Scientific Research and Essays Vol. 6(20), pp. 4414-4420, 19 September, 2011
Available online at http://www.academicjournals.org/SRE
DOI: 10.5897/SRE11.901
ISSN 1992-2248 ©2011 Academic Journals

Full Length Research Paper

3D electromagnetic study of transformers' flux line distribution and losses determination under harmonic distortion caused by electronic equipments

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Accepted 16 August, 2011

Voltage and current distortions caused by nonlinear characteristic of electronic and power electronic devices may cause a large number of problems for electrical equipments such as, mal-operation, additional losses, heat and excessive insulating stresses. Transformers are the most important equipments in power and distribution networks. So, their reliable operation is very critical for utility companies. In this paper, the effects of current distortions caused by electronic devices on the losses of a transformer have been evaluated using 'finite element method'. Also, the effects of high frequency components of current harmonics on the flux distribution into the transformer's core are investigated.

Key words: Distortion, distribution transformers, electronic devices, electronic phase control, finite element method, high frequency flux lines.

INTRODUCTION

Distribution transformers are generally designed to supply sinusoidal loads at rated frequency. Harmonic distortion in current and voltage waveforms are unavoidable problems in power and distribution system that most of the time is due to nonlinear loads. The Electric Power Research Institute (EPRI) gives an approximate estimation that nonlinear loads which were only 1.5% of the total electric utility loads in1987 have been increased to 50% in 2000 and this trend in rising is expected to reach 80% in the year 2010 (Radmehr et al., 2006; Sankaran, 2002; Arrillaga and Watson, 2003; Radmehr et al., 2007; Saracoglu, 2010; Morsi and El-Hawary, 2009; Vatansever, 2010). Several methods by Olivares et al. (2003) are offered to decrease losses of distribution transformers. The most important one was using electromagnetic aluminum shield which decreases stray loss. Harmonic behavior of power transformer under non-sinusoidal condition is investigated in Mohammed et al. (2006). The analysis is performed by coupling finite element analysis with circuit equations. Also, harmonic behavior of transformer current and DC current of load is analyzed using wavelet transform. Distribution network losses and especially transformers are investigated by Leal et al. (2009) using neural-network model. A new digital data-acquisition method by Fuchs et al. (2006) for measuring derating and reactive power demand of three-phase transformers under nonlinear load has been proposed. The measuring circuit was based on potential- and current-transformers, voltage dividers or hall sensors, A/D converter and microprocessor. The most important sources of current distortion in distribution networks are electronic phase controls, power electronic devices, high frequency and switching equipments. In Sadati et al. (2010) and Yazdani-Asrami et al. (2010), the

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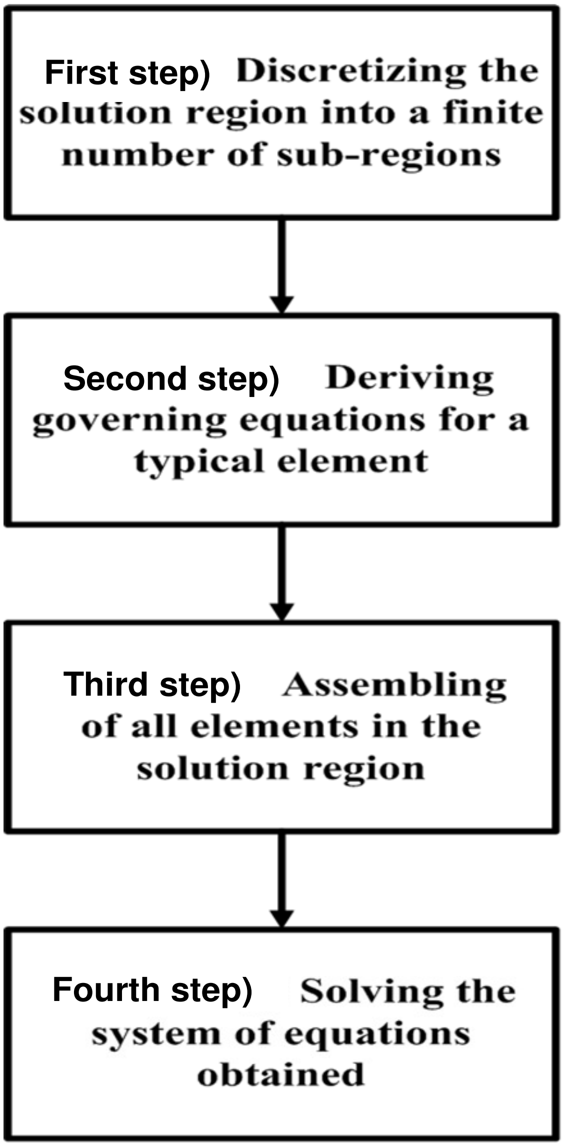

