The DC Bias Model and Simulation Analysis of Three-phase Five-limps Transformer Based on EIC Principle

To cite this article: Li Wenfeng et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 452 042159

You may also like

- Analysis and Countermeasure Study on DC Bias of Main Transformer in a City
  PengChao Wang, Hongtao Wang, Xinpu Song et al.

- Size dependence of phosphorus doping in silicon nanocrystals
  Wei He, Zhengping Li, Chao Wen et al.

- Reduction in plasma potential by applying negative DC cathode bias in RF magnetron sputtering
  Masao Isomura, Toshinori Yamada, Kosuke Osuga et al.
The DC Bias Model and Simulation Analysis of Three-phase Five-limps Transformer Based on EIC Principle

Wenfeng Li\textsuperscript{1, a}, Hongkun Bai\textsuperscript{1, b}, Fangmin Bao\textsuperscript{1, c}, Libing Liu\textsuperscript{2, d}, Tao Zhang\textsuperscript{3, e}, Yubin Mao\textsuperscript{1, f}, Yongmin Liu\textsuperscript{1, g}, Feifei Bo\textsuperscript{1, h}, Yuanpeng Hua\textsuperscript{1, i}, Ding Han\textsuperscript{1, j}, Yaoyu Yang\textsuperscript{3, k} and Yang Liu\textsuperscript{1, l}

\textsuperscript{1}Grid Henan Electric Power Company Institute of Economics and Technology, Henan 450000, China
\textsuperscript{2}State Grid Henan Xu Ji Group Corporation, Henan 450000, China
\textsuperscript{3}Zhengzhou University, Henan 450000, China

\textsuperscript{a}809406879@qq.com, \textsuperscript{b}1420254015@qq.com, \textsuperscript{c}baofangmin@ha.sgcc.com.cn, \textsuperscript{d}liulibing@126.com, \textsuperscript{e}154754759@qq.com, \textsuperscript{f}yb_mao@163.com, \textsuperscript{g}liuamin@163.com, \textsuperscript{h}bofeifei272@163.com, \textsuperscript{i}13783661352@163.com, \textsuperscript{j}913023263@qq.com, \textsuperscript{k}502376698@qq.com, \textsuperscript{l}93682202@qq.com.

Abstract. In this paper, the model of transformer DC bias simulation is established based on EIC principle. This model considers the hysteresis loss and eddy current loss of the transformer core through the J-A model and the Bertotti theory. This model simulates the electromagnetic characteristics of the transformer under DC bias more accurately, providing a basis for reliable evaluation of transformer resistance to DC bias and determination of effective and reasonable control measures. Based on this model, the effects of DC bias on the operating characteristics of single-phase transformers are analyzed. Moreover, this paper summarizes the variation of field current and leakage flux as well.

1. Introduction

When the ultra HVDC transmission is operated in a monopole operation mode with earth return, strong DC power may cause DC bias in nearby transformers, resulting in greatly increased saturation of the core, highly distorted excitation current, increased reactive power loss, and increased temperature rise, protection against erroneous actions and other serious threats to the safe and stable operation of AC-DC hybrid power grids [1-2].

In view of this, some scholars have established a magnetic coupling model of the transformer circuit [3], described the magnetization curve of the transformer core by an empirical formula, proposed a frequency-dependent nonlinear reluctance calculation formula of the core, and established a model in the frequency domain [4]. Some scholars have established an integrated circuit model of transformer based on the dual principle. Only one circuit can be used to represent the electromagnetic behavior of the entire transformer, but the duality theory is only applicable to transformers with a planar magnetic topology, which limits the application of this model [4].

In this paper, considering the key elements of core hysteresis curve, core hysteresis and turbine effect, core topological structure and so on, using EIC principle, J-A model and Bertotti theory to build a three-
phase five-limps transformer model to solve the conflict between accuracy and complexity effectively. Based on this model, the effect of DC bias on the operation characteristics of three-phase five-limps transformer was analyzed, and the variation law of excitation current, leakage flux, and core flux were summarized.

2. Description of the models

2.1. Establish circuit model based on three-phase five-limps transformer core topology and transformer parameters

(1) Nonlinear resistance characterization of transformer core eddy current losses

Set \( l, d, A, \tau, \sigma, B \) are the number of turns, the length, the thickness, the crosssectional area of the core lamination and the lamination width, the conductivity and the magnetic induction, respectively.

