

# A Vibration Method for Identifying the Looseness of Windings for Large Power Transformers

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**Abstract.** The safe operation of large power transformers is very important for the electricity system, while the looseness of winding clamping pressure is one of the main failure reasons. To deal with this problem, a two-degree-of-freedom nonlinear mechanical model for one winding is proposed and analyzed to study the influence of clamping pressure looseness on the windings' vibration characteristics. The simulation of this model studies the influence of clamping pressure changes on the winding's natural frequency and its amplitude. Based on this study, the vibration method under swept frequency with constant current is put forward to identify the looseness of the windings. The experiments were conducted on one real large power transformer, which testifies that this method is effective by exactly identifying the windings' looseness.

**Keywords:** condition monitoring; transformer winding; vibration; swept frequency

## 1. Introduction

The power transformers play an important role in the electricity system. It's most important to continuously monitor and assess the condition of transformers to ensure reliability of power supply. During their operation, the looseness of windings' clamping pressure is one of the main reasons for transformers' failure[1-4]. Therefore, how to effectively identify the looseness and deformation of windings is important to keep the safety of transformers' operation[5].

The traditional methods to identify the windings' deformation include the short-circuit reactance method[6] and the frequency response analysis[4, 7], both of which adopt electrical measurement methods. However, when the winding undergoes a small deformation, these methods are disabled in identifying the real condition. The looseness or deformation of windings essentially affects the mechanical characteristics of transformers' body[8], which can be indentified and analyzed by measuring the related vibration signals.

Sanz-Bobi *et al.*[9] studied how to measure the vibration of windings with the accelerometer sensor located on the inner of transformers. Mechefske[10] reported an experiment about tank vibration monitoring over two twin units with the vibration signals recorded from outside the transformer tank, and found that the frequency spectra changes obviously when the windings were loose. McDonald and MIT[11, 12] developed an inspection system based on artificial neural network. Xie poan *et al.*[13] built a finite-element model of a single winding. The clamping pressure was identified by estimating the 100-Hz vibration magnitude of the tank with simulation and experiment. García and Alonso[14, 15] developed a mathematical model with electrical current, voltage, and temperature as input. The state of transformer was identified by comparing the 100-Hz vibration magnitude of the tank.

The aforementioned researches mainly proposed the methods of identifying the windings' state based on the 100-Hz vibration magnitude of the tank. The change of winding's state, for example clamping pressure,

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can be shown on the vibration magnitude of 100-Hz. The reason is that the natural frequency offsets because of the winding's structure characteristics change, which lead to the change of the 100-Hz vibration magnitude. Monitoring the change of the 100-Hz vibration magnitude in fact estimates the offset of windings' natural frequency. Therefore, the windings' states can be more precisely monitored by directly measuring the change of the windings' structure characteristics.

Motivated by the above considerations, a two-degree-of-freedom nonlinear mechanical model is proposed and analyzed for the windings. Then the simulation studies the change of the windings' mechanical characteristics caused by the looseness of their clamping pressure. Therefore, this paper proposes the vibration method under swept frequency with constant current in order to monitor the states of the windings. The experiments have been conducted to validate the proposed method.

## 2. Windings' Nonlinear Vibration Model

According to the structure characteristics of transformer winding, mass-spring system can be used to model the winding by considering clamp plates as rigid elements, disc coils as concentrate masses, and insulation cardboard and end loops as nonlinear elastic elements. If two-disc-winding is considered, the corresponding mass-spring system is shown in Fig. 1.

Because the relation between electromagnetic force and the current is:

$$F = bi^2 \quad (1)$$

$$i = I \cos \omega t \quad (2)$$

where  $\omega$  is the power frequency.

Axial electromagnetic force can be derived by substituting (2) for  $i$  into (1):

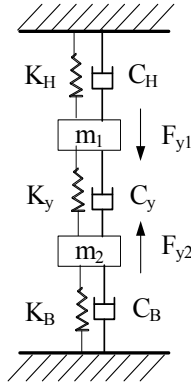


Fig. 1: Mass-spring system

$$F_y = \frac{1}{2} bI^2 (1 + \cos 2\omega t) \quad (3)$$

According to related reports and a large amount of experiments, insulation cardboard's stress-strain property, within a certain scope of stress, can be expressed as[8]:

$$\sigma = a\varepsilon + b\varepsilon^3 \quad (4)$$

Where  $\sigma$  is stress,  $\varepsilon$  is strain,  $a$  is linearity coefficient and  $b$  is hardening coefficient. Values of  $a$  and  $b$  are obtained by experiments.

