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Finite Element Study of Ferroresonance in single-phase Transformers Considering Magnetic Hysteresis

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The occurrence of ferroresonance in electrical systems including nonlinear inductors such as transformers will bring a lot of malicious damages. The intense ferromagnetic saturation of the iron core is the most influential factor in ferroresonance that makes nonsinusoidal current and voltage. So the nonlinear behavior modeling of the magnetic core is the most important challenge in the study of ferroresonance. In this paper, the ferroresonance phenomenon is investigated in a single phase transformer using the finite element method and considering the hysteresis loop. Jiles-Atherton (JA) inverse vector model is used for modeling the hysteresis loop, which provides the accurate nonlinear model of the transformer core. The steady-state analysis of ferroresonance is done while considering different capacitors in series with the no-load transformer. The accurate results from copper losses and iron losses are extracted as the most important specifications of transformers. The validity of the simulation results is confirmed by the corresponding experimental measurements.

Keywords : ferroresonance, finite element method, transformers, Jiles-Atherton (JA) vector model, power loss

1. Introduction

The ferroresonance is an oscillating phenomenon which occurs in an alternating electric circuit consisting of nonlinear inductor and capacitor. In the electrical systems, there are a large number of capacitors such as cables, long lines, capacitor-voltage transformers, series or shunt capacitor banks, voltage-grading capacitors in circuit breakers, metal clad substations, and the saturable inductors in the form of power transformers, voltage measurement inductive transformers (VT) and shunt reactors. The ferroresonance can cause the overvoltage and the overcurrent which highly distorts the waveforms of current and voltage and makes severe damages to equipment. Other ferroresonance effects are overheating in transformers and reactors, continuous and excessive loud sound and problems related to protection systems. All these phenomena and effects can be disastrous for the electrical systems [1, 2].

The ferroresonance is essentially a low-frequency phenomenon and generally has a frequency spectrum below 2 kHz. In general, the ferroresonance is classified as fundamental, subharmonic, and chaotic modes. The fundamental mode is characterized by the current and voltage waveforms with the frequency similar to the electrical system which can either have the harmonic content or not. In the subharmonic mode, current and voltage waveforms have submultiple frequencies of the power system frequency. The chaotic mode presents a wide spectrum of frequencies [2, 3]. The aim of the present work is accurate behavior investigation of transformer in the fundamental ferroresonance mode, which requires an accurate model of the transformer core.

Several research works based on the magnetic circuit analysis have been proposed for the ferroresonance analysis; for instance, a hysteresis model of an unloaded transformer has been introduced [1]. Analyzing the electromagnetic transients using the Preisach model of magnetic hysteresis has been done [4], and also a flux-current methodology using an inverse JA approach has been employed to model the hysteresis behavior of a nonlinear inductor [5]. However, magnetic circuit analysis does not allow considering the real dimensions of transformers and also the dynamic and nonlinear behavior of ferromagnetic core. Therefore, the accurate characteristics such as transformer losses can't be investigated. Although the ferroresonance phenomenon with the help of the Finite Element (FE) method for an autotransformer has been investigated

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[6], but in this analysis the B-H curve is used to model the core which can't describe the actual nonlinear behavior of the core. Thus, in the present work an accurate nonlinear model of transformer core is proposed using the FE method and then the transformer characteristics will be investigated under the ferroresonance condition.

For the magnetic field analysis in electromagnetic devices, when the local magnetic field is rotating or if the materials have anisotropic property, the directions of magnetic flux density and magnetic field intensity are not parallel, but rather there is a lagging angle between B and H [7]. The interaction between B and H in such conditions can only be achieved using a vector model. Moreover, the losses due to the rotational flux has a significant share in the total loss of electromagnetic devices such as transformer. Thus, it is necessary to model the magnetic field in vector form [8, 9]. Preisach model and extensions of its original model have been used to effectively simulate the magnetic fields in recent years. However, taking account the rotation of the magnetic fields, the anisotropic vector Preisach model becomes more complex and the Preisach distribution function (PDF) has to be identified by measuring a set of reversal curves [10].

One of the famous methods for simulation of nonlinear characteristics of magnetic materials is the JA model. This model has been widely employed due to some advantages such as a relatively low number of physical parameters and little computational effort [11]. The JA hysteresis vector model using the magnetic differential reluctivity tensor is incorporated in the FE with vector potential formulation, which is more common than the numerical inversion model that the magnetic induction vector is used as the independent variable [12]. Thus, in the present work the JA inverse vector model is chosen.

