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RESEARCH ARTICLE

Quantitative Research on Accumulative Effect of Transformer Winding Deformation and Its Influence Degree Based on Time-Frequency Analysis of Vibration Signal

SHUGUO GAO[1], LU SUN[1], XINYU WANG[2], YUAN TIAN[1], JIANGHAI GENG[2], AND HONGLIANG LIU[1]

[1]State Grid Hebei Electric Power Research Institute, Shijiazhuang 050021, China
[2]Hebei Provincial Key Laboratory of Power Transmission Equipment Security Defense, North China Electric Power University, Baoding 071000, China

Corresponding author: Xinyu Wang (wangxy1996@ncepu.edu.cn)

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ABSTRACT Winding deformation caused by short-circuit is one of the main causes of transformer damage. Even if the transformer successfully withstands one short-circuit impact, accumulative effect of multiple short-circuit impacts will cause sudden permanent deformation of the winding. Internal winding deformation is a hidden fault due to the visual blocking of the shell of transformer, so it is extremely important to measure the accumulative effect and analyze its influence. In this paper, a SFSZ7-31500/110 transformer was used for short-time multiple short-circuit impact tests. The measurability of accumulative effect was determined by calculating the difference between measured value and reference value of the acceleration of the time-domain vibration acceleration signal, and then a time-frequency matrix was constructed based on Wigner-Ville Distribution (WVD) time-frequency analysis. Based on Fuzzy C-Means (FCM) clustering and the singular values of the matrix, the membership degree of winding mechanical state was calculated, and the influence degree of the accumulative effect was quantitatively analyzed. Results show the method can reflect the deformation trend and degree of winding before the impedance change rate. Research provides some reference for the mechanical state evaluation and fault early warning of windings, and also has a guiding significance for the safe and stable operation of transformers.

INDEX TERMS Accumulative effect, multiple short-circuit, time-frequency analysis, transformer winding.

I. INTRODUCTION

With rapid development of the power grid in China, grid capacity continues to increase, and transformer damage events caused by short circuits are on the rise. According to the statistics of the State Grid, more than 60% of damage and faults of transformer windings are caused by external short circuits, and remarkable electromagnetic forces arise during short-circuit or inrush current situations which may cause elastic and plastic deformations on transformer windings and catastrophic failure of transformer, mainly manifested by winding distortion, inclination, bulging and displacement [1], [2], [3], [4].

Lots of achievements have been made in the diagnosis of transformer winding deformation at home and abroad. Common diagnosis methods of winding deformation include frequency response method, low-voltage pulse method, short-circuit reactance method, and vibration method [5], [6], [7], [8], [9]. The frequency response method (FRA) has the advantage of easy detection and positioning. In the literature [10], the influence of the parameters of the test platform such as excitation signal frequency and temperature on corresponding frequency test results was studied successively. A winding deformation detection system was developed

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based on the pattern recognition technique of a neural network algorithm. However, this method can only be used when the transformer is offline. In recent years, researchers have tried the online frequency response analyze, while the online monitoring needs the applicable transfer function, but it is not mature and with poor universality [11]. In the literature [12], [13], a low-voltage pulse detection test was carried out on the transformer winding, and fault diagnosis of winding deformation was carried out based on wavelet transformation. However, the low-voltage pulse method has such problems as low signal-to-noise ratio, poor repeatability and proneness to electromagnetic interference, so it is not quite reliable in practical maintenance applications. The short-circuit reactance method is a widely accepted deformation diagnosis standard for transformers of different capacities and voltage levels developed after years of repeated engineering application research [14]. However, in the case of winding looseness and slight deformation, the sensitivity of this method is not high enough. The vibration method is an effective method to evaluate transformer condition in recent years [15], [16]. Using the method of wavelet packet, Shenyang University of Technology realized diagnosis of the vibration characteristic parameters of windings such as looseness and deformation [17]. In his latest research, Ji Shengchang of Xi'an Jiaotong University obtained the vibration characteristics and law of flowing deformation under different operating conditions and provided guidance and suggestions for on-line winding detection [18]. However, the vibration method is easily disturbed by noise, resulting in distortion of vibration law.

The above research mainly focuses on how to judge whether winding deformation occurs, but in fact, the mechanical properties of the winding may have changed and resulted in a latent fault under the influence of the accumulative effect before deformation [19], [20]. Even if the winding is not deformed and damaged under a single short-circuit impact, its mechanical stability tends to degrade to a small extent irreversibly, and such degradation is constantly intensified after each impact. Actual short circuit resistance then decreases at an accelerated rate until sudden instability deformation occurs. Therefore, study of the influence of short-circuit impact on the stability of transformer windings, attention must be paid to the presence of the accumulative effect. Proper measurement and evaluation of the influence of accumulative effect will help the realization to early warnings of winding deformation and avoid sudden instability. At present, it is difficult to directly observe the mechanical condition of windings with the naked eye, and the traditional electrical measurement technology is also difficult to find the deterioration trend of transformer windings. There is a lack of means to monitor and diagnose the accumulative effect of short circuit impact and its influence, and sample data that can truly characterize the short-circuit fault of transformers in operation is inadequate, it is imperative to carry out relevant research. Cluster analysis can diagnose the state according to the characteristics of the samples. Fuzzy clustering is a soft clustering method and reflects the degree of the samples' tendency to various states by membership, which is very suitable for analyzing the influence of accumulative effect.

FIGURE 1. Test transformer.

