Study of the Three Phase Transformers under DC Bias and Suppression Measure

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Abstract—A novel transmission-line model (TLM) of the three phase transformers under direct current(DC) bias is built. In the model, the differential terms in the transformers circuit model are discretized. The saturation characteristic and the hysteresis effect of the core material are described on the basis of the Jiles-Atherton ferromagnetic hysteresis theory, and the eddy-current losses resulting from the flux paths through legs are replaced by an equivalent resistance. Furthermore, the copper losses and the leakage inductance of the primary and the secondary windings are also included. The nonlinear differential-algebraic equations can be obtained. At last, the Newton-Raphson technique is chosen to calculate the equations. The calculation results confirm the correctness and validity of the proposed the TLM for the three phase transformers under DC bias. At last, suppression measures of the DC bias are presented. The peak values of the exciting currents become smaller, and their distortion is partially reduced after taking the suppression measures.

Keywords-three phase transformers; DC bias; hysteretic effect; eddy-loss; saturation characteristic

I. INTRODUCTION

The DC bias phenomenon is abnormal for transformers. There are two reasons for generating DC bias, which one is geomagnetic induced current[1] (GIC, its frequency is lower then 0.01Hz and can be considered to be DC); the other is DC transmission system (when DC transmission system uses earth as its current return path, great DC will flow in the earth, which will bring great ground potential differences in a large area around the DC grounding electrodes.) [2-3]. The DC bias can cause acute vibration, great noise, high temperature of the transformer, even make the protection misoperation. In addition, a lot of harmonics will be produced which can lower the power quality.

Some calculations and experiments have been done by a lot of researchers domestic and abroad. The main research contents included five parts as follows: (1) simulation analysis of exciting current [4-6]; (2) experiments research of the vibration, great noise, local high temperature of the transformer [7-8]; (3) research of leakage flux[9]; (4) measurement and simulation analysis of magnetization characteristic curve [10]; (5) research of restrain measures of DC bias [11-12]. Some achievements and progress have been achieved at above mentioned aspects.

This paper proposes a novel transmission-line model (TLM) of three phase transformers under DC bias. The differential terms of the transformers are replaced in TLM by the discrete transform. In the model, *B-H* curve is defined on the basis of the Jiles-Atherton ferromagnetic hysteresis theory; eddy-current losses are replaced by an equivalent resistance. Furthermore, the copper losses and leakage inductance of the primary and the secondary windings are also included. The Newton-Raphson technique is chosen for its efficiency and stability to calculate the hysteretic behavior and exciting currents.

II. TLM OF THREE PHASE TRANSFORMERS

The equivalent electric circuit of the three phase transformers under DC bias is shown as Fig.1. Where V_{sa}, V_{sb} and V_{sc} are the three-phase AC voltages. R_{cua}, R_{cub}, R_{cuc}, R_{cuA}, R_{cuB}, R_{cuC} are the resistances of the primary and the secondary windings respectively. e_a, e_b, e_c, e_A, e_B, e_C are the induced electromotive forces of the primary and the secondary windings respectively. i_a, i_b, i_c, i_A, i_B, i_C are currents of the primary and the second windings respectively. L_{Las}, L_{Lbs} and L_{Lcs} are the equivalent leakage magnetic inductions which couple with the primary windings. L_{LAS}, L_{LBS} and L_{LCS} are the equivalent leakage magnetic inductions which couple with the secondary windings. R_{LA}, R_{LB} and R_{LC} are load resistances. L_{LA}, L_{LB} and L_{LC} are load inductances. M is the mutual inductance of the first windings and the second windings. U_0 is the DC voltage.

The eddy-current losses of the transformers iron core are replaced by adding single-turn winding loaded by an

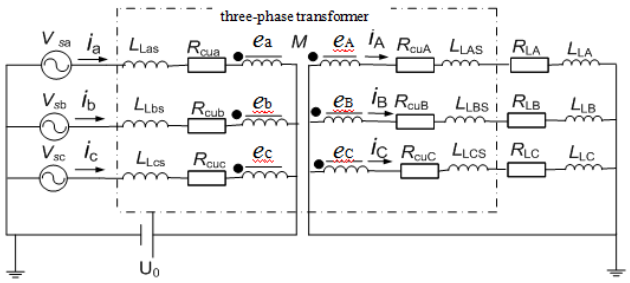


Figure 1. Electric circuit of the three phase transformers under DC bias

equivalent resistance R_e given by[13]:

$$R_e = \frac{12A}{t^2 \sigma_{fe} V_c K_{fe}} \qquad (1)$$

Where A is the area of the iron core, K_{fe} is the lamination factor of the iron core, V_c is the volume of the iron core, σ_{fe} is the iron core conductivity, t is the lamination thickness.