Figure 1. The steps of FE analysis.

derating and loss calculation of distribution transformers have been done using different analytical and simulation based methods. For example in Sadati et al. (2010), MATLAB/SIMULINK has been used as widely used software to estimate and calculate transformer losses under harmonic loads. In Yazdani-Asrami et al. (2011) and Sadati et al. (2010), the losses and remaining life of transformers have been calculated using simulation and experimental based methods. For example, two-dimensional (2D) finite element method (FEM) has been used for life estimation of distribution transformers.

This paper studies the effects of high frequency components in the load current of a distribution transformer on the losses and its core flux distribution using three-dimensional (3D) finite element (FE) analysis.

ELECTROMAGNETIC STATEMENT OF PROBLEM

FEM is a very sophisticated tool widely used by engineers, scientists and researchers to solve engineering problems especially electromagnetic problems. Nowadays, FEM is clearly the dominant numerical analysis method for simulation of physical field distributions. Indeed, the FEM finds the solution to any engineering problem that can be described by a finite set of partial derivative equations with appropriate boundary conditions. The FE analysis of any problem involves basically four steps as shown in Figure 1 (Liu and Quek, 2003; Jin, 2002; Rao, 2004). Also, one elliptic object has been shown in Figure 2 that has shown the concept of FE study. There are different models for transformers under various conditions. However, the frequency dependency of the transformer parameters is not easy to include, especially in circuit based methods. FE modeling can include all of these effects and provide an efficient way for analysis, simulation and optimization of transformers. FE analysis solves the electromagnetic field problems by solving Maxwell's equations in a finite region of space with appropriate boundary conditions. Electromagnetic quasi-static analysis is valid under the assumption that: $\partial D/\partial t = 0$. This implies that Maxwell's equations can be rewritten:

$$\nabla\times\mathbf{H} = \mathbf{J} = \sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B}) + \mathbf{J}^e \qquad \nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \tag{1}$$

$$\nabla\cdot\mathbf{B} = 0,\ \nabla\cdot\mathbf{J} = 0,\ \nabla\cdot\mathbf{D} = \rho \tag{2}$$

Here, J^e is an externally generated current density and $\mathbf{v}$ is the velocity of the conductor. The crucial criterion for validation of quasi-static approximation is that the currents and the electromagnetic fields vary slowly. This means that dimensions of the structure in problem should be small compared to the wavelength. Note that B and E are used uniquely in magnetic or electric solution respectively, but are fully coupled here. Using the definitions of the potentials:

$$\mathbf{B} = \nabla\times\mathbf{A} \tag{3}$$

$$\mathbf{E} = -\nabla\mathbf{V} - \frac{\partial\mathbf{A}}{\partial t} \tag{4}$$

And the constitutive relation $B = \mu_0(H+M)$, Ampere's law

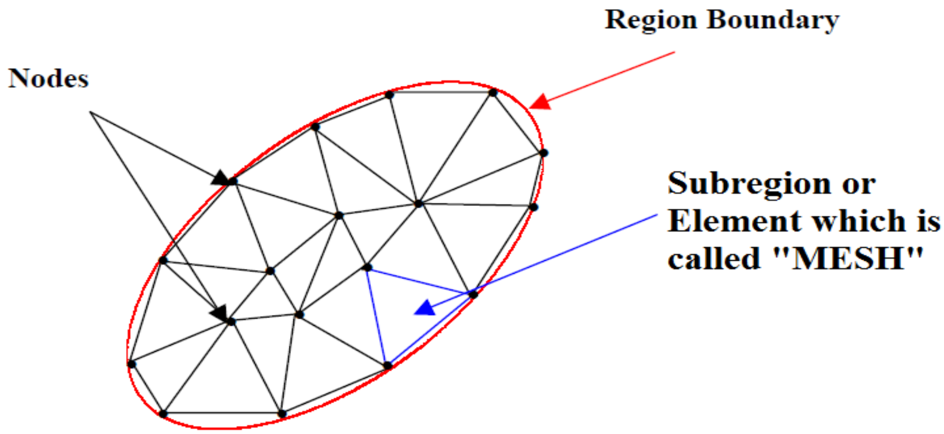

Figure 2. Introducing the concept of FEM.

