Energy and Power Engineering, **2013, 5, 1097-1100**
doi:10.4236/epe.2013.54B209 Published Online July 2013 (http://www.scirp.org/journal/epe)

Effects of DC Magnetic Bias on the Magnetic and Sound Fields of Transformer

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Received March, 2013

ABSTRACT

DC bias current flowing into the neutral point of power transformer will seriously affect the normal operation of AC power system. In this paper, exciting current, harmonic component of the excitation current, magnetic flux density and noise of transformer were analyzed when the transformer is in the no-load operation state based on field-circuit coupled method. Through the calculation and analysis, some reference bases are provided for design of transformer.

Keywords: DC Magnetic Bias; Exciting Current; Harmonic; Magnetic Flux Density; Noise

1. Introduction

As the implementation of the "transmit the electricity from west to east, north and south to send each other, nationwide network" strategy of China's power grid, high-voltage direct current transmission (HVDC) technology [1-2], which is suitable for high power and long-distance transmission, has been used more and more widely. Under unipolar-earth way, the DC into the earth will be large up to 3 kA [3]. It causes the uneven distribution of surface potential. Thus there is potential difference between different grounds which makes some of the DC flows from one transformer end and sides out from the other end. Field tests show that only a small DC flows through the transformer neutral point will seriously harm or even affect the normal operation of alternating-current power system. Therefore, it is necessary to pay more attention to the problem of transformer DC magnetic bias.

Taking a single-phase transformer as an example, on the basis of field-circuit coupled finite element method, this paper simulates the DC magnetic bias's impact on exciting current, exciting current harmonic, magnetic flux density and noise of transformer when the transformer is switched to the zero-loaded state. It will be of a great significance for the further study of controlling DC magnetic bias.

2. Model of Transformer under DC Magnetic Bias

*This work was supported by NSFC, under Project 51177103 and Program for LNIRT in University (LT2011002).

2.1. Finite Element Modeling

A single-phase transformer with a parameter of 240 MVA was chosen as an example. In order to analyze the DC magnetic bias's impact on transformer, field-circuit coupled finite element method was used and the finite element model is shown in **Figure 1**. The field domain was shown on the left side of **Figure 1**, and the circuit domain was on the right.

2.2. Calculation on Excitation Current

Zero-loaded is an operating state, it refers to disconnect in the secondary side and rated voltage in the primary side. The exciting current was consisted of core loss current I_{Fe} (active current) and magnetizing current I_μ (reactive current), which is shown in **Figure 2**.

$$\begin{cases} I_0(\%) = \dfrac{P_o}{10S_N} \\ I_\mu(\%) = \dfrac{K_{I0}}{10S_N} \bullet (q_{Fe} \bullet G_{Fe} + N_f q_\delta \bullet A_f) \end{cases} \tag{1}$$

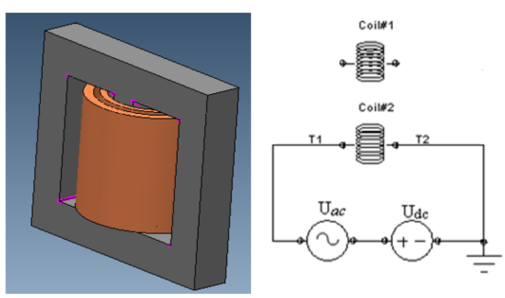

Figure 1. Field-circuit coupled finite element model.

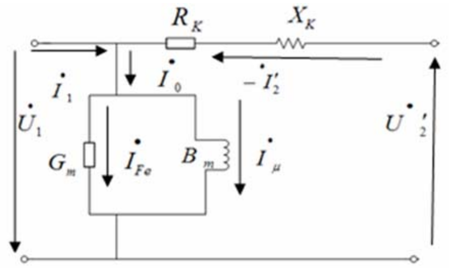

Figure 2. Phase diagram of transformer on zero-load.