To sum up, multiple short-circuit full-scale tests on a large capacity transformer were carried out, and the test data of vibration acceleration and impedance change ratio was obtained. The time-domain and frequency-domain numerical characteristics of vibration waveform were pertinently analyzed. According to the difference between the measured value and the reference value of the vibration acceleration, the measurability of accumulative effect is obtained. In addition, the vibration time-frequency characteristic matrix was constructed by singular value decomposition, and the quantitative analysis of accumulative effect is realized by FCM clustering method with the membership matrix. The calculated results are in good agreement with the change ratio of impedance. The research in this paper provides engineering guidance and reference for the mechanical state assessment and deformation early warning of transformer windings.

II. TEST SETUP AND SIGNAL ACQUISITION

A. TEST SETUP AND TRANSFORMER MODIFICATION

In order to study the change of mechanical state of windings when a transformer suffers from multiple short-circuit impacts, a decommissioned SFSZ7-31500/110 core-type transformer was used as the test model and was modified accordingly. Its parameters were measured by installing corresponding sensors. The rated capacity of the transformer is 31500 kVA, the rated voltage is 110/38.5/10.5 kV, the rated current is 165/472/1732 A, and the connection mode is Yyn0d11.

The transformer is equipped with a vibration acceleration sensor. The sensor is installed at the outer wall of the oil tank close to the test phase. After modification, the core type transformer passed all factory tests. The sensor will not affect operation of the transformer. The vibration sensor is arranged on the fuel tank to collect vibration acceleration waveforms during a short circuit. The vibration sensor has a range of ±20g, a resolution of 0.001g, and a frequency measurement range up to 5000Hz. Sensor parameters can effectively meet

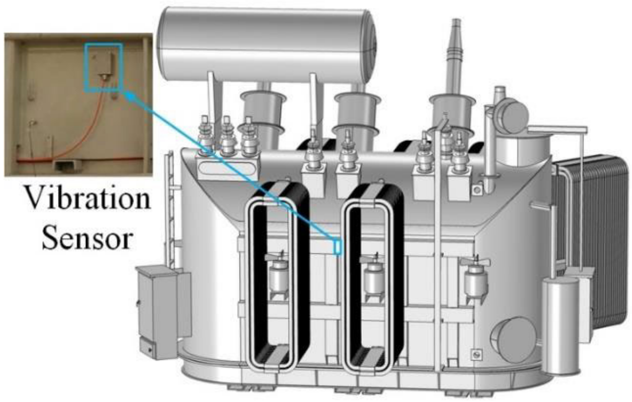

FIGURE 2. Sensor arrangement schematic.

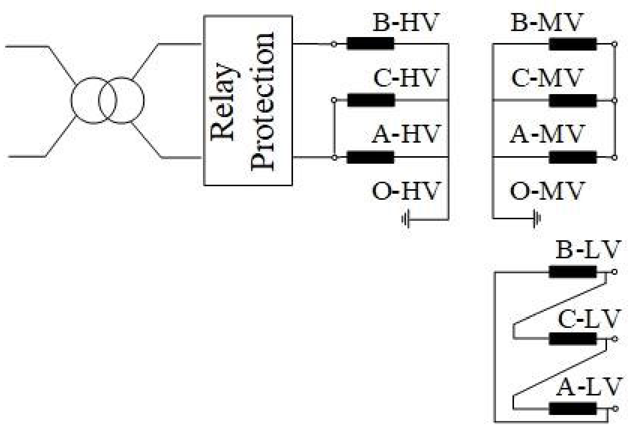

FIGURE 3. Short-circuit test wiring diagram.

the requirements of measurement. The installation location is shown in Fig. 2.

B. TEST SCHEME OF MULTIPLE SHORT-CIRCUIT IMPACTS

In this paper, high voltage to medium voltage short-circuit impact tests at phase B (HV-MV B) were taken, and the wiring diagram for the test is shown in Fig. 3. After the three-phase medium voltage winding was short-circuited and the low voltage winding was opened, the high-voltage side voltage was regulated to make the high-voltage side current of phase B reach 60%, 80%, 85%, 90%, 100% and 105% of rated current, in turn. Among them, 105% short-circuit current was applied three times for a total of eight short-circuit tests. The current flowing through the short-circuit phase is shown in Table. 1. The test was carried out in accordance with the requirements of GB 1094.5-2016 [21]. The duration of each short-circuit impact was 250±25 ms, and the interval between two tests was 20 min. Real-time vibration acceleration waveform was collected during the tests. The sampling time was 0.1 ms, and the sampling frequency was 10 kHz. Since the short-circuit test is destructive, the axial compression force and impedance change rate of the winding need to be measured after each test, and the short-circuit test needs to be stopped when the impedance change rate exceeds 2%.

TABLE 1. Short-circuit current set.

Test No.	Percent(%)	Actual test current(A)	Safety current(A)
1	60	914	1181
2	80	1176	
3	85	1262	
4	90	1346	
5	100	1483	
6	105	1550	
7	105	1551	
8	105	1547	

III. TIME-FREQUENCY ANALYSIS OF VIBRATION WAVEFORM

Before the transformer winding undergoes sudden instability and deformation, each short-circuit impact will also cause slight irreversible change to its mechanical state, resulting in a difference in vibration response during the next impact from the previous one and accumulative effect that finally causes winding instability and deformation. To learn about the change rule of transformer winding state under multiple short-circuit impacts, time-frequency analysis is conducted on the vibration waveform to obtain the response after each impact [22], [23].

