Single-Phase DC Magnetic Bias Model and Simulation Analysis Based on EIC Principle

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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.

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 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 three-limps transformer model to solve the conflict between accuracy and complexity effectively.

2. Description of the models

2.1. Establish circuit model based on single-phase transformer core topology and transformer parameters

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

Set l, d, A, τ, σ, 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:
Among them, \( H_i \) denotes magnetic field strength related to core eddy current, the dimensionless constant \( G = 0.1356 \), \( H_o \) 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:

\[
r_c = \frac{N_i^2}{k_c}
\]  

(2)

The magnetic potential generated by the eddy current can be written as \( F_{cp} = H_i l_p \), which can be available as:

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

(3)

The magnetomotive force acting on the primary and secondary winding currents and the eddy current of the iron core are:

\[
F = N_1 i_1 - N_2 i_2 - k_c \frac{d\Phi}{dt}
\]

\[
= N_1 \left( i_1 - \frac{k_c}{N_i^2} \left( N_1 \frac{d\Phi}{dt} \right) \right) - N_2 i_2
\]

(4)

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 \( i_i = i_1 - k_c / N_i^2 (N_1 d\Phi / dt) \). According to the single-phase transformer core form and magnetic circuit model, the core eddy current loss resistance \( r_c \).

(2) Single-phase transformer circuit model

For any single-phase transformer, according to the above derivation, the single-phase transformer primary circuit model can be represented as \( r_c \) and \( r_p \) in parallel or in series with other parameters. The secondary circuit model can be represented as a series connection between the parameters. Take a single-phase three-limp transformer as an example, the circuit model can be shown in Fig. 1.

![Figure 1. Single-phase three-limp double-winding core type transformer core structure.](image-url)
Among them, \( A_{ci} \), \( L_{ci} \), \( N_{ci} \), \( i_{ci} \), \( \Phi_{ci} \), \( r_{ci} \), \( r_{ci} \), \( L_{ci} \), \( L_{ci} \) 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:

\[
\begin{align*}
\Gamma_i &= R_{mi} \Phi_i - F \\
R_{mi} \Phi_i &= H_i \Gamma_i 
\end{align*}
\]  

Among them, \( R_{mi} \) is the magnetic resistance corresponding magnetic pressure drop, \( R_{mi} \) is the iron core effective magnetoresistance, \( F \) is the magnetomotive force, \( \Phi_i \) is the magnetic flux, \( i \) 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:

\[
\begin{align*}
\frac{df}{dt} &= \frac{d(R_{mi} \Phi_i)}{dt} - \frac{dF}{dt} \\
&= R_{mi} \frac{d\Phi_i}{dt} - \frac{dF}{dt} \\
d(R_{mi} \Phi_i) &= d(H_i \Gamma_i) \\
&= \Gamma_i \frac{dH_i}{dt} \\
&= \Gamma_i \left( \frac{dH_i}{dB} \right) \frac{dB}{dt} \\
&= \frac{1}{A_{ci}} \left( \frac{dH_i}{dB} \right) \frac{dB}{dt} \\
&= \frac{1}{A_{ci}} \frac{d\Phi_i}{dt} \\
&= R_{mi} \frac{d\Phi_i}{dt} 
\end{align*}
\]  

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 \( \mu_{di} = dB_i / dH_i \), and the differential reluctance is \( R_{mi} = \frac{1}{A_{ci}} (\mu_{di} A_{ci}) \). 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 single-phase transformer differential magnetic circuit model based on single-phase transformer parameters

Based on the EIC principle, a single-phase three-limb transformer is taken as an example. The magnetic circuit model is shown in Fig. 2. Among them, \( \frac{dF_i}{dt}, \frac{dF_i}{dt} \) are the primary and secondary differential magnetomotive forces, respectively. \( R_{m1}, R_{m2}, R_{m3}, R_{m4}, R_{m5}, R_{m6} \) are core and yoke differential magnetic reluctance. The corresponding differential flux are \( \frac{d\Phi_{ma}}{dt}, \frac{d\Phi_{ma0}}{dt}, \frac{d\Phi_{m0}}{dt} \).