In formula (1), P_0 is the zero-load loss, S_N is the rated capacity. q_{Fe} is the magnetization capacity of unit mass, q_δ is the magnetization capacity of unit area at seam crossing, G_{Fe} is the total weight of the core, A_f is the net area at seam crossing and N_f is the Number of joints;

$$I_0(\%) = \sqrt{I_{Fe}(\%)^2 + I_\mu(\%)^2} \tag{2}$$

3. Magnetic Field Characteristics under DC Magnetic Bias

3.1. Exciting Current of Different DC Magnetic Bias Level

The relation between allowable DC current and rated current was defined in the reference 4. The allowable DC current was 0.3% rated current in single-phase transformer, 0.5% rated current in three-phase five-limb transformer and 0.7% rated current in three-phase three- limb transformer [4]. The allowable DC current of single-phase three-limb transformer in this paper is 2.27 A. The DC current applied in this simulation is 0.6 A、1.13 A、2.27 A、4.54 A、6.81 A、9.08 A (0.07%、0.15%、0.3%、0.6%、0.9%、1.2% rated current respectively). Changing rule of exciting current is calculated when different DC current flows through the winding. Results are shown in **Table 1**.

Table 1. Exciting current peak of different dc magnetic bias level.

DC Current/A	Peak of Positive Half-cycle/A	Peak of Negative Half-cycle/A
0	1.51	-1.51
0.6	7.93	-0.30
1.13	13.1	-0.25
2.27	22.1	-0.16
4.54	27.1	0.11
6.8	32.5	-0.05
9.08	35.2	-0.002

With the increasing of DC current, the exciting current wave get distortion, and the distortion become serious with the increase of DC current. The peaked wave of the positive half cycle is more obvious, and the amplitude of the wave increase. The negative half-cycle is approximately flat-topped wave, and the amplitude tends to zero. When the DC current is 9.08 A, the amplitude in positive half-cycle is 35.1944 A, in negative half-cycle is -0.0025 A. After DC current exceeds 4.54 A, the exciting current change slowly with the DC current growth. The main reason is that ferromagnetic material has been highly saturated. Therefore, changing the magnetic characteristics of ferromagnetic material is a method of inhibiting DC bias.

3.2. Analysis of Exciting Current

Based on formula 3, exciting current waveform's Fourier transform is analyzed. Results are shown in **Figures 3-4**.

$$i(t) = I_0 + \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{3}$$

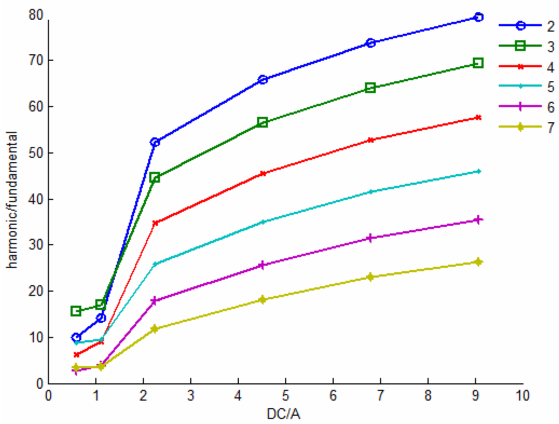

Figure 3. Change curves of exciting currents' harmonic ratios along with DC current.

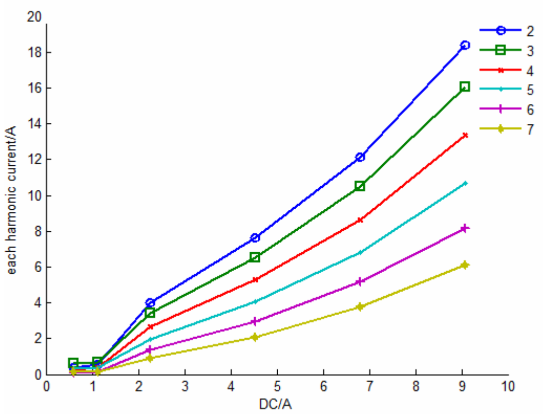

Figure 4. Change curves of exciting currents' harmonic components along with DC current.

As shown in **Figure 3**, with the increasing of DC current, the ratio of each exciting current harmonic to fundamental exciting current increase rapidly, and the second exciting current harmonic is the most obvious. When the DC current is 2.27A, the increment speed of current harmonic ratios begin stable.