According to Bertotti’s theory, the instantaneous power loss of the core transformer core is

\[
P_c = H_c \frac{dB}{dt} A_c l_c
\]

\[
= \frac{\sigma d^2 l_c}{12 A_c} \left( \frac{Gd\tau H_c \sigma c^2}{A_c} \right)^{0.5} \left( \frac{d\Phi}{dt} \right)^{-0.5}
\]

\[
= \frac{k_c}{N_i^2} (N_i \frac{d\Phi}{dt})^2
\]

Among them, \( H_c \) denotes magnetic field strength related to core eddy current, the dimensionless constant \( G = 0.1356 \), \( H_c \) is related to the internal potential caused by the magnetic domain wall of the iron core lamination, and is generally related to the maximum magnetic induction intensity \( B_{\text{max}} \).

\( N_i \frac{d\Phi}{dt} \) has the dimension of voltage, so \( k_c / N_i^2 \) has the reciprocal of the resistance dimension, that is \( \Omega^{-1} \), the core eddy current loss can be characterized as:

\[
r_c = N_i^2 / k_c
\]

When the differential magnetic circuit model of the transformer is determined, the equivalent eddy current loss resistance \( r_c \) of the core can be determined according to the Eq. (2). The magnetic potential generated by the eddy current can be written as \( F_{cp} = H_c l_p \), which can be available as:

\[
F_{cp} = k_{cp} \left( \frac{d\Phi_p}{dt} \right)
\]

The magnetomotive force acting on the primary and secondary winding currents and the eddy current of the iron core are:
The Eq. (4) shows that the eddy current loss of the core can be represented by a non-linear resistor connected in parallel with the primary winding, where $i_1 = i_1 - k_c/N_1^2(N_1\phi/dt)$. According to the single-phase transformer core form and magnetic circuit model, the core eddy current loss resistance $r_c$ can be obtained.

(2) Three-phase five-limps transformer circuit model

According to the above derivation, the three-phase five-limps transformer primary circuit model can be represented as $r_1$, $r_2$, $r_3$ and $r_p$, $r_{p1}$, $r_{p2}$, $r_{p3}$ parallel or other parameters in series. The secondary circuit model can be represented as a series connection between the parameters. The circuit model can be shown in Fig. 1.

$$F = N_1i_1 - N_2i_2 - k_c \frac{d\phi}{dt}$$

$$= N_1[i_1 - \frac{k_c}{N_1^2}(N_1 \frac{d\phi}{dt})] - N_2i_2$$

$$= N_1i_1 - N_2i_2$$

(4)

Figure 1. Three-phase five-limps double-winding core type transformer core structure

Among them, $A_{ci}$, $L_{ci}$, $N_p$, $N_s$, $i_p$, $i_s$ and $\Phi$, $r_p$, $r_s$, $r_c$, $L_p$, $L_s$ are the number of turns, core cross-sectional area, core length, primary and secondary winding turns, primary and secondary winding current, core flux, primary and secondary winding resistance, core eddy current loss resistance, primary and secondary winding inductance, respectively.

2.2. Establish differential magnetic circuit model based on differential magnetic circuit principle

(1) Differential magnetic circuit principle

The transformer core magnetic branch can be obtained:

$$\begin{cases} f_i = R_m \Phi_i - F \\ R_m \Phi_i = H_i i_{ci} \end{cases}$$

(5)
Among them, $f_{r_{mi}}$ is the magnetic resistance corresponding magnetic pressure drop, $R_{mi}$ is the iron core effective magnetoresistance, $F$ is the magnetomotive force, $i_\Phi$ is the magnetic flux, $f_i$ is the branch magnetic pressure, $\Phi_i$ is the iron core magnetic flux.

Calculate derivative of time $t$ at both ends of the above formula shows that:

$$
\begin{align*}
\frac{df_i}{dt} &= \frac{d(R_{mi}\Phi_i)}{dt} - \frac{dF}{dt} \\
&= R_{mi}(\frac{d\Phi_i}{dt}) - \frac{dF}{dt} \\
\frac{d(R_{mi}\Phi_i)}{dt} &= \frac{l_i dH_i}{dt} \\
&= \frac{l_i}{A_{ci}}(dH_i/dB_i)(dB_i/dt) \\
&= \frac{l_i}{(A_{ci}\mu_0)}(d\Phi_i/dt) \\
&= R_{mi}(d\Phi_i/dt)
\end{align*}
$$

Among them, $A_{ci}$, $L_{ci}$, $N_{ci}$, $i$ are the number of turns, core cross-sectional area, core length, winding turns, and winding current, respectively. The differential permeability is $\mu_{ci} = dB_i/dH_i$, and the differential reluctance is $R_{mi} = l_i/(\mu_A A_{ci})$. The first equation of Eq. (6) represents the relationship between branch magnetic pressure, branch flux, the rate of change of magnetomotive force, and the EIC principle.

