is proposed for the fault diagnosis of high-voltage circuit breakers. The collected data is firstly processed by gray relational analysis, and the processed results are used as the basic probability assignment of D-S evidence theory. Then the final diagnosis result is obtained by using the corresponding combination rules. The method can be used for reference for the operation and maintenance of power system.

2. Diagnostic method based on gray correlation analysis Ease of Use

In the multiple parameter high-voltage circuit breaker fault diagnosis, the gray correlation analysis method is mainly used, and this method is also called gray correlation multiple parameter fault diagnosis method. Firstly, there is a set of test samples in the system, which is used as a reference sequence, contains the detection value with m eigenvalues. Then, there is a set of comparison sequences, which can be used as typical samples of the system. The typical samples are a set of data which can reflect the states of circuit breakers based on previous operation experience. Typical samples also contain typical values of the corresponding m characteristic parameters in the test samples. The typical sample space is composed of m typical samples.

The expressions of test samples and typical sample spaces required for gray correlation analysis are shown in formulas (1) and (2).

\[
X_0 = \left[ X_0(1) X_0(2) \cdots X_0(n) \right]
\]

\[
X = \left[ \begin{array}{cccc}
X_1(1) & X_1(2) & \cdots & X_1(m) \\
X_2(1) & X_2(2) & \cdots & X_2(m) \\
\vdots & \vdots & \ddots & \vdots \\
X_n(1) & X_n(2) & \cdots & X_n(m)
\end{array} \right]
\]

Based on the test samples obtained from on-site monitoring and the typical sample space obtained from previous operational experience, the specific steps for fault detection and diagnosis using the gray correlation analysis are as follows.

(1) The obtained samples are standardized as shown in Formula (3).

\[
x(K) = (x(k) - \bar{x}) / \sigma
\]

(2) A reasonable resolution coefficient is selected and the correlation coefficient[11] is calculated according to formula (4).

\[
\rho_i(k) = \min_{i} \min_k \left[ \frac{|X_o(k) - X_i(k)| + \rho \max_{i} |X_o(k) - X_i(k)|}{|X_o(k) - X_i(k)| + \rho \max_{i} |X_o(k) - X_i(k)|} \right]
\]

Generally speaking, the smaller the resolution coefficient is, the stronger the resolution ability is. Generally, the value range of is between 0 and 1, and 0.5 is generally used in the calculation. Its value can be adjusted according to the actual situation.

(3) The gray correlation degree \( \gamma_i \) corresponding to various faults is obtained by artificially weighted gray relational degree analysis.
It is assumed that the importance of data at different times is different, and different weight coefficients \( a(k), k = 1, 2, \cdots, m \), can be assigned according to their degree. Then the weighted correlation degree obtained by the weighting method is expressed as formula (5).

\[
\gamma_i = \sum_{k=1}^{m} a(k) \epsilon_i(k)
\]  

(4) The gray correlation degrees calculated by the above method are sorted, and the correlation degree of the sample detected by the system and that of the typical sample is compared, and the calculated correlation degree is sorted from large to small, and then the fault type of high voltage circuit breaker can be determined.

Figure 1. The method flow chart of fault diagnosis which based on gray correlation analysis

The flowchart of the circuit breaker fault diagnosis method based on the gray correlation analysis is shown in Figure 1. This method is simpler to calculate, requires fewer test samples, and is well understood, but it also has greater subjectivity. The artificial weighting method is adopted in the weighted calculation of gray correlation degree, so its credibility needs to be improved. In view of this problem, in this paper, D-S evidence theory is combined with above methods to detect and diagnose various faults occurring in high voltage circuit breakers.

3. Diagnostic method based on gray relational analysis and D-S evidence theory

Considering the shortcomings of using only the gray correlation analysis, the DS evidence theory is introduced into the fault diagnosis of the circuit breaker. The flowchart of the fault diagnosis method based on both the gray correlation analysis and the DS evidence theory is shown in Figure 2. Firstly, the collected data samples and typical samples are analyzed by gray correlation method. The methods and steps are the same as the above-mentioned diagnostic method that only considers the gray correlation analysis. Then the gray correlation coefficient calculated by the test samples is used as the input value of the subsequent evidence theory method. And then based on the relevant combination rules of D-S evidence theory and according to the final scores of each fault states, the type of fault occurring in circuit breaker is diagnosed.
Figure 2. The flow chart of fault diagnosis method which based on gray correlation analysis and D-S evidence theory.

