Design of Multi-Nanoparticles Technique for Enhancing Magnetic Characterization of Power Transformers Cores

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Abstract. *The structure of magnetic materials is an essential parameter for specifying magnetic characterization of the transformer core. This paper presents enhancing magnetic characterization of transformer cores by using new nanotechnology techniques. The effective magnetic parameters of new magnetic nanocomposites materials for the transformer cores (single-phase and three-phase) have been predicted based on recent theoretical approaches. The new design, the effects of variant types and concentrations of magnetic multi-nanoparticles on magnetization loss of transformers cores were studied with respect to traditional transformer cores. Optimal types and concentrations of nanoparticles were defined for controlling of reluctance and magnetization loss of transformer cores using multi-nanoparticles technique. A comparative study depicted the industrial features for using multi-nanoparticles against separate nanoparticles in transformers cores.*

Keywords

Core loss, effective permeability, magnetization, nanocomposites, nanoparticles, reluctance, transformer core.

1. Introduction

Magnetic composites challenge materials like soft magnetic ferrites and electrical steels in applications with alternating magnetic fields. The characterization of the concentration and therefore the form of inclusions are enclosed expressly within the mixing rules. Also, account for different morphological characteristics is tried by a correct choice of the mathematical form of mixing rules [1]. Importance of improving electrical core performance is very active for enhancing power transformer behaviour. Better manufacturing techniques have been developed as a consequence of a better understanding of the factors that influence magnetic properties. The quality of electrical steel, that has impact on core loss of electrical steel, is characterised by: (a) quality of sheet insulation, (b) percentage of silicon in the alloy, (c) chemical impurities, (d) grain size, (e) crystal orientation control and (f) core lamination thickness [2], [3], [4], [5], [6], [7], [8] and [9]. Under normal circumstances, power transformers are designed to operate mostly within the linear part of the core's magnetization curve. Therefore, a reasonable amount of linearity is retained to stay below flux density values that would incur excessive losses. However, it is facing more challenges of saturation. One of the most important magnetic properties of electrical steels, the nonlinear AC magnetization curve (B-H curve), is a key for the design of power transformers and motors with reduced size and improved performance. The B-H curve is also essential for transformers and reactors modelling in power system switching transient studies such as ferroresonance. The nonlinear B-H curve expressed in an explicit equation form is particularly useful and preferred to yield accurate results while saving computer time [10], [11], [12], [13] and [14]. The current concepts of the physical origin and mechanism of losses in magnetic materials are reviewed under three traditional categories: hysteresis losses, eddy current or dielectric losses and residual losses [15], [16], [17] and [18]. The trend in nanotechnology science leads to the development of electric and magnetic materials that will enhance their potential applications in future energy storage/transmission devices. Nanotechnology techniques have relationships with the interfacial behaviour between the nanoparticles and the polymer matrix in such nanocomposites [19], [20], [21] and [22].

This paper discusses the progress in effective material parameter (permeability) by using different types of magnetic nanocomposites cores for single-phase and three-phase transformers. New magnetic materials nanocomposites are presented based on multi-nanoparticles technique in order to obtain new enhanced transformers cores. The magnetic characterization of new transformer core nanocomposites magnetic materials is studied against varieties and concentrations of chosen multi-nanoparticles. Also, the effect of types and concentrations of nanoparticles on nonlinear magnetization characteristics and magnetic flux density of transformer core is concerned.

2. Theoretical and Simulation Models

2.1. Magnetic Parameters for Transformer Core Multi-Nanocomposites

The effective permittivity and permeability of nanocomposites materials are calculated in different ways, with the high-frequency mixing rule and from the S-parameters. Maxwell-Garnett mixing rule provides the effective electrical permittivity of spherical inclusions embedded in the host material and is derived with the belief that the spherical inclusions are often replaced by static electric dipoles [23] and [24]. Mie theory explains precisely the scattering mechanism of standalone spherical particles of any size and offers an analytic solution in form of infinite series [25]. Furthermore, new mixtures and composites have been produced by mixing solids and composites [26], [27], [28] and [29]. Thus, it supposes three concentric magnetic permeability disks with permeabilities μ_h, μ_i, and μ_j that are embedded inside the effective medium with the magnetic permeability μ_{eff}. To establish the equivalent magnetic circuit of the core, each section of the magnetic core is represented by its reluctance $\mathcal{R}$, which provides a relation between the corresponding flux Φ and the magneto-motive force F required to establish that flux along the length of the section. Magnetic characteristics of transformer core using individual nanoparticles are described by the reluctance $\mathcal{R}_i$ which depends on the complex effective relative permeability $\widehat{\mu}_{effi}$ of core lamination and the individual nanoparticles that are embedded in transformer core material. The reluctance is defined as follows [32], [33] and [34]:

