Frequency Response Analysis for New Magnetic Power Transformer Composite Crystalline Core

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Abstract—Characterization of composite materials is an important topic in modern electromagnetics, thus, suggested new microstructure electromagnetics materials that will be able to realize enhancing the electromagnetic properties of transformer core and its characterization has been studied in this paper. This paper also presents a theoretical analysis to study the effective permeability prediction of the suggested magnetic composite materials with adding various types and percentages of particles (Fe, Silicon steels, Metglas, Co-Fe, Ni-Fe, MnZn, MgZn, NiZn) for formulating new magnetic composite transformer core materials. Theoretical analysis is introduced to study the influence of inclusion types and their concentration on the permeability. Numerical results show that significant aberration of inclusion types and their concentration on the effective permeability with respect to conventional magnetic materials. Frequency Response Analysis (FRA) is used to investigate transformer core magnetic composites and specifying enhancing magnetic effective complex relative permeability of transformer core magnetic composites with respect to variant frequencies (10^2Hz – 10^3Hz).

Index Terms— Magnetic Composites, Particles, Transformer Core, Permeability, Magnetism.

I. INTRODUCTION

Nowadays, computer modeling and simulations of electromagnetic processes in power transformers have become a popular method for analyzing their performance and defining ways for design improvements. The characterization and the study of artificial materials is an important topic in modern electromagnetics. The properly designed micro-structured materials may enable the realization of compact resonators, and the formation of transformer equivalent circuits [1-4]. The main goal of material science is developing new magnetic composite industrial materials. Thus, it is concluded that Mn-Zn ferrites present high permeability and permittivity simultaneously within the frequency range of kHz through MHz [5-11]. Also, it is established that Silicon steel is the most popular soft magnetic material in the electric power industry as the core material of electrical machines. Grain-oriented silicon steel is mainly used in manufacturing of transformer cores, which provides the required magnetic anisotropy and lowest losses when magnetized in the rolling direction [12, 13]. In order to estimate the effective material parameters of the composite materials and mixtures so far Maxwell–Garnett and Bruggeman formulas are introduced [14-18].

Recently, frequency response analysis (FRA) has been recognized as the most reliable monitoring technique for transformer winding displacement and deformation assessment. It is established upon the fact that the shape of a winding frequency response at high frequencies is associated with winding geometry. The appearance of clear shifts in resonance frequencies or new resonant points on a response may characterize faulty conditions of windings [19, 20]. Fig 1 shows the Frequency Response Analysis (FRA) spectral regions and the associated dominant parts of the transformer. Research activities have been undertaken to utilize FRA in the development of suitable lumped parameter mathematical models of transformer windings [21-25]. This method is especially useful when the quantities of interest cannot be measured directly. Such situations appear, for example, when evaluating inductances of transformer windings at their first resonance frequencies, which are necessary for interpretation of FRA data [26, 27].
The new developed materials become particularly important because its physical properties change dramatically with the size and with the local structure of the grains. One important application is considered for transformer core materials, these materials should be of low cost and easy to prepare, allowing them to be highly competitive with the conventional existing ones. With respect to soft magnetic materials that play an important role in broad applications, such as transformers. These materials are used in electromagnetic applications, can be described as ferromagnetic powder particles surrounded by an electrical insulating film [28-31]. The objective of this work is to characterize magnetic behavior of power transformer composite crystalline core using frequency response analysis which has become increasingly popular for the assessment of mechanical integrity in power transformers. FRA technique is made of the fact that the shape of the response at higher frequencies is uniquely determined by the geometrical construction of the transformer.

Therefore, new magnetic composite transformer core materials have been suggested for enhancing power transformer magnetic characterization response related to types and concentrations of selected particles. Numerical results predict that power transformer core characterization results in difference between conventional types than those using variant types of particles in cores. This is will be good agreement with experimental results. Therefore, many microparticle composites with different particles are investigated to reach the best fillers significantly increase of magnetic permeability.

II. ANALYTICAL MODEL

This paper focuses on calculation techniques for the effective permeability of magnetic composite transformer core materials consisting of micron/submicron-sized particles embedded in different matrices. So that, based on the previous analytical models [14, 18] have been used to formulate theoretical models for predicting the effective permeability of magnetic composite materials. With respect to Maxwell-Garnett formula that plays an important role in two dimensions composite materials [14], the effective permeability for random distribution of particle size as two dimensions spherical shapes significantly is given as follows:

\[
\mu_{eff} = \mu_m + 2\mu_m \phi (\mu_i - \mu_m) / (\mu_i + \mu_m - \phi (\mu_i - \mu_m))
\]  
(1)

Where,
\( \mu_i \) is permeability of inclusions in the composites,
\( \mu_m \) is permeability of main matrix of the composites,
\( \phi \) is the volume fraction of inclusions inside the main matrix.

For more accurate approach it is assumed that estimation of the magnetic composite material structure to be periodic, and the unit cell, which is the minimum volume, is regarded as homogeneous magnetic substances [18]. The effective permeability of magnetic composite materials is defined on the basis of magnetic energy balance in the unit cell, and it is assumed, in this approach, that the original cell and the homogenized cell include equivalent magnetic energy when both unit cells are immersed in equivalent magnetic field as shown in Fig. 2.

Thus, this method has possibility to apply to any structure as follows:

\[
\mu_{eff} = \frac{\int_{S_{homa}} B_{homa} H_{homa} dS}{\int_{S_{homa}} B_{org,Horig} dS}
\]  
(2)

Where,
\( S_{homa} \) is the square of the original cell, \( B_{homa} \) is the magnetic flux density, and \( H_{orig} \) is the magnetic field.
Schematic diagram and the equivalent magnetic circuit of the transformer core model [20] are established as shown in Fig. 3. The magnetic core of the transformer is divided into three sections with respect to uniform fluxes $\phi_A$, $\phi_B$, and $\phi_C$ of each transformer limb. Each section of the magnetic core is represented by its reluctance $R_e$, the reluctance of a section is determined by the magnetic parameters of lamination and the core geometry as follows [3, 4]:

$$R_e = \frac{F}{\phi} = \frac{l}{\mu_{\text{core eff} A}}$$

(3)

Where, $F$ is the magneto-motive force that required for establishing the flux along the length of the section, $\phi$ is produced magnetic flux, $l$ is the length of the magnetic flux path along each section, $A$ is the cross section area of the core, $\mu_{\text{core eff}}$ is complex effective relative permeability of transformer core, and $\mu_r$ is the free space permeability.

Therefore, the effective local magnetic permeability of suggested magnetic composite transformer core materials can be predicted by using the above approaches based on inclusions permeability, weight percentages of inclusions inside the matrix and main matrix permeability of magnetic transformer core composite materials. Thus, the complex effective relative permeability of transformer core is defined as follows:

$$\mu_{\text{core eff}} = \mu_{\text{core eff}}' - j\mu_{\text{core eff}}'' = k_{fe} \mu_r \frac{\tanh(1+jb/\delta)}{(1+jb/\delta)}$$

(4)

Where, $\delta$ is the skin depth, $k_{fe} = 2b/h$ represents the stacking factor, $h$ and $2b$ are the thicknesses of a single lamination sheet of the core with and without insulation layer included respectively, and $\mu_r$ is the local magnetic permeability. The skin depth $\delta$ depends on the angular frequency $\omega$ of the magnetic field as follows:

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu_r}}$$

(5)

Where, $\sigma$ is the conductivity of lamination materials, whatever, using composite crystalline materials for transformer core laminations required deterministic the effective conductivity [32, 33]. However, in this paper, the influence of types and concentration of inclusions particles on the performance of effective permeability of magnetic composite power transformer core is investigated.

### III. SELECTED PARTICLES AND MAGNETIC INDUSTRIAL MATERIALS

Nowadays, nanotechnology science can be made huge enhancement in the magnetic properties of transformer core materials, then; the choice of magnetic composite material is complex and depends on many factors, the primary ones being frequency, the size of the component, the physical...
strength and the magnetic properties. Thus, the suggested particles size like iron high purity particles (single crystals in preferred directions), Silicon steels, Metglas, Co-Fe, Ni-Fe, MgZn_Ferrite, and NiZn_Ferrite have been depicted the enhancement in performance of transformer core magnetic properties. Table I depicts the main electrical description properties of usage of particles which have been used for enhancing magnetic properties of transformer core materials.