can be rewritten:

$$\sigma\frac{\partial \mathbf{A}}{\partial t}+\nabla\times(\mu_0^{-1}\nabla\times\mathbf{A}-\mathbf{M})-\sigma\mathbf{v}\times(\nabla\times\mathbf{A})+\sigma\nabla V=\mathbf{J}^e \quad (5)$$

Taking the divergence of Equation 5, the continuity equation is written as follows:

$$-\nabla\cdot\left(\sigma\frac{\partial \mathbf{A}}{\partial t}-\sigma\mathbf{v}\times(\nabla\times\mathbf{A})+\sigma\nabla V-\mathbf{J}^e\right)=0 \quad (6)$$

Equations 5 and 6 give a system of equations for two potentials A and V.

$$-\nabla\cdot[-\sigma\mathbf{v}\times(\nabla\times\mathbf{A})]+\sigma\nabla V-\mathbf{J}^e=0 \quad (7)$$

$$\nabla\times(\mu_0^{-1}\nabla\times\mathbf{A}-\mathbf{M})-\sigma\mathbf{v}\times(\nabla\times\mathbf{A})+\sigma\nabla V=\mathbf{J}^e \quad (8)$$

The term $\sigma\mathbf{v}\times(\nabla\times\mathbf{A})$ represents the current generated motion with a constant velocity in a static magnetic field $\mathbf{J}^B=\sigma\mathbf{v}+\mathbf{B}^e$. Similarly, the term $-\sigma\nabla\mathrm{V}$ represents a current generated by a static electric field $\mathbf{J}^E=\sigma\mathbf{E}^e$. When $\mathbf{J}^B=0$, including $\mathbf{J}^E$ in the external current results in:

$$\nabla\times(\mu_0^{-1}\nabla\times\mathbf{A}-\mathbf{M})=\tilde{\mathbf{J}}^e \quad (9)$$

Where,

$$\tilde{\mathbf{J}}^e=\mathbf{J}^e+\mathbf{J}^E$$

This equation can be solved independently. The electric and magnetic potentials are not uniquely defined from the electric and magnetic fields through Equations 3 and 4. Considering $\partial\Psi$, two new potentials will be introduced:

$$\tilde{\mathbf{A}}=\mathbf{A}+\nabla\Psi \quad (10)$$

$$\tilde{V}=V-\frac{\partial\Psi}{\partial t} \quad (11)$$

$$\mathbf{E}=-\frac{\partial\mathbf{A}}{\partial t}-\nabla V=-\frac{\partial(\tilde{\mathbf{A}}-\nabla\Psi)}{\partial t}-\nabla(\tilde{V}+\frac{\partial\Psi}{\partial t})=-\frac{\partial\tilde{\mathbf{A}}}{\partial t}-\nabla\tilde{V} \quad (12)$$

$$\mathbf{B}=\nabla\times\mathbf{A}=\nabla\times(\tilde{\mathbf{A}}-\nabla\Psi)=\nabla\times\tilde{\mathbf{A}} \quad (13)$$

The variable transformation of potentials is called a gauge transformation. To obtain a unique solution the gauge should be chosen, that means putting constraints on Ψ that makes the solution unique. Another way of expressing this additional condition is to put a constraint on $\nabla\cdot\mathbf{A}$. The $\mathbf{A}$ vector field would be defined uniquely up to a constant if both $\nabla\cdot\mathbf{A}$ and $\nabla\times\mathbf{A}$ are given. This is called Helmholtz's theorem. One particular gauge is the Coulomb gauge given by the constraint $\nabla\cdot\mathrm{A}=0$. When using assemblies with interface pairs, it might also be necessary to activate an equation fixing a gauge. This must be done when vector elements are coupled over a pair and the meshes on each side are incompatible. The gauge is the Coulomb gauge for 'magneto-statics and quasi-statics' for electric and induction currents. Quasi-statics for induction currents use other equations when fixing the gauge. These equations are shown as

Table 1. Parameters of a single phase transformer.

Parameter	Value	Unit
Rated apparent output power	25	kVA
Rated frequency	50	Hz
Primary voltage	20000	Volt
Secondary voltage	231	Volt
Rated primary current	1.25	Ampere
Rated secondary current	108	Ampere
Load loss	750	Watt
Core steel type	M5	0.3 mm
Maximum ambient temperature	40	℃
Cooling type	ONAN	

follows, where Equation 14 is for time-harmonic problems and Equation 15 is for transient problems.

$$\nabla \cdot \mathbf{J} = 0 \Rightarrow \nabla \cdot (\sigma \mathbf{A}) = 0 \quad (14)$$

In time-harmonic case, Ampere's equation includes the displacement current:

$$\nabla \times \mathbf{H} = \mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + j\omega \mathbf{D} + \mathbf{J}^e \quad (15)$$

In transient case, the inclusion of this term would lead to a second-order equation in time, but in the harmonic case there are no such complications. Using definition of the electric and magnetic potentials, the system of equations takes the form:

$$-\nabla.\left((j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} - \sigma\mathbf{v}\times(\nabla\times\mathbf{A}) + (\sigma + j\omega\varepsilon_0)\nabla V - (\mathbf{J}^e + j\omega\mathbf{P})\right) = 0 \quad (16)$$

$$(j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} + \nabla\times(\mu_0^{-1}\nabla\times\mathbf{A} - \mathbf{M}) - \sigma\mathbf{v}\times(\nabla\times\mathbf{A}) + (\sigma + j\omega\varepsilon_0)\nabla V = (\mathbf{J}^e + j\omega\mathbf{P}) \quad (17)$$

The constitutive relation $D = \varepsilon_0 E + P$ has been used for the electric field. Choosing $\Psi = -\mathrm{j}V/\omega$ in the gauge transformation, a particular gauge can be obtained that reduces the system of equation.

$$\tilde{\mathbf{A}} = \mathbf{A} - \frac{j}{\omega}\nabla V \qquad \tilde{V} = 0 \quad (18)$$

Because $\tilde{V}$ vanishes from the equations, we only need the second equation in Equation 16, that is $(\sigma + j\omega\varepsilon_0)\nabla V$ is eliminated in Equation 16. Working with $\tilde{\mathbf{A}}$ is often the best option when it is possible to specify all source currents as external currents $\mathbf{J}^e$ or as surface currents on boundaries.

RESULTS AND DISCUSSION

Here, an oil-filled single-phase distribution-transformer is studied. Its parameters and specifications are tabulated in Table 1. A 3D model of studied transformer is shown in Figure 3. Also, the nonlinear load specification is presented in Table 2 and this current has been shown in Figure 4. Actually, the transformer is a 3D system and therefore a 3D model is usually required in order to include all influencing parameters for simulation purposes such as chemical, electrical and geometrical specifications. As a major problem with 3D modeling, a long simulation time is required to solve the modeling problem, which may take hours upon hours to simulate just one running of simulation. This is the reason why 2D simulation has been used in literature in this area. Also, 3D analysis should be performed by fast computers which may not be available for many researchers. Therefore, some simplifications such as part modeling, choosing coarse mesh sizes and 2D modeling can be used to overcome this problem. In other words, the 2D simulation is quicker than 3D but the accuracy of 3D simulation is much more than 2D. So, authors decide to use 3D simulation to increase and guarantee the accuracy of the results. First of all, a 3D model of transformer should be introduced in FE software. Then, the behavior of transformer under linear load (sinusoidal current) and nonlinear load current (distorted current) is simulated. For simulation, firstly the sinusoidal load current has been applied to the transformer winding. Then, the losses under sinusoidal condition have been calculated. Next, each harmonic current with its frequency is applied to windings and after simulation; load loss has been calculated. Table 3 shows the results of load loss calculation under linear and nonlinear load using FE