$$\mathcal{R}_i = \frac{l}{A\mu_0\widehat{\mu}_{effi}}, \tag{1}$$

where; l is the length of the magnetic flux path along each section, A is the cross-sectional area of the core, μ_0 is the free space permeability:

$$\widehat{\mu}_{effi} = \mu'_{effi} - j\mu''_{effi} = = \mathcal{K}_{fe}\mu_{reffi} \cdot \frac{\tanh\left(\frac{(1+j)^t}{2\delta_{effi}}\right)}{\left(\frac{(1+j)^t}{2\delta_{effi}}\right)}, \tag{2}$$

where; μ_{reffi} denotes the effective relative permeability of core lamination material with individual nanoparticles embedded in transformer core material [29]. $\mathcal{K}_{fe}$ is stacking factor which is defined by the following expression:

$$\mathcal{K}_{fe} = \frac{t}{h}, \tag{3}$$

where; h is the fraction of steel in the laminated core, t is the thicknesses of a lamination sheet of the core.

However, the effective skin depth using unique nanoparticles δ_{effi} depends on the angular frequency ω of the magnetic field and is defined as follows:

$$\delta_{effi} = \sqrt{\frac{2}{\omega\,\sigma_{effi}\,\mu_{reffi}\,\mu_0}}, \tag{4}$$

where; σ_{effi} is the effective electrical conductivity of magnetic nanocomposites materials using a unique nanoparticle that is used for identification of the transformer core lamination parameters of transformer windings.

In any case, σ_{effi} is defined as follows:

$$\sigma_{effi} = (1-\xi_i)\sigma_h + \xi_i\sigma_i, \tag{5}$$

where; ξ_i is the volume fraction of the first type nanoparticles and base matrix materials. σ_h is the electrical conductivity of base matrix, σ_i is the electrical conductivity for the first type of inclusion material.

Furthermore, magnetic characteristics of transformer core using multi-nanoparticles described by the magnetic reluctance $\mathcal{R}_j$ is defined by the following expression:

$$\mathcal{R}_j = \frac{l}{A\mu_0\mu_{clefj}}, \tag{6}$$

$$\mu_{clefj} = \mu'_{clefj} - j\mu''_{clefj} = = \mathcal{K}_{fe}\mu_{reffj} \cdot \frac{\tanh\left(\frac{(1+j)^t}{2\delta_{effj}}\right)}{\left(\frac{(1+j)^t}{2\delta_{effj}}\right)}. \tag{7}$$

The effective relative permeability μ_{reffj} of core lamination material with multi-nanoparticles embedded in transformer core material is defined as follows [29]:

$$\mu_{reffj} = \mu_{reffi}\frac{x_j^3 + 3i\xi_j b_{1j}(m_j x_j)}{x_j^3 - \frac{3}{2}i\xi_j b_{1j}(m_j x_j)}, \tag{8}$$

where; $i = \sqrt{(-1)}$ is the imaginary unit, x_j is the size parameter of second type nanoparticles, m_j is the contrast of the refractive index of multi nanoparticles, ξ_j is the volume fraction of the second type nanoparticles and new base matrix material, and b_{1j} is the Mie coefficient [29] and [34]. The effective skin depth using multi-nanoparticles δ_{effj} is defined as follows:

$$\delta_{effj} = \sqrt{\frac{2}{\sigma_{effj}\omega\mu_{reffj}\mu_0}}. \tag{9}$$

The skin depth δ depends on the angular frequency ω of the magnetic field and the effective electrical conductivity for multi-nanoparticles σ_{effj} which is defined as:

$$\sigma_{effj} = (1-\xi_j)\sigma_{effi} + \xi_j\sigma_j, \tag{10}$$

where; σ_j is the electrical conductivity for the second type of inclusion material.

2.2. Nonlinear Magnetization Curves Characteristics of New Transformer Core Multi-Nanocomposites

Non-linear magnetization curves characteristics of transformer core using multi-nanoparticles are described by the magnetic flux density B_j which is based on MATLAB Simulink programs for transformer (B-H Curve) as follows:

$$B_j = B_{sat}\tanh\left(H\cdot\operatorname{atanh}\left(\frac{1}{2}\right)\frac{B_{sat}}{2\,\mu_{clefj}\,\mu_0}\right), \tag{11}$$

where; B_{sat} is maximum magnetic flux density in core, H is magnetic field strength.