(2) Establish transformer differential magnetic circuit model based on three-phase five-limb transformer parameters

For the three-phase five-limb transformer, the magnetic circuit model is shown in Fig. 2. Among them, $Rm1$, $Rm2$, $Rm3$, $Rm4$, $Rm5$, $Rm6$ and $Rm7$ are core and yoke differential magnetic reluctance. $Rma$, $Rma0$, $Rmb$, $Rmb0$, $Rmc$, $Rmc0$, $Rm01$, $Rm01$, $Rm02$, $Rm03$ are differential leakage resistance between windings. The corresponding differential flux are $d\Phi_{ma}/dt$, $d\Phi_{ma0}/dt$, $d\Phi_{mb}/dt$, $d\Phi_{mb0}/dt$, $d\Phi_{mc}/dt$, $d\Phi_{mc0}/dt$ and $d\Phi_{m0}/dt$. The Primary and secondary differential magnetomotive force of A, B, and C phases are $dFp1/dt$, $dFs1/dt$, $dFp2/dt$, $dFs2/dt$, $dFp3/dt$, $dFs3/dt$, respectively.

![Figure 2](image-url)
Differential magnetoresistance is obtained by a single core magnetization curve or a Jiles-Atherton model. For the Jiles-Atherton model, the differential permeability can be expressed as:

\[
\begin{align*}
\mu_{di} &= \mu_0 (1 + \frac{dM_{eri}}{dH_i} + \frac{dM_{revi}}{dH_i}) \\
\frac{dM_{ani}}{dH_i} &= \frac{M_{ani} - M_{eri}}{k\delta - \alpha_1 (M_{ani} - M_{ani})} \\
\frac{dM_{revi}}{dH_i} &= c\left(\frac{dM_{ani}}{dH_i} - \frac{dM_{int}}{dH_i}\right) \\
M_{ani}(H) &= M_s[c\text{coth}\left(\frac{H + \alpha_1 M}{\alpha_2}\right) - \frac{\alpha_2}{H + \alpha_1 M}] \\
\delta &= \text{sign}(dH / dt)
\end{align*}
\] (7)

Among them, \(M_{ani}\), \(M_s\), \(\alpha_1\) are the number of turns, non-hysteresis magnetization, saturation magnetization and mean field parameters, respectively. \(\alpha_2\) represents the shape of the non-hysteresis magnetization curve, \(k\) reflects the motion of the magnetic domain, \(c\) is the reversible susceptibility, and \(0 < c < 1\).

2.3. Derive the relationship of Core differential flux, differential magneto motive force, flux linkage and loop differential flux relationship based on differential magnetic model

Based on the differential magnetic circuit model of the three-phase five-limb transformer, the relation between the differential flux matrix and the circuit differential flux matrix can be obtained:

\[
\begin{align*}
\frac{d}{dt} \begin{pmatrix} 
\Psi_{p1} \\
\Psi_{p2} \\
\Psi_{p3} \\
\Psi_{sl} \\
\Psi_{s2} \\
\Psi_{s3}
\end{pmatrix} &= \begin{pmatrix} 
N_{p1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & N_{s2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & N_{p3} & 0 & 0 & 0 & 0 & 0 & 0 \\
-N_{s1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -N_{s2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -N_{s3} & 0 & 0 & 0 & 0 & 0 & 0 
\end{pmatrix}
\begin{pmatrix} 
\Phi_1 \\
\Phi_2 \\
\Phi_3 \\
\Phi_4 \\
\Phi_5 \\
\Phi_6
\end{pmatrix} \\
\end{align*}
\] (8)

The relation between differential magnetomotive force matrix \(d\mathbf{F}/dt\) and differential current matrix \(d\mathbf{I}_{ps}/dt\) is:
2.4. Based on the conclusion of step 2.3, derivation of the differential inductance matrix
The differential inductance matrix is the bridge that connects the transformer magnetic circuit to the
circuit, characterized the core saturation characteristics and hysteresis effect. The differential inductance
matrix $L_d$ is:

$$\frac{d\Psi}{dt} = L_d \frac{dI_{ps}}{dt} \quad (10)$$

Among them, $\Psi$ is the primary, secondary winding magnetic flux matrix, $I_{ps}$ is the primary,
secondary winding current matrix.