The TLM of three phase transformers[14] under DC bias is given as Fig.2 and the equations can be derived as (2).

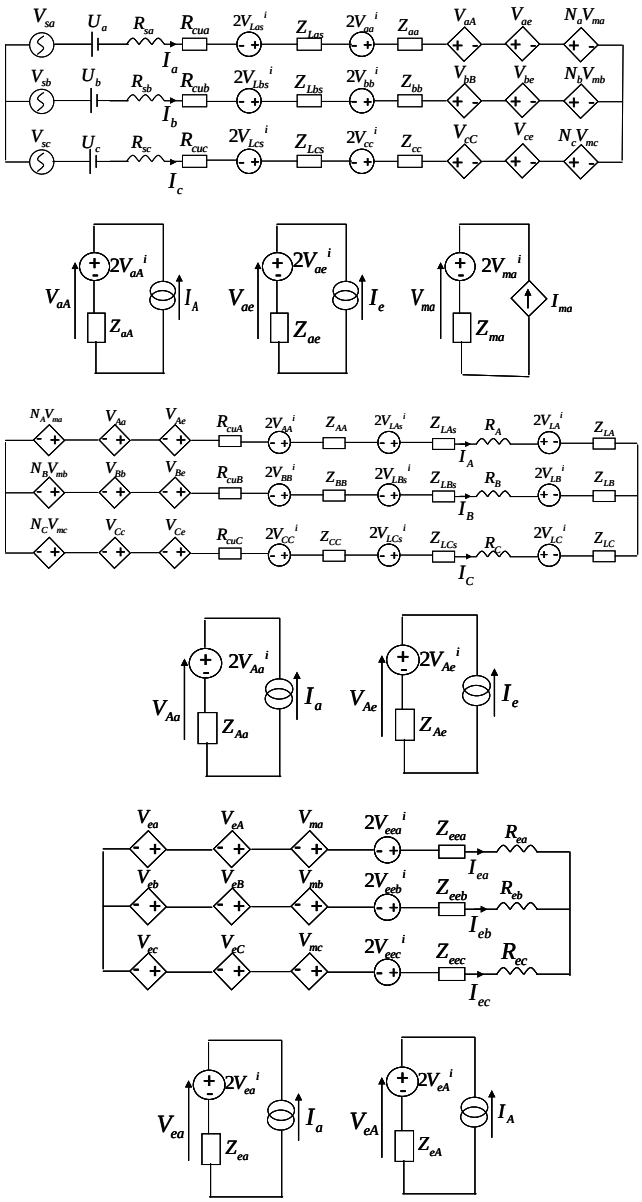


Figure 2. The TLM model of three-phase transformer

$$V_{sp} + U_p = R_{sp} I_p + R_{cup} I_p + L_{Lps} \frac{dI_p}{dt} + L_{pp} \frac{dI_p}{dt} + L_{pP} \frac{dI_P}{dt} + L_{pe} \frac{dI_e}{dt} + N_p L_m \frac{dI_m}{dt}$$
$$0 = R_{cuP} I_P + L_{PP} \frac{dI_P}{dt} + L_{LPs} \frac{dI_P}{dt} + L_{Pp} \frac{dI_p}{dt} + L_{Pe} \frac{dI_e}{dt} + N_P L_m \frac{dI_m}{dt} + R_{LP} I_P + L_{LP} \frac{dI_P}{dt}$$
$$0 = L_{eep} \frac{dI_e}{dt} + L_{ep} \frac{dI_p}{dt} + L_{eP} \frac{dI_P}{dt} + L_m \frac{dI_m}{dt} + R_{ep} I_{ep} \qquad (2)$$

Where the small letter subscripts represent the primary side parameters, the capital letter subscript represent the secondary side ones, and the letter e subscript represents the additive winding. V_{sp} is AC voltage, U_p is DC voltage; R_{sp} are the internal resistances of the sources, R_{cu} are the resistances of the windings, R_{LP} are the resistances of the loads; I_p, I_P and I_{ep} are the currents of the winding; N_p and N_P are the primary and the secondary winding turns; L_{Ls} are the leakage inductances; L_{pp}, L_{PP} and L_{eep} are the self-inductances, L_{pP}, L_{Pp}, L_{pe}, L_{Pe}, L_{ep} and L_{eP} are the mutual inductances, L_{LP} are the inductances of the loads.

