Study on Influence of Aging on Vibration Characteristics of Transformer

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Abstract. It is important to assess the insulation aging state of transformers, which can not only avoid equipment faults, but also improve the economic benefits of transformer operation. The main negative effect of transformer insulation aging is the decline of insulation mechanical properties, which will eventually lead to transformer fault. In this paper, the transformer vibration characteristic test platform is built and the vibration characteristic variables are defined to describe the vibration characteristic quantitatively. Then, the vibration characteristics and vibration variables of transformer tank surface under different aging time are studied by accelerated aging test in the laboratory. Finally, the vibration signals of transformers in service under different operation time are measured. And the vibration characteristics and vibration variables of in-service transformers under different operation time are analyzed and studied. This paper directly aims at the mechanical characteristics of insulation, and studies the relationship between insulation aging state and vibration of transformer. It provides a basis for more effective and direct monitoring of insulation aging state.

Keywords: Power transformer, condition monitoring, insulation aging, vibration.

1. Introduction
Power transformer is one of the most important power equipment in power system. However, the long-term operation of power transformers in the harsh working environment, fault rate has been very high [1]. The oil immersed power transformer is widely used in power system. The safety and reliability of the oil-paper insulation system is the prerequisite for the normal operation of the transformer, and the insulation system determines the service life of the transformer. More than 80% of the total faults of transformers are caused by insulation problems of transformers, and the faults caused by insulation aging account for a large proportion [2,3]. On the one hand, the mechanical and electrical properties of insulation materials continue to decline during aging, which can eventually lead to insulation failure. The statistical results show that the unplanned outage rate of transformers that have been put into operation for more than 20 years is much higher than that of transformers that have been put into operation for 5 to 10 years [4]. On the other hand, there are a large number of relatively new transformers in China. 62.7% of the transformers have been put into operation within 10 years. The average operation time is far lower than the average operation life of transformers in mature power grids. Moreover, the
service life of retired transformers in China is far less than the design life, which is generally 30 years. Therefore, the research of transformer insulation aging assessment technology, not only helps to find the insulation fault of transformer in time, but also can accurately judge the state of insulation and make full use of the service life of transformer.

Up to now, most of the assessment technology is based on chemical and electrical characteristics. However, there are more or less problems such as easy to be disturbed, poor accuracy and difficulty in implementation. The transformer condition detection technology based on vibration signal has many advantages, such as strong anti-interference ability and easy operation, and it can obtain a lot of internal mechanical state of transformer. The service life of oil immersed transformer mainly depends on the service life of solid insulation represented by insulating paper and laminated paperboard. And the mechanical properties of paper insulation are the main criteria to assess the paper insulation. Therefore, it is important and necessary to study the relationship between insulation aging state and vibration of transformer.

In this paper, the transformer vibration characteristic test platform is built to study the relationship between insulation aging state and vibration characteristics. Firstly, the vibration characteristic variables are defined to describe the vibration characteristic quantitatively. Then, the aging-vibration transformer test platform is built in the laboratory, and the vibration signals of the transformer tank surface under different aging time are studied through the accelerated aging test. Finally, the vibration characteristics of transformers in service in different operating time are analyzed. And according to the aging vibration characteristics of laboratory transformer and in-service transformers, the vibration characteristic variables which may evaluate the aging state of transformer insulation are obtained.

2. Vibration characteristic test platform

The axial vibration and radial vibration of the transformer winding can be transmitted to the surface of transformer oil tank. The axial vibration can be transmitted through fasteners such as pressboard and transformer oil, while the radial vibration is mainly transmitted by transformer oil. Therefore, the aging vibration characteristics of transformer can be studied according to the vibration signals of the tank surface.

The vibration characteristic test platform of transformer is built in the laboratory environment, as shown in Fig. 1. The transformer is a single-phase transformer, whose winding is tightly connected with the upper cover of the tank. The test transformer specifications are shown in Table 1. The measuring points are selected at 1/4 and 3/4 height of the transformer tank surface, where are close to the winding and far away from the stiffener. The position of the measuring points is shown in Fig. 1.

![Figure 1. Vibration characteristic test platform in the laboratory.](image-url)
Table 1. Test transformer specifications.

| Type       | Parameter  |
|------------|------------|
| Rated frequency | 50Hz       |
| Rated capacity    | 50kVA      |
| Rated voltage    | 10kV/400V  |
| Rated current    | 5A/125A    |
| Cooling mode    | Oil-immersed self-cooling type |

The transformer vibration measurement system is composed of vibration sensor, signal acquisition card and computer. For facilitate installation on site, the vibration sensor uses 603c01 acceleration sensor of PCB company. The sensor can be fixed on the measuring point on the surface of transformer tank by magnet adsorption.

The vibration measurement system used in field transformer is same. The selection of measuring points is similar to that of the laboratory transformer, and the location far away from the stiffener can better reflect the vibration of the winding. The winding of large oil immersed transformer on site is generally connected with the lower base, so the measuring point should be selected in the plane area facing each phase winding, and the height is 1 / 3 of the tank height close to the base. The schematic diagram of the measuring points is shown in Fig. 2.

