Hybrid Methodology based on Extension Theory for Partial Discharge Fault Diagnosis of Power Capacitors

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Abstract Power capacitors are widely used in power systems, and any internal capacitor failures will affect the safe operations of the systems. The most common failures include humidity, partial discharge, aging, or insulating material degradation and structural damage. The purpose of this study is to detect the types of power capacitor failures by using a human-machine interface diagnostic system in order to determine the real-time status of the power capacitors. Partial discharge data measurement and diagnostic analysis were mainly conducted on power capacitors operating at a low voltage for a long time. Defects were pre-processed before capacitance measurement, and then, an electric testing machine was used to conduct a partial discharge test for capacitor enclosures and to continuously apply voltage until the occurrence of a partial discharge. A high frequency oscillograph was used to capture the voltage and partial discharge signals. Subsequently, the empirical mode decomposition (EMD) was applied to identify the characteristics of the discharge signals and to build the chaos and error scatter map by combining the chaotic synchronization detection and analysis method. Moreover, eyes of chaos were taken as the characteristics of fault diagnosis, and an extension algorithm was used to identify capacitance failures. The advantages of this method are to reduce the characteristics’ captured data and to effectively detect the minimum movement of the voltage signal discharged from power capacitors, so that the operating states of the power capacitors can be detected and determined, in order to carry out emergency measures in advance and prevent major disasters. After verification through actual measurement, the proposed method has a detection rate of 84% based on the extension theory, which proves that the method used in this study is applicable to partial discharge detection of power capacitors.

Key words: Power capacitors; Extension Theory; Empirical Mode Decomposition; Chaos Synchronization Detection; Fault Diagnosis

1. Introduction

Recently, the requirement of power systems has gradually increased due to the rapid development of power systems in many countries [1, 2]. The power capacitors, playing the function of a static volt-ampere reactive (VAR) compensator, are indispensable for maintaining the safe and stable operation of power system devices in power transmission and distribution systems. However, when the power capacitor is operated at a high voltage and high temperature environment for a long time, it will age and even fail, causing power loss. If the operation and repair can be stopped immediately when the power capacitor fails, it will reduce downtime and economic losses, and achieve a stable and safe operation of the power system.

Related studies have introduced several methods for detecting power capacitors including the tanδ dielectric loss angle measurement method [3, 4], leakage current method [5, 6], partial discharge method [7, 8, 9, 10, 11, 12], oil-dissolved gas detection [13], etc. Among them, the leakage current method measures the current flowing when the device is in use to detect the status of the power capacitor. Partial discharge, referring to the phenomenon of insulation defects such as bubbles or impurities, is caused by the concentration of the electric field in some parts of the power capacitor and decreases the performance of insulation. The oil-dissolved gas method detects the change in the dissolved gas in the insulating oil of the power capacitor caused by partial discharge, heat generation, or aging on the oil paper. The types of gases produced and the amount vary according to the different fault situations. However, most of the current research on power capacitors is based on measurement and manual judgement, in which the sampling procedure is complicated and signal error occurs during sampling. The fault diagnosis method proposed in this study is based on the signals of the voltage and current. Based on line voltage and current measurement, the signals are decomposed into low, moderate, and high frequency signals through empirical mode decomposition. The chaos synchronization detection method is used to capture the features of failure signals according to the signal types. Finally, the extension method conducts the fault diagnosis of the power capacitor. The concept of extension theory contains matter-element model and extension set theory was first introduced by Cai to solve contradictory problems [14]. The extension set is to extend the fuzzy logic value from [0, 1] to (-∞, ∞), which determines any data in the domain and has given hopeful results in many fields [15, 16].

2. Power capacitors partial discharge test procedure

This study aims to measure the partial discharge pulse of power capacitors. Due to the high frequency of the discharge signal and long period of time, the amount of data is huge.

A disproportionate amount of interference occurred during the experiments and the partial discharge signals were accompanied by an excessive amount of noise which
made them difficult to visualize. An effective high-pass filter was used to obtain the high-frequency signal and eliminate the noisy low frequencies [17].

An electrical machine testing platform was used to determine the power capacitors. The primary objective was the determination of insulation performance. In this study, an Alternating Current (AC) voltage resistance test was used to measure the capacitor insulation performance in which the voltage was applied to a grounded single-phase terminal with a power tester. The High Frequency Current Transformer (HFCT) was connected to the ground end, and the discharge pulse was coupled to the HFCT sensor [18, 19]. An oscilloscope was used to receive the signal, which was also transmitted to a computer via Universal Serial Bus (USB) for analysis, as shown in Fig. 1. When the rising single-phase voltage achieves the extreme point of the capacitor insulation, the discharge pulse will damage the insulation layer.