While Elastic modulus  $E = \frac{d\sigma}{d\varepsilon}$ , so

$$E = a + 3b\varepsilon^2 \quad (5)$$

Because  $K$  is the stiffness coefficient of insulation cardboard, there exists

$$K = \frac{df}{dl} \quad (6)$$

Where  $l$  is the thickness of the insulation cardboard,  $f$  is the force on the insulation cardboard.

$$df = A_s \cdot d\sigma \quad (7)$$

$$dl = l \cdot d\varepsilon \quad (8)$$

Where  $A_s$  is the area of insulation cardboard.

The following equation can be derived by substituting (7) and (8) into (6),

$$K = \frac{A_s \cdot d\sigma}{l \cdot d\varepsilon} = \frac{A_s}{l} E$$

that is,

$$K = \frac{A_s}{l} (a + 3b\varepsilon^2) = \frac{A_s}{l} \left( a + 3b \left( \frac{\Delta l}{l} \right)^2 \right) \quad (9)$$

Where  $\Delta l$  is the change in the insulation cardboard's thickness.

Besides, coefficient of damping [16] is

$$\begin{aligned} C_H &= 0.00025 \frac{A_s a}{l_H} \\ C_y &= 0.00025 \frac{A_s a}{l_y} \\ C_B &= 0.00025 \frac{A_s a}{l_B} \end{aligned} \quad (10)$$

Where  $l_H, l_y, l_B$  are separately the thickness of  $K_H, K_y, K_B$  in Fig. 1.

As shown in Fig. 1, motion equations of mass elements are:

$$\begin{aligned} m_1 \frac{d^2 Y_1}{dt^2} + C_H \frac{dY_1}{dt} + C_y \left( \frac{dY_1}{dt} - \frac{dY_2}{dt} \right) + \frac{A_s}{l_H^3} a l_H^2 (Y_1 + \Delta l_H) + \frac{3A_s b}{l_H^3} (Y_1 + \Delta l_H)^3 \\ + \frac{A_s}{l_y^3} a l_y^2 (Y_1 - Y_2 - \Delta l_y) + \frac{3A_s b}{l_y^3} (Y_1 - Y_2 - \Delta l_y)^3 = F_{y1} \\ m_2 \frac{d^2 Y_2}{dt^2} + C_y \left( \frac{dY_2}{dt} - \frac{dY_1}{dt} \right) + C_B \frac{dY_2}{dt} + \frac{A_s}{l_y^3} a l_y^2 (Y_2 - Y_1 + \Delta l_y) + \frac{3A_s b}{l_y^3} (Y_2 - Y_1 + \Delta l_y)^3 \\ + \frac{A_s}{l_B^3} a l_B^2 (Y_2 - \Delta l_B) + \frac{3A_s b}{l_B^3} (Y_2 - \Delta l_B)^3 = F_{y2} \end{aligned} \quad (11)$$

Where,

$$F_{y1} = -\frac{1}{2} b I^2 (1 + \cos 2\omega t)$$

$$F_{y2} = \frac{1}{2} b I^2 (1 + \cos 2\omega t)$$

The static compression of insulation cardboard is derived by

$$\begin{aligned} T &= \frac{A_s}{l_H^3} a l_H^2 \Delta l_H + \frac{3A_s b}{l_H^3} \Delta l_H^3 \\ m_1 g + T &= \frac{A_s}{l_y^3} a l_y^2 \Delta l_y + \frac{3A_s b}{l_y^3} \Delta l_y^3 \\ (m_1 + m_2) g + T &= \frac{A_s}{l_B^3} a l_B^2 \Delta l_B + \frac{3A_s b}{l_B^3} \Delta l_B^3 \end{aligned} \quad (12)$$

As shown in (11), there exists a nonlinear item of stiffness because the insulation cardboard is nonlinear. The exact and approximated solutions for (11) are difficult to obtain. Therefore, simulation is used to study the effect of clamping pressure changes on vibration characteristics.

### 3. Simulation Experiments

The natural frequency and the peak amplitude are the major reference characteristics showing the changes of windings' vibration characteristics. Because (11) contains nonlinear items of stiffness, the change of windings' clamping pressure affects the windings' natural frequency. To study this influence, the electromagnetic force is assumed constant with  $F^m = 1000\text{N}$ . In these simulation experiments, the parameters of gaskets' material are determined by testing those in the large power transformer. In the model, the concentrate mass is assumed as that of one disc coil.

In the simulation, electrical current of 50Hz was used to excite the winding. The winding's vibration response can be derived by calculation, as shown in Fig. 2. This figure shows that the winding's vibration amplitude increases with the looseness of clamping pressure. The amplitude-frequency relation can be derived by the Fourier transform for its response signals, as shown in Fig. 3. From this figure, we can see that the 100 Hz electromagnetic force response amplitude excited by the current of 50 Hz increases with the decrease of the clamping pressure. In addition, the response signal contains harmonic components, whose changing regularity is different from that of 100Hz.