3. Vibration characteristic variables

The continuous vibration signal can be obtained by the vibration measurement system, and the characteristic variables of the vibration signal can be extracted by time-domain, frequency-domain and time-frequency-domain analysis.

For a steady-state transformer, the vibration frequency spectrum can be analyzed, and the vibration amplitude of different frequency components can be obtained. The following characteristic variables of vibration signal are defined. Two times of power frequency is defined as the fundamental frequency of vibration signal. Generally, when the power frequency is 50 Hz, the 100 Hz vibration component is the fundamental frequency component of the vibration signal. The amplitude off frequency component in vibration spectrum is defined as $A_f$, which is called f frequency component amplitude, and the vibration amplitude of fundamental frequency component is called fundamental frequency amplitude. The frequency corresponding to the maximum vibration amplitude in the spectrum is defined as the main frequency. The main frequency amplitude is the maximum vibration amplitude in the spectrum. There are many 100Hz and 100Hz multiple frequency vibration components, and even many 50 Hz and odd harmonic vibration components in the frequency spectrum of the actual vibration signal. The main frequency may not be 100 Hz. When the modal shape of the whole winding structure changes, the vibration response of each frequency may change. The vibration amplitude may be affected by the current. In order to realize normalization, the proportion of the square of the amplitude of the frequency
component f to the sum of the amplitudes of all the frequency components in the spectrum is defined as the frequency proportion $p_f$, as shown in formula (1).

$$p_f = \frac{A_f^2}{\sum_{f=50}^{1000} A_f^2} \times 100\% \quad (1)$$

In the formula (1), only the amplitude squared of 50 Hz and its multiple frequency within 1000 Hz are considered, because most of the vibration is concentrated on these vibration components. The frequency proportion of the fundamental frequency component is defined as the fundamental frequency proportion, and the frequency proportion of the main frequency component is the main frequency proportion. Define the harmonic like 50 Hz, 150 Hz, …, 950Hz is odd harmonic, and the sum of their frequency proportion is the odd harmonic proportion. Define the harmonic like 100 Hz, 200 Hz, …, 1000Hz is even harmonic, and the sum of their frequency proportion is the even harmonic proportion. The sum of the squares of the amplitude of odd harmonic vibration is defined as the odd energy, and the sum of the squares of the amplitude of the even harmonic vibration is defined as the even energy. Define the power spectrum center as shown in formula (2).

$$C = \frac{\sum_{f=50}^{1000} f A_f^2}{\sum_{f=50}^{1000} A_f^2} \quad (2)$$

4. Influence of aging on vibration characteristics of transformer

4.1. Influence of aging on vibration characteristics of transformer in the laboratory

In order to study the influence of aging on the vibration characteristics of transformer in the laboratory, the single-phase transformer is put into a high-temperature test chamber in the laboratory for accelerated aging test, the specific test process is as follows:

(1) A sufficient amount of silica gel desiccant is placed in the high-temperature test chamber, and the transformer is put into the high-temperature test chamber, and the temperature is set at 120°C for accelerated thermal aging for 720h.

(2) Take out the transformer every 120h, interrupt the aging, and measure the vibration characteristics after the transformer temperature is cooled to room temperature. Based on the transformer vibration characteristic test platform, the steady-state short-circuit test method is adopted to adjust the high-voltage side voltage to make the low-voltage side current of 120A, and measure the vibration acceleration at measuring point.

(3) After repeated accelerated thermal aging test and vibration characteristic test, the vibration spectrum of transformer under different aging time was measured as shown in Fig. 3. The relationship between the vibration amplitude of each frequency component and aging time is analyzed. The odd harmonic components are shown in Fig. 4, and the even harmonic components are shown in Fig. 5. In odd harmonics, the components of 50 Hz, 150 Hz and 250 Hz increase monotonously to varying degrees with aging, while the amplitude of 350 Hz component is small and almost does not change with aging. This shows that the coupling effect of magnetic field and vibration is gradually strong with the aging degree deepening, and the coupling effect on the gain of 50 Hz is the most obvious. In even harmonics, the 100Hz component decreases monotonically with aging. This shows that with the aging process, the modal vibration mode of the winding structure changes, and the natural frequencies of each order decrease. The 100Hz response of the winding vibration amplitude frequency response gradually decreases with aging. The 200Hz component increases monotonically with aging. This shows that the 200Hz response of the winding vibration amplitude frequency response increases with aging. The amplitudes of 300Hz and 400Hz components are small and hardly change with aging. Due to the dispersity of winding structure, the mode shapes of different winding structures are different from each other. With the aging process, the natural frequency decreases, the variation of amplitude of 100Hz and its multiple frequency components is not universal, so the aging state cannot be judged simply by the amplitudes of 100Hz and its multiple frequency vibration components increase or decrease.
According to the vibration characteristic variables defined in section 3, the variation law of vibration characteristic variables with aging of transformer is studied. The fundamental frequency proportion, main frequency amplitude, main frequency, power spectrum center, main frequency proportion, odd harmonic proportion, even harmonic proportion, odd energy and even energy are calculated respectively. The vibration characteristic variables of transformer under different aging time are shown in Fig. 6.
Fundamental frequency proportion

