Research on Coupled field of the transformer vibration influenced by DC bias using Fast-ICA method

Hao Tian1 and Xingmou Liu1*
1College of Automation, Chongqing University of Posts and Telecommunications, Chongqing, 400065, China
*E-mail: liuxm@cqupt.edu.cn

Abstract. This paper proposes a multi-physical coupling model, which is an association of mathematical models of transformer core vibration analysis. The purpose of this model is transformer vibration analysis. Under different DC biases, the vibration process of the transformer core is simulated and analyzed by using the primary voltage as the excitation condition. The Fast-ICA algorithm is proposed, which evidences that the vibration when the transformer is no-load is the core vibration. The experimental results show that the Fast-ICA algorithm is used to analyze the transformer vibration signal under different DC bias conditions and obtain better results, which provides a new method for studying the transformer DC bias vibration.

1. Introduction
With the growth development of high-voltage power grids, the capacity and voltage level of transformers are progressively increasing, so the electromagnetic force inside the transformer is also increasing. Geomagnetically induced current is a hot topic for scholars, especially the DC bias voltage caused by geomagnetically induced current[1]. Most researchers have discussed the mechanism of transformer vibration[2]. However, under DC bias, there are relatively few research areas on transformer vibration analysis. Therefore, on the basis of DC bias, this article expounds the relevant research of transformer vibration[3-4]. In the case of DC bias, based on the vibration theory of the transformer, the displacement equation of the transformer core and the electromagnetic force equation of the transformer are derived in a series. Based on the influence of magnetostrictive electromagnetic structure on transformer vibration, a multi-physical coupling field model is proposed. Relevant researches are carried out on the magnetic flux density, mechanical stress distribution and tension displacement distribution inside the transformer.

A research method of blind source separation technology based on Fast-ICA is proposed. Its purpose is to establish the connection between DC bias and transformer vibration. Based on this research method, the transformer core vibration signal is extracted, and the transformer vibration signal obtained through the test is compared and analysed with the original normal vibration signal of the transformer, which provides a better explanation for whether there is a problem in the vibration analysis of the transformer under DC bias. At the same time, a new method is provided to analyse the transformer vibration signal under DC bias.

2. Electrical-magnetic-force coupling model of transformer core
For theoretical analysis of transformer core vibration problems, the exciting and response source are electrical quantity mechanical quantity respectively[5-6]. Based on the elastic mechanics and...
electromagnetic theory, the electromagnetic vibration mathematical model is established to describe the transformer core sinusoidal alternating electromagnetic field. It is can be expressed this formula:

\[ D_x \left( \frac{\partial^2 \psi}{\partial t^2} + 2 \frac{\partial \psi}{\partial x} - \frac{\partial^2 \psi}{\partial x^2} \right) = \frac{\omega \sin 2\omega t}{2} \int \frac{1}{\Delta I_x} dV \]  

(1)

\[ D_o = \frac{E^t}{12(1-\nu)^2} \]  

(2)

Where \( E \) is elasticity modulus, \( \nu \) is Poisson ratio, \( \lambda_z \) is magnetostriction coefficient in direction of axis. Through experimental analysis and verification, the accuracy of vibration results can meet the needs of the application[7]. Base on the simplified excitation model, linear or isotropic ferromagnetic material volume force density of magnetic force can be described as:

\[ f = J \times B - \frac{1}{2} \nabla H^2 - \frac{1}{2} \nabla H \cdot \nabla \tau \]  

(3)

In formula (3), the volume force density vector is denoted by \( f \), the current density is showed by \( J \), the magnetic induction intensity is indicated by \( B \), and the permeability of the medium and the volume density of the medium are expressed by \( u \) and \( \tau \) respectively. This formula consists of three parts: Lorentz force, volume force of material and surface tension of material. Therefore, the equation of magnetostrictive magnetic field force is:

\[ F_{m} = \frac{1}{2} \nabla (H^2 + \tau) \cdot \nabla \]  

(4)

Since the magnetostrictive period is half of the power period, the fundamental frequency of magnetostriction caused by the vibration of the transformer core is equal to twice that of the magnetostrictive power frequency[8]. If the magnetostrictive fundamental frequency is \( \omega \), then the magnetostrictive power frequency is \( 0.5 \omega \). It is assumed that the change of the magnetic field force is the same. Applying Fourier transform, the magnetic field force can be expressed as:

\[ F_{m} = F_{max} \sin 2\omega t + \sum_{i=3}^{n} F_{i} \sin i\omega t \]  

(5)

