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3D non-linear magneto-thermal behavior on transformer covers

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ABSTRACT

In real 3D metallic structures excited by electromagnetic fields some areas are strongly saturated while others not. In particular, this performance has to be taken into account when analyzing the 3D magneto-thermal behavior on transformer covers. To have a deep understanding of these complex phenomena the influence of the material non-linear magnetic characteristic is explained in detail based on a non-linear penetration depth electromagnetic analytical model. Concerning the thermal analysis, it is crucial to accurately set the subsequent thickness of the heat source volume regions from the concept of the magnetic field non-linear penetration depth, which is the novelty introduced in this paper. The temperature distribution is computed with the Finite Element (FE) Method (FEM) on metallic cover plates heated by electromagnetic induction and results are compared with measurements for the validation of the presented model.

1. Introduction

This paper is motivated by the fact that over temperatures and hot spots in bushing adapters of power transformers significantly affect their service reliability and availability and are the one of the most common reasons of their failures involving high economic costs [1,2]. Over temperatures in the transformer cover and tank wall are caused by electromagnetic induction due nearby low voltage leads which carry currents of several kA. This is a well known yet undesired performance and thus manufacturers and designers are more concerned about it due to the combination of factors: the increasing of power rating in power transformers, the high cost of materials, and the reduction of the overall size of the transformer imposed by a more and more competitive market [3,4]. The main design criterion of the bushing adapters is the limit temperature rise caused by leakage field due to the high current leads, where a reference value of temperature limit of 140 °C is considered for all the transformer metallic parts [5].

The calculation of stray losses in the bushing adapters is, of course, also important to guarantee the total losses. However, it is difficult to directly measure the stray losses in the bushing adapter itself and therefore verify the computed values. Meanwhile it is a fact that the surface temperature can be easily monitored nowadays by means of temperature sensors available at the market. Hence, a coupled electromagnetic-thermal analysis indirectly permits to verify the underlying leakage field and stray losses calculation [6].

To this effect, authors have presented in [7] a methodology where an electromagnetic analytical formulation is linked with 3D thermal Finite Element (FE) Method (FEM) to compute the temperature distribution on transformer covers. As result of that work, this paper deeps into the subject and analyzes the concept of non-linear penetration depth in the computational methodology to take into account the saturation of ferromagnetic materials, allowing thus a better understanding and more insight into the electro-thermal behavior on transformer covers.

2. Background

The evaluation of stray losses on flat metallic structural parts and the performance of electromagnetic leakage field penetration depth inside metals is a 3D phenomenon and widely discussed in the literature [8–10]. However, some problems arise associated to the accurate modeling of the phenomenon when applying the nowadays generally used 3D FEM, such as the discretization into the small skin depth, saturation and hysteresis of ferromagnetic materials [11–13].

Additionally, the difficulties when solving 3D eddy current problems with FEM are connected with a proper and adequate

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mathematical formulation [14]. The reason is that in three-dimensional eddy current problems, both the electric and the magnetic field must be described in conductors while in eddy current-free regions only the magnetic field needs to be taken into account. These fields can be formulated from potentials in various ways leading to several FEM formulations. One of the crucial points is the appropriate selection of these formulations for the solving process. In particular, the requirement of numerical stability demands formulations involving the uniqueness of the potentials and the minimization of the number of variables [15]. In addition to this, the main question here is how to ensure all the interface conditions and the ability to treat discontinuities in material properties when dealing with multiply-connected regions [14].

In this scenario, it comes that solving a 3D eddy current problem with FEM is not straightforward and requires advanced knowledge on the formulations, particularly when dealing with a multiply-connected domain, such is the case of the tank cover plate having the conductor holes. Modeling and solving still demand much time and effort in the scale of a rapid response in market time, and it does require expert users. Moreover, for the computation of the stray losses and resulting temperature from the electromagnetic induction heating, such accurate model must be taken into account if calculations are to be reliable [7].

Recently, to avoid the problems related with formulations on eddy currents modeling and discretization into the penetration depth, a practical 3D methodology has been published by authors in [7], where an analytical formulation for the stray losses computation is linked with FEM for thermal analysis to compute the overheating on transformer covers. An analytical approximation for the non-linear magnetic permeability has been already introduced to the methodology in [16]. In this paper authors are going further in this issue introducing into the computational methodology the non-linear penetration depth. This concept is crucial to accurately take into account the saturation of ferromagnetic materials in the electromagnetic model, and on the other hand allowing to set the heat sources volume thickness in the thermal model.