A. VIBRATION MECHANISM UNDER SHORT-CIRCUIT IMPACTS

Generally, the vibration of transformers includes core vibration and winding vibration. Core vibration is caused by magnetostriction and is greatly affected by voltage, while winding vibration is caused by winding current and magnetic leakage field. Under normal operating conditions, vibration is mainly contributed by the core, but when the transformer is short-circuited, current flowing through the winding may reach tens to hundreds of times the rated value. At this point, the vibration effect of the winding will far exceed core vibration. Therefore, the vibration waveform studied in this paper is mainly analyzed from the point of view of the winding vibration mechanism.

The winding vibration structure can be simplified as a double-beam model structure of wires and spacers as shown in Fig. 4, and a plurality of models constitute the whole winding. Then the vibration equation of each model unit can be expressed as in (1):

$$M\ddot{x} + Kx - \frac{\mu l}{2\pi d} i^2(t) + \frac{\mu l}{2\pi d^2} i^2(t)\, x = 0 \tag{1}$$

where x is the vibration displacement of the wire, $\ddot{x}$ is the second-order derivative of the displacement, i.e., the vibration acceleration, M is the mass of the wire, K is the stiffness of the pad, l is the span of the pad, d is the spacing between upper and lower wires, and μ is the permeability of the oil.

The steady-state solution of vibration displacement x and its second-order derivative $\ddot{x}$ are given as in (2)-(3):

$$x = \frac{\mu l I^2}{2\pi d_0 K} + \frac{\mu l I^2}{2\pi d_0 K} \frac{\cos(2\omega t)}{K - 4\omega^2 M} \tag{2}$$

$$\ddot{x} = \frac{2\omega^2 \mu l I^2}{\pi d_0 K} \frac{\cos(2\omega t)}{4\omega^2 M - K} \tag{3}$$

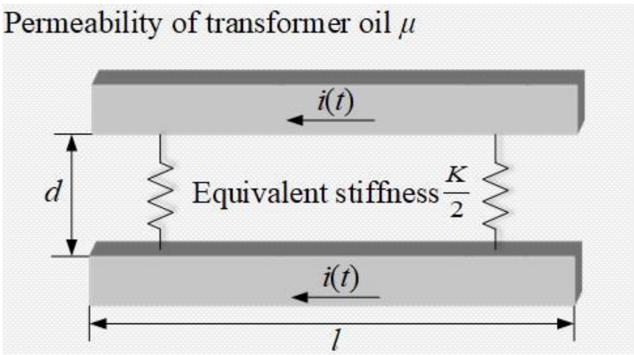

FIGURE 4. Winding vibration structure model.

where I is the current amplitude, d_0 is the steady-state spacing between upper and lower wires.

B. TIME-DOMAIN CHARACTERISTICS OF VIBRATION WAVEFORM

Characteristics in the time domain mainly include amplitude, effective value, mean value, peak-to-peak value, variance, waveform similarity and so on. In the short-circuit test, the applied short-circuit current is a decaying non-periodic signal. Excited by this signal, the vibration response of the winding will also be a non-stationary signal. The effective value (root mean square value, RMS) can be applied to analysis of the changes of non-stationary signal amplitude over time, and it also can avoid the problem of abnormal peak variation caused by too high occasional peak.

For the time-domain waveform obtained by the recording wave, the effective value is calculated as the analysis value of vibration acceleration. The effective value XRMS reflects the energy magnitude of the waveform $f(x)$ by averaging the time, expressed as in (4):

$$X_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T f^2(x)\,dt} \tag{4}$$

where T is the length of the waveform.

C. FREQUENCY-DOMAIN CHARACTERISTICS OF VIBRATION WAVEFORM

Frequency spectrum is the most intuitive key feature that can be used to describe signals, except the effective value. Simple spectrum can obtain various frequency components and their contents contained in the signal from statistical characteristics, while completely losing the time information. Ignoring the time information may cause lack of distinction between different non-stationary signals. For non-stationary signals, the frequency spectrum obtained by Fourier transform cannot represent the content of frequency components in a certain period of time in the time domain waveform, and the discarded time domain information may be very important.

To solve the problem of insufficient time resolution, Fourier transform has been extended to many analysis methods that can simultaneously represent the time domain and frequency domain information, such as short time

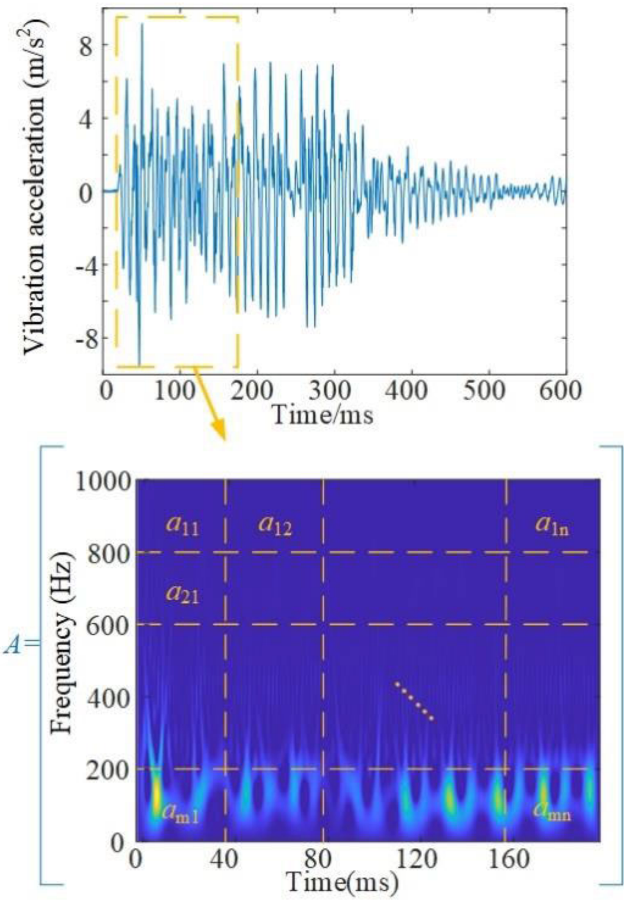

FIGURE 5. Winding vibration structure model.

Fourier transform (STFT), Wigner Ville Distribution (WVD), Wavelet Transform (WT) [24], etc.

Short time Fourier transform divides the time domain waveform through a fixed width window to obtain frequency domain information at a certain time resolution, as shown in Formula (5):

$$G(\omega) = \mathcal{F}[f(t,u)] = \int_{-\infty}^{\infty} f(t)\,g(t-u)e^{-jwt}\,dt \tag{5}$$

where, g(t-u) is a window function. Windows will make the time and frequency resolution cannot be considered at the same time, which is not accurate enough for the application of non-stationary signals. Wavelet transform has the characteristics of multi-resolution analysis, and the window width can be dynamically adjusted according to the specific shape of the signal. However, in the low frequency band, the window is large and the time resolution is still low. When studying the characteristics of the winding vibration signal, the main frequency component is 100Hz and its double frequency component, mainly concentrated in the low frequency band. The wavelet transform still cannot provide good results.

Wigner-Ville Distribution is the Fourier transformation of the instantaneous symmetric correlation function of signals, and the problem of mutual restraint between time-frequency resolutions can be avoided through time-frequency analysis without windowing. Therefore, it is a time-frequency analysis method widely used in non-stationary signals, expressed as in (6):

$$WVD\,(t,\omega) = \int_{-\infty}^{\infty} f\left(t+\frac{\tau}{2}\right) f^{*}\left(t-\frac{\tau}{2}\right) e^{-j\omega\tau} d\tau \qquad (6)$$

where, f^* represents complex conjugate.

As is shown in Equation (5), the correlation function is time-varying under WVD, so WVD can be regarded as the Fourier transformation of the signal-time autocorrelation function. Different from short-time Fourier transformation (STFT), the resolution of WVD is completely independent of the determination of window function and window width, avoiding the choice of time width and bandwidth. In addition, compared with wavelet analysis, WVD can still maintain high resolution without improper selection of wavelet basis function.

In order to suppress the influence of cross terms, a parameterized function is introduced for smoothing, as shown in (7):

$$SPWVD\,(t,\omega) = \int_{-\infty}^{\infty} g\,(t) H\,(\omega) f\left(t+\frac{\tau}{2}\right) \times f^{*}\left(t-\frac{\tau}{2}\right) e^{-j\omega\tau} d\tau \qquad (7)$$

where g(t) and $H(\omega)$ are time window functions and frequency window functions respectively, and $g(0) = H(0) = 1$.

Considering the excitation time of short-circuit current is 250±25 ms, the vibration state of winding is only damped after short circuit current excitation is removed [3]. In order to study the influence of each short-circuit shock on the mechanical state of the winding and the accumulative effect, this paper mainly observes the response difference of the winding under the excitation of short-circuit currents. Therefore, only the vibration response period of the winding under excitation (that is, the vibration time-domain waveform within 200 ms) is used in the time-frequency analysis.

In order to more accurately quantify the characteristics of time-frequency spectrum, the vibration time-frequency spectrum obtained by WVD smoothing is divided into time-frequency panes, and the power spectral density in each pane is calculated, to build a time-frequency matrix A as shown in Fig. 5 to simultaneously characterize the time, frequency and amplitude distribution of the signal.

D. TIME-FREQUENCY ANALYSIS RESULTS AND RULES

In order to explore the relationship between vibration waveforms and the mechanical properties of transformer windings, the vibration waveforms of transformer B-phase high-voltage to medium-voltage (HV-MV B) under 8 different short-circuit currents are taken as the research object for time-frequency analysis as described in Sections B and C.

First, the effective value of the time domain waveform 200 ms before short-circuit excitation is calculated. In order

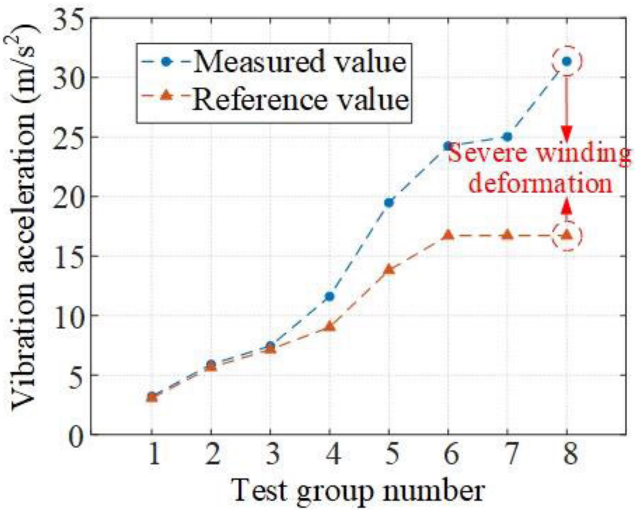

FIGURE 6. Vibration measurement value and reference value under short-circuit shock.

to consider the accumulative effect, it is necessary to eliminate the corresponding increase of vibration acceleration caused by the increase of short-circuit current. Therefore, this paper first calculates the reference value of vibration acceleration under different currents, and the difference between the reference value and the measurement value (effective value).

From Section A, the vibration acceleration of winding is square with current, and no comparative no-load test is conducted before the short-circuit shock test of each phase winding due to the time limit of the test site. Therefore, considering the 60% short-circuit current test, the winding is in normal or no obvious deformation state, the acceleration reference value is calculated by the vibration acceleration measurement value of the current applied by this group, and the reference value curves under different short-circuit currents are fitted. FIGURE 6 shows the variation curve of vibration acceleration measurement value and reference value under 8 groups of tests, and Table 2 shows the measured value, Reference valve value and corresponding impedance variation rate.

As shown in Fig. 6, the measurement value of vibration acceleration deviates from the reference value continuously after each shock. During the last short-circuit shock test, the measurement value of vibration acceleration deviates from the reference value from 49.6% of the previous test to 87.5%, and the impedance variation rate increases sharply from 0.57% to 2.28%, at which time the winding is severely deformed.

According to GB/T 1094.5-2016, the impedance variation rate is a reliable index to evaluate whether winding is severely deformed. However, if the winding is slightly deformed, the impedance variation rate may not be obvious, that is, the impedance variation rate cannot reflect the accumulative effect. According to the above calculation and analysis, the difference of vibration acceleration increases much faster than the impedance variation rate under multiple short-circuit

TABLE 2. Measurement value, reference value and corresponding impendence variation rate.

Test group number (Short-circuit current percentage)	Vibration acceleration difference (m/s^2)	Impedance change ratio (%)
1(60%)	0.144	0.11
2(80%)	0.256	0.18
3(85%)	0.289	0.25
4(90%)	2.582	0.25
5(100%)	5.668	0.39
6(105%)	7.511	0.50
7(105%)	8.291	0.57
8(105%)	14.631	2.28

tests. The former can reflect the change of winding mechanical state more quickly and clearly, which shows that the more times of shock, the greater the changes of winding mechanical state, the higher the degree of deviation from stability, the greater the difference of vibration acceleration, and the easier it is to generate deformation risk. That is to say, the acceleration deviation degree could reflect the accumulative effect under multiple short-circuit impulse.

But as a one-dimensional parameter, the deviation cannot accurately reflect the influence degree of accumulative effect, so related studies will be carried out by other methods. Therefore, WVD time-frequency analysis will be performed on the time-domain signals, and the time-frequency spectrum with time and frequency resolutions of 0.1 ms and 5 Hz under each short-circuit shock will be obtained as shown in Fig. 7(a)-(h).

With repetition of the short-circuit test, the cross component gradually decreases and the periodicity of the main frequency band becomes more and more obvious, indicating the amplitude of vibration acceleration in main frequency band (<200Hz) increases continuously with the increase of short-circuit current, and the contents of second harmonic band (200-400Hz) and high frequency band (>400Hz) also increase in varying degrees with the increase of short-circuit times [4], [25].

The amplitude change of each frequency band can reflect the distribution of absolute quantity in the time-frequency spectrum but cannot reflect the influence of different test conditions (short circuit times, short circuit current and winding mechanical state) on vibration acceleration at the same time. In order to determine the influence of short-circuit times on frequency response and eliminate amplitude change caused by different short-circuit currents, the energy fraction diagram can be used to analyze, integrate and normalize the energy of three frequency bands, as shown in the following Fig. 8.

As is shown in Fig. 8, during several short-circuit shocks, the proportion of each frequency band changed significantly, the proportion of high-frequency band gradually increased. Compared between the first and the last test, the ratio of high-frequency band increased from 22% to 47%. And its growth trend approximately followed the impedance variation rate, which indicated the winding mechanical state had changed, and there might be looseness, reduced preload and pad material approaching nonlinear state [26].

IV. CONSTRUCTION OF VIBRATION SIGNAL CHARACTERISTIC QUANTITY

A. SINGULAR VALUE DECOMPOSITION OF TIME-FREQUENCY MATRIX

For a matrix $A = (a_{ij})^{m\times n} \in R^{m\times n}$, there are orthogonal matrices $U \in R^{m\times m}$ and $V \in R^{n\times n}$ satisfying that

$$A = U\Sigma V^T \tag{8}$$

where $\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix}$, $\Sigma_1 = diag\left(\sqrt{\lambda_1}, \sqrt{\lambda_2}, \cdots, \sqrt{\lambda_r}\right)$.

The arithmetic square roots $\sqrt{\lambda_1}, \sqrt{\lambda_2}, \ldots, \sqrt{\lambda_r}$ of non-negative eigenvalues $\lambda_1, \lambda_2, \ldots, \lambda_r$ with $A^T A \geq 0$ are the singular values of matrix A. If the singular values are set in order of magnitude, the matrix can be decomposed into the weighted sum of r rank-one matrices, that is, $A = \sqrt{\lambda_1} u_1 v_1^T + \sqrt{\lambda_2} u_2 v_2^T + \ldots + \sqrt{\lambda_r} u_r v_r^T$. The matrix A is represented by several singular values and eigenvectors through decomposition, which describe the local characteristics of the matrix to a certain extent. The singular value of the matrix is a relatively stable algebraic feature of a matrix, which has good robustness and generalization ability and better stability that is not easily affected by disturbance. At the same time, the singular value is scale invariant and rotation invariant, which is not affected by normalization, row-column transformation and other operations in state recognition, and meets the requirements of stability, rotation and scale invariance [27]. Therefore, the matrix singular value can be used to represent the characteristic quantity of signals in state recognition.

Singular value decomposition is carried out on the time-frequency matrix obtained from the short-circuit shock tests, and each singular value can reflect the proportion of each frequency band of vibration signal, thus describing the vibration in different mechanical states. If the singular value changes, it will indicate the amplitude proportion of each frequency band of the vibration waveform corresponding to the time-frequency matrix will change, and the winding mechanical state may change.