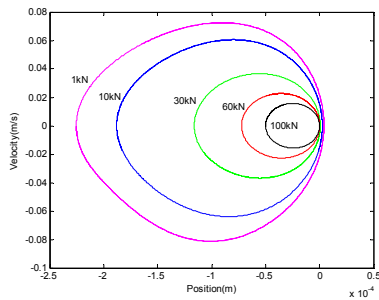


Fig. 2: Position-velocity phase plane portrait under different clamping pressure ( $\omega = 50\text{Hz}$ )

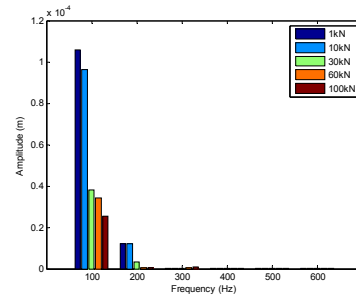


Fig. 3: The amplitude-frequency relation under different clamping pressure ( $\omega = 50\text{Hz}$ )

The winding was excited separately by the constant current of 350 Hz and 600 Hz. The amplitude-frequency relation with different frequency could be derived by simulation. Fig. 4 and 5 show that with the change of clamping pressure, the corresponding response amplitude of electromagnetic force changes with different changing regularities. To explain this phenomenon, the swept-frequency figure was obtained by the simulation, as shown in Fig. 6.

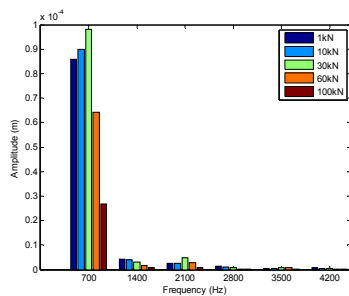


Fig.4: The amplitude-frequency relation under different clamping pressure ( $\omega = 350\text{Hz}$ )

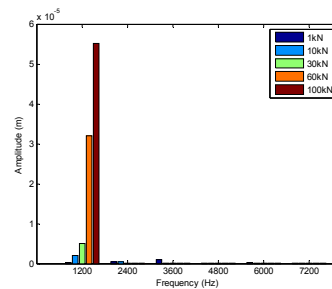


Fig.5: The amplitude-frequency relation under different clamping pressure ( $\omega = 600\text{Hz}$ )

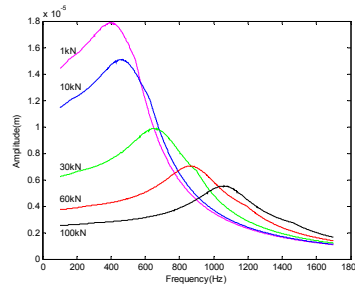


Fig. 6: The swept-frequency curves with different clamping pressure

Fig. 6 shows that, when the clamping pressure decreases from 100kN to 1kN, peak frequency of windings decreases gradually, while the corresponding peak amplitude increases. When the winding is excited by the constant current of 50Hz, 350Hz and 600Hz separately, the amplitude change relations under the response frequency of 100Hz, 700Hz and 1200Hz with different clamping pressure are consistent with Fig. 3~5. Therefore, this means that the response amplitude change is mainly because of the looseness of clamping pressure and the offset of the natural frequency. The changing regularities of its response amplitude are determined by the relative place between the electromagnetic force response frequency and windings' natural frequency.

This simulation result shows that the looseness of windings' clamping pressure can be shown on the change of response amplitude of exciting frequency and the offset of windings' natural frequency. Windings' swept frequency with constant current can show the scope of winding's natural frequency. So it can determine the looseness of windings' clamping pressure.

#### 4. Windings' Swept Frequency Experiments for Large Power Transformers

To validate the proposed method in this paper, it's necessary to conduct the swept frequency experiments with constant current on the real large power transformers. However, it's too expensive by artificially loosening the clamping pressure and there's no historical data of this experiment. Therefore, considering that phase A and C are symmetrical structure, the experimental data of phase C was thus proposed to be used as the reference for the primary diagnose of the state of phase A. The measuring points were located as shown in Fig. 7.

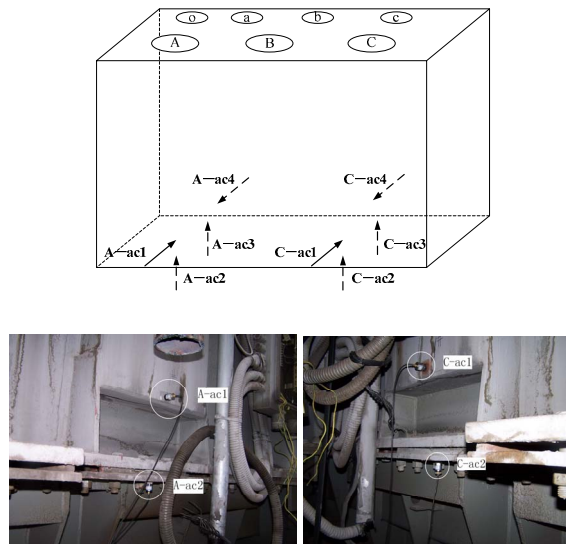


Fig.7 : The location of measuring points on the transformer

Note: A-ac4 denotes the 4th accelerometer for phase A.