Main frequency amplitude

Main frequency and power spectrum center

Main frequency proportion

Odd harmonic proportion

Even harmonic proportion

Odd energy

Even energy

**Figure 6.** Vibration characteristic variables of transformer under different aging time.

From Figure 6, the fundamental frequency proportion monotonically decreases with aging. The main frequency is always 100Hz, so the main frequency characteristic is the fundamental frequency characteristic in this case, and the main frequency proportion is the same as the fundamental frequency proportion. The power spectrum center gradually increases with aging, which is because the fundamental frequency gradually decreases and the higher harmonic increases. The odd energy gradually increases, while the even energy has a downward trend, which indicates that with the aging
process, the power spectrum gravity center increases gradually, the results show that the coupling effect of magnetic field and vibration of winding is gradually enhanced, and the corresponding mode of even harmonic is gradually reduced. The proportion of odd harmonic increases obviously with aging, while the proportion of even harmonic is opposite.

4.2. Influence of aging on vibration characteristics of in-service transformers

On the basis of laboratory tests, field tests were carried out on several in-service power transformers. The operation time of each transformer was recorded and field vibration characteristic tests were carried out. In order to reduce the interference of other factors and mainly study the influence of aging on the vibration characteristics of field transformer, the transformers with rated voltage of 110kV are selected, and their historical operation conditions and load conditions are similar. In this way, the aging caused by long-term operation will be the main factor affecting the vibration characteristics of these transformers. Due to dispersion, the average value of six measuring points is taken for each transformer. The relationship between vibration amplitude of each frequency component and operation time is shown in Fig. 7.

![Graphs](attachment:diagram.png)

(a) The relationship between the odd harmonic component amplitude and operation time.  
(b) The relationship between the even harmonic component amplitude and operation time.

**Figure 7.** The relationship between each frequency component amplitude and operation time.

According to Fig. 7, it can be found that the variation law of vibration amplitude of each frequency component with operation time is not monotonic, but there is a certain trend in statistics. Among the odd harmonic components, the amplitude of 250Hz is generally larger, the amplitudes of 150Hz and 50Hz are smaller. This shows that the coupling of magnetic field and vibration of 110kV transformer winding mainly acts on the odd harmonic of 250Hz. Similar to the aging vibration characteristics of laboratory transformer, with the increase of operation time, the vibration amplitude of 250Hz component increases significantly, the vibration amplitude of 150Hz component slightly increases, and the vibration amplitude of 50Hz component almost does not change. This is because with the increase of operation time, the aging of insulation, the elastic coefficient of insulation paper material such as insulation pad decreases, and the magnetic field vibration coupling effect of winding is enhanced. The difference is that the odd harmonic component of laboratory transformer which increases with aging time obviously is 50Hz component. It can be inferred that this is mainly due to the difference of main frequency. The main frequency of laboratory transformer is 100Hz, while the main frequency of field transformer is generally large, mostly 200Hz and 300Hz. Therefore, the magnetic field vibration coupling effect is mainly reflected in 250Hz and 150Hz. Among the even harmonic components, the amplitudes of 200Hz and 300Hz are larger and 100Hz is the smallest. With the increase of operation time, the vibration amplitude of 200Hz and 300Hz components increased in varying degrees, while the vibration amplitude of 100Hz component increased slightly. This shows that the nonlinear mechanical characteristics of
The insulation pad in actual 110kV transformer are more significant. With the increase of operation time, the aging degree is generally deepened, and the 200Hz and 300Hz components of modal vibration mode tend to increase.

5. Conclusions
Combined with the aging-vibration characteristics of laboratory transformer and in-service transformers, it can be concluded that the frequency spectrum of transformer vibration signal contains a large number of vibration characteristic variables which can characterize the aging degree of transformer insulation mainly including the vibration amplitude of each frequency component, the fundamental frequency proportion, the main frequency amplitude, the main frequency, the power spectrum center, the main frequency proportion, the odd harmonic proportion, the even harmonic proportion, the odd energy and the even energy.

However, any single vibration characteristics variable cannot evaluate the aging degree of transformer insulation, especially the in-service transformer. And it is necessary to use the vibration characteristics variables to model, and then conduct comprehensive evaluation in the future.

References
[1] Jialin Wang, Dajian Li, Accidents and defects analysis of 110kV and above voltage transformers [J], Guangxi Electric Power, 2014, 37(4):63-64.
[2] Ruijin Liao, Fumin Sang, Gang Liu, Lijun Yang, Study on neutral acid and water dissolved in oil for different types of oil-paper insulation compositions of transformers in accelerated ageing tests [J], Proceedings of the CSEE, 2010, 30(04):125-131.
[3] Xiaobo Gu, Yijun Zhang, Research and application of insulation ageing for power transformer based on frequency domain spectroscopy [J], Zhejiang Electric Power, 2010, 29(1):13-17.
[4] National energy administration, China electricity council. Annual report of national electric power reliability in 2017 [R/OL], Beijing, 2018-06-06