B. FUZZY C-MEANS (FCM) CLUSTERING ALGORITHM

Commonly used clustering methods can be divided into Partition-based Methods, Density-Based Methods, Hierarchical Methods, etc.

Partition-based Method, namely Distance-based Method such as K-means method needs to specify the number of clusters or the cluster center in advance, and then iterate repeatedly until the goal that the points in the cluster are close enough and the points between clusters are far enough is reached. Partition-based Method is good at dealing with convex data. Data can be divided into spherical clusters according to distance, but for nonconvex data, this method is not able to propose proper clusters. At this time, Density-Based Methods

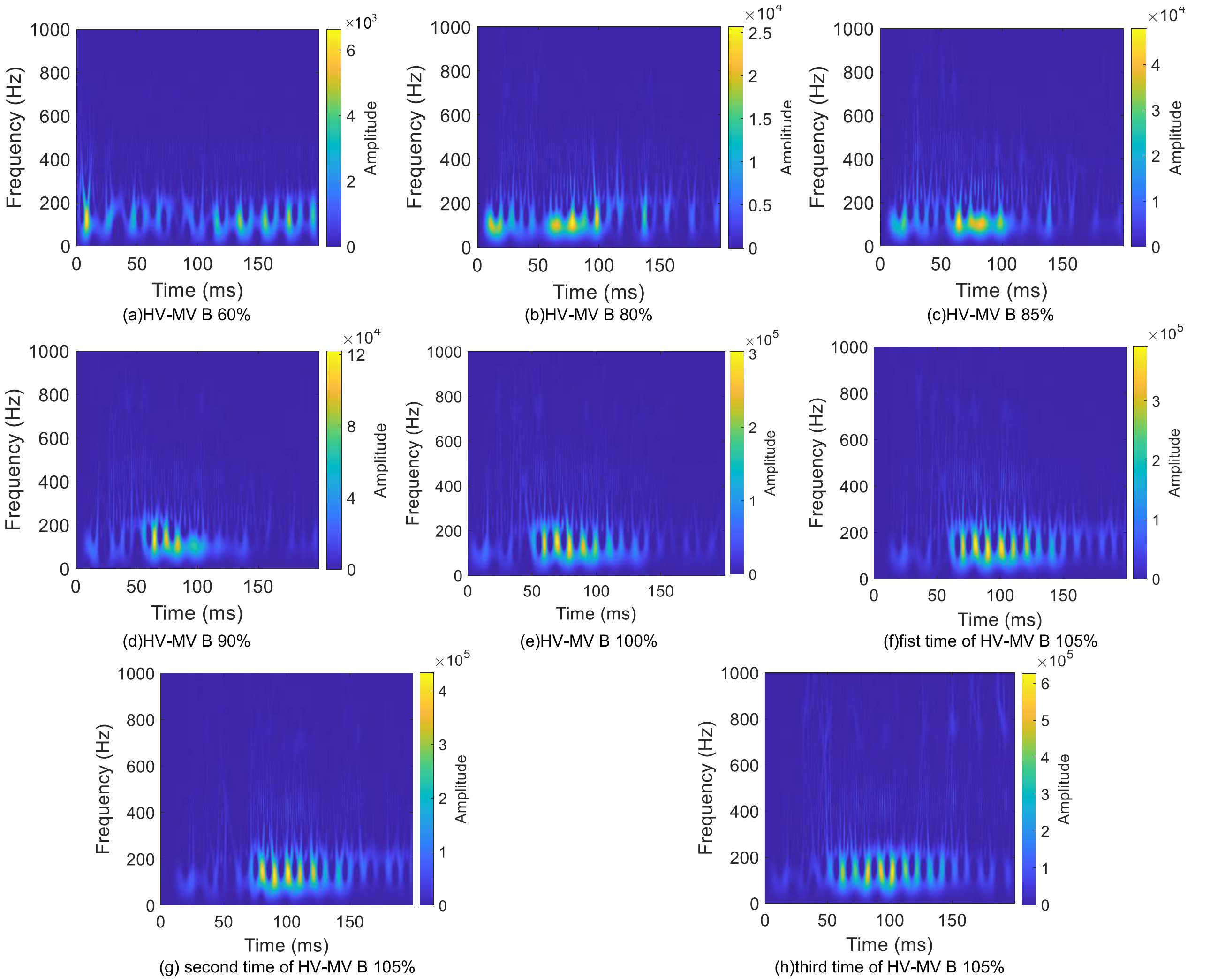

FIGURE 7. **Wigner-Ville Distribution of vibration acceleration.(the value in parenthesis means the short-circuit current).**

is needed. This method needs to define neighborhood radius of density and neighborhood density threshold. DBSCAN is a typical example. This method needs to determine the values of ε and M except the number of clusters in advance, and is sensitive to initial value selection but not to noise. Last but not least, it is not good for data aggregation with uneven density. Hierarchical Methods could divide the data into clusters layer by layer. That is to say, the clusters generated by the latter layer are based on the results of the previous layer. It can solve clustering errors caused by similarity transfer. However, distance calculation is required between every two points, which is inefficient.

The sample data in this paper is consist of singular value matrixes, and the samples have convex distribution. The classification is based on the distance of sample points. After comprehensive consideration, it is considered that Partition-based Clustering Method can better solve the classification with this data. However, K-means method will give clear classification results, which belongs to hard classification. In order to represent the gradual change process of signal state between two categories, on the basis of the method of K-means, the fuzzy C-means clustering method (FCM) is selected, which belongs to soft classification. The membership matrix represents the possibility of the belonging to clusters of each sample, so as to realize the quantitative research of the impact of accumulative effect on vibration signals [28], [29], [30].

