**Transformer Vibration Feature Extraction Method Based on Recursive Graph Quantitative Analysis**

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**Abstract**—Transformer condition monitoring has always been a very important subject, and the proposed vibration-based monitoring method provides a new idea for it. In the limited vibration information, fully excavating the transformer state information contained in it is still an important task at present. This paper considers that the traditional frequency domain analysis method will ignore some frequency information of signals, and drawing on the experience of the construction field such as bridges, uses phase space reconstruction technology and quantitative recursive graph method based on the time series of vibration data to restore the original response characteristics of the vibration system. On this basis, using the principal component analysis method and comparing with the typical stationary signal quantifies the vibration stability of the transformer. Considering the actual operation of the transformer, the stability evaluation method proposed in this paper does reflect the stability of the transformer.

**Keywords**—transformer, vibration, phase space reconstruction, quantized recursive graph

**I. INTRODUCTION**

Transformers are important power equipment in the power system. Especially high-voltage transformers are the basis for the normal and stable operation of the power grid. As the scale of the power system continues to expand and the operating years of large transformers continue to increase, the transformer failure rate remains high. Current transformer fault diagnosis mainly includes oil chromatography detection method, acoustic wave detection method, partial discharge detection method, etc.[1]. They can achieve accurate fault diagnosis and fault location, but generally require the transformer to be shut down for detection. Obviously, for the transformer in operation, the vibration detection method that can realize online detection is an ideal transformer monitoring method. At the same time, the rich transformer state information contained in transformer vibration also provides a conditional basis for this detection method.[2].

Extracting effective quantitative data from transformer vibration is the basis of vibration detection. At present, commonly used transformer vibration characteristics include fundamental frequency amplitude, main frequency, odd-even harmonic ratio, frequency complexity, energy similarity and vibration stability, and some scholars have proposed the use of vibration matching level and the time of controllable switching process as a diagnostic indicator[2-6]. When extracting these feature quantities, there are currently EMD (Empirical Mode Decomposition), HHT (Hilbert Yellow Transform), HAS (Hilbert Spectral Analysis), EEMD (Improved Empirical Mode Decomposition), BREMD (Limited Bandwidth Empirical Mode Decomposition), CWT (Continuous Wavelet Transform), DWT (Discrete Wavelet Transform) and STFT (Short-Time Fourier Transform) and other methods[2-7],[8] dealt with the nonlinear problem very well. Through some parameter identification method, with 50Hz voltage and current as input and 100Hz vibration as output, a vibration prediction model was established, and the accuracy is practical. The fitting method used in it can be used to analyze the nonlinear information contained in the transformer vibration, including the information from vibration stability. [16] proposed three diagnostic indicators, such as linear correlation, vibration energy and the ratio of fundamental frequency energy, and used AHP for normalization. [9] uses recursive graphs to analyze the non-stationary transition patterns in network traffic sequences, and quantitatively evaluate the dynamic evolution patterns of the sequences. At present, there are some achievements in the academic community on how to quantify non-stationarity, but there are few methods specifically applied to transformer vibration. Therefore, it is practical to propose some quantification methods that can be used for transformer vibration.

This paper proposes a non-stationary analysis method based on the time series of vibration data. The high-dimensional phase space reconstruction of the data series is used to analyze the recursive characteristics of the state of the vibration system. The method of recursive graph analysis is used to study the non-stationary characteristics of the vibration system itself and quantify it according to certain rules. Experimental results show that the method proposed in this paper can effectively analyze...
the non-stationary characteristics of vibration data, which is helpful for the further development of transformer vibration detection technology.

II. VIBRATION NON-STATIONARY CHARACTERISTIC ANALYSIS

A. Phase Space Reconstruction Model

For the data in the time domain, it is regarded as a response sequence generated by a certain nonlinear system, and we can restore and characterize the motive force system through phase space reconstruction technology. In this way, we can use the collected transformer vibration data to obtain some characteristics of the transformer vibration system, and use some methods, such as recursive graph analysis, to quantify it. This is for fault diagnosis and the analysis of vibration characteristics has profound significance.