According to elastic mechanics theory, when the elastic material happens to deform, actually, the magnetostriction coefficient \( \lambda \) is magnetic material maximum dependent variable. The unit volume dependent energy of magnetic material could be expressed like this:

\[ u(\lambda) = \frac{1}{2} E \lambda^2 \]  

(6)

Where \( E \) is elasticity modulus. After ignoring the high frequency, the simplified magnetic field force with \( z \) direction is:

\[ F_{cz} = F_{max} \sin 2\omega t = \frac{\omega \sin 2\omega t}{2} \int \frac{1}{\Delta I_x} dV = \frac{\omega \sin 2\omega t}{\Delta I_x} \]  

(7)

3. Transformer coupled field simulated analysis

3.1 Electromagnetic field model establishment and analysis

In order to carry out the relevant experiments of the transformer, this paper uses a 5kVA/400V three-phase dry-type transformer as the research object of the transformer vibration signal analysis, and the expression of the electric field equation under the electric field module is:

\[ \varepsilon_0 \left( \frac{\partial \varepsilon \varepsilon_0 V}{\partial t} \right) + \nabla \left( \sigma \nabla V - J_e \right) = 0 \]  

(8)

In formula (8), \( \varepsilon_0 \) represents the permittivity of free space, its size is \( 8.85 \times 10^{-12} \)F/M, \( \varepsilon_1 \) is the relative permittivity, \( \sigma \) says the electrical conductivity, the external current density is showed by \( J_e \), and \( V \) denotes the potential. Based on the analysis of the electromagnetic field, this paper uses the field-circuit coupling model method to couple the circuit model of the transformer with the physical model[9]. Take the external current density as a known condition and place it in a magnetic field to stimulate the magnetic field. Thus the expression of the magnetic field equation in the solution domain is:
\[
\frac{\partial A}{\partial t} - \nabla \times (\mu_0 \mu_r \nabla \times A) = J'
\]  

(9)

For the formula (9), the permeability of free space is expressed by \(\mu_0\), and its size is \(4\pi \times 10^{-7}\) H/m. The relative permeability is represented by \(\mu_r\), and the vector magnetic potential is represented by \(A\). In the case of different DC biases, the distribution of the magnetic field is obtained by analysing the vibration of the transformer. The simulation results are shown in Figures 1, 2 and 3.

### 3.1.1 Magnetic field distribution when DC bias voltage \(U_{DC}=0\) V

As shown in Figure 1 (a) and (b), it indicates the distribution of the magnetic core magnetic field extreme value of the positive and negative half-periods at 0.005 s and 0.015 s respectively. The arrow demonstrates the size of the magnetic flux density distribution at that moment. From the figure above it can be seen that the magnetic flux density distributions in the positive and negative half cycles are equal, but their directions are opposite.

### 3.1.2 Magnetic field distribution when DC bias voltage \(U_{DC}=10\) V

If the applied DC voltage is 10 V, the flux density distribution of positive and negative half periods is shown in Figure 2.

### 3.1.3 Magnetic field distribution when DC bias voltage \(U_{DC}=20\) V

As shown in Figure 3, when the DC bias voltage is applied to 20 V, the distribution of the positive and negative half-cycle magnetic flux density is more obvious for the imbalance phenomenon. Especially the magnetic flux density with the increase of the extreme value is more serious, which makes the
magnetostriction coefficient of the iron core larger, and the transformer vibration is more obvious.

![Figure 3. DC=20V Transformer magnetic flux density distribution.](image)

### 3.2 Simulation result and analysis

#### 3.2.1 Core stress simulation results and analysis

Considering it is a special situation when the no-load. Transformer vibration is mainly from core vibration. So, this model is built under the transformer secondary side open circuit, no-load condition. Due to the real transformer core iron yoke are hold by devices. We must fix the upper and lower boundary of core in the model. Figure 4 shown the stress distributions of core at $t_1=0.0025$ s and $t_2=0.0075$ s respectively. Those are the maximums of the positive and negative half cycle.

![Figure 4. The core stress and deformation.](image)

As shown in Figure 4, the maximum pressure of the transformer core is distributed on the side of the yoke, and the most obvious position of transformer vibration, which is the same as the previous experimental results.

### 4. Experiment and Fast-ICA analysis

Experimental simulations show that under load and no-load operation of the transformer, the blind source separation fast independent component analysis (Fast-ICA) method is used in this paper to effectively separate the vibration signal of the iron core. The function of blind source separation is to separate the transformer core vibration signal from the mixed signal of multiple independent sources, and then process the result of the blind source separation of the transformer vibration signal through independent component analysis. In this paper, the Fast-ICA method can be used to separate the transformer vibration signals quickly and in parallel. More importantly, the memory requirement for separating the transformer vibration signals is small and the separation effect is also very good. It provides strong evidence for the judgment of transformer faults, and has been widely used in actual engineering calculations.