2. JA Hysteresis Vector Model

In order to investigate the accurate behavior and characteristics of transformer in fundamental mode of ferroresonance, the FE method is used to analysis the transformer. The use of a vector model for modeling the nonlinear core allows the magnetic fields are applied in the principal directions so that the approximation of the average permeability in each FE is avoided, and the more realistic calculations are performed [8]. The JA inverse vector model chosen in this study is able to represent the anisotropic behavior of steel as well as the rotational flux in the T-joints of transformer. The transformer chosen in this work has the isotropic laminations and therefore the rotational flux in the transformer T-joints is considered by this method. This model reduces itself to a scalar model if the flux does not change its space direction.

2.1. Nonlinear model of core

Bergqvist proposed a generalized vector of the JA scalar hysteresis model that The JA vector model is able to represent isotropic and anisotropic electrical steels [12]. J. V. Leite and his colleague proposed reverse version of the original model equations [13]:

$$d\overline{M} = \frac{1}{\mu_0}[1 + f_\chi(1-\vec{\alpha}) + \vec{c}\vec{\xi}(1-\vec{\alpha})]^{-1} \cdot [f_\chi + \vec{c}\vec{\xi}]d\overline{B} \tag{1}$$

with $f_\chi = \vec{\chi}_f|\vec{\chi}_f|^{-1}\vec{\chi}_f$ where the auxiliary variable $\vec{\chi}_f$ is defined by $\vec{\chi}_f = \vec{k}^{-1}(\overline{M}_{an} - \overline{M})$. $\overline{M}_{an}$ and $\overline{M}$ are respectively the anhysteretic magnetization and the total magnetization. I and $\vec{\xi}$ are the diagonal unity matrix and the diagonal matrix of the derivatives of anhysteretic functions, respectively. $\vec{k}$, $\vec{\alpha}$, and $\vec{c}$ are second rank tensors which must be obtained experimentally.

Using $d\overline{M}$ obtained from (1), can be written $d\overline{H} = \|\partial v\| d\overline{B}$, where $\|\partial v\|$ is the differential reluctivity tensor [8]. For the 3-D case the differential reluctivity tensor can be written as:

$$\|\partial v\| = \begin{bmatrix} \frac{dH_x}{dB_x} & \frac{dH_x}{dB_y} & \frac{dH_x}{dB_z} \\ \frac{dH_y}{dB_x} & \frac{dH_y}{dB_y} & \frac{dH_y}{dB_z} \\ \frac{dH_z}{dB_x} & \frac{dH_z}{dB_y} & \frac{dH_z}{dB_z} \end{bmatrix} = \begin{Vmatrix} \partial v_{xx} & \partial v_{xy} & \partial v_{xz} \\ \partial v_{yx} & \partial v_{yy} & \partial v_{yz} \\ \partial v_{zx} & \partial v_{zy} & \partial v_{zz} \end{Vmatrix} \tag{2}$$

tensor terms in (2) are given in details in [13].

2.2. Voltage fed and magnetic vector potential formulation

By specifying the electric scalar potential V and magnetic vector potential $\overline{A}$, The formulation is obtained from the weak form of the Ampere's law [13]

$$(\|\partial v\|\mathrm{rot}\overline{A}, (t, \Delta t)\mathrm{rot}\overline{A'})_\Omega - (\|\partial v\|\mathrm{rot}\overline{A}, \mathrm{rot}\overline{A'})_\Omega$$
$$+ (\overline{H}(t), \mathrm{rot}\overline{A'})_\Omega + (\sigma\partial_t A, \overline{A'})_{\Omega c} + (\sigma\,\mathrm{grad}V, \overline{A'})_{\Omega c}$$
$$- (J, \overline{A'})_{\Omega s} = 0, \quad \forall \overline{A'} \in F_a(\Omega) \tag{3}$$

Where $F_a(\Omega)$ the function of space is defined on Ω which contains the basis functions for the vector potentials $\overline{A}$ and the test function $\overline{A'}$. The conducting regions of Ω is denoted as Ωc and the parts of stranded conductors is denoted as Ωs. The block $(.,.)_\Omega$ denotes the volume integral in Ω of produced scalar or vector fields. The electric field $\overline{E}$, the magnetic flux density $\overline{B}$, the magnetic field intensity $\overline{H}$, and the current density $\overline{J}$, are