3. Non-linear penetration depth computational model

Since conductive structural parts of power transformers have mostly non-linear behavior, the magnetic *BH* curve characteristic, and in consequence non-linear magnetic permeability, must be taken into account when analyzing their magneto-thermal performance [16]. It is done here by means of a non-linear penetration depth model, where its importance relies in that it is possible to represent the distribution of non-linear magnetic quantities on the electromagnetic analytical model. The non-linear penetration depth model provides more accuracy for stray loss non-linear electromagnetic and thermal computation taking into account saturation, whose most important issues are analyzed in detail in the following sections.

3.1. Stray losses applying Poynting's vector

For the calculation of stray losses per unit surface area P_s in conducting steel plates Poynting's vector formulation might be used [17] for time harmonic fields

$$P_s = \iint_s Re(\boldsymbol{Z}_s)\frac{|H_{ms}(x,y)|^2}{2}dx\,dy \tag{1}$$

where x and y are the Cartesian coordinates of each point, H_{ms} is the maximum value of the field intensity at the metal surface, and $\boldsymbol{Z}_s$ the complex surface impedance (SI). The concept of SI was first introduced into field theory by Schelkunoff in 1938 for time harmonic fields [12]. At the surface of good electrical conductors into which the penetration of the field is limited, the tangential component of the electric field $\boldsymbol{E}$ can be considered under sinusoidal performance proportional to the tangential component of magnetic field $\boldsymbol{H}$, yielding

$$\boldsymbol{Z}_s = \frac{\boldsymbol{E}}{\boldsymbol{H}} = (1+j)\frac{1}{\sigma\delta} \tag{2}$$

Where δ is defined in (3) and represents the electromagnetic field penetration depth in a solid conductor, on which this computational model is focused.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{3}$$

Being ω the angular frequency, σ the linear electric conductivity and $\mu$the magnetic permeability of the material. If the magnetic permeability μ is considered constant in all directions, then (3) is referred to as the linear penetration depth δ_L and (2) the linear SI $\boldsymbol{Z_L}$. Nevertheless, when dealing with structural steel of real power transformers non-linear magnetic permeability must be considered in all directions, i.e. on the metal surface (*xy*-plane) and inside metal (*z*-direction). These key concepts and how they are introduced in the non-linear penetration depth analytical model are explained in detail in the next subsections.

3.2. Non-linear permeability on the metal surface

In the case of transformer cover plates, the incident magnetic field distribution $H_{ms}(x,y)$ on the metal surface ($z=0$) can be calculated from Biot–Savart law [7]. Thus, the surface value of the non-linear magnetic permeability μ_s (H_{ms},x,y) defined in (4) can be easily considered from the real *BH* curve of the material as seen in Fig. 1.

$$\mu_s(H_{ms},x,y) = \frac{B(H_{ms})}{H_{ms}(x,y)} \tag{4}$$

In this case, it is important to note that the value of the penetration depth from (3) considering $\mu = \mu_s$ (H_{ms},x,y), represents the maximum – or absolute – depth δ_{abs} the ac magnetic field H_{mz} wave front penetrates into the conductor [18], as seen in Fig. 2.

3.3. Non-linear permeability inside metal

In addition to the variation of the surface permeability, in real materials presenting a non-linear *BH* characteristic the magnetic permeability behavior inside metal has to be also taken into account. It has a significant practical importance on the accuracy of the non-linear penetration depth model. Having that the envelope of the maximum magnetic field H_m changes with field penetration in the direction of propagation z from the surface as $H_m(z) = H_{ms}\,e^{-\alpha z}$ [18], it does cause also a variation of the magnetic permeability in the z-direction $\mu(H_m,z)$ as seen in Fig. 2.

If the magnetizing force reaching the surface H_{ms} is strong enough, the value of the saturation flux density B_0 might be considered constant within the penetration depth and a step function becomes a satisfactory approximation of the *BH* curve as it is shown in Fig. 3. Such simplification allows the analytical derivation of equations for the SI in the case of a rectangular (step) *BH* characteristic [19].

McLean in 1953 [20] from the solution of Maxwell equations inside metal and assuming sinusoidal magnetic field, stated that a multiplier coefficient a_p of 1.69 should be applied to the linear theory (2) in order to take into account saturation [17]. An important remark is that the sinusoidal magnetic field formula is valid when the magnetic field reaches the surface in a mostly tangential direction, as it does occur in the case of transformer tank covers [18]. The