Vibration Properties of Two-stage Magnetic-valve Controllable Reactor

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This paper investigates the vibration properties of a two-stage magnetic-valve controllable reactor (MCR) under different working conditions. The vibration mechanism of the MCR core is analyzed from the perspective of conservation of mechanical and internal energy. The transient field-circuit coupling FEM model of a 5400 Var two-stage MCR is established. The core vibration of the two-stage MCR is analyzed at two working conditions (with and without DC current) by using FEM. Finally, an experiment platform is built to test the vibration acceleration of the two-stage MCR core, and the calculation results are compared with the experimental ones.

***Index Terms*—Magnetostriction, vibration, DC bias, magnetic-valve controllable reactor**

I. Introduction

The magnetic-valve controllable reactor (MCR) is one of the key devices for the reactive power compensation of UHV transmission lines. But the magnetic-valve of MCR is saturated by the addition DC excitation current, which leads to a large increase of the vibration and noise of the MCR. Therefore, it is of great theoretical significance and practical value in engineering to study the vibration characteristics of two-stage MCR.

The core's vibration is mainly caused by magnetostrictive effect of silicon steel sheets [1,2]. Many researches have been done on the transformer core's vibration. Some experimental data of magnetostrictive elongation have been tested, and used to calculate the corresponding magnetostrictive forces according to the stress-strain constitutive relations [3]. Some studies focus on the measurement and analysis of the vibration frequency response functions [4]. But there is still a big lag on the vibration study of MCR.

In this paper, the coupling model of the external circuit with the electromagnetic field for the two-stage MCR is established. The coupling equations of magnetic magnetization with mechanical strain induced by the core magnetostriction are inserted into the FEM software, the vibrations of the iron core of two-stage MCR are analyzed at two different working conditions (with DC bias and without DC bias). An experiment platform is built to measure the vibration acceleration of two-stage MCR core.

II. Coupling Analysis of Electromagnetic Field and Mechanical Field

A. Electromagnetic field equations

When the reactor is in normal working state, the differential equation of magnetic field is as follows：

$$\sigma\frac{\partial A}{\partial t}+\nabla\times\left(\mu_0^{-1}\mu_r^{-1}\nabla\times A\right)=J \tag{1}$$

In the above formula, μ_0 is the vacuum permeability, μ_r is the relative permeability, $\boldsymbol{A}$ is the vector magnetic potential. The magnetic flux density of the iron core and the winding current density are calculated as follows:

$$B=\mu_0\mu_r H=\nabla\times A \tag{2}$$

$$J=\frac{NI}{S} \tag{3}$$

In the above formula, $\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{H}$ is the magnetic field intensity, $\boldsymbol{J}$ is the winding current density, N is the coil turns, S is the cross-sectional area of the coil, I is the winding current.

B. Vibration mechanism of iron core

The core vibration of two-stage MCR is mainly caused by magnetostriction. When the core of two-stage MCR is under the action of the alternating magnetic field, the strain of core is composed of magnetostrictive strain and prestressed elastic strain. From the perspective of conservation of mechanical and internal energy, the magnetostrictive intrinsic model which is suitable for grain oriented silicon steel sheets is established as follows [5-7].

$$\varepsilon_p=\frac{\sigma_p}{E}+\lambda_0\left(\sigma_p\right) \tag{4}$$

$$\begin{aligned}\varepsilon_c=&\frac{\lambda_m(0)-\lambda_0(0)}{M_s\left(\sigma_p\right)^2}M^2+\\&\theta\frac{\lambda_m(0)-\lambda_0(0)}{M_s\left(\sigma_p\right)^4}\left(M-M_s\left(\sigma_p\right)\right)^4\end{aligned} \tag{5}$$

$$\theta=\begin{cases}-2 & M-M_0\left(\sigma_p\right)\geq 0\\ 0 & M-M_0\left(\sigma_p\right)<0\end{cases} \tag{6}$$

ε_p is the elastic strain under prestress, the first term in the equation (4) are the strain under prestress σ_p, where E is the inherent Young's modulus, $\lambda_0\left(\sigma_p\right)$ is the initial magnetostrictive strain. ε_c is the magnetostrictive strain, and M_{ws} is the saturation magnetization when prestressing force is 0. $M_0(\sigma)$ is the saturated wall moving magnetization intensity under prestressed force. $\lambda_m(0)$ is the saturation magnetostrictive coefficient, and σ_{ps} is the maximum prestressed force.