The corresponding relation between each exciting current harmonics and DC Bias current is shown in **Figure 4**. The DC magnetic bias's impact on each exciting current harmonics are basically identical, it is approximately linear relationship. Lower-order harmonic is influenced by DC Magnetic Bias sensitively, higher-order harmonic is less affected.

3.3. DC Magnetic Bias's Impact on Flux Density

The calculated position of flux density is shown in **Figure 5**. Position A is in the halfway of core window height. Position B is the centre line of iron beam. Position C is in the middle of the two windings.

Transformer operates in inflection point of B-H curve. Core model in this paper is 30 RGH120, the linear region is 1.7-1.75 T. As shown in **figures 6-8**, when a current in DC nature in the transformer exists, with the growth of DC current, the magnetic flux density increases significantly. The Maximum flux density on the iron beam is changed from 1.8347 T to 1.94994 T, on ferrite yoke is changed from 1.707 T to 1.866T. With the increasing of DC current, the magnetic flux density increases, but the amplitude is narrow. Because of the influence of DC current, ferromagnetic material is easy to get saturated. The flux density in air way increases significantly. It changed from 3.664 to 10.84 mT. It is shown that DC magnetic bias makes leakage magnetic field rise seriously.

4. Acoustical Characteristic of Core under DC Magnetic Bias

Audible noise is generated due to the vibration of the transformer. DC bias current flowing through the neutrals of ac power transformers with the neutral grounded, will force the transformer to generate more leak magnetic flux. Therefore, the core and windings would vibrate strongly due to the magnetostriction and the electrodynamics effects. The audible noise level of ac power transformers neighboring the dc grounding electrode increase with the increase of the DC current.

In this paper, the characteristics of structural acoustic radiation are investigated by the indirect boundary element method. In order to simulate the ground, symmetry plane is added in the bottom of transformer core. The plane is regarded as rigid plane and has no normal acceleration, then the noise is reflected entirely. This model can simulate noise caused by core accurately.

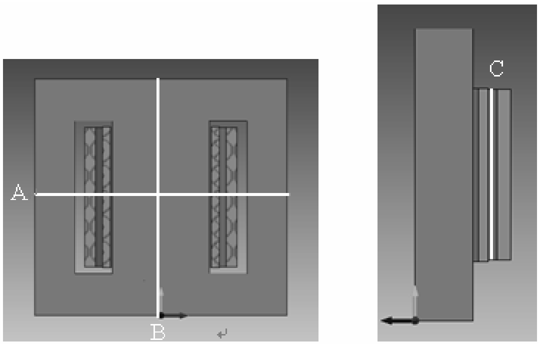

Figure 5. Calculated position of flux density.

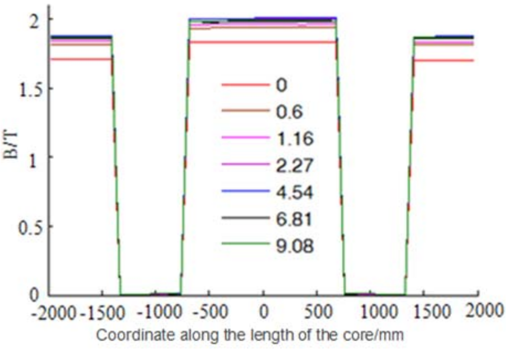

Figure 6. Flux density of position A.

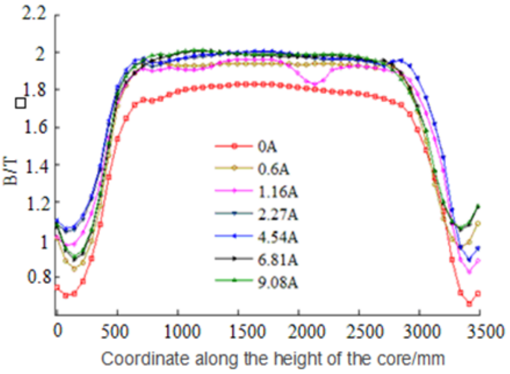

Figure 7. Flux density of position B.