For any of the collected time-domain vibration data sequences \(\{x(i), i = 1,2,\ldots,n\}\), this paper uses the delay embedding theory proposed by Takens to construct a phase space reconstruction model[10]:

\[
X_m = [x(i), \ldots, x(i + (d - 1)\tau)], 1 \leq i \leq n - (d - 1)\tau \quad (1)
\]

Among them, \(X_m\) is the constructed phase space state vector, \(\tau\) is the delay time parameter, and \(d\) is the embedding dimension.

The most important thing for phase space reconstruction is to determine the two parameters. There are currently methods for determining the delay time parameters, such as the autocorrelation function method and interactive information method. The determination of the embedded dimension parameters currently includes the geometric invariant method, the false nearest neighbor method, the Cao-improved false nearest neighbor method, and other improvements based on this extension [11]. For the convenience of the method, this paper adopts the interactive information method to determine the delay time parameter and the Cao-improved false nearest neighbor method for false nearest neighbor method to determine the embedded dimension.

B. Recursive graph analysis model

Recursive graph is a method to extract the dynamic recursive behavior of the system through the time series of data. What is on the surface is a kind of bitmap generated by phase space nodes, and then quantitative features can be calculated and the original system characteristics can be analyzed.

The calculation expression of the recursive matrix is shown in the formula (2).

\[
R_{i,j} = \theta(\varepsilon - \|X_i - X_j\|), X_i, X_j \in X_m, i, j = 1,2,\ldots,N. \quad (2)
\]

Among them, \(R_{i,j}\) is a recursive matrix element, \(\varepsilon\) is a preset distance threshold, according to experience [12], usually \(\varepsilon = 10\%\), \(\|\|\) represents Euclidean distance, \(\theta(x)\) represents Heaviside function, when \(x\) is greater than or equal to 0, the value is 1, otherwise it is 0. The recursive graph represents the 1-value point as a black dot and the rest as white dots, which can reflect the recursive characteristics of the system on a two-dimensional plane.

Generally speaking, the basic graphics of recursive graphs contain certain system behavior information. Diagonal lines indicate the phenomenon of similar state changes in the time period. Vertical / horizontal lines indicate slow changes of states. Isolated points indicate the instantaneous approximation of spatial points. Quickly separate. These characteristics can be used for the qualitative analysis of the recursive characteristics of the system. At present, some people have proposed a quantitative recursive analysis method [9], which uses five quantitative parameters: Recurrence Ratio(RR), Determinism(DET), Maximum Length(Lmax), Entropy and Trend etc.

C. Stationarity analysis based on recursive quantification

Mathematically, the definition of the stationarity of a group of signals is the degree of correlation between statistical parameters and time. Non-stationary signals often mean complex frequency changes. In transformer vibration, non-stationarity means complex frequency changes, which may come from faults or unrelated vibration sources. Studying the stability of transformer vibration is of great significance for distinguishing between normal operating conditions and fault conditions, unreachable fault conditions, and different signal sources.

In order to simplify the analysis and take into account the effect of various quantization parameters on the stability evaluation, this paper decided to use \(RR, \ DET, \ Lmax\) and TREND as the calculation input. The expressions for the four parameters are given below,

\[
RR = \frac{1}{N^2} \sum_{i=1}^{N} R_{i,j} \quad (3)
\]

\[
DET = \frac{\sum_{i=1}^{N-1} \sum_{j=1}^{N} R_{i,j}}{\sum_{i=1}^{N} R_{i,i}} \quad (4)
\]

\[
L_{max} = \max \{\|l_i; i = 1, \ldots, N_i\|\} \quad (5)
\]

\[
TREND = \frac{\sum_{i=1}^{N} (1 - N/2) R_{i,i}}{\sum_{i=1}^{N} R_{i,i}} \quad (6)
\]

Considering that the sine signal is a very stable signal, in order to evaluate the stability of the vibration signal, this paper uses the principal component analysis method to calculate the similarity of the vibration signal and the sine according to the above four parameters, and use this as the evaluation of the stability of the vibration signal.

