Analysis of DC Bias Effects on Core Vibration of UHV Transformer Based on SRVCM

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This paper analyzes the relationship between vibration characteristics of ultra-high voltage (UHV) transformer and DC bias current. The main source of UHV transformer’s no-load vibration is the magneto-strictive vibration of the magnetic core. However, unlike the small power transformer, the characteristic of large inductance to small resistance of UHV transformer which can easily lead to not only a long transient process but also the inundation of the small DC voltage relative to the 1000 kV AC voltage during the iterative calculation. Thereby, a fast solution called series resistance and voltage compensation method (SRVCM) is utilized to make the simulation reach the steady state quickly. The correctness of the method is verified by comparing the value of DC bias current and DC component of excitation current. By means of SRVCM, the vibration displacement, acceleration and its harmonics under different DC bias are calculated by a weak magneto-mechanical coupling model.

Index Terms—UHV transformer, SRVCM, Magneto-mechanical coupling, Vibration, DC bias.

I. INTRODUCTION

Eight 1000-kV ultra-high voltage (UHV) AC power transmission projects have been put into operation in China and over 100 UHV transformers have been put into service. Their safe and stable operation is directly related to the safety of UHV transmission system [1]. UHV transformers mostly use self-coupling structure, and the transformer group composed of the single-phase autotransformer has less tolerance to the DC-bias caused by monopole operation of HVDC transmission [2] or geomagnetic storm [3], which could attain up to 100 A per phase for 1 min [4].

The DC bias current is detrimental to transformer for the half-cycle saturation [5], consequently, a series of problems occur, such as the serious distortion of excitation current, partial overheating and increase of vibration and noise [6-7]. Thus, precise and in-depth vibration characteristic analysis of DC bias effects on UHV transformer is necessary for the safe and stable operation of equipment and transmission system.

II. MAGNETO-MECHANICAL COUPLING MODEL

Initially, the time-domain field-circuit coupling finite element model is used to calculate electromagnetic quantities of transformer. Then, the core vibration characteristics caused by magnetostriction can be obtained by a weak magneto-mechanical coupling model.

A. Magnetic-circuit coupling model

The UHV transformer structure and circuit model are presented in Fig. 1 and Fig. 2, respectively. The magnetic field solution using vector magnetic potential \( A \) and field equation according to Maxwell is given by

\[
\nabla \times \frac{1}{\mu} \nabla \times A = J
\]

(1)

Where, \( \mu \) is permeability of magnetic material, \( J \) is current density.

Flux linkage equation of the nonlinear model is given by

\[
\psi = L_d \frac{d^2 i}{dt^2} + L_D \frac{di}{dt}
\]

(2)

Where, \( \psi \) is flux linkage, \( i \) is winding current, \( L_D \) is dynamic inductance.

Referring to (2), the transient differential equations of the circuit is shown as

\[
u = u_0 + u_x = L_D \frac{di}{dt} + (R + r)i
\]

(3)

Where, \( R \) is series resistance, \( r \) is winding resistance.

B. Solid mechanical model

The strain caused by magnetostriction in a simplified model [8] is given by

\[
\varepsilon_{VIB} = \frac{\lambda_0 - \lambda_0(\sigma)}{M^2_w} M^2
\]

(6)

Where, \( M_w \) is the magnetisation when the domains wall shift reaches saturation, \( \lambda_0 \) denote the saturation magnetostriction, \( M \) is the magnetization, \( \lambda_0(\sigma) \) describe the magnetoelastic coupling characteristics of the material.

Under DC bias, the transformer core is saturated by the DC flux, thereby odd terms and high order terms of \( M \) are introduced as

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The relationship between stress and strain of elastic material is a linear function, which satisfies Hooke’s law. Thereby, the stress caused by magnetostriction on the core is

\[ \sigma = D \varepsilon \]  

(8)

Where, \( \sigma \) is stress, \( \varepsilon \) is strain, and \( D \) is elastic tensor.

The force caused by magnetostriction can be obtained as follows

\[ \nabla \cdot \sigma = -F_{\text{ms}} \]  

(9)

The differential equation of mechanical force field is established as follows

\[ m \frac{d^2 u}{dt^2} + C \frac{du}{dt} + ku = F_{\text{ms}} \]  

(10)

Where, \( m \), \( C \) and \( k \) are the mass, damping and stiffness matrix, respectively. \( u \) is the displacement vector, \( F_{\text{ms}} \) is the magnetostriction force.

Then, the weak magneto-mechanical coupling model is shown as follows

\[ \begin{bmatrix} M & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} A \\ u \end{bmatrix} = \begin{bmatrix} J \\ F \end{bmatrix} \]  

(11)

Where, \( M \) is magnetoelastic coefficient matrix, \( K \) is mechanical elastic coefficient matrix.

### III. Series Resistance and Voltage Compensation

Unlike small power transformers, the resistance of the UHV autotransformer is extremely small compared to its large inductance. In order to solve these problems, the series resistance and voltage compensation method (SRVCM) is proposed, which is expressed as

\[ \max_k |u_k - U_{m1} \cos(\omega t)| \leq 1%U_m \]  

(11)

\[ u_{k+1} = U_m \cos(\omega t) + U_{di} + R(i_k - I_{kid}) \quad k = 1, 2, \ldots \]  

(12)

Where, \( U_{di} \) is the imposed DC voltage, \( i_k \) is \( k \)th current in steady state, \( I_{kid} \) is DC component in steady state.

### IV. Simulation and Analysis of No-load Vibration Characteristics Under DC Bias

The excitation current and its harmonics magnitudes of UHV transformer without load under DC bias are shown in Fig. 5 and Fig. 6. The displacement and acceleration under DC bias are presented in Fig. 7 and Fig. 8.

### V. Conclusion

A weak magneto-mechanical coupling model combined with SRVCM are utilized in this paper, which can reach the steady state quickly and accurate. By means of this model, the vibration characteristics of UHV transformer under DC bias are calculated. More details will be presented in full paper.

### References