Table I Permeability and Resistivity of Suggested Transformer Core Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\mu_r$</th>
<th>$\rho$ ($\Omega.m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metglas</td>
<td>$10^6$</td>
<td>$142x10^8$</td>
</tr>
<tr>
<td>Fe (High Purity)</td>
<td>$10^3$</td>
<td>$10x10^5$</td>
</tr>
<tr>
<td>Silicon Steels</td>
<td>$10^7$</td>
<td>$45x10^5$</td>
</tr>
<tr>
<td>MnZn_Ferrite</td>
<td>5000</td>
<td>1</td>
</tr>
<tr>
<td>MgZn_Ferrite</td>
<td>800</td>
<td>0.5</td>
</tr>
</tbody>
</table>

IV. RESULTS AND DISCUSSIONS

Magnetic transformer core can enormously concentrates the strength and increases the effect of magnetic fields produced by electric currents and permanent magnets. The effect of core laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude, the; thin core laminations are generally used on high-frequency transformers, with some of very thin steel laminations able to operate up to 10 kHz. In practice, the parameters of core transformer, such as dimension of winding, core lamination...etc. is usually determined using a lamination sample [26, 27]. The following are results of study carried out on the complex effective relative permeability and reluctance of the new transformer core composite magnetic materials that have been suggested for enhancing the magnetic characterization response with respect to types and concentrations of selected particles.

A. Magnetic Characterization of Cost-fewer Composites Materials

Using analytical model described above by MATLAB program for the simulation of the transformer core model composites materials has been investigated to study the characterization of effective permeability of the composites with various types and concentrations to obtain cost-fewer composite materials. The results will be verified the ability of the suggested composites to modify the core lamination parameters with respect to the reference values. With respect to the growing interest in investigating high-frequency phenomena in transformers, this paper presents suggested composites for parameter identification of a laminated core of power transformers based on reference frequency response analysis. Fig4 shows complex effective relative permeability of various magnetic composites by various percentages of iron, Metglas, Silicon steels, and Ferrite MgZn particles randomly distributed, then; Fig. 4 shows enhancing effective complex relative permeability of magnetic composite materials that requires adding magnetic particles have higher permeability than the base matrix and via.

**Fig. 4 Effective Complex Relative Permeability With Various Volume Fractions of Soft Magnetic Particles**

Noting that, type of particles has the main factor for specifying performance of the effective permeability of the composites as shown in Fig. 4. Metglas particles are effective particles for enhancing effective permeability of the composites, whatever; MgZn, and Silicon steels particles have bad effect effective permeability of the composites.

B. FRA for Cost-fewer Transformer Core Magnetic Composites

Fig. 5 shows effective complex relative permeability of various transformer core magnetic composites that has been varied by adding certain distribution percentage (30%wt) of Metglas, Silicon steels, Ferrite MnZn, and Ferrite MgZn particles to iron base matrix. Frequency response analysis (FRA) of cost-fewer transformer core magnetic composites has been investigated (10-2Hz – 103Hz) for specifying enhancing magnetic effective complex relative permeability of transformer core magnetic composites depends on higher permeability of magnetic particles the base matrix and via.
Transformer core reluctance of cost-fewer magnetic composites has been investigated (10-2Hz – 103Hz) with respect to varying types at certain concentration of magnetic particles as shown in Fig. 7. It illustrates the reluctance of various transformer core magnetic composites that has been varied by adding certain percentage (30%wt) of Metglas, Silicon steels, Ferrite MnZn, and Ferrite MgZn particles randomly distributions to iron base matrix.

On the other hand, Fig. 8 shows performance of transformer core reluctance with various volume fractions of Ferrite_MgZn particles randomly scattered in iron matrix material. Magnetic particles in the composite occur
changing in magnetic reluctance of the composite with respect to changing effective complex transformer core relative permeability. The obtained results are in agreement with that reported by [32, 33].

V. CONCLUSION

- Enhancing the effective complex relative permeability of magnetic composite materials requires adding magnetic particles having higher permeability than the base matrix and via, then; cost-fewer transformer core magnetic composites depend on the used magnetic particles type.

- Magnetic reluctance of the magnetic composite materials varies with respect to changing effective complex transformer core relative permeability; thus, it will be changing magnetic equivalent circuit reluctances.

- Mixing magnetic composite for transformer core magnetic composites resultant changing in the effective permeability of magnetic composite with respect to the change of their other electrical properties at lower and higher frequencies with respect to points out.

REFERENCES


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