By means of online monitoring, this paper collects and processes the electrical parameters and vibration of the transformer at no-load and rated load. The frequency spectrum analysis of the transformer core vibration signal under no-load and rated load conditions is carried out. The results of the specific simulation analysis experiment are shown in Figure 5 and Figure 6.
As shown in Figures 5 and 6, Fast-ICA can separate the vibration signal of the transformer core. It can be seen more intuitively from the separated signal frequency spectrum that with the increase of the DC offset, the change law of vibration is the same as the result of experimental analysis. It can be seen from the result of signal separation frequency spectrum that the component at the 50Hz double frequency is the condition of the frequency of the main core vibration signal, and the transformer vibration signal enhances with the change of the DC bias.

5. Conclusion
This paper uses theoretical analysis to establish a method combining model and experimental simulation, and conducts related research on the vibration signal of the transformer under different DC bias. Firstly, the mathematical model of electromagnetic vibration theory is used to describe the model of transformer core under DC bias field. Then simulate and calculate the magnetic field and force of the transformer core. The experimental research and analysis of transformer magnetic flux density under different DC bias voltages verify the effectiveness of the proposed transformer magnetic field coupling analysis method under DC bias voltage.

In this paper, Fast-ICA is used as a method for separating the vibration signal of a transformer, but
the statistical independence of the source signal is required for this method. Therefore, this article assumes that the core vibration signal of the transformer is statistically independent. In addition, the experiment of transformer vibration signal separation in this paper is to conduct experimental analysis and extract the vibration signal of the transformer through the rated capacity 5kVA dry-type transformer. But in actual engineering operations, most belts have cooling devices. However, the vibration and noise of other transformers cannot be overlooked, and further research is needed. Perhaps the segmentation algorithm of transformer vibration signal demands to be further advanced, but it provides a new method for transformer vibration signal separation under DC bias, which lays a certain foundation for future research on transformer vibration.

Acknowledgements
The work was financially supported by National Natural Science Foundation of Chongqing Project, China (cstc2020jcyj-msxmX0368).

References:
[1] Price, R.P. (2002) Geomagnetically Induced Current Effects on Transformers. IEEE Transactions on Power Delivery., 17: 1002-1008.
[2] He, J., Yu, Z.Q., Zeng, R., Zhang, B. (2012) Vibration and Audible Noise Characteristics of AC Transformer Caused by HVDC System Under Monopole Operation. In: IEEE Transactions on Power Delivery., 27: 1835-1842.
[3] Kitagawa, W., Ishihara, Y., Todaka, T., Nakasaka, A. (2010) Analysis of Structural Deformation and Vibration of a Transformer Core by Using Magnetic Property of Magnetostriction. Electrical Engineering in Japan., 172: 19-26.
[4] Li, Q., Wang, X., Zhang, L., Lou, J., Zou, L (2012) Modelling methodology for transformer core vibrations based on the magnetostrictive properties. Let Electric Power Applications., 6: 604-610.
[5] Hu, J.Z., Liu, D.C., Liao, Q.F., Liang, S.S. (2016) Electromagnetic vibration noise analysis of transformer windings and core. Let Electric Power Applications.10:251-257.
[6] Phophongviwat, Teeraphon. (2013) Investigation of the influence of magnetostriction and magnetic forces on transformer core noise and vibration. Information Communication & Society., 17: 986-1000.
[7] Yang, Y., Xu, D. (2013) Development and Application of On-line Monitoring Device of Transformer Vibration. Telkomnika Indonesian Journal of Electrical Engineering., 11:4721-4728.
[8] Ji, S.C., Luo, Y.F., Li, Y.M. (2006) Research on extraction technique of transformer core fundamental frequency vibration based on OLCM. IEEE Transactions on Power Delivery., 21: 1981-1988.
[9] Han, R.D., Wang, T.Z., Wang, Q., Li, X.J. (2016) Research on circuit model of shunts based on field-circuit coupling method. In: 2016 IEEE International Conference on Computational Electromagnetics (ICCEM). Guangzhou. pp. 95-97.
[10] Shao, Y.Y., Hong. G., Jin, Z.J., Rao, Z.S. (2012) The Fault Detection of Transformer Windings' Deformation Based on Vibration Frequency Response Analysis. In: International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering. New York: pp. 713-718.