III. EXPERIMENT AND ANALYSIS

The data of the simulation experiment in this paper comes from the vibration test data of 110kV Chazishan 1 # main transformer provided by Beijing Electric Power Research Institute. The test data includes a total of seven sensors in four positions. The frequency is 400 Hz and the sample length is 60,000.
The traditional frequency domain analysis method always loses the information of unstableness such as frequency changes and cannot fully reflect the vibration characteristics.

This article considers the use of recursive graph methods to analyze this change. First, the phase space reconstruction method is used to recover the state trajectory of the transformer vibration system from the sensor data. After adopting the interactive information method to determine the delay time parameter and the modified-Cao method to determine the false nearest neighbor method of the embedded dimension, the calculation results are shown in Fig.1 and Fig.2. And we chose the delay time parameter and embedding dimension as shown in the TABLE.I.

![Interactive information method to determine delay time parameters](image)

**Fig. 1.** Interactive information method to determine delay time parameters

![Selection of embedding dimension](image)

**Fig. 2.** Selection of embedding dimension

<table>
<thead>
<tr>
<th>Sensor Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Time Parameter</td>
<td>674</td>
<td>689</td>
<td>699</td>
<td>713</td>
<td>724</td>
<td>702</td>
<td>731</td>
</tr>
<tr>
<td>Embedding Dimension</td>
<td>16</td>
<td>11</td>
<td>11</td>
<td>16</td>
<td>7</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

According to the set delay time and embedding dimension parameters, we can get the recursive spectrum of transformer vibration data according to the above recursive calculation formula, as shown in the Fig.3.
At this time, we can see that the recursive graph has a diagonal structure, and the overall distribution is relatively uniform, with certain certainty, but the degree of quantification of these features is insufficient. In order to better compare the effectiveness of the parameters, this paper lists the periodic functions and typical non-stationary signals as a comparison. According to the stationarity evaluation method proposed in this paper, sinusoidal signal is used as contrast signal. The calculated correlation coefficient is shown in the Table II.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoidal signal</td>
<td>1</td>
</tr>
<tr>
<td>Gaussian white noise</td>
<td>0.01328</td>
</tr>
<tr>
<td>Sensor 1’s signal</td>
<td>0.57183</td>
</tr>
<tr>
<td>Sensor 2’s signal</td>
<td>0.74231</td>
</tr>
<tr>
<td>Sensor 3’s signal</td>
<td>0.72711</td>
</tr>
<tr>
<td>Sensor 4’s signal</td>
<td>0.67234</td>
</tr>
<tr>
<td>Sensor 5’s signal</td>
<td>0.83537</td>
</tr>
<tr>
<td>Sensor 6’s signal</td>
<td>0.63468</td>
</tr>
<tr>
<td>Sensor 7’s signal</td>
<td>0.57324</td>
</tr>
</tbody>
</table>

As a result, it can be seen that the stability of the transformer vibration data is close to the periodic function, the stability is high, and the frequency characteristics of the data are relatively stable. This is because the data we used is derived from the normal transformer in operation, and its stability should be high, and the vibration system is not very stable considering the existence of interference, so this result is consistent with the facts, which proves the proposed stability parameter is valid.

**IV. CONCLUSION**

Recursive graph is a method that can reconstruct dynamic system characteristics from limited data and obtain system state information. This paper considers that the traditional frequency domain analysis method will ignore some frequency information of signals. Drawing on the experience of the construction field such as bridges, phase space reconstruction technology and quantitative recursive graph method are used to restore the original response characteristics of the vibration system. On this basis, the principal component analysis method is used to quantify the vibration stability of the transformer. Taking into account the actual operation of the transformer, the stability evaluation method proposed in this paper does reflect the stability of the transformer.

Automatically extracting relevant features from online measured data and applying them to online vibration monitoring systems is currently the more mainstream method. The method in this paper provides a practical parameter for this, which can effectively improve the effectiveness and comprehensiveness of the detection method. However, in the calculation process, the calculation burden is large, which is not conducive to the application of online monitoring methods. And there are several empirical parameters in the calculation process, which means that this method also has considerable room for improvement, which can improve the calculation efficiency and the effectiveness of the calculation results.

**REFERENCES**