$$L_{pp} = \mu_0 N_p^2 A/l, \quad L_{PP} = \mu_0 N_P^2 A/l, \quad L_{eep} = \mu_0 A/l,$$
$$L_{pP} = L_{Pp} = \mu_0 N_P N_p A/l, \quad L_{ep} = L_{pe} = \mu_0 N_p A/l,$$
$$L_{eP} = L_{Pe} = \mu_0 N_P A/l, \quad Z_k = 2L_k / dt.$$

III. JILES-ATHERTON THEORY

The magnetization is split into two parts, the anhysteretic magnetization and the irreversible magnetization. In normalized form, this is expressed by

$$I_m = \beta_c I_{an} + (1-\beta_c) I_{irr} \qquad (3)$$

Where β_c is the weighting coefficient with $0 \le \beta_c \le 1$. The anhysteretic magnetization dependence is given by a modified Langevin function.

$$I_{an} = I_s \left[\coth\left(\frac{I_h + \alpha I_m}{I_a}\right) - \frac{I_a}{I_h + \alpha I_m} \right] \qquad (4)$$

Where I_s is the normalized saturation magnetization, α is the interdomain coupling coefficient, and I_a is the normalized anhysteretic magnetization form factor. The derivative of the normalized irreversible magnetization is

$$\frac{dI_{irr}}{dI_h} = \frac{\delta_M (I_{an} - I_{irr})}{\delta I_c - \alpha (I_{an} - I_{irr})} \qquad (5)$$

Where the migration flag δ_M is given by

$$\delta_M = \begin{cases} 1, if \ \frac{dI_h}{dt} > 0 and I_{an} > I_{irr} \\ 1, if \ \frac{dI_h}{dt} < 0 and I_{an} < I_{irr} \\ 0, otherwise. \end{cases} \qquad (6)$$

IV. CALCULATION AND SIMULATION RESULT

A. Solution of the Transformer Model

The Newton-Raphson technique is chosen to calculate the model.

$$f = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}_{9\times1} \qquad (7)$$

Where $f_1 = \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \end{bmatrix}_{3\times1}$, $f_2 = \begin{bmatrix} f_{21} \\ f_{22} \\ f_{23} \end{bmatrix}_{3\times1}$, $f_3 = \begin{bmatrix} f_{31} \\ f_{32} \\ f_{33} \end{bmatrix}_{3\times1}$

$$
\begin{aligned}
f_{11} &= (R_{sa} + R_{cua} + Z_{aa} + Z_{Las})I_a + Z_{aA}I_A + Z_{ae}I_e + N_a Z_{ma} I_{ma} - V_{sa} - U_a + 2(V_{aa}{}^i + V_{Las}{}^i + V_{aA}{}^i + V_{ae}{}^i + N_a V_{ma}{}^i) \\
f_{21} &= (R_A + R_{cuA} + Z_{AA} + Z_{LAs} + Z_{LA})I_A + Z_{Aa}I_a + Z_{Ae}I_e + N_A Z_{ma} I_{ma} + 2(V_{AA}{}^i + V_{LAs}{}^i + V_{Aa}{}^i + V_{Ae}{}^i + N_A V_{ma}{}^i) \\
f_{31} &= (R_{ea} + Z_{eea})I_e + Z_{ea} i_a + Z_{eA} I_A + Z_m I_m + 2(V_{eea}{}^i + V_{ea}{}^i + V_{eA}{}^i + V_m{}^i)
\end{aligned}
\tag{8}
$$

f_{12} and f_{13}, f_{22} and f_{23}, f_{32} and f_{33} are expressions of b and c phase.

Jacobean matrix is

$$
J = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}_{9\times 9} \tag{9}
$$

Then the current can be solved.

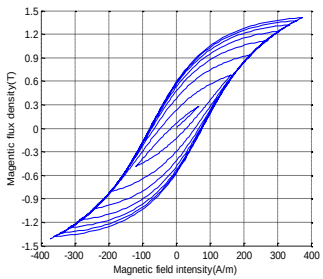
$$
\begin{bmatrix} I_a \\ I_b \\ I_c \\ I_A \\ I_B \\ I_C \\ I_{ea} \\ I_{eb} \\ I_{ec} \end{bmatrix}_{k+1} = \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_A \\ I_B \\ I_C \\ I_{ea} \\ I_{eb} \\ I_{ec} \end{bmatrix}_k - [J]^{-1}{}_k \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ f_{22} \\ f_{23} \\ f_{31} \\ f_{32} \\ f_{33} \end{bmatrix}_k \tag{10}
$$

Where k is the iteration number.

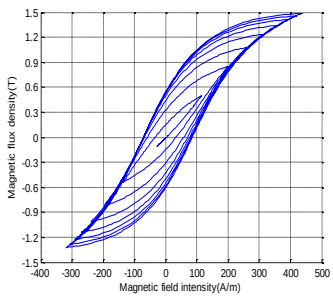
B. Simulation Results

To demonstrate the modeling procedure, a 100KVA, 10KV/400V three phase two-winding transformers was modeled using MATLAB soft.

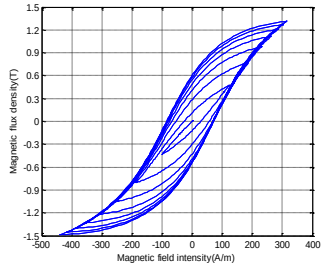
Fig.3~4 show the simulated *B-H* curve without DC bias and with 5V DC voltage respectively. It can be seen that the curves are not symmetrical at the positive and negative Y axis any more with DC bias. The three phase transformers tends to saturate at the positive half of Y axis.



(a) a phase

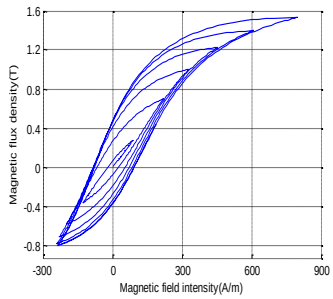


(b) b phase

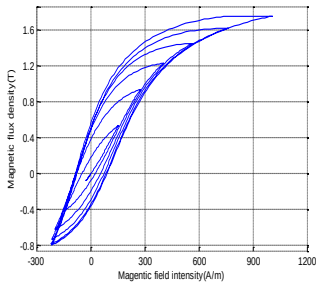


(c) c phase

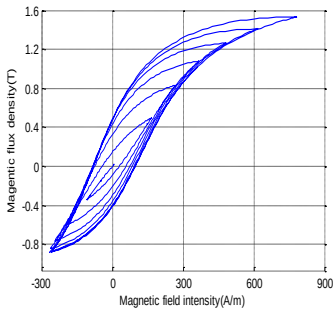
Figure 3. *B-H* curve of the three-phase transformer without DC voltage



(a) a phase



(b) b phase



(c) c phase

Figure 4. *B-H* curve of the three-phase transformer with 5V DC voltage

Fig.5~6 are the exciting current simulated waveforms without DC bias and with 5V DC voltage respectively. It is obvious that the exciting currents waveforms get distorted with DC bias, and the larger the DC voltage is, the more seriously the exciting current waveforms distorted. The waveforms shift up and they are no longer symmetrical, which indicates that there are even harmonics occurred.

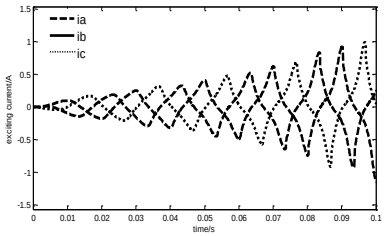


Figure 5. Exciting current waveform without DC voltage

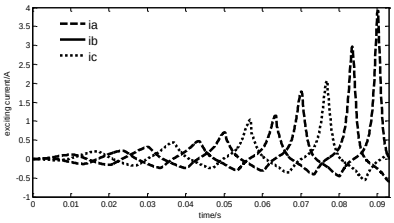
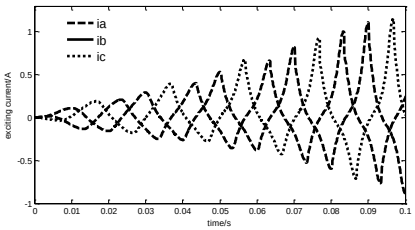


Figure 6. Exciting current waveform without 5V DC voltage

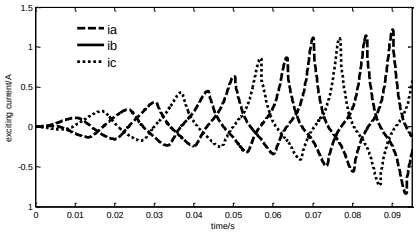
V. SUPPRESSION MEASURE OF THE DC BIAS

There are three main measures to restrain DC bias. They are (1) putting a resistor in series between the transformers neutral and ground, (2) putting a capacitor in series between the transformers neutral and ground, (3) putting a reverse DC injection at the neutral of the transformers.