![Fig. 1. Power capacitors test flow chart.](image)

### 2.1 Power capacitor defect construction

An internal capacitor 440 V/50 kvar specification made by the Shilin Electric Machinery Co, Ltd. was used for the partial discharge experiments. The specifications and numbers of the healthy and aging power capacitors (healthy capacitors attenuated by 20%, 40%, 60%, 80%) are shown in Table I, and the experimental capacitors used in this study are shown in Fig. 2. The power capacitors are normally operated in a closed environment for a long time. Cast swells, oil spills, or poor insulation of the power capacitor occur due to poor heat dissipation under a high temperature and high voltage environment, which result in the failure of the power capacitor. Figure 3 displays aging power capacitors.

![Fig. 2. The experimental power capacitors (including healthy and aging capacitors).](image)

![Fig. 3. Aging Power Capacitors.](image)

### 2.2 Partial discharge detection circuit

The signals measured during the practical experiments were full of noise. In order to reduce low-frequency interference and filter out the signal, a passive high-pass filter was used. The filter collected discharge signals with longer vibrations [20]. Also, to ensure that the discharge signal passing through the high-pass filter circuit maintained amplification and had not been severely distorted, a high speed, high frequency, low distortion, dynamic response current feedback amplifier circuit was used. This amplification circuit can achieve 35 MHz at a G=10 and 350 MHz at a G=1 bandwidth. The non-inverting amplifier was used with negative feedback to stabilize the amplifier gain. The circuit of the designed high-pass filter and non-inverting amplifier is shown in Fig. 4.

![Fig. 4. Partial discharge detection circuit.](image)

### 3. Proposed Methods

The failure phenomenon is not obvious in the initial failure state of the power capacitor. In order to detect the symptoms of the failure at the initial state, this study proposes the empirical mode decomposition (EMD) method to transform the frequencies of the original signals and display them in the form of an intrinsic mode function (from IMF1 to IMF6). The IMF1 was derived from the discharge waveform of the power capacitor after EMD, and the chaos error scatter map was generated by the Lorenz chaotic synchronization detection method. After that, dividing the data in the scatter map into left and right halves to calculate the center of gravity coordinate (chaos eye) and then, store the values of the X-axis and Y-axis separately in an array for algorithm identification. The proposed method improves the efficiency and accuracy of fault diagnosis while greatly reducing the amount of data acquisition. Finally, with the advantage of fast and simple calculation, the extension theory plays the core role of the fault diagnosis of power
capacitors. The proposed methods are shown in Fig. 5.

| Partial discharge detection circuit | Empirical mode decomposition | Chaotic synchronization detection method | Extension theory | Results |
|------------------------------------|-------------------------------|----------------------------------------|-----------------|---------|

**3.1 Empirical mode decomposition**

The EMD method can decompose the original signal into the numerous intrinsic mode functions (IMF) proposed by fluid mechanics expert, Huang, and a sum of the mean trend components were employed [21, 22]. EMD decomposition, based on the implementation of the signal local characteristic time scale, is used to gain the IMFs and can process different time signals and non-linear or unstable signals.

The EMD decomposition process is as stated below:

Assume the signals of the time series are \( x(t) \). The upper and lower envelop curves, \( u_0(t) \) and \( v_0(t) \), respectively, were identified through combining all the extreme values on \( x(t) \). The average curve of the upper and lower envelop curves, \( u_0(t) \) and \( v_0(t) \), is as follows:

\[
m_0(t) = \frac{1}{2} [u_0(t) + v_0(t)]
\]

(1)

The function \( h_{l0} \) is defined by subtracting \( m_0(t) \) from \( x(t) \), which may become an IMF component.

Repeat the process of replacing \( x_{l0} \) by \( h_{l0} \) and calculating \( u_{00} \) and \( v_{00} \) to satisfy all the requirements of IMF as follows:

\[
\begin{align*}
m_{l1}(t) &= \frac{1}{2} [u_{l1}(t) + v_{l1}(t)] \\
h_{l2}(t) &= h_{l1}(t) - m_{l1}(t) \\
\vdots \\
m_{lk-1}(t) &= \frac{1}{2} [u_{lk-1}(t) + v_{lk-1}(t)] \\
h_k(t) &= h_{k-1}(t) - m_{k-1}(t)
\end{align*}
\]

(2)