![Figure 2. Single-phase three-limb double-winding core-type transformer differential magnetic circuit model.](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:

\[ \mu_{ij} = \mu_0 \left( 1 + \frac{d M_{i}}{d H_j} + \frac{d M_{j}}{d H_i} \right) \]
\[ \frac{d M_{i}}{d H_j} = k \delta - a_1 (M_{i} - M_{j}) \]
\[ \frac{d M_{j}}{d H_i} = c_1 \left( \frac{d M_{i}}{d H_i} - \frac{d M_{j}}{d H_j} \right) \]
\[ M_{i}(H) = M_{i}\left[ \coth \left( \frac{H + \alpha_1 M_i}{\alpha_2} \right) - \frac{\alpha_1}{H + \alpha_1 M_i} \right] \]
\[ \delta = \text{sign}(dH/dt) \]

(7)

Among them, \( M_m, M_s, \alpha_1 \) 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 magnetomotive force, flux linkage and loop differential flux relationship based on differential magnetic model

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

\[ \frac{d (\Psi_p)}{dt} = \begin{pmatrix} N_1 & 0 & 0 \\ -N_2 & 0 & 0 \end{pmatrix} \Phi_1 \]

(8)

The relation between differential magnetomotive force matrix \( d\mathbf{F}/dt \) and differential current matrix \( d\mathbf{l}_p/dt \) is:

\[ \begin{pmatrix} 0 \\ -E_2 \\ -E_1 + E_2 \\ -E_1 - E_2 \end{pmatrix} = \begin{pmatrix} -N_1 & 0 & 0 & 0 \\ 0 & -N_2 & 0 & 0 \\ 0 & 0 & N_2 & 0 \\ 0 & 0 & 0 & N_1 \end{pmatrix} \begin{pmatrix} -I_2 \\ I_1 + I_2 \\ I_1 - I_2 \end{pmatrix} \]

(9)

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 \( \mathbf{L}_d \) is:

\[ \frac{d\Psi}{dt} = \mathbf{L}_d (d\mathbf{l}_p/\mathbf{dt}) \]

(10)

Among them, \( \Psi \) is the primary, secondary winding magnetic flux matrix, \( \mathbf{l}_p \) is the primary, secondary winding current matrix.

Substituting (8)-(9) into (10) gives the differential inductance matrix \( \mathbf{L}_d \):
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 single-phase three-limb 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.

\[
\frac{d\Psi}{dt} = N_p \frac{d\Phi}{dt} = N_p C (R \frac{dF}{dt})
\]

\[
= N_p CR^2 (N_p \frac{dI_p}{dt}) = L_s \frac{dI_s}{dt}
\]

\[
\Rightarrow L_s = N_p CR^2 N_p
\]

3. Influence of DC bias on operation characteristics of single-phase transformer

3.1. Influence of DC bias on leakage flux of transformer

The influence of DC bias on the single-phase 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).

It can be seen that when the DC bias is applied, the leakage flux of the three-phase transformer increases and serious distortion occurs. This shows that the core has been highly saturated and the leakage flux waveform is similar to the excitation current waveform to some extent.

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 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 group transformer core becomes larger as a whole, and the waveform is slightly distorted.
4. Conclusion

(1) Based on the EIC, J-A and Bertotti theory, the DC bias model of three-phase three-limb 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. It can be further applied to the modeling of complex transformers with core structures. 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 excitation current is quickly distorted and each harmonic current component increases rapidly. Each harmonic component is approximately in direct proportion to the intruding DC current. The increase of low harmonics is obviously higher than that of higher harmonics.

2) With the increase of DC current, each harmonic of the leakage flux increases linearly. The growth of low-order harmonics is faster than that of higher harmonics, and the fundamental and lower-order harmonic components occupy larger components.

References
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