The sample category shall be determined in advance under fuzzy C-means clustering. In order to determine the influence degree of the accumulative effect, the samples are divided into two categories: normal working condition and severe deformation working condition, that is, the accumulative influence of several short-circuit shocks on the samples can be determined according to the membership degree of the samples close to severe deformation after each shock.

Take the singular value of the time-frequency matrix as the sample observation data $X = \{A_1, A_2, \ldots, A_8\}$, and set two category centers at the same time; the membership degree of each sample point A_j belonging to a certain category C_i is u_{ij}, and the objective function of FCM, that is, its constraint

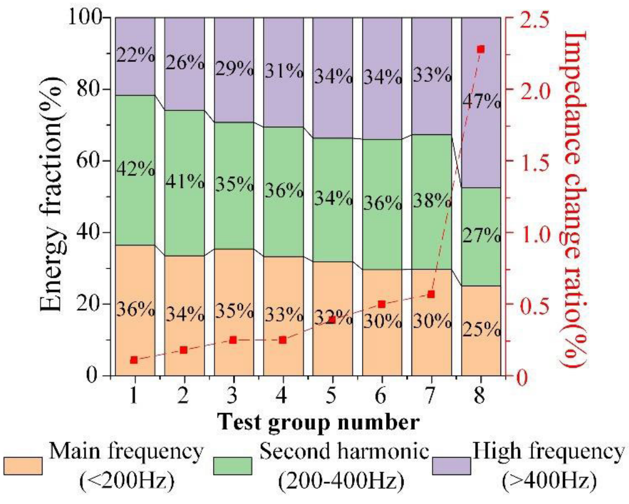

FIGURE 8. Energy fraction diagram.

conditions, satisfies the following formulas as in (9)-(11):

$$\min J = \sum_{i=1}^{2}\sum_{j=1}^{8} u_{ij}^{m}\left\|A_j - C_i\right\|^2 \tag{9}$$

$$0 \leq u_{ij} \leq 1 \tag{10}$$

$$\sum_{i=1}^{2} u_{ij} = 1, \quad j = 1, 2, \cdots, 8 \tag{11}$$

where m is the weighted index; $||A_j\text{-}C_i||$ is the Euclidean distance from the j_{th} sample point to the center of the i_{th} category.

The Lagrange multiplier method is used to sort out the above formulas to build a new objective function, and the Lagrange multiplier of the expansion constraints is shown in (12):

$$\begin{aligned}\min J = &\sum_{i=1}^{2}\sum_{j=1}^{8} u_{ij}^{m}\left\|A_j - C_i\right\|^2 + \lambda_1\left(\sum_{i=1}^{2} u_{i1} - 1\right)\\ &+ \lambda_2\left(\sum_{i=1}^{2} u_{i2} - 1\right) + \cdots + \lambda_8\left(\sum_{i=1}^{2} u_{i8} - 1\right)\end{aligned} \tag{12}$$

Derive the input parameters u_{ij} and C_i and make them equal to 0, and obtain the iterative formula and termination conditions, as shown in (13)-(15):

$$C_i = \frac{\sum_{j=1}^{8} u_{ij}^{m} A_j}{\sum_{j=1}^{8} u_{ij}^{m}} \tag{13}$$

$$u_{ij} = \frac{1}{\sum_{k=1}^{2}\left(\frac{\|A_j - C_i\|}{\|A_j - C_k\|}\right)^{\frac{1}{m-1}}} \tag{14}$$

$$s.t.\ \max_{ij}\left\{\left|u_{ij}^{(k+1)} - u_{ij}^{(k)}\right|\right\} < \varepsilon \tag{15}$$

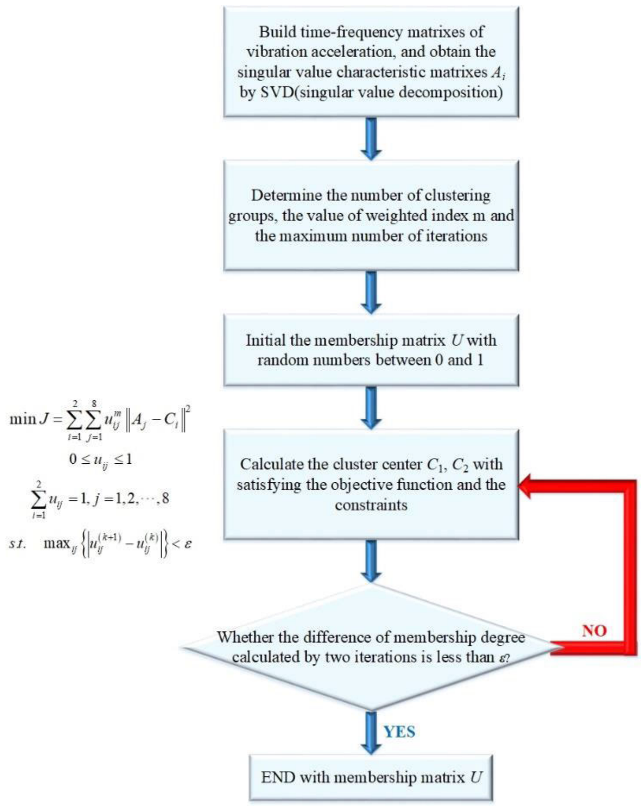

FIGURE 9. FCM calculation flow diagram.

where k is the number of iterations and ε is the iteration termination factor.

