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Estimation of Core Loss in Transformer by Using Finite Element Method (FEM)

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Abstract: Transformers are the most important component in power system and are interfaces between consumers and suppliers. Users and manufacturers of transformers are nowdays capitalising the core losses while considering the costings.Therefor, a software package witch enables an engineer to predict within a short period the approximat core loss in transformer of any rating and geometry will be very useful. The use of Finite Element Methods for transformer design and analysis has been proven as a very powerful tool over recent years. This paper describs a numerical solution to use a 2D Finite element method (FEM) to accurately calculate the flux distribution and total core losses in single phase transformer with PDE toolbox of MATLAB software. It also presents the localised flux density and loss over a core. This computational result of core loss agrees with experimental result obtained by us in machine laboratory.

Key words: Core loss · B-H loop · 2D Finite element method (FEM) · Magnetic flux · Hot spot

INTRODUCTION

Transformers are essential and important element of power system. Core loss in transformers are much lower than those found in transformers a decade age because of the availability of better quality core materials and improvements in thire usage nowdays, however in order to save more energy, there is a need for better understanding flux distributions and loss in transformer cores built with different materials using various configurations [1].

For calