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# Research on Transformer Core Vibration under DC Bias Based on Multi-field Coupling Method

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***Abstract:*** *The Mathematical models for DC bias vibration analysis of the transformer core are developed in this paper. The model is combined into multi-physical field coupling modeling for vibration analysis of the transformer. By applying the primary voltage as excitation and under different DC bias, vibrations of the transformer core is simulated and analyzed.*
***Keywords:*** *DC bias, Core, Transformer, Vibration, Multi-field coupling*

## I. Introduction

With the development of ultra-high-voltage (UHV) power grid, the inside electromagnetic force of transformer is growing with the unceasing enhancement of voltage level and the increasing capacity of transformer [1-3]. Scholars have carried out a lot of related researches about the transformer vibration mechanism [3-6]. But, few research concerns the change of transformer vibration mechanism under the DC bias affect.

In this paper, considering the DC bias effect and combing with the existing transformer vibration related theory, the electromagnetic force equations and displacement equations of transformer core have been deduced. Rules of core following the DC bias value are discussed. Based on the model, inside magnetic flux density of transformer, mechanical stress distribution change rule under the DC bias influence are investigated.

## II. Electrical-Magnetic-Force Coupling Model

For Theoretical analysis of transformer core vibration problems, the exciting and response source are electrical quantity mechanical quantity respectively. So it is an essential problem of solve coupled fields. Based on the elastic mechanics and electromagnetic theory, transformer core is selected as the research object, basing on theory of energy conservation, concepts of volume strain energy density in elastic mechanics for describing the energy change of magnetostriction phenomenon is introduced [7-10]. The electromagnetic vibration mathematical model is established to describe the transformer core sinusoidal alternating electromagnetic field. It is can be expressed:

$$\mathrm{D}_0\left(\frac{\partial^4 v}{\partial x^4}+2\frac{\partial^4 v}{\partial x^2\partial y^2}+\frac{\partial^4 v}{\partial y^4}\right)=\frac{\omega\sin 2\omega t}{\Delta I_x}\int_v \frac{1}{2}E\lambda_z^3 dV \quad (1)$$

$$\mathrm{D}_0=\frac{Et^3}{12(1-v^2)} \quad (2)$$

where $E$ is elasticity modulus,$v$ 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.

Base on the simplified excitation model, linear or isotropic ferromagnetic material volume force density of magnetic force can be described as:

$$\boldsymbol{f}=\boldsymbol{J}\times\boldsymbol{B}-\frac{1}{2}H^2\nabla u+\frac{1}{2}\nabla\left(H^2\tau\frac{\partial u}{\partial\tau}\right) \quad (3)$$

Where $f$ is volume force density vector,$\boldsymbol{J}$ is current density, $\boldsymbol{B}$ is magnetic induction,$H$ is magnetic field intensity,$u$ is magnetic permeability of medium,$\tau$ is volume density of medium. In equation (3), the first term is the Lorentz force, the second term is the material's volume force, and the third term is material's surface tension. The magnetic field force of magnetostriction is:

$$F_c=\int\frac{1}{2}\nabla\left(H^2\tau\frac{\partial u}{\partial\tau}\right)d\vec{s} \quad (4)$$

Because of the magnetostriction cycle is half of power cycle, the magnetostriction fundamental frequency caused by transformer core vibration is twice of power frequency. If power frequency is $\omega$,the relative magnetostriction frequency is *2ω*. Assuming that the magnetic field force is the same with variation. By applying the Fourier transform, the magnetic field force can be expressed as:

$$F_c = F_{c\max} \sin 2\omega t + \sum_{i=4}^{2n} F_i \sin i\omega t \quad (5)$$

n=3,4,5…

According to elastic mechanic's 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:

$$u(\lambda) = \frac{1}{2} E \lambda^3 \quad (6)$$

where *E* is elasticity modulus.

After ignoring the high frequency, the simplified magnetic field force with *z* direction is:

$$F_{cz} = F_{c\max} \sin 2\omega t = \frac{\omega \sin 2\omega t}{\Delta l_z} \int_v u(\lambda_z) dV = \frac{\omega \sin 2\omega t}{\Delta l_z} \int_v E \lambda_z^3 dV \quad (7)$$

## III. Indentations and Equations

Simulation method is to select the electromagnetic module of COMSOL software. The electric field is established based on the transient current source model. And the calculation results are excitation source for magnetic field model, electric-magnetic field coupling modeling first. Study magnetic field distribution under dc bias. Through physical stress and strain part of structural mechanics module to get the structural mechanics equations. The electromagnetic force is calculated by electromagnetic field coupling get into the mechanics model, the second coupling. Finally, the simulation results are obtained.