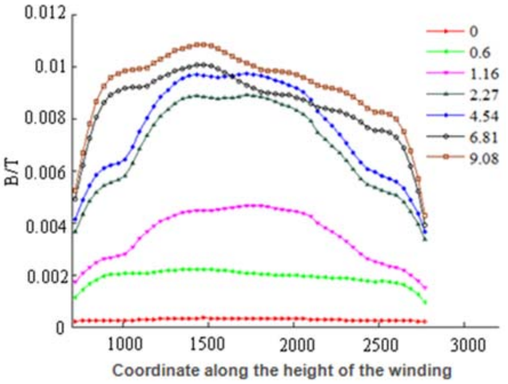

Figure 8. Flux density of position C.

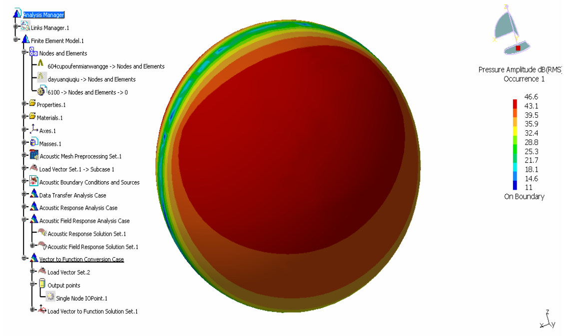

Figure 9. Sound pressure distribution.

Table 2. Sound pressure level of different dc magnetic bias level (db)

I_{dc} /A	100/Hz	200/Hz	300/Hz	400/Hz	500/Hz
0	52.88	76.51	69.3	46.3	60.3
0.6	62.21	86.17	79.7	58.6	69.5
1.13	65.8	85.68	76.3	67.4	69.3
2.27	65.2	86.74	82.2	58.7	67.1
4.54	70.85	94.68	85.4	70.7	78.5
6.8	76.53	99.69	98.2	75.6	67.5
9.08	77.18	100.70	90.7	78.0	82.4

Audible noise is generated due to the vibration of the transformer. DC bias current flowing through the neutrals of ac power transformers with the neutral grounded, will force the transformer to generate more leak magnetic flux. Therefore, the core and windings would vibrate strongly due to the magnetostriction and the electrodynamics effects. The audible noise level of ac power transformers neighboring the dc grounding electrode increase with the increase of the DC current.

In this paper, the characteristics of structural acoustic radiation are investigated by the indirect boundary element method. In order to simulate the ground, symmetry plane is added in the bottom of transformer core. The plane is regarded as rigid plane and has no normal acceleration, then the noise is reflected entirely. This model can simulate noise caused by core accurately.

The basic frequency of transformer noise is twice as high as the source frequency, videlicet 100 Hz. There are also high frequency noise integer times of basic frequency. Study show that, low-frequency noise is a large percent in the noise spectrum of frequencies. Therefore, the noise below 500 Hz was taken into account.

As seen in **Table 2**, noise mainly concentrates in the frequency of 100、200、300 Hz. The noise level increases with the increase of the DC current. The noise level is 76.51 dB when there is no DC current and 100.71 dB when DC current rise to 9.08 A.

5. Conclusions

Based on field-circuit coupled finite element method, this paper analyzes the DC magnetic bias's impact on exciting current, exciting current harmonic, magnetic flux density and noise of transformer.

1) With the increasing of DC current, the exciting current wave get distortion, and the distortion become serious with the increase of DC current. When the DC current is 9.08 A, the amplitude in positive half-cycle is 35.1944 A, in negative half-cycle is -0.0025 A. After DC current exceeds 4.54 A, the exciting current change slowly with the DC current growth. The main reason is that ferromagnetic material has been highly saturated.

2) It is approximately linear relationship between each exciting current harmonics and DC Bias current. Lower-order harmonic is influenced by DC Magnetic Bias sensitively.

3) With the increase of DC magnetic bias current, the flux density in air way changed from 3.664 to 10.84 mT, has increased by 197 percent. It is shown that DC magnetic bias makes leakage magnetic field rise seriously.

4) The audible noise level of transformer increase with the increase of the DC magnetic bias current. When the DC magnetic bias current change from 0 to 9.08 A, the amplitude of the sound increase from 76.51 dB to 100.70 dB.

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