When there is a direct current in the coil, the DC magnetic flux can make the magnetic valve fully saturated quickly, and the magnetization $\boldsymbol{M}$ is established as follows

$$M = M_{dc} + M_a \cos wt \tag{7}$$

By substituting (7) into (5), the magnetostrictive strain under DC-bias is obtained by

$$\varepsilon_{mdc} = a + b\cos wt + c\cos 2wt + d\cos 3wt + e\cos 4wt \tag{8}$$

Comparing with (5), the formula (8) shows that 50 Hz (the power frequency) and 150 Hz component of the core vibration spectrum will obviously increase.

III. Simulation Results and Analysis

In this paper, a dry-type two-stage MCR is designed and made. The specific parameters and simulation model of two-stage MCR are shown in Table I and Fig.1. Without taking into account the damping effect, the model of two-stage MCR is meshed into 6618 domain elements, 1243 boundary elements, the calculation step length is 0.1ms.

TABLE I
Parameter of Two-Stage MCR

Parameter	Numerical value
Rated capacity/Var	5400
Rated voltage/V	380
Each core column winding turns number	798
The tap ratio δ	0.04135
Winding resistance/Ω	0.8493
First-stage valve's area/ cm^2	11.33
Second-stage valve's area	22.66

The vibration acceleration waveform of point A without DC-biased are shown in Fig.2(a). It can be seen that the vibration acceleration waveform shows obvious periodic and the acceleration amplitude is about 6m/s^2 and mainly concentrates in 100Hz. Then, when the conduction angle of the thyristor are 144°, 135° and 126° respectively, the DC component passed through coil rises to 1.53A, 2.34A and 3.29A. The vibration acceleration spectrum of point A of two-stage MCR at different DC currents is shown in Fig.2(b). It can be seen that vibration at 50 Hz and 150 Hz increases significantly.

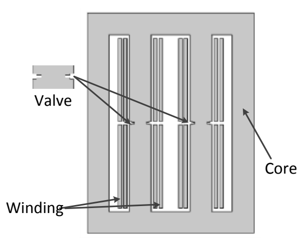
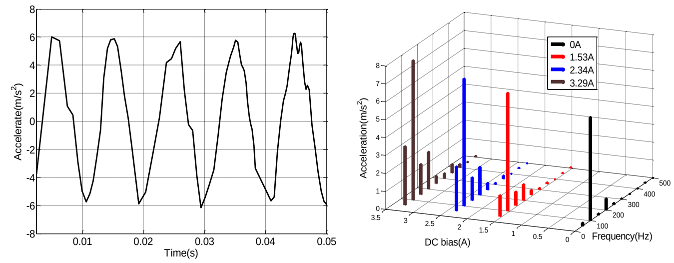


Fig. 1. The simulation model of two-stage MCR

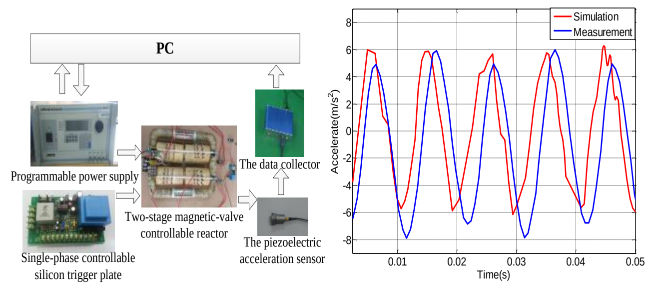
IV. Experiments

The acceleration sensor is used to measure the vibration acceleration of two-stage MCR under rated voltage. In order to fully measure the vibration acceleration, the sampling frequency of the data acquisition system is 12.5 kHz, the vibration experiment devices is shown in Fig.3(a). The vibration acceleration waveforms calculated and measured when two-stage MCR working without DC bias current are shown in Fig.3(b). It can be seen that the vibration acceleration time domain waveform of point A in the experiment and simulation are basically consistent, and the amplitude of vibration acceleration are both about 6 m/s^2. There is a certain error between the actual measured data and simulation data, but the simulation results show a consistent rule with the experiment results.



(a) (b)

Fig.2. (a) The vibration acceleration of point A without DC current (b) The vibration acceleration spectrum different DC currents



(a) (b)

Fig. 3. (a) The vibration experiment devices (b) Comparison of experiment and simulation data

V. Conclusion

The 3D multi-physics coupling model of two-stage MCR is established in this paper, magnetic field distribution and vibration acceleration waveform of time domain and spectrum analysis is calculated by FEM software. An experiment platform is built to verify the correctness of simulation. The vibration results of simulation are consistent with the experiment results, which shows that the model used in this paper can well simulate the actual situation.

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