### 3.1 Electromagnetic field model establishment and analysis

For subsequent transformer corresponding experiment, use a 5kVA/400V three phase dry type transformer as a model object. Electric field equation under electric field module is:

$$-\nabla \bullet \frac{\partial(\varepsilon_0 \varepsilon_r \nabla V)}{\partial t} - \nabla \bullet (\sigma \nabla V - \boldsymbol{J}^e) = 0 \quad (8)$$

where $\varepsilon_0$ is permittivity of free space, 8.85×10-12F/M. $\varepsilon_r$ is relative dielectric constant. $\sigma$is conductivity. $J^e$ is external current density. *V* is potential.

In the electromagnetic field analysis, the physical model of the transformer and circuit model coupled together use field-circuit coupling method. The external current density is calculated as the stimulus of magnetic field put into the magnetic field in the module. Magnetic field equation for solving domain is:

$$\sigma \frac{\partial A}{\partial t} + \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times A) = \boldsymbol{J}^e \quad (9)$$

In equation (9), $\mu_0$ is permeability of free space， $4\pi\times10^{-7}$H/m. $\mu_r$ is relative permeability. *A* is vector magnetic potential.

To get the magnetic field distribution with different dc bias, include ***H***and ***B***. Simulation results are shown in Fig.1 and Fig. 2

#### 3.1.1 A magnetic field distribution when DC bias voltage $U_{DC}$=0A.

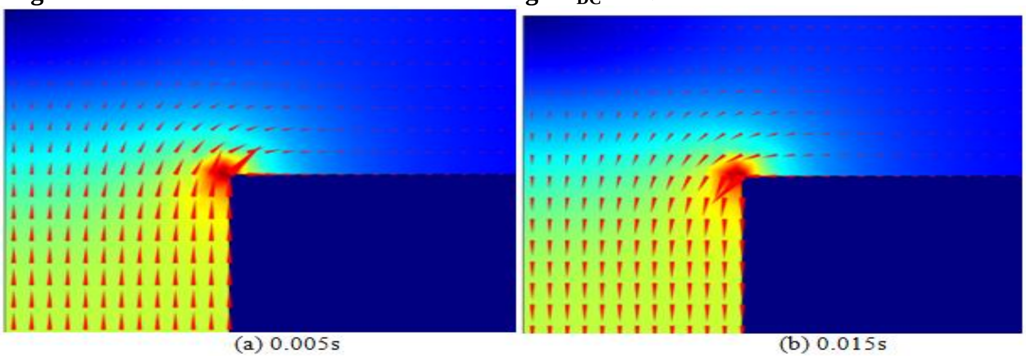
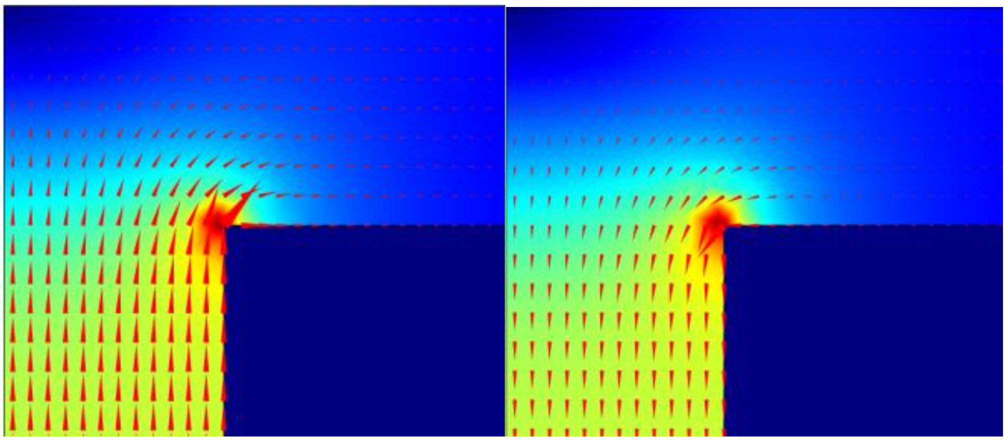



**Fig.1**: $U_{DC}$=0V Transformer magnetic flux density distribution

The core magnetic field extremum of the positive and negative half cycle at 0.005s and 0.015s are shown in Fig.1(a) and (b) respectively. Arrow size ratio reflects the distribution of magnetic flux density at that moment. We can find that the magnitude of magnetic flux density distributions of positive and negative half cycle are the same, but the direction is opposite.