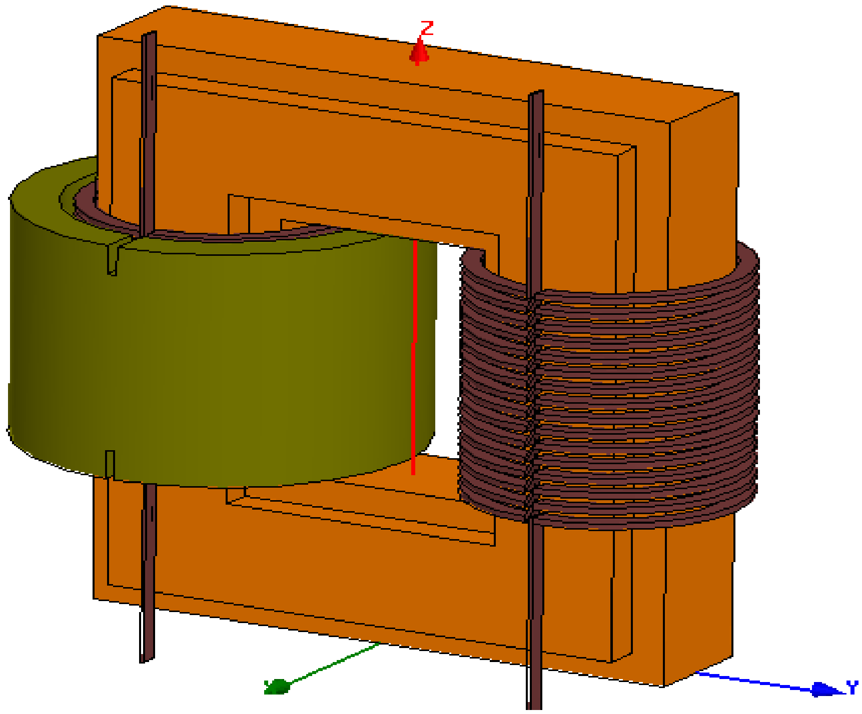

Figure 3. 3D modeling of transformer.

Table 2. Non-linear load specification.

Harmonic order (h)	Percent (%)
1	100
7	10.8
13	2.7
17	1.5
THD	12

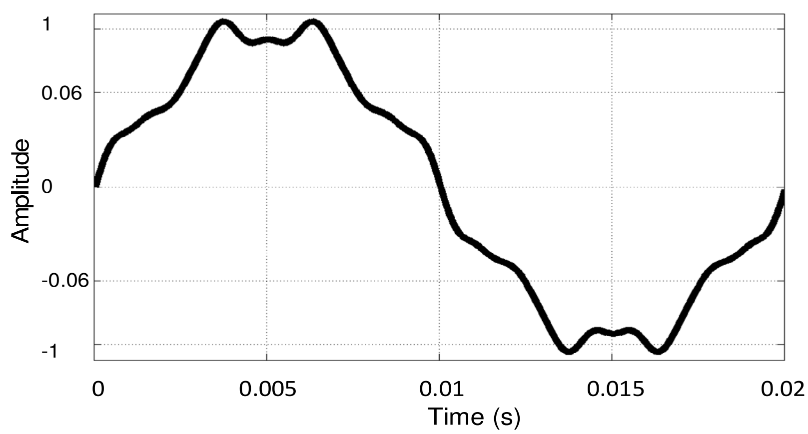

Figure 4. Nonlinear current generated by electronic devices.

Table 3. The calculation of load loss under harmonic load using FE method.

Harmonic order (h)	Load loss (watt)
Under sinusoidal wave	768
Under distorted wave	881.3