The \( h_l(t) \) becomes the first IMF of the original signal when the repeating process meets a certain requirement. The \( h_l(t) \) is set as \( y_{l1}(t) \) and the other signals are set as \( r_{l0} \):

\[
\begin{align*}
y_{l1}(t) &= h_{lk}(t) \\
r_{l1}(t) &= x(t) - y_{l1}(t)
\end{align*}
\]

(3)

Where \( y_{l0} \) is the first component obtained from the original data, which is the highest frequency component in \( x(t) \) of the original signal, and \( r_{10} \) is the corresponding residual component. Repeat the EMD replacing process by treating \( r_{10} \) as the new original signal to calculate the second IMF \( y_{20} \). The repeating process stops when it reaches a monotonic signal or its value is smaller than the pre-set value:

\[
\begin{align*}
r_{l1}(t) - y_{l2}(t) &= r_{2}(t) \\
r_{l1}(t) - y_{l2}(t) &= r_{2}(t) \\
\vdots \\
r_{l1}(t) - y_{ln}(t) &= r_{n}(t)
\end{align*}
\]

(4)

The repeated decomposition of the EMD method extracts the important information in the fault signal and eliminates the interference of noise.

**3.2 Chaotic synchronization detection method**

The chaotic synchronization detection method was first proposed by Edward Norton Lorenz [23, 24, 25], and this theory focuses on exploring the unstable phenomena in a non-linear dynamic system. In a chaotic system, even small changes in initial conditions can cause very huge differences in the results because of long-term continuous amplification. The two chaotic systems are called the master and slave. When the master and slave systems have two different initial values, the operation tracks of the two systems will be different. A tracking system, which has a controller on the end of the slave system to track the master system, and then, uses the controller to make the operation tracks of the two different chaotic signals the same after a period, is called a chaotic synchronization system. Equation (5) shows the basic formula for chaotic synchronization [26]:

\[
\lim_{t \to \infty} \| y_{slave,i}(t) - X_{master,i}(t) \| = 0
\]

(5)

where \( X_{master} \) is the master system data, and \( Y_{slave} \) is the slave system data. This method was used to conduct chaotic synchronization detection on partial discharge signals. The master and slave chaotic system are shown as Eq. (6) and Eq. (7), where \( x_1 \) to \( x_n \) and \( y_1 \) to \( y_n \) are the location of the synchronization error point on the chaotic map:

\[
\begin{align*}
x_1 &= f_1(x_1, x_2, \ldots, x_n) \\
x_2 &= f_2(x_1, x_2, \ldots, x_n) \\
\vdots \\
x_n &= f_n(x_1, x_2, \ldots, x_n)
\end{align*}
\]

(6)

\[
\begin{align*}
y_1 &= f_1(y_1, y_2, \ldots, y_n) \\
y_2 &= f_2(y_1, y_2, \ldots, y_n) \\
\vdots \\
y_n &= f_n(y_1, y_2, \ldots, y_n)
\end{align*}
\]

(7)

where \( f_i \) \((i=1, 2, \ldots, n-1, n)\) is a non-linear function. The dynamic error is gained by subtracting Eq. (6) from Eq. (3) to form Eq. (4). The dynamic error equation is shown as Eq. (9):

\[
\begin{align*}
e_1 &= y_1 - x_1 \\
e_2 &= y_2 - x_2 \\
\vdots \\
e_n &= y_n - x_n
\end{align*}
\]

(8)

\[
\begin{align*}
e_1' &= f_1(x_1, x_2, \ldots, x_n) - f_1(y_1, y_2, \ldots, y_n) = H_1 \\
e_2' &= f_2(x_1, x_2, \ldots, x_n) - f_2(y_1, y_2, \ldots, y_n) = H_2 \\
\vdots \\
e_n' &= f_n(x_1, x_2, \ldots, x_n) - f_n(y_1, y_2, \ldots, y_n) = H_n
\end{align*}
\]

(9)

Two Lorenz chaotic systems were used to generate the dynamic map of chaotic dynamic error in this study. The focal point was used as the feature value to identify the
occurrence of a partial discharge signal. Eq. (10) and Eq. (11) display the master and slave systems. The dynamic error condition equation was calculated and displayed in matrix form, as shown in Eq. (11):

\[ \begin{aligned}
X_{\text{master}}: & \quad \dot{x}_1 = \alpha (x_2 - x_1) \\
& \quad \dot{x}_2 = \beta x_1 - x_1x_3 - x_2 \\
& \quad \dot{x}_3 = x_1x_2 - \gamma x_3 \tag{10}
\end{aligned} \]