The swept frequency experiments were done respectively to phase A and C under the constant current. The swept frequency increased from 80Hz to 260Hz, 1Hz every time. Therefore, the vibration response

frequency of every phase of the transformer was from 160Hz to 520Hz, and the gap was 2Hz. The comparison of the experimental results is shown as follows:

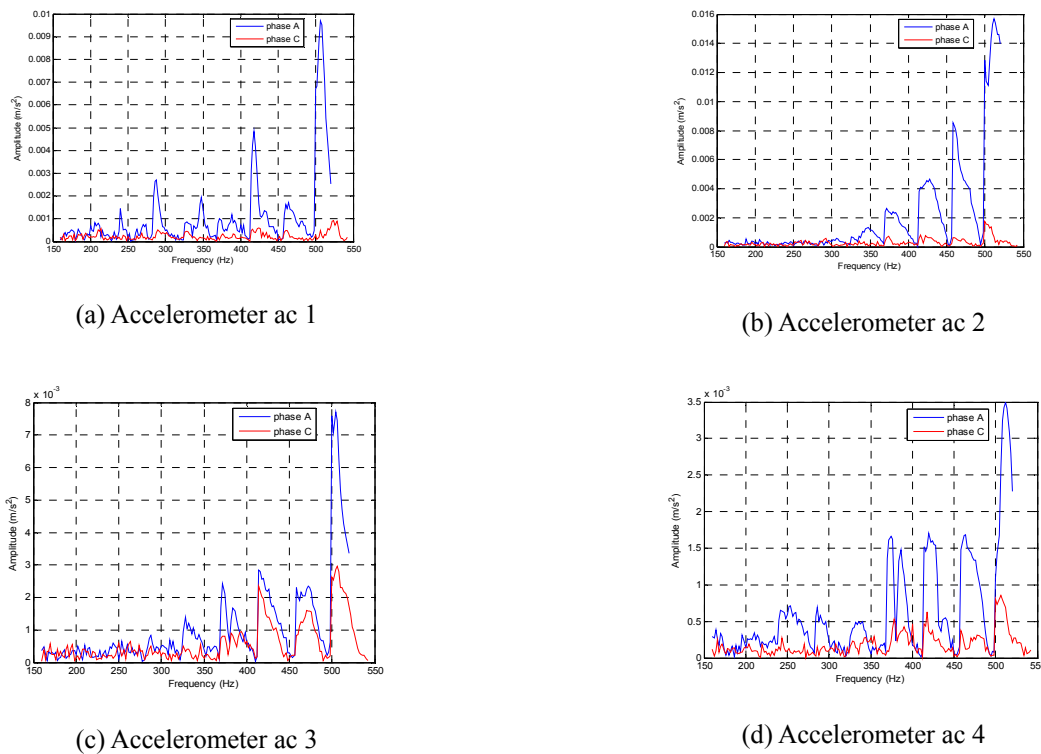


Fig. 8: The swept frequency experimental results comparison for phase A and C

Fig. 8 shows that the 4 corresponding measuring points have the similar response peak at the same frequency, which means the swept frequency experiments can be used to estimate the natural frequency of windings. At the same time, the peak amplitude of phase A is obvious greater than that of phase C at the corresponding natural frequency. According to the result of the simulation, we can see that the clamping pressure of phase A is less than that of phase C.

After examining the transformer, it was found that the clamping pressures of phase A was only 1/4 of that of C, obviously smaller than that of C. It matched with the analytical result, which meant the swept frequency experiments can exactly identify the changes of clamping pressure of transformer's windings

## 5. Conclusions

This paper develops a two-degree-of-freedom nonlinear mechanical model for the winding. By simulation and the following swept frequency experiments on the real transformer's windings, the following conclusions are drawn:

(1) With the change of clamping pressure, the peak frequency and peak amplitude changes obviously, which lead to the change of response amplitude under the corresponding exciting frequency;

(2) The scope of windings' natural frequency can be estimated by swept frequency with constant current. At the same time, the change of peak frequency and amplitude can show the change of clamping pressure. Therefore, the swept frequency experiments with constant current can more exactly reflect the change of windings' mechanical structure characteristics.

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