A study of characteristic extraction for transformer oscillation wave based on DWT analysis

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Abstract. In order to improve the reliability of transformer winding state evaluation method, the analysis of oscillation wave based on high voltage direct current (HVDC) power supply is proposed. Firstly, different noise reduction methods are adopted dealing with the measured oscillation wave data, and a suitable noise reduction method for field experiments is obtained. Then the discrete wavelet transform (DWT) is applied on denoising data. Finally, the characteristics that can be used to evaluate the state of windings are obtained by analysing the wavelet detailed signals. The results show that the waveform characteristics of windings obtained by discrete wavelet transform have good repeatability and can reflect the differences between different windings.

1. Introduction
Transformer is one of the most core power transmission and transformation equipment in the power system and plays an important role in voltage conversion and power transmission [1]. The mechanical deformation of windings is one of the main causes of transformer failure. According to the statistics of Chinese state grid corporation, the damage rate of transformers of 35 kV and above is as high as 50% due to short-circuit fault [2]. Therefore, it has been a hot topic in power system that how to detect and diagnose the transformer winding faults early and prevent the transformer from catastrophic accidents. Many scholars have studied the detection methods of transformer winding deformation in recent years. A sweep impedance method combining short-circuit impedance and frequency response analysis is proposed in [3], and it is verified by simulation and experiment. In order to obtain the characteristic parameters of transformer winding transfer function, a winding deformation test method based on pseudo-random M sequence excitation is proposed in literature [4]. In [5-7], the identification of winding fault types is further studied based on finite element analysis. The correlation coefficient method is used to analyse frequency response signal data in literature [8]. However, these transformer winding detection methods are still under study, and there is no large-scale practical application at present. Furthermore, most of the above methods are driven by low voltage power supply, ranging from dozens to hundreds of volts. When testing on substation site, it is easy to be interfered by the field environment, resulting in test errors, which may cause misjudgement. Studies have shown that the higher the voltage level of the input signal is, the higher the signal noise ratio (SNR) of its response will be, thus improving the detection accuracy [3]. However, there are few studies on the detection method of transformer windings under the excitation of high voltage power supply.
In this paper, a method to obtain the transformer winding oscillation wave based on the excitation of HVDC power supply is proposed. The method utilizes the coupling circuit formed by the capacitance and inductance of transformer winding to generate an oscillation signal at the end of winding by DC high voltage power supply, to explore the change of oscillation wave of transformer winding and the feasibility of transformer winding deformation detection. A 220 kV/150 MVA oil-immersed three-phase power transformer is taken as the research object. The winding oscillation of transformer at different output terminals of the transformer under different voltage levels of HVDC excitation is analysed through field test. Firstly, the comparison of denoising field data between fast Fourier transform and wavelet transform is studied. Then discrete wavelet transform is applied to the oscillation wave data of transformer windings and the corresponding characteristic parameters are extracted. This can be used as a reference for judging transformer winding deformation by using transformer winding oscillation wave.

2. Field test and principle of winding oscillation

2.1 Principle of winding oscillation

A large number of experiments show that the transformer winding can be equivalent to the circuit model consisting of capacitance, inductance and resistance when the frequency is greater than 1 kHz [9,10]. The principle of frequency response method is to analyse the windings by measuring the transfer function characteristics of the system under different ac frequencies. However, it is more cost-effective to use HVDC for detection in engineering, because ac power supply equipment is larger and more expensive than dc equipment. In this paper, HVDC equipment is used to accomplish the transient change of excitation by high voltage switch. In addition, the oscillation signal is generated under the coupling reaction of transformer leakage reactance, capacitive bushing and windings to ground and interturn stray capacitance and inductance. The characteristics of the oscillation signal are related to the transformer winding structure and parameters such as amplitude, response time and frequency.

As shown in Fig 1, the field offline test was carried out. Firstly, the capacitors between the ground and windings are charged by applying high-voltage dc voltage to the neutral point of the star winding. Then the neutral point is quickly grounded to produce a steep drop edge, so that the excitation has a large component in the high frequency band, which satisfies the equivalent circuit of transformer winding [11]. Finally, the equivalent capacitance of the transformer windings discharge after the loss of excitation. The transformer windings show strong sensibility under the influence of the transformer core, and generate damped oscillation discharge. It is the transformer winding oscillation discussed in this paper.

The capacitance and inductance will change when transformer winding internal fault occurs. The capacitance inductance coupling also changes, which affects the oscillation wave of the transformer windings. Therefore, it is important to study the oscillation wave and find out the characteristic parameters which can be used to identify.

![Figure 1. Experimental schematic](image-url)
2.2 Field test

Schematic diagram of field test is shown in figure 2. The oscilloscope in the figure is DPO5204B Tekker oscilloscope, which can collect three output terminal waveforms at the same time, and the sampling rate is 1 MS/s. The high-voltage dc power supply used in the experiment can generate excitation up to 110 kV. Firstly, the neutral point of high voltage winding is injected excitation, and the turn-off time is controlled by the high voltage controllable switch. The response signals can be received from the high-voltage side, medium-voltage side and low-voltage side of the transformer by using the bushing terminal capacitance and partial voltage capacitance.

The measured data excited by 30 kV power supplies at the output measurement ports of the high-voltage side, the medium-voltage side and the low-voltage side are shown in figure 3. Under the transient excitation of the high-voltage dc power supply, the winding ends have obvious oscillation attenuation signals. As shown in figure 3, the output winding oscillation waves on the high-voltage side of different excitation voltage levels have obvious differences. The amplitude of winding oscillation varies greatly and is easy to distinguish.

Therefore, the winding oscillation waves of transformer have good repeatability in each phase under HVDC excitation, which can reduce the measurement error. A method of winding oscillation wave acquisition based on discrete wavelet transform is proposed in this paper in order to analyse the winding oscillation wave under HVDC excitation and extract the characteristic parameters. The field noise is removed by wavelet soft threshold function, and then the winding oscillation wave is obtained by discrete wavelet transform in this method.

3. Measured signal denoising

As shown in figure 3, the output noise of the transformer oscillation wave on the high voltage side is obvious. The on-site data shall be de-noised, in order to analyse the measured data, remove the sudden burr and other noises and reduce the noise interference.
Fast Fourier denoising and wavelet denoising are commonly used in denoising. Fast Fourier transform, wavelet hard threshold de-noising and wavelet soft threshold de-noising were respectively used to conduct de-noising analysis on the measured winding oscillation in this paper to obtained suitable denoising. Through a lot of simulation, sym8 wavelet is selected to decompose noise signal in 6 layers. According to literature [12], [13], adaptive threshold denoising of mixed threshold rule 'heursure' was selected. Three denoising performance indexes were made to, namely SNR and root-mean-square error and smoothness, quantitative analysis of the denoising effect of signals in order to make an comparison of the above three denoising methods.

(1) The SNR formula is defined as:

$$ SNR = 10\log \left( \frac{ \sum_{i=1}^{n} x^2(i) }{ \sum_{i=1}^{n} (x(i) - X(i))^2 } \right) $$

(2) The root-mean-square error of the measured signal and the denoising signal is defined as:

$$ RMSE = \sqrt{ \frac{1}{n} \sum_{i=1}^{n} (x(i) - X(i))^2 } $$

(3) Smoothness index is defined as follows:

$$ R = \frac{ \sum_{i=1}^{n-1} [X(i+1) - X(i)]^2 }{ \sum_{i=1}^{n-1} [x(i+1) - x(i)]^2 } $$

Denoised signal at $X(i)$, measured signal at $x(i)$, n is the number of sampling points. It is defined as follows: the higher the SNR value of the new signal is, the smaller the RMSE value is, and the lower the smoothness index is, indicating that it is closer to the original signal after denoising. The denoising results of each function are shown in table 1. In general, the wavelet soft threshold function can effectively remove the field noise and excess noise, and the denoising effect is better than FFT and wavelet hard threshold.

Table 1. The denoising contrast results of different denoising methods

| Denoise                | SNR   | RMSE  | smoothness |
|------------------------|-------|-------|------------|
| FFT                    | 11.347| 0.2508| 7.6725     |
| Wavelet hard threshold | 12.508| 0.2201| 4.4377     |
| Wavelet soft threshold | 12.807| 0.2127| 1.8938     |

4. Acquisition and characteristic analysis

The signal noise interference is reduced after denoising the measured data. A method of analysing the winding wave based on discrete wavelet transform is proposed in order to extract the characteristic parameters and analyse the oscillation wave. Discrete wavelet transform is applied to the measured signal after denoising to obtain the discrete wavelet detail signal. Finally, the characteristic parameters for analysis is extracted.

4.1 Discrete wavelet transform

Wavelet transform has the ability of denoting local signal characteristics in time domain and frequency domain, which is a fixed window size but the shape variable [14-16]. And the time window and frequency window can change, such ad in the low frequency part with high frequency resolution and low time resolution, the high frequency part with high temporal resolution and low frequency resolution [17].
When $\Psi(t)$ is part of $L^2(R) \cap L^2(R)$ represents the square integrable real space, the FFT transformer is $\phi(\omega)$. If $\phi(\omega)$ satisfies the constraint condition

$$\int_R \frac{|\hat{f}(\omega)|^2}{|\phi(\omega)|^2} d\omega < \infty$$

(4)

In this case, $\Psi(t)$ is called a basic wavelet or a mother wavelet. The wavelet transform of a continuous time signal is defined as

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \cdot \psi' \left( \frac{t-b}{a} \right) dt$$

(5)

DWT is relative to continuous wavelet transform. DWT is the discretization of CWT (a,b) by using discrete values $a = 2^m$ and $b = 2^m n$ as scale factor and displacement factor.

$$DWT(m,n) = \frac{1}{\sqrt{2^m}} \int_{-\infty}^{\infty} f(t) \psi' \left( \frac{t-2^m n}{2^m} \right)$$

(6)

$m$ and $n$ are frequency and time respectively, and are natural numbers. Select the appropriate wavelet transform, and then through multi-resolution analysis (MRA), the signal $f(t)$ can be decomposed into approximate term low-frequency part $\phi_{m,n}(t)$ and detail term high-frequency part $\Psi_{m,n}(t)$.

4.2 Acquisition of winding oscillation wave

The acquisition method of winding oscillation wave based on discrete wavelet transform is proposed to process the winding oscillation signals output on the high-voltage side excited by 40 kV. In the process of discrete wavelet transform, sym8 wavelet was used to decompose the measured signal of winding oscillation in six layers to obtain the best result after a lot of simulation verification [18]. The processing results are shown in figure 4. Figure 4(a) is the comparison between the measured data and the filtered data, and figure4 (b) is the detail signal d1-d6 of the discrete wavelet transform.

According to the research figure4 (b), it can be seen that the value of detail signal d1-d3 is small, which is the interference caused by the high frequency of field noise [19]. The waveform d4-d6 reflects the winding oscillation, in which d5 mainly focuses on the large mutation, d4 contains the main signal of the self-excited oscillation, and d6 presents the attenuation process of the oscillation wave. Therefore, d4-d6 reflect the winding oscillation wave, while the d6 signal has no noise interference, and the analysis of the oscillation wave is more intuitive by comparing the cases of different phases, amplitudes and output points. Therefore, after the discrete wavelet transform, d6 is the main parameter and d4-d5 are the auxiliary parameters for the study of the oscillation wave.

Compared with the measured signals, the discrete wavelet transform of the detail signal diagram contains less noise, more intuitive. It can reflect the winding oscillation wave in different phases, excitation amplitude, output terminal, the detail signal. To sum up, the winding oscillation wave based on discrete wavelet transform is easier than the measured signal, and corresponding characteristic parameters d4, d5 and d6 can be extracted for further analysis of different phases, excitation amplitudes and output terminals.
4.3 Feature extraction analysis method

Discrete wavelet transform is adopted to carry out n-level decomposition. After decomposition, the average value of detail coefficient of the original signal at the $j$-level decomposition can be defined as follow.

$$A_j(t) = \frac{1}{2^jN_{dj}} \sum_{i} d_j(i)$$

(7)

In this paper, two characteristic parameters are used to characterize the properties of winding oscillation waves. The standard deviation of the detail coefficient when a characteristic parameter is defined as the $j$-level decomposition is

$$S_j(t) = \sqrt{\frac{1}{2^jN_{dj}} \sum_{i} \left( |d_j(i)| - A_j(i) \right)^2}$$

(8)

And define a feature parameter as the detail coefficient with a variance of

$$C_j(t) = \frac{1}{N_{dj}} \sum_{i} (d_j - \text{mean}(d_j))$$

(9)

Where, $j$ is the decomposition series; $d_j$ is the detail coefficient of the $j$-level decomposition; $N_{dj}$ is the number of detail coefficients of the $j$-level decomposition.

The detailed signals obtained after discrete wavelet transform are processed, and the changes of characteristic parameters in different phases, excitation amplitudes and output terminals are studied, as shown in table 2-4. As can be seen from the table, there are differences in the winding oscillation waves generated by different phases, excitation amplitudes and output terminals. The two characteristic parameters proposed in this paper can characterize the differences in the winding oscillation waves generated by different phases, excitation amplitudes and output terminals.

Table 2. Comparison of low-voltage side parameters of 20kV excitation

| The output phase | parameter | d4     | d5     | d6     |
|------------------|-----------|--------|--------|--------|
| a phase          | C_6       | 0.7433 | 1.2527 | 6.3605 |
|                  | S_{d6}    | 0.1957 | 0.1526 | 0.3114 |
| b phase          | C_6       | 0.3195 | 1.1764 | 4.3863 |
|                  | S_{d6}    | 0.1350 | 0.1115 | 0.2212 |
| c phase          | C_6       | 0.7290 | 0.1191 | 3.9008 |
|                  | S_{d6}    | 0.1545 | 0.1281 | 0.2135 |

Table 3. Comparison of phase b parameters at medium pressure side
Table 4. Comparison of 20kV a excitation phase parameters

| Voltage | parameter | d4     | d5     | d6     |
|---------|-----------|--------|--------|--------|
| 20kV    | C6        | 1.0752 | 0.0356 | 3.4126 |
|         | Sd6       | 0.1943 | 0.3587 | 0.4861 |
| 30kV    | C6        | 0.8052 | 0.2631 | 10.6327|
|         | Sd6       | 0.7713 | 0.4178 | 1.3242 |
| 40kV    | C6        | 0.5548 | 3.0673 | 19.4815|
|         | Sd6       | 0.6136 | 1.5808 | 2.4766 |

According to the data in Table 2, the two characteristic parameters of a phase are greater than b phase and c phase, and b phase and c phase are close to each other in the same output side. As shown in Table 3, the characteristic values of d4 and d5 do not change significantly with different excitation amplitudes, and both characteristic parameters of d6 signal increase by multiples. In Table 4, the difference between the low pressure side and the middle pressure side is small, and the characteristic values on the high pressure side are both higher than the former two. D6 signal is more obvious in characterizing the variation of winding oscillation wave and more suitable for reflecting the properties of transformer winding oscillation wave compared with d4 and d5 components.

As shown in Figure 5, the detail d6 signals after discrete wavelet transform in different phase diagram Figure 5(a), excitation amplitude Figure 5(b) and output Figure 5(c) can reflect the change of the winding oscillation wave compared with the measured signal in Figure 3. D6 signals of oscillation waves in different conditions are different, with good repeatability, and it is easier to analyze and study by combining with characteristic parameters. Therefore, d6 characteristic parameters, combined with d4 and d5 auxiliary parameters, are used to characterize the winding oscillation waves, and the characteristic parameters can be extracted from the measured data.
5. Conclusion

The feature extraction method based on HVDC transient excitation response signal proposed in this paper has the feature of high test efficiency. The method of extracting the oscillation wave characteristics of the transformer windings based on discrete wavelet transform is studied through analysing the measured data. The main conclusions are as follows:

1) The winding oscillation wave based on the discrete Fourier transform proposed in this paper has obvious differences in different phases, excitation amplitudes and output ends. Taking d6 signal as the main research object, the standard deviation and variance of the defined characteristic parameters are extracted.

2) The wavelet soft threshold function is better than the wavelet hard threshold and fast Fourier transform in removing the oscillating field noise and excess noise in the field data denoising research.

3) Based on the discrete wavelet transform to filter data processing, analysis of detail coefficient d1-d6, d4-d6 characteristic parameters reflect the characteristics of winding oscillation wave, especially the d6 signal, can reflect the winding oscillation wave changes under different circumstances.

In the field test, there are differences in the winding phase, excitation amplitude and output terminals under normal conditions, which provides a reference for the transformer winding oscillation wave to judge the transformer winding deformation. Subsequent studies can be carried out to analyze the changes of corresponding characteristic parameters under different faults of transformer winding oscillation waves, the research on classification and identification of fault characteristic parameters, and the differences of winding oscillation waves between different transformers.

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