\[ \begin{aligned}
Y_{\text{slave}}: & \quad \dot{y}_1 = \alpha (y_2 - y_1) \\
& \quad \dot{y}_2 = \beta y_1 - y_1y_3 - y_2 \\
& \quad \dot{y}_3 = y_1y_2 - \gamma y_3 \tag{11}
\end{aligned} \]

\[ \begin{bmatrix}
\dot{e}_1 \\
\dot{e}_2 \\
\dot{e}_3
\end{bmatrix} = 
\begin{bmatrix}
-\alpha & \alpha & 0 \\
\beta & -1 & 0 \\
0 & 0 & -\gamma
\end{bmatrix}
\begin{bmatrix}
e_1 \\
e_2 \\
e_3
\end{bmatrix} + 
\begin{bmatrix}
y_2y_3 - x_2x_3 \\
-\gamma y_1x_3 + x_1x_3 \\
y_1y_2 - x_1x_2
\end{bmatrix} \tag{12}
\]

where \( x \) is the master system data, and \( y \) is the slave system data. \( e_1, e_2, \) and \( e_3 \) are the master and slave systems’ chaotic dynamic error values. The adjusted error value parameters are \( \alpha, \beta \) and \( \gamma \), \( \alpha = 10, \beta = 28 \), and \( \gamma = -(8/3) \).

3.2 Extension theory

Some problems cannot be solved directly by given conditions, but the problem can become solvable via some appropriate transformation. The Laplace transformation is one of the generally used methods in engineering fields, and the concept of fuzzy sets is a generalization of famous standard sets. The extension theory attempts to solve incompatible or contradictory problems through the transformation of the matter element.

The extension theory was originally proposed by Professor Cai in 1983 to solve contradictions and incompatibility problems [27, 28]. The extension set and the matter-element theory are the two main points of the extension theory. The extension set aims to extend the fuzzy logic value from \([0, 1]\) to \((-\infty, \infty)\), and the matter-element researches the transformation properties and extensibility [29, 30], which permits us to determine any data in the domain and has given hopeful results in many fields as follows:

1. Definition of matter-element. A matter-element model includes three elements: a name denoted by \( N \), a feature denoted by \( C \), and the value of a feature denoted by \( U \). The matter can be expressed as below:

\[ R = (N, C, U) \tag{13} \]

where \( R = (N, C, U) \) to be a multidimensional matter-element, \( C = [c_1, c_2, \ldots, c_n] \) to be a characteristic vector, and \( U = [u_1, u_2, \ldots, u_n] \) to be a value vector of \( c \). Then, a multidimensional matter-element is as below:

\[ R = \begin{bmatrix}
N, & c_1, & u_1 \\
& c_2, & u_2 \\
& \cdots \\
& c_n, & u_n
\end{bmatrix} \tag{14} \]

2. Definition of extension set. Let \( U \) be the universe of discourse; then, an extension set \( \hat{A} \) on \( U \) is defined as a set of ordered pairs as follows:

\[ \hat{A} = \{(u, y) | u \in U, y = K(x) \in (-\infty, \infty)\} \tag{15} \]

where \( y = K(x) \) is called the correlation function for extension set \( \hat{A} \).

The extended correlation function \( K(x) \) maps each element of \( U \) to a membership grade between \(-\infty \) and \( \infty \). The higher degree and the more elements belong to the set. The correlation functions have many forms depending on applications. If we set \( X_o = \langle a, b \rangle \), \( X = \langle a_o, b_o \rangle \) and \( X_o \in X \), then the extended correlation function can be defined as follows:

\[ K(x) = \frac{\rho(x, X_o)}{D(x, X_o, X)} \tag{16} \]

where

\[ \rho(x, X_o) = \frac{\|x - a + \frac{b-a}{2}\|}{\frac{b-a}{2}} \tag{17} \]

\[ D(x, X_o, X) = \begin{cases} 
\rho(x, X_o) - \rho(x, X_o) & x \notin X_o \in X_o \\
-1 & x \in X_o
\end{cases} \tag{18} \]

In a particular condition, where \( 0 \leq K(x) \leq 1 \), it corresponds to the normal fuzzy set. When \( K(x) < 0 \), it indicates the degree to which \( x \) does not belong to the set. When \( 0 \leq K(x) \leq 1 \), this describes the degree to which \( x \) belongs to the set.

4. Results

Figure 6 shows the practical wiring of the experimental device. The power test machine continues to increase its voltage to the power capacitor until partial discharge occurs. The HFCT is used as the sensor for extracting partial discharge signals and is installed on the ground end of the power capacitor. The changes in the extracted signals are transmitted to the filter amplifier circuit via the BNC (Bayonet Neill-Concelman). EMD and chaotic synchronization analysis were used to analyze the partial power discharge signal. The master chaos synchronization detection system was set to 0, which serves as the power capacitor benchmark under healthy status.