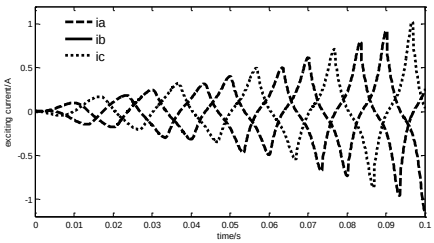
Fig.7 is the exciting current simulated waveforms with 5V DC voltage after applying suppression measures. It can be seen that the peak values of the exciting currents are smaller, and their waveforms distortion was partially reduced.



(a) putting a resistor



(b) putting a capacitor



(c) putting a reverse dc injection

Figure 7. Exciting current waveforms with 5V DC voltage after applying suppression measure

VI. CONCLUSIONS

1) The *B-H* curves are not symmetrical at positive and negative Y axis any more under DC bias. The three phase transformers tends to saturate at the positive half of Y axis.

2) The exciting current waveforms get distorted under DC bias, and the larger the DC voltage is, the more seriously the exciting current waveforms distorted.

3) The peak values of the exciting currents are smaller, and their waveforms distortion was partially reduced after applying suppression measure.

REFERENCES

[1] Cui Mingde, Liu Chunming, Liu Lianguang. Assessment of the influence caused by solar storm on sichuan power grid rated 500 kV[J]. High Voltage Engineering, 2010, 36(11):2849-2855.

[2] M.A.S. Masoum, P.S. Moses, Impact of balanced and unbalanced direct current bias on harmonic distortion generated by asymmetric three-phase three-leg transformers[J]. IET Electr. Power Appl. 2010,4(7):507-515.

[3] Yang Yongming, Liu Xingmou, Chen Tao, et al. Impact of soil structure adjacent to ground electrodes of UHVDC power transmission lines on DC bias of power transformers[J]. Power System Technology, 2012, 36(7):26-32.

[4] Li Xiaoping, Wen Xishan. DC Bias Computation Study on Three-phase Five Limbs Transformer[J]. Proceedings of the CSEE, 2010,30(1):127-131.

[5] Zhao Xiaojun，Zhang Xiaoxin，Li Huiqi, et al. Frequency Domain Coupled Model between Magnetic and Electric Circuits of DC Biased Transformers by Harmonic Balance Method[J]. Transactions of China Electrotechnical Society. 2014,29(9):211-218.

[6] Zhao Xiaojun, Li Lin, Cheng Zhiguang. et a1. Analysis of the DC bias phenomenon in transformers based on harmonic-balanced finite element method[J]. Proceedings of the CSEE, 2010,30(21)：103-108.

[7] Wang Jin-gang, Mao Kai, Duan Xu, et al. Simulation and test of transformer vibration under DC bias[J]. Electric Machines and Control, 2015,19(1):58-67.

[8] Zhao Zhigang, Liu Fuguil, Cheng Zhiguang, et al. Eddy current Loss of Copper Shielding Under DC--biased Condition in HVDC [J]. High Voltage Engineering. 2011,37(4):990-995.

[9] Guo Jie, Huang Hai, Tang Xin, et al. Analysis on 500 kV Power Transformer Vibration Under DC M agnetic Biasing[J]. Power System Technology, 2012,36(3):70-75.

[10] Zhao Z, Liu F, Cheng Z. Measurements and calculation of core-based B-H curve and magnetizing current in DC-biased transformers[J], IEEE Transactions on Applied Super conductivity, 2010, 20(3):1131-1134.

[11] Zhu Yiying, Jiang Weiping, Zeng Zhaohua, et al. Studyiing on Measures of Restraining DC current Through Transformer Neutrals[J]. Proceedings of the CSEE,2005,25(13):1-7.

[12] Huang FuCheng, Ruan Jiangjun, Zhang Yu, et al. DC Magnetic Bias Induced Current Effects on Transformer and Restricting Methods[J]. High Voltage Engineering,2006,32(9):117-120.

[13] Lu Changbai, Zhu Yinghao. Theory and calculation of power transformer[M]. 2006: LiaoNing Science and Technology Press.

[14] D.W.P Thomas, J. Paul, O.Ozgonenel, C. Christopoulos: Time-Domain Simulation of Nonlinear Transformers Displaying Hysteresis[J]. IEEE Transaction on Magnetics, 2006, 42(7)：1820-1827.