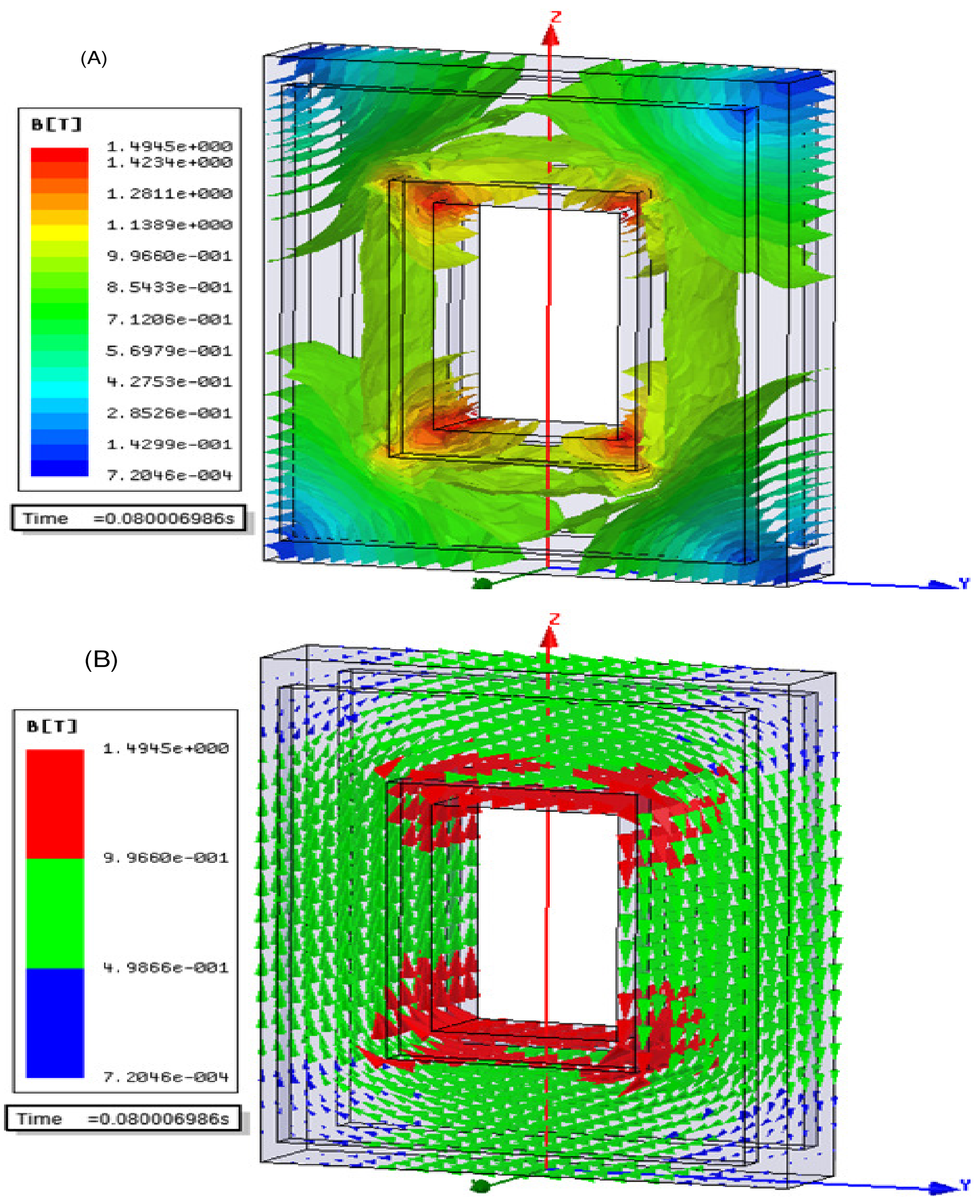

Figure 5. a) Flux density in the transformer core and b) distribution of flux lines in the transformer core.

analysis after solution. Magnetic current and flux amplitude is very low in the core. Flux density and flux distribution in the transformer core have been shown in Figure 5. These figures indicate that by increasing the frequency of the harmonic, the flux amplitude will be decreased. In addition, it can be seen that the flux lines will diffuse into the core and also, the study shows that the leakage flux lines will be increased outside of transformer core because of high frequency behavior of distorted current. This phenomenon leads to loss increasing in distribution transformer, because the flux density has been decreased from its normal value.

The normal value for flux density in distribution transformers under linear load and normal condition is about 2 Tesla, but under studied distorted current flux density decreased to 1.49 Tesla. So, for overcoming these problems that is caused by electronic equipments, 'active power filters' should be installed into distribution substations and network (Rahim and Radzi, 2010).

Conclusion

In this paper, FE analysis has been utilized as a very precise method for calculating distribution transformer loss under high frequency distorted load current that is generated by electronic devices. The distribution and behavior of flux lines under distorted current has been investigated. Results show that the effect of nonlinear loads on ohmic loss and other stray loss is low, while its effect on winding eddy current loss is high. Also, the study indicate that by increasing the frequency of harmonics, the flux amplitude will be decreased and flux lines will be diffused into the core and also, simulation results show that the leakage flux lines will be increased outside of transformer core because of high frequency behavior of distorted current. As a result, this incremented leakage flux will increase the amount of other stray loss in tank and other metallic parts of transformers and eventually, lead to energy and economic loss.

ACKNOWLEDGEMENT

The authors wish to thank Mr. Mohammadreza Barzegaran Baboli (Florida International University, Miamai, USA) for his helpful discussions during this research.

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