![Fig. 6. The whole measurement devices.](image-url)
data was put through EMD. The measured discharge signals of 6 layers (IMF1 to IMF6) from high frequency to low frequency are obtained through the EMD method. Three centers of gravity coordinates \((e_1, e_2), (e_1, e_3),\) and \((e_2, e_3)\) in the chaotic scatter maps are obtained after performing Lorentz master-slave chaos system calculations on each layer. The coordinates are compared with each other based on the root mean squared error (RMSE, Eq. 19), and the largest feature value \((e_1, e_3)\) and the layer (IMF 1) are selected, as shown in Table II. The IMF of the healthy capacitor and the IMF of the simulated aged power capacitor are shown in Fig. 7 and Fig. 8, respectively.

\[
Z = \sqrt{(X_{11} - X_{12})^2 + (Y_{11} - Y_{12})^2 + (X_{12} - X_{13})^2 + (Y_{12} - Y_{13})^2} \quad (19)
\]

| Layers | \((e_1, e_2)\) | \((e_1, e_3)\) | \((e_2, e_3)\) |
|--------|----------------|----------------|----------------|
| IMF1   | 2.56           | 0.92           | 196.48         |
| IMF2   | 6.15           | 0.66           | 34.79          |
| IMF3   | 7.65           | 0.8            | 60.15          |
| IMF4   | 3.762          | 0.32           | 36.75          |
| IMF5   | 20.56          | 2.15           | 131.49         |
| IMF6   | 18.74          | 1.72           | 9.62           |

The largest RMSE of feature value of gravity centers.

![Fig. 7. Healthy capacitor IMF.](image)

![Fig. 8. Aged capacitor IMF.](image)

![Fig. 9. Healthy capacitor - IMF1 chaotic dynamic error distribution map and chaos eye.](image)

![Fig. 10. Aging capacitor - IMF1 chaotic dynamic error distribution map and chaos eye.](image)

This study used MATLAB for the EMD, chaos synchronization detection, and extension method program composition. To evaluate the performance of the proposed method, 50 sample set of aged power capacitor types were collected for recognition, and the experimental results were compared with the accuracies from several multilayer neural networks. The neural networks of other architectures were tested with four coordinate inputs and two types of outputs. In order to better validate the results of the proposed method, the hidden layer architecture setting was adjusted and tested with 6, 8, 10, 12, and 15 hidden layers. In terms of learning and overall recognition rates, the recognition accuracy rate of 10 hidden layers was the highest at 76%. The recognition result was compared with the proposed method, as shown in Table III. The proposed extension method achieves the highest accuracy at 84%. The multilayer neural network (4-10-2) takes second place at 76%, and the multilayer neural network (4-6-2) is the lowest at 62%. The main advantage of the proposed method is that the proposed method does not need to learn or to tune any parameters.

| Algorithms                        | Training iterations | Accuracy rate (%) | Ranking | Execution times (Seconds) |
|-----------------------------------|---------------------|-------------------|---------|---------------------------|
| Proposed method                   | N/A                 | 84                | 1       | 0.6                       |
| Multilayer neural network(4-10-2)| 10000               | 76                | 2       | 15                        |
| Multilayer neural network(4-8-2)  | 10000               | 75                | 3       | 15                        |
| Multilayer neural network(4-12-2)| 10000               | 74                | 4       | 16                        |
| Multilayer neural network(4-15-2)| 10000               | 66                | 5       | 16                        |
| Multilayer neural network(4-6-2)  | 10000               | 62                | 6       | 15                        |

5. Conclusions

In this study, we conducted the fault analysis on power capacitors’ partial discharge signals. The EMD was used to obtain the IMF. Chaotic synchronization analysis was then used to extract the minute feature parameters. The extension theory method was employed to detect the fault types. The experimental results showed that the proposed method can significantly reduce data output and only requires two chaotic eyes (four coordinate values) to obtain meaningful feature values. According to the research findings, the
accuracy of the proposed method was as high as 84%, compared with the multilayer neural network algorithm. The contributions of this study include two major items: First, the proposed EMD method has simple calculation procedures, and it is fast and can be matched with chaotic synchronization analysis to further improve the malfunction detection rate in power capacitors. Second, the proposed chaotic distribution map can be used as fault detection criterion for power capacitors, and it also can be extended to a fault-related diagnosis field. Besides, the proposed method does not need specific artificial parameters and training iterations. In addition, the calculation of the proposed method is fast and simple.

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