**3.1.2A magnetic field distribution when DC bias voltage $U_{DC}$=10V.**

When dc voltage is 10V, the flux density distributions of positive and negative half cycle are balance no longer.



(a) 0.005s (b) 0.015s

**Fig. 2**: $U_{DC}$=10V Transformer magnetic flux density distribution

It is shown that flux density at 0.005s is larger than that at 0.015s. and it is larger than that of without dc bias. Combined with the previously mentioned, the magnetostrictive coefficient of correlation theory. At this time, Transformer core magnetostriction will increase. It lead to the transformer vibration enhancement.

**3.2 Structure force field modeling and analysis**

In the process of COMSOL structure force field analysis, choose physical stress module. Variables (*u*,*v*,*w*) used for solving domain equations:

$$\mathbf{m}\frac{d^2u}{dt^2}+\xi\frac{du}{dt}+\mathbf{k}u=\mathbf{f}(t) \quad (10)$$

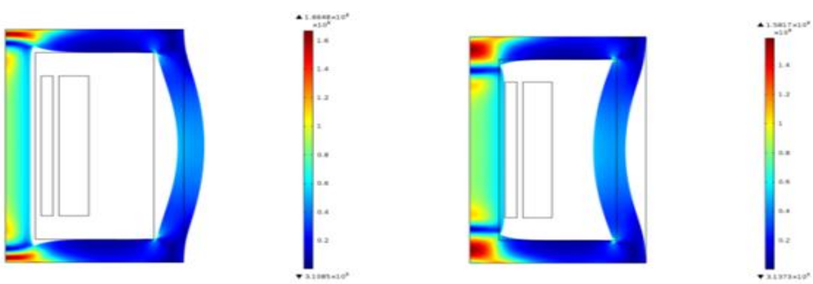
where, **m** is mass matrix，***k*** is stiffness matrix，$\xi$ is damping coefficient matrix.

Substituting the calculated ***B***, ***J***into the structure field domain equation, hence the displacement distribution and force situation can be obtained. Our object is dry type transformer, so the filler is air under a standard atmospheric pressure. Iron core choose the copper material and silicon steel materials in the COMSOL.

In this paper, HB curve used to specify the constitutive relation of core silicon steel. To achieve flux density ***B***and the magnetic field *H* correspondence relation by interpolation method.

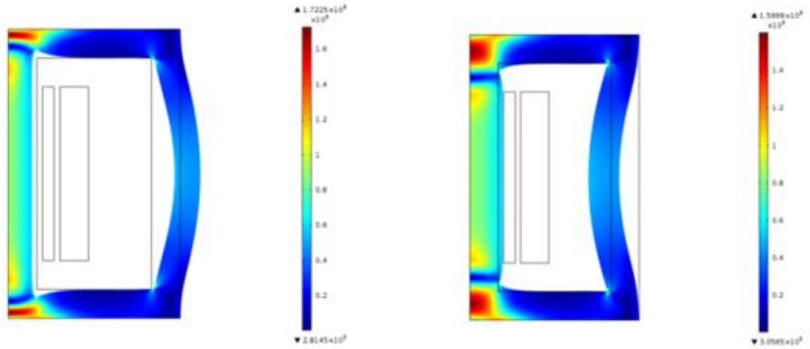
**3.3 Simulation result and analysis**

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. Fig.3 shown the stress distributions of core at t= 0.0025 s and t= 0.0075s respectively. Those are the maximums of the positive and negative half cycle.



0.0025s 0.0075s

(a) $U_{DC}$=0V



0.0025s 0.0075s

(b) $U_{DC}$=10V

**Fig 3:** The core stress and deformation

As shown as Fig.3, Stress distribution of the core maximum is in the side position of the yoke. It is also the most obvious vibration place, consistent with the previous experiment conclusion.

## IV. Conclusion

In this paper, method of theoretical analysis is used to research the transformer vibration under dc bias. Set up mathematical model of electromagnetic vibration to describe transformer core under dc bias field, then, getting the magnetic field and force of transformer core by simulation calculation of COMSOL. The simulation results verify the method which is proposed transformer magnetic vibration field coupling analysis with dc bias is effective.

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