In the application process of the combination rules of d-s evidence theory, there are two basic rules of combination. And we can suppose $Bel_1$ and $Bel_2$ are two basic allocation functions on the consent recognition framework $\Omega$, which has two independent basic probability assignments on corresponding $2^\Omega$ are $m_1$ and $m_2$, and the focal elements are $A_1, A_2, \ldots, A_k$ and $B_1, B_2, \ldots, B_r$. Then $K_1$ can be expressed as follows.

$$K_1 = \sum_{A_i \cap B_j \neq \emptyset} m_i(A)m_2(B) < 1$$  \hspace{1cm} (6)

Then we can get the formula (7).

$$m(C) = \begin{cases} \sum_{A_i \cap B_j \neq \emptyset} m_i(A)m_2(B) & \text{if } K_1 \neq 1, \\ 1 - K_1 & \text{if } C = \Omega, C \neq \emptyset \\ 0 & \text{if } C \neq \emptyset \end{cases}$$  \hspace{1cm} (7)

In the formula, if $K_1 \neq 1$, then $m$ determines a basic probability assignment. If $K_1 = 1$, then $m_1$ and $m_2$ contradicts each other, and no basic probability combination is assigned. This evidence combination rule is called dempster combination rule. If there are $n$ pieces of evidence to be combined, the combination of the two evidences should be performed first by using the above rules. Then the obtained results are combined with other evidences in turn until they are combined with the $n$th evidence and the final combined result is obtained. In the combination process, the order of the combinations will not have any effect on the final result.

4. Examples of Fault Detection and Diagnosis

Some electrical characteristics are often used as key indicators for intelligent diagnosis of circuit breakers, such as various signals that can be monitored by corresponding sensors, like the coil current signals of circuit breakers during the entire process of opening and closing. According to the change of coil current at different time when the circuit breaker is switched on and off, it can be indirectly judged whether the operating mechanism of the circuit breaker is faulty. In the verification of this chapter, only the coil current signal at different time during the switching process of the circuit breaker is selected as the monitoring data for the fault diagnosis of the operating mechanism. The equivalent circuit diagram of the high voltage circuit breaker when it is switching on and off is shown in Figure 3.
Figure 3. Equivalent circuit diagram of the high voltage circuit breaker while switching on and off

Figure 4 shows the current signal curve when the typical high-voltage circuit breaker is closed. It can be clearly seen from the figure that there are five stages in the closing process of high-voltage circuit breaker.

Stage 1: $t_0 - t_1$ stage. The current in the coil increases gradually from 0 to $I_1$. Before the current reaches $I_1$, it is not enough to make the iron core move. After the current reaches $I_1$, the iron core starts to move. This phase reflects the coil condition when the circuit breaker is closed.

Stage 2: $t_1 - t_2$ stage. The iron core starts to move at time $t_1$. The action of the iron core generates a counter electromotive force to the circuit, and the current in the coil is reduced. Therefore, this stage reflects the situation of the iron core, and the failure of the iron core, such as tripping and sticking, can be judged by the current value.

Stage 3: $t_2 - t_3$ stage. At this stage, the action of the iron core has completely stopped, so the current continues to rise. After the moment of $t$, the current signal in the coil is basically stable.

Stage 4: $t_3 - t_4$ stage. In this stage, the current in the coil oscillates slightly near the steady-state value $I_3$.

Stage 5: $t_4 - t_5$ stage. This stage is the disconnection stage, and the current value decreases rapidly from $I_3$ to zero.

Figure 4. Coil Current Signal Curve of Typical High Voltage Circuit Breaker while closing

It can be seen from the above analysis that there are eight parameters $\left\{ t_0, t_1, t_2, I_1, t_3, t_4, t_5, I_3 \right\}$, that can be used to judge the current signal when the circuit breaker is closed. Then, three possible
situations of high-voltage circuit breaker are selected, namely, the iron core jamming, the operation mechanism failure and the normal state, and typical sample spaces are established to express these three cases. Typical sample spaces corresponding to eight parameters in these three cases are constructed based on field operation experience, as shown in Table 1.