Substituting (8)-(9) into (10) gives the differential inductance matrix $L_d$:

$$\begin{align*}
\frac{d\Psi}{dt} &= N_p \frac{d\Phi}{dt} = N_p C (R^{-1} \frac{dF}{dt}) \\
&= N_p CR^{-1} (N_F \frac{dI_{ps}}{dt}) = L_d \frac{dI_{ps}}{dt} \\
\Rightarrow L_d &= N_p CR^{-1} N_F
\end{align*} \quad (11)$$

2.5. Establish single-phase transformer group circuit model based on single-phase transformer
winding connection form
Based on the above theory, a Y/Y-connected three-phase three-limp transformer is taken as an example,
and a circuit magnetic circuit coupling equation is established to realize the DC bias magnetic simulation
of the transformer.

$$\begin{align*}
\begin{bmatrix}
E_p \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
&= \begin{bmatrix}
-R_p & 0 & 0 & I_p \\
0 & R_s & 0 & I_p \\
0 & 0 & R_L & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p \\
0 & 0 & 0 & I_p
\end{bmatrix}
\begin{bmatrix}
\frac{dI_p}{dt} \\
\frac{dI_s}{dt} \\
\frac{dI_L}{dt} \\
\frac{dI_p}{dt} \\
\frac{dI_s}{dt} \\
\frac{dI_L}{dt} \\
\frac{dI_p}{dt} \\
\frac{dI_s}{dt} \\
\frac{dI_L}{dt} \\
\frac{dI_p}{dt} \\
\frac{dI_s}{dt} \\
\frac{dI_L}{dt} \\
\frac{dI_p}{dt} \\
\frac{dI_s}{dt} \\
\frac{dI_L}{dt}
\end{bmatrix}
\end{align*} \quad (12)$$

Wherein $p, s$ represent the primary, secondary, $R, L$ are matrices of resistance and inductance matrix.
$K$ represents the unit matrix.
3. Influence of DC bias on operation performance of three-phase five-lims

3.1. Influence of DC bias on leakage flux of transformer
The influence of DC bias on the three-phase five-limp transformer is calculated based on the external magnetic leakage resistance R of the high voltage winding of the transformer. The results are shown in Fig. 3 (a) and (b).

![Figure 3](image)

*Figure 3. (a)/ (b) Leakage flux at I\text{DC}=0/24.8A*

It can be seen that the DC bias magnetic flux increases the leakage flux amplitude of the three-phase five-limp transformer. At the same time, the waveform is also seriously distorted, showing an irregular form, which is related to the complex electromagnetic coupling properties of a three-phase five-column transformer.

3.2. Effect of DC bias on transformer core flux
This section examines the effects of DC bias on the magnetic flux of a three-phase five-limp transformer core. The results are shown in Fig. 4. It can be seen that when the DC bias is applied, the magnetic flux of the three-phase five-limp transformer core increases as a whole and the waveform shows slight distortion.

![Figure 4](image)

*Figure 4. (a)/ (b). Core flux at IDC=0/24.8A*

4. Conclusion
(1) Based on the EIC, J-A and Bertotti theory, the DC bias model of three-phase five-limp transformer is established. The model comprehensively considers the connection mode of core and winding, dynamic eddy current loss of core, core hysteresis loss, magnetic flux leakage and space...
coupling of coils, etc. And effectively solves the contradiction that both precision and complexity cannot
be achieved.

(2) Based on this model, the influence of DC bias on the excitation current, leakage flux, and core
flux of the three-phase transformer of YN/d are analyzed. The results show:

1) With the increase of DC current, the harmonics of leakage flux increase approximately linearly.
The increase rate of low-order harmonics is faster than that of higher-order harmonics. The fundamental
wave and low-order harmonics occupy larger components.

2) With the increase of DC current, the magnetic flux of the three-phase five-limp transformer core
has become larger as a whole and the waveform has been slightly distorted.

References

[1] LUO Zhi-jian, YE Jie-hong. Influence of harmonic on shunt capacitor in HVDC monopolar
operation [J]. Power Capacitor & Reactive Power Compensation, 2009, 30(5): 58 - 61.

[2] WEN Jun, LIU lian-guang, XIAN Song, Ma Xue-ling, LI Wei-xia. Influence of geomagnetic
induced current on safe and stable operation of power grid [J]. China Science and Technology
Review, 2010, 34 (11): 24 - 30.

[3] LI Xiao-ping, WEN Xi-shan, LAN Lei, etc. Test and simulation for single-phase transformer
under DC bias [J]. Proceedings Of The Chinese Society For Electrical Engineering. 2007, 27
(9): 33 - 40.

[4] LI Hong-zhi, CUI Xiang, LU Tie-bing, etc. Electric circuit and magnetic circuit combined model
of DC biased power transformer. Proceedings of the CSEE. 2009, 29 (27): 119 - 125.