2.3. Magnetic Loss Characteristics of New Transformer Core Multi-Nanocomposites

Energy loss is called hysteresis loss at power frequency, and the eddy current loss in transformer core is due to the eddy currents formed in the body of magnetic core by alternating magnetic field, an induced voltage [35] and [36]. Eddy current losses per unit volume at power frequency excitation can be estimated theoretically [37], [38] and [39]. Therefore, the magnetic loss characteristics of new transformer core nanocomposites by using multi-nanoparticles are described by W_{jtotal} that consists of hysteresis losses (W_{jh}) and eddy current losses (W_{je}) of new nanocomposites transformer core per unit volume at power frequency excitation as follows:

$$W_{jtotal} = W_{jh} + W_{je} = \\ = \frac{2f\eta B_{sat}}{\mu_0\,\mu_{reffj}} + \frac{\sigma_{effj}(t\cdot\pi\cdot fB_{sat})^2}{6}, \tag{12}$$

where; η is the shape factor, f is the power frequency.

3. Specifications of Magnetic Nanoparticles and Transformer Models

Knowledge of specifications of magnetic materials is the first step for designing new multi-nanocomposites transformer core with high nonlinear magnetization characteristics (B-H Curve) and low magnetic loss characteristics. Table 1 shows the specifications of traditional magnetic materials (Ferrite, Ni-Ferrite, NiZn-Ferrite) that are used for designing new multi-nanocomposites transformer core. Furthermore, Tab. 1 depicts the main parameters and properties of single-phase and three-phase transformers models which are used for simulation and calculations.

Tab. 1: Characteristics and specification of selected magnetic materials and transformer models [40].

Materials	Electric and Magnetic properties		
	μ_r	ϵ_r	σ ($\mathrm{S{\cdot}m^{-1}}$)
Ferrite	100–2000	13–16	0.01
Ni-Ferrite	2000–2500	18.6	0.019
NiZn-Ferrite	2500–5000	12.5	0.0001
Fe-Si Steel	2000–6000	11.7–12.9	$2\cdot10^6$
Specifications	**1^{Φ} Trans.**	**3^{Φ} Trans.**	**SI Units**
Power Rating	5	500	KVA
Voltage Rating	11/0.400	11/0.433	kV
Stacking factor	0.9	0.9	
Cross section of core transformer	0.00687	0.0378	$\mathrm{m^2}$
Thickness of single lamination core	0.35	0.35	mm
Power frequency	50	50	Hz
Number of primary turns	6560	1100	(per phase)
Maximum magnetic flux density	1.1	1.2	$\mathrm{Wb{\cdot}m^2}$

4. Results and Discussion

The aim of this work is obtaining new magnetic materials for the electric and electronic applications that have high magnetic characterization, low eddy current loss, and low hysteresis loss. In last few years, researchers have been trying to use individual nanoparticles inside base matrix for enhancing electrical, magnetic and thermal properties. The following results show an efficient multi-nanoparticles technique that uses variant nanoparticles for obtaining the best magnetic materials characterization.

4.1. Effective Permeability of Multi-Nanocomposites

Figure 1 describes the enhancement of effective relative permeability for Fe-Si Steel transformer core by increasing volume fraction of individual nanoparticles and multi-nanoparticles of Ferrite, Ni-Ferrite and NiZn-Ferrite. Enhancement of effective relative permeability can be achieved by arranging positions of nanoparticles inside the base matrix in case of multi-nanoparticles technique; like that, Ferrite (μ_1) and NiZn-Ferrite (μ_2) are recorded as the best inclusions and arrangements for enhancing the effective relative permeability of Fe-Si Steel multi-nanocomposites. Therefore, the arrangement of multi-nanoparticles NiZn-Ferrite, Ni-Ferrite or Ferrite inside Fe-Si Steel nanocomposites transformer core lamination is an important factor for enhancing the effective permeability of Fe-Si Steel nanocomposites.

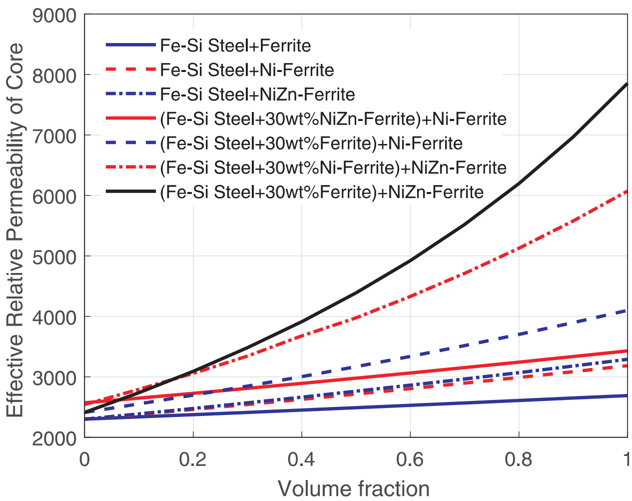

Fig. 1: Effective relative permeability of Fe-Si Steel nanocomposites and multi-nanocomposites.

4.2. Reluctance of Transformer Core Multi-Nanocomposites

Figure 2 shows the reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer core with various volume fractions of individual and multi-nanoparticles respectively. An increase in the volume fraction of individual nanoparticles (Ni-Ferrite or Ferrite or NiZn-Ferrite) decreases the reluctance of Fe-Si Steel nanocomposites for single-phase transformer core. Moreover, multi-nanoparticles increase the decline in the reluctance of Fe-Si Steel nanocomposites transformer core more than individual nanoparticles. For example, adding 30wt% of Ni-Ferrite as first nanoparticles into Fe-Si Steel and then increasing the volume fraction of NiZn-Ferrite as a second type nanoparticles enhance the decline in the reluctance of Fe-Si Steel nanocomposites transformer core more than using the reverse arrangement of multi-nanoparticles. Therefore, the arrangement of multi-nanoparticles inside magnetic base matrix is an essential step for increasing the decline of transformer core reluctance.

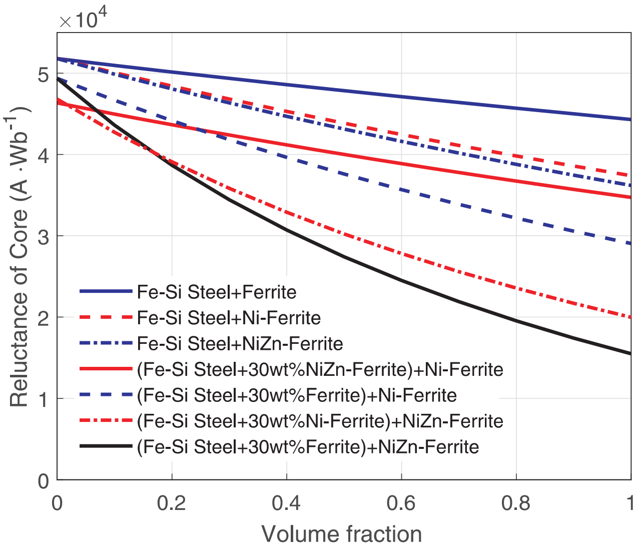

Fig. 2: Reluctance of Fe-Si Steel nanocomposites and multi nanocomposites for single-phase transformer core.

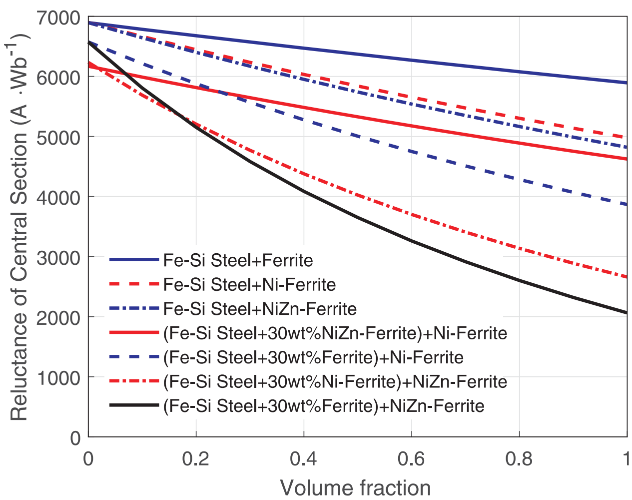

Fig. 3: Reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites of central section for three-phase transformer core.

On the other hand, Fig. 3 shows the reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites for the central section of three-phase transformer core with various volume fractions using individual and multi-nanoparticles respectively. The reluctance of the central section Fe-Si Steel nanocomposites core decreases with increasing the volume fraction of Ferrite, Ni-Ferrite or NiZn-Ferrite individual nanoparticles in the Fe-Si Steel core. Multi-nanoparticles technique enhances the decrease in reluctance of Fe-Si Steel nanocomposites; as shown in Fig. 3, the arrangement of multi-nanoparticles "Ferrite, and Ni-Ferrite" inside the host base matrix "Fe-Si Steel" changes the reluctance of multi-nanocomposite for the central section of three-phase transformer core.

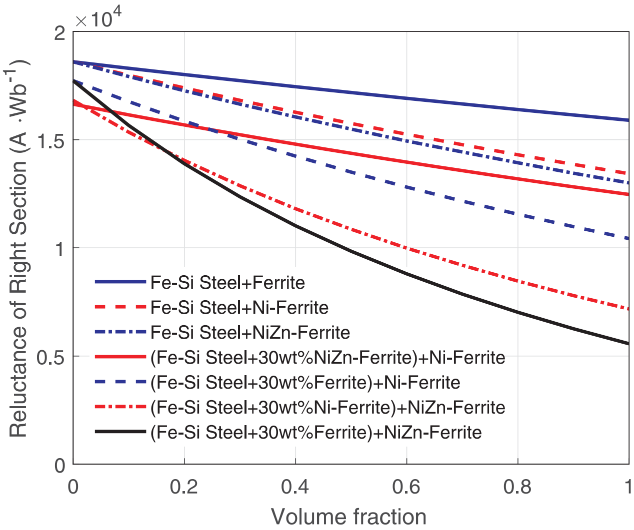

Fig. 4: Reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites for right section of three phase transformer core.

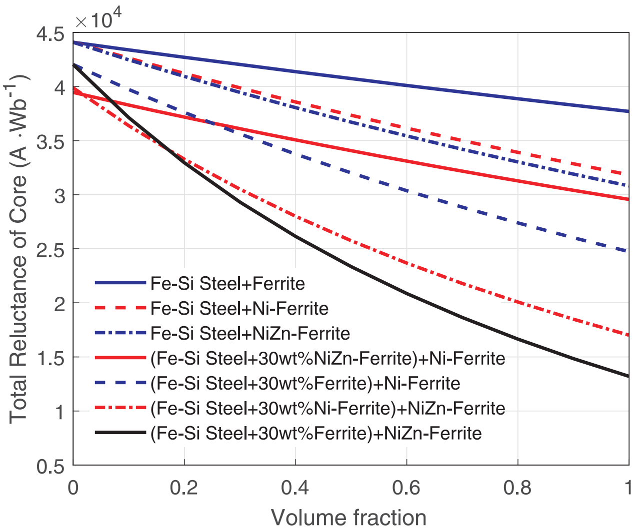

Fig. 5: Total reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites for three-phase transformer core.

Moreover, Fig. 4 illustrates the reluctance of Fe-Si Steel core nanocomposites and multi-nanocomposites for the right section of three-phase transformer core with various volume fractions by using individual and multi-nanoparticles respectively. Due to length of the right section flux path which is higher than the length of central section flux path; the reluctance of Fe-Si Steel nanocomposites for the right section of three-phase transformer core is higher than the reluctance of Fe-Si Steel nanocomposites for the central section of three-phase transformer core along increasing volume fraction. Generally, Fig. 5 shows the total reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites of three-phase transformer core with various volume fractions by using individual and multi-nanoparticles respectively. The performance of the total reluctance Fe-Si Steel nanocomposites for three-phase transformer core is similar to the reluctance of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer core.

4.3. B-H Curves Characteristics of New Transformer Core Nanocomposites

Figure 6 illustrates the nonlinear magnetization characteristics of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer core using single-type nanoparticles and multi-nanoparticles at different specified volume fractions.

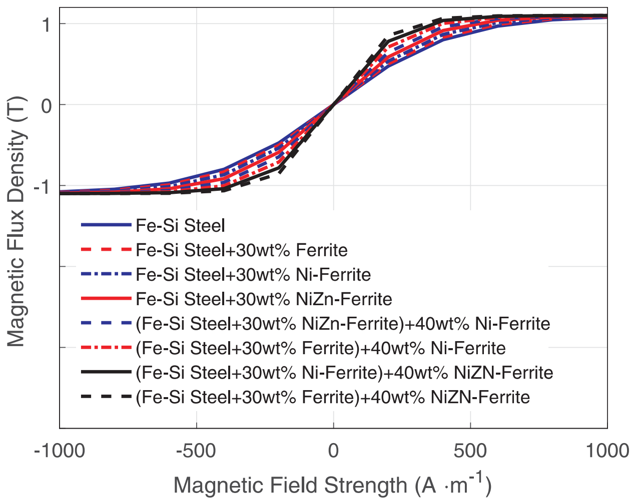

Fig. 6: B-H curves for Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer core nanocomposites.

The individual nanoparticles of Ni-Ferrite, Ferrite or NiZn Ferrite improve the magnetic flux density of nanocomposites Fe-Si Steel for single-phase transformer core. In any case, adding a certain concentration of NiZn-Ferrite (eg.: 40wt%) as second type nanoparticles into Fe-Si Steel increases the magnetic flux density of Fe-Si Steel nanocomposites single-phase transformer core. Therefore, multi-nanoparticles (30wt% Ferrite + 40wt% NiZn-Ferrite) are the best inclusions for increasing the magnetic flux density of Fe-Si Steel below the saturation value of magnetic flux density of single-phase transformer. On the other hand, Fig. 7 shows the effect of volume fraction of individual nanoparticles and multi-nanoparticles on the magnetic flux density of Fe-Si Steel for a single-phase transformer core at maximum magnetic field strength. A slight increase in the magnetic flux density of Fe-Si Steel nanocomposites transformer core occurs by increasing volume fraction of Ferrite individual nanoparticles. However, high increase in magnetic flux density of Fe-Si Steel nanocomposites core occurs due to addition of variant concentrations of NiZn-Ferrite or Ni-Ferrite as second type nanoparticles for single-phase transformer core.

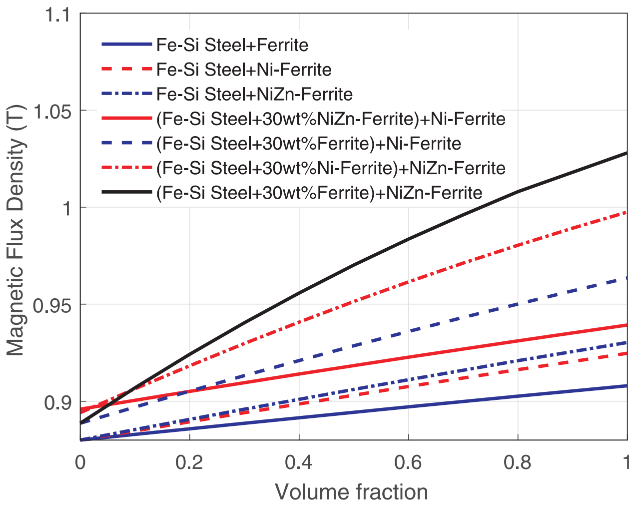

Fig. 7: Magnetic flux density of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer at maximum magnetic field strength of Silicon Steel single-phase transformer.

In our technique, the arrangement of multi-nanoparticles inside magnetic base matrix of transformer core appears to be an important parameter. Thus, the magnetic flux density of nanocomposites (Fe-Si Steel + 30wt% Ni-Ferrite) increases by adding variant concentrations of NiZn-Ferrite as second type nanoparticles for single-phase transformer.

4.4. Magnetic Loss Characteristics for New Transformer Core Nanocomposites

Figure 8 describes the magnetic loss characteristics of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer core. In traditional transformer core, the total loss of Fe-Si Steel core of single-phase transformer is increased by increasing magnetic flux density; but, it is decreased by adding individual nanoparticles (Ni-Ferrite, NiZn-Ferrite or Ferrite). Moreover, multi-nanocomposite (Fe-Si Steel + 30wt% Ferrite + 40wt%NiZn-Ferrite) is the best compound for decreasing the total loss of single-phase transformer.

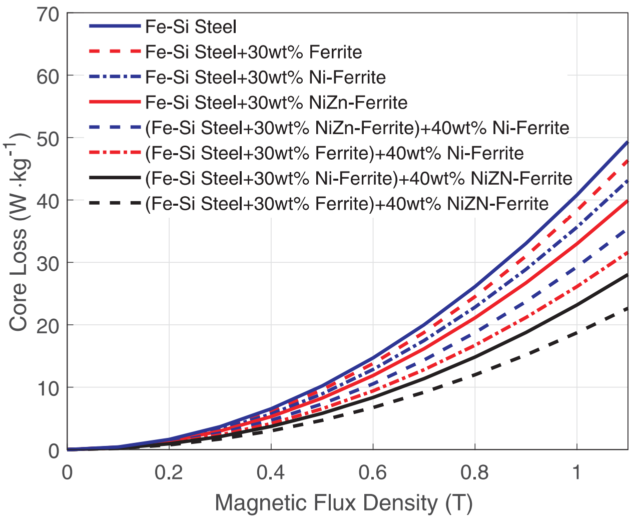

Fig. 8: Core loss of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer.

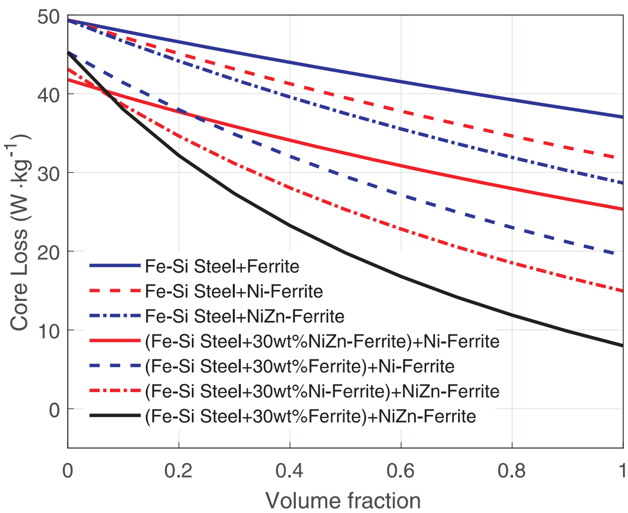

Fig. 9: Core loss of Fe-Si Steel nanocomposites and multi-nanocomposites for single-phase transformer.

Figure 9 describes the effect of volume fraction on the magnetic loss characteristics of Fe-Si Steel nanocomposites and multi-nanocomposites core of single-phase transformer at maximum magnetic flux density (1.1 T). The total loss of Fe-Si Steel nanocomposites transformer core is decreased by increasing the concentration of individual nanoparticles (NiZn-Ferrite, Ni-Ferrite or Ferrite) in the Fe-Si Steel transformer core. In addition, adding individual nanoparticles (Ni-Ferrite or NiZn-Ferrite) to nanocomposite (Fe-Si Steel + 30wt% Ferrite) enhances the reduction in the core loss of Fe-Si Steel nanocomposites for single-phase transformer. So that, using multi-nanoparticles technique is able to enhance the reduction in the total loss of Fe-Si

Steel transformer core of single-phase transformer more than using individual nanoparticles technique. Figure 9 describes the effect of volume fraction on the magnetic loss characteristics of Fe-Si Steel nanocomposites and multi-nanocomposites core of single-phase transformer at maximum magnetic flux density (1.1 T). The total loss of Fe-Si Steel nanocomposites transformer core is decreased by increasing the concentration of individual nanoparticles (NiZn-Ferrite, Ni-Ferrite or Ferrite) in the Fe-Si Steel transformer core. In addition, adding individual nanoparticles (Ni-Ferrite or NiZn-Ferrite) to nanocomposite (Fe-Si Steel + 30wt% Ferrite) enhances the reduction in the core loss of Fe-Si Steel nanocomposites for single-phase transformer. So that, using multi-nanoparticles technique is able to enhance the reduction in the total loss of Fe-Si Steel transformer core of single-phase transformer more than using individual nanoparticles technique.

4.5. Magnetic Characterization for Three Phase Transformer Cores

The magnetic characterization of nanocomposites and multi-nanocomposites for three-phase transformer core follows the same behaviour as for single-phase transformer core. In any case, the maximum value of magnetic flux density of three-phase transformer (1.2 T) is higher than the magnetic flux density of single-phase transformer (1.1 T). As shown in Tab. 2, the magnetic flux density of Ferrite, or Fe-Si Steel nanocomposites for three-phase transformer core is higher than the magnetic flux density of the same nanocomposites for single-phase transformer. An increase of the magnetic field strength occurs in case of using multi-nanoparticles. Moreover, Tab. 2 shows the total loss performance of three-phase transformer core and single-phase transformer with increasing magnetic flux density.

5. Trends of Multi-nanoparticles Technique in Magnetic Transformer Cores

Nanoparticles of Fe-Si Steel, Ni-Ferrite and NiZn-Ferrite are used to enhance magnetic characteristics of nanocomposites and multi-nanocomposites. Table 2 shows total core loss of new single-phase and three-phase transformer cores that are designed from Fe-Si Steel nanocomposites and multi-nanocomposites, respectively. The arrangement of nanoparticles inside the base magnetic matrix is an essential parameter for specifying the magnetic characteristics of transformer core such as decreasing the total core loss. New multi-nanocomposite for a transformer core (Fe-Si Steel + 30 wt% Ferrite + 40 wt% NiZn-Ferrite) is represented as the best selection for decreasing the total core loss of single-phase transformer core at 52.90 %. And so, the multi-nanocomposite (Fe-Si Steel + 30wt% Ferrite + 40wt%NiZn-Ferrite) is recorded as the best inclusions for enhancing the magnetic flux density of Fe-Si Steel nanocomposites single-phase and three-phase transformer cores with percentage 9.16 %, and 9.19 % respectively.

6. Conclusion

- Multi-nanoparticles technique gives high magnetic characterization, low core loss and low magnetic reluctance of transformer core lamination against individual nanoparticles and traditional magnetic materials. New design enhances the effective relative permeability by controlling the type and volume fraction of each nanoparticle inside multi-nanocomposite. Multi-nanoparticles technique is the best trend for controlling the reluctance of magnetic nanocomposites core laminations with respect to using individual nanoparticles; therefore, the newly designed multi-nanocomposites have the best magnetic characteristics for power transformer cores.
- Type, concentration and arrangement of magnetic nanoparticles are the essential parameters in multi-nanoparticles technique to decrease the total loss of nanocomposites core and increase the magnetic flux density higher than by using individual nanoparticles technique. Moreover, Ferrite, Ni-Ferrite and NiZn-Ferrite nanoparticles are interesting for enhancing the performance of Fe-Si Steel nanocomposites transformer core.
- In manufacture process, Fe-Si Steel nanoparticles are recorded to be the best individual nanoparticles for enhancing the effective relative permeability and decreasing the reluctance of Ferrite nanocomposites core lamination of single-phase and three-phase transformers. In any case, NiZn-Ferrite is recorded to be the best individual nanoparticles for enhancing the effective relative permeability and decreasing the reluctance of Fe-Si Steel nanocomposites core lamination for single-phase and three-phase transformers.

Tab. 2: Total core loss of Fe-Si steel transformers cores.

NEW Nanocomposites Materials	Core of SINGLE-PHASE transformer				Core of THREE-PHASE transformer			
	W_t (W·kg^{-1})	% Reduction	B (T)	% Modification	W_t (W·kg^{-1})	% Reduction	B (T)	% Modification
Fe-Si Steel Pure	49.36	-	0.8756	-	58.75	-	0.9552	-
20wt% Ferrite	46.59	5.61 %↓	0.8858	1.17 %↑	55.44	5.63 %↓	0.9663	1.16 %↑
30wt% Ferrite	45.26	8.31 %↓	0.8887	1.50 %↑	53.87	8.31 %↓	0.9694	1.49 %↑
40wt% Ferrite	43.98	10.90 %↓	0.8915	1.82 %↑	52.34	10.91 %↓	0.9725	1.81 %↑
30wt% Ferrite + 20wt% NiZn-Ferrite	32.15	34.87 %↓	0.9242	5.55 %↑	38.26	34.88 %↓	1.0080	5.53 %↑
30wt% Ferrite + 30wt% NiZn-Ferrite	27.32	44.65 %↓	0.9405	7.41 %↑	32.51	44.66 %↓	1.0260	7.41 %↑
30wt% Ferrite + 40wt% NiZn-Ferrite	23.25	52.90 %↓	0.9558	9.16 %↑	27.67	52.90 %↓	1.0430	9.19 %↑
30wt% Ferrite + 20wt% Ni-Ferrite	37.97	23.08 %↓	0.9052	3.38 %↑	45.18	23.09 %↓	0.9875	3.38 %↑
30wt% Ferrite + 30wt% Ni-Ferrite	34.86	29.38 %↓	0.9132	4.19 %↑	41.49	29.38 %↓	0.9962	4.29 %↑
30wt% Ferrite + 40wt% Ni-Ferrite	32.05	35.07 %↓	0.9210	5.19 %↑	38.14	35.08 %↓	1.0050	5.21 %↑
20wt% Ni-Ferrite	45.10	8.63 %↓	0.8894	1.58 %↑	53.68	8.63 %↓	0.9703	1.58 %↑
30wt% Ni-Ferrite	43.14	12.60 %↓	0.8941	2.11 %↑	51.34	12.61 %↓	0.9753	2.10 %↑
40wt% Ni-Ferrite	41.27	16.39 %↓	0.8986	2.63 %↑	49.11	16.41 %↓	0.9803	2.63 %↑
30wt% Ni-Ferrite + 20wt% NiZn-Ferrite	34.62	29.86 %↓	0.9183	4.88 %↑	41.20	29.87 %↓	1.0020	4.90 %↑
30wt% Ni-Ferrite + 30wt% NiZn-Ferrite	31.14	36.91 %↓	0.9298	6.19 %↑	37.05	36.94 %↓	1.0140	6.16 %↑
30wt% Ni-Ferrite + 40wt% NiZn-Ferrite	28.05	43.17 %↓	0.9408	7.45 %↑	33.38	43.18 %↓	1.0260	7.41 %↑
20wt% NiZn-Ferrite	44.15	10.56 %↓	0.8907	1.73 %↑	52.54	10.57 %↓	0.9716	1.72 %↑
30wt% NiZn-Ferrite	41.79	15.34 %↓	0.8959	2.32 %↑	49.73	15.35 %↓	0.9773	2.31 %↑
40wt% NiZn-Ferrite	39.58	19.81 %↓	0.9010	2.90 %↑	47.10	19.83 %↓	0.983	2.91 %↑
30wt% NiZn-Ferrite 20wt% Ni-Ferrite +	37.71	23.60 %↓	0.9051	3.37 %↑	44.87	23.63 %↓	0.9873	3.36 %↑
30wt% NiZn-Ferrite 30wt% Ni-Ferrite +	35.84	27.39 %↓	0.9096	3.88 %↑	42.66	27.39 %↓	0.9923	3.88 %↑
30wt% NiZn-Ferrite 40wt% Ni-Ferrite +	34.09	30.94 %↓	0.9140	4.39 %↑	40.57	30.94 %↓	0.9971	4.39 %↑

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