| Characteristic Parameter | Typical Sample Space |
|-------------------------|----------------------|
|                         | $A_1$ | $A_2$ | $A_3$ |
| $i_1$                   | 1.61  | 1.62  | 1.62  |
| $i_2$                   | 1.11  | 1.13  | 1.17  |
| $i_3$                   | 2.23  | 2.21  | 2.21  |
| $t_1$                   | 30.10 | 24.21 | 24.50 |
| $t_2$                   | 43.50 | 37.57 | 37.80 |
| $t_3$                   | 49.10 | 43.25 | 43.50 |
| $t_4$                   | 52.40 | 50.02 | 46.70 |
| $t_5$                   | 56.10 | 54.09 | 50.30 |

Test samples are established by a set of monitoring data when a high voltage circuit breaker encountered faults during past operation, as shown in Table 2.

| Characteristic Parameter | $i_1$ | $i_2$ | $i_3$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Monitoring Data         | 1.56  | 1.16  | 2.25  | 30.15 | 43.46 | 49.13 | 52.49 | 56.02 |

According to the fault diagnosis method based on gray correlation analysis in chapter 2, the gray relational analysis is adopted for the monitoring data samples in Table 2 in the same interval of characteristic parameters. The resolution coefficient is 0.5, and the gray correlation coefficients of the monitoring data samples after gray correlation analysis are shown in Table 3.

| Characteristic Parameter | $A_1$ | $A_2$ | $A_3$ |
|-------------------------|-------|-------|-------|
| $i_1$                   | 0.9813| 0.8968| 0.8734|
| $i_2$                   | 0.9817| 0.9410| 0.9438|
| $i_3$                   | 0.9978| 0.9142| 0.8814|
| $t_1$                   | 0.9862| 0.3491| 0.4466|
| $t_2$                   | 0.9800| 0.4789| 0.7976|
| $t_3$                   | 1.0000| 0.5668| 0.8543|
| $t_4$                   | 0.9689| 0.4076| 0.7565|
| $t_5$                   | 0.9577| 0.3361| 0.6142|

Based on the typical sample space of the high voltage circuit breaker in three different states, the corresponding recognition framework is established. Then the gray correlation coefficient in Table 3 is used as the input value of D-S evidence theory, and meanwhile it is normalized. The calculation results of the basic probability of monitoring data samples are shown in Table 4.
TABLE 4. BASIC PROBABILITY ALLOCATION TABLE

| Characteristic Parameter | $m(A_1)$ | $m(A_2)$ | $m(A_3)$ |
|--------------------------|----------|----------|----------|
| $i_1$                    | 0.3566   | 0.3259   | 0.3174   |
| $i_2$                    | 0.3424   | 0.3282   | 0.3292   |
| $i_3$                    | 0.3571   | 0.3272   | 0.3155   |
| $t_1$                    | 0.5534   | 0.1959   | 0.2506   |
| $t_2$                    | 0.4343   | 0.2122   | 0.3534   |
| $t_3$                    | 0.4130   | 0.2341   | 0.3528   |
| $t_4$                    | 0.4542   | 0.1910   | 0.3545   |
| $t_5$                    | 0.5019   | 0.1761   | 0.3219   |

The basic probability assignment in Table 4 is combined with the combination rules of evidence theory, and the final results are shown in Table 5.

TABLE 5. THE FINAL RESULTS OF EVIDENCE COMBINATION

| Target Mode | $m(A_1)$ | $m(A_2)$ | $m(A_3)$ |
|-------------|----------|----------|----------|
| Combination Results | 0.8995   | 0.099    | 0.0015   |

According to the results in Table 5, the score of obtained by the evidence combination is the highest, and it can be judged that the core jamming has occurred in the high-voltage circuit breaker. However, if only the gray correlation analysis is used, then it cannot be clearly seen which state the high-voltage circuit breaker is in according to Table 4, and therefore the result cannot be clearly diagnosed.

5. Conclusion
In this paper, a fault diagnosis method for high voltage circuit breaker based on gray correlation analysis and D-S evidence theory is proposed. The diagnosis results of high voltage circuit breaker using this method is compared with the results using only gray correlation analysis, and the comparison result is as follows.

(1) When the output result of the gray correlation analysis is used as the basic probability assignment of the evidence in the D-S evidence theory, and the calculation and reasoning are based on the corresponding combination rules of the evidence theory, the accuracy and reliability of the basic probability assignment are higher.

(2) Compared with the diagnosis method based on only the gray correlation analysis, the method based on both gray correlation analysis and D-S evidence theory can avoid more subjectivity, therefore increasing the reliability of results.

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