To sum up, the calculation flow of analyzing the time-frequency characteristics of vibration acceleration under several short-circuit tests by using fuzzy C-means clustering algorithm is shown in Fig. 9.

C. CASE STUDY

Eight groups of singular values of vibration time-frequency matrix under short-circuit shock tests are taken as state sample data and input into FCM. Given there are two sample states, the number of clusters is set to 2, the weighted index code m is 2, the iteration termination factor ε is 10^{-5}, and the maximum number of iterations k_{max} is 100. The calculated membership degree is shown in Table. 3 and Fig. 10 below.

As shown in Fig. 10, sample points are located in the layer with the initial state degree of 0.9, and the corresponding impedance variation rate is less than 0.4% under the first five short-circuit shocks. The sample points are located in the layers with initial state degree of 0.7 and severe deformation state degree of 0.2, and the corresponding impedance variation rate exceeds 0.5% under the sixth short-circuit shock, which can be considered certain deformation has been accumulated. The sample points are located in the layer with a severe deformation degree of 0.95, and the corresponding impedance variation rates are 0.57% and 2.28%, respectively, under the last two short-circuit shocks. According to the membership degree, the winding can be considered to be in a

TABLE 3. Membership degree of winding mechanical state under several short-circuit shock.

No.	Category 1 initial status	Category 2 Severe deformation
1(60%)	0.9918	0.0082
2(80%)	0.9695	0.0305
3(85%)	0.9491	0.0509
4(90%)	0.9141	0.0859
5(100%)	0.9005	0.0995
6(105%)	0.7887	0.2113
7(105%)	0.0062	0.9938
8(105%)	0.0012	0.9988

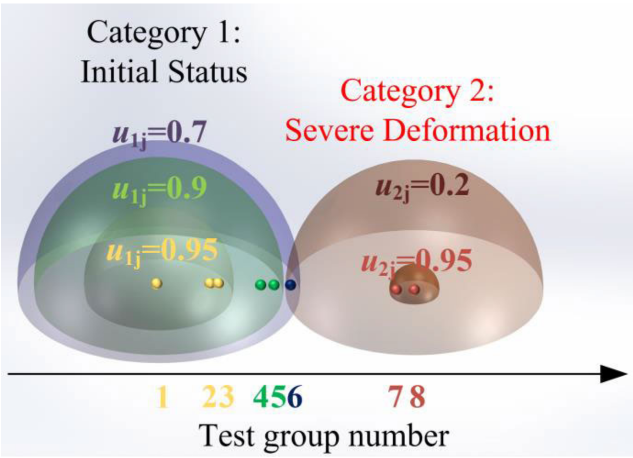

FIGURE 10. Membership degree of winding mechanical state under several short-circuit shock.

state of imminent serious deformation or severe deformation after two tests. Therefore, the membership degree obtained by FCM clustering algorithm can quantitatively reflect the influence of several short-circuit shocks on winding mechanical state to a certain extent.

V. CONCLUSION

In this paper, through conducting short time and multiple short circuit impact true type tests, recording and analyzing the time-frequency characteristics of vibration signals during the test process, the following conclusions are obtained: the accumulative effect will be generated when the transformer suffers multiple short circuit impacts, which will lead to changes in the mechanical properties of the windings. On the one hand, for the time-domain characteristics, the difference of vibration acceleration will gradually increase with the increase of the number of short circuits, which determines the measurability of the accumulative effect of the transformer. The time difference of the last short circuit is 14.631m/s2, which deviates from the reference value by 87.5%. Compared with the 2% deformation criterion of the impedance method, the vibration acceleration can deviate earlier, reflecting the early deformation of the winding under the accumulative effect in advance, which has more sensitive advantages; On the other hand, for the frequency domain characteristics, the high frequency component (>400Hz) of the vibration spectrum increases from the initial 22% to 47%, showing obvious nonlinearity. In order to quantify the characteristics of frequency spectrum changes, the membership matrix of all previous vibration signals tending to the normal state and deformation state of the winding is obtained by constructing the vibration time-frequency singular characteristic matrix and combining with the FCM clustering algorithm. The analysis and calculation results are consistent with the change rule of impedance change rate, and the quantitative analysis of the influence of the accumulative effect of the transformer is realized.

Considering the strong randomness of transformer winding deformation, in the future research, the author will deeply analyze the common characteristics of physical parameters in the process of multiple short circuits, improve the generalization of the accumulative effect analysis method, optimize the installation and configuration of sensors in the test process, and promote the fault location research of winding deformation.

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SHUGUO GAO was born in China, in 1982. He received the master's degree. He is currently a Senior Engineer at a level of researcher. His research interests include transformer state inspection and fault diagnosis.

LU SUN was born in 1988. He received the master's degree from Shanghai Jiao Tong University. He is currently a Senior Engineer at the State Grid Hebei Electric Power Research Institute. His research interests include high voltage power equipment condition detection, health assessment, and fault analysis.

XINYU WANG was born in 1996. He is currently pursuing the Ph.D. degree with North China Power Electric University. His research interest includes power equipment on-line detection.

YUAN TIAN was born in 1990. He received the Ph.D. degree from North China Power Electric University. He is currently a Senior Engineer at the State Grid Hebei Electric Power Research Institute. His research interests include high voltage power equipment condition detection, health assessment, and fault analysis.

JIANGHAI GENG was born in 1980. He received the Ph.D. degree from North China Power Electric University. He is currently a Senior Engineer with North China Power Electric University. His research interests include high voltage and insulator technology.

HONGLIANG LIU was born in 1980. He received the bachelor's degree. He is currently a Senior Engineer at a level of researcher. His research interests include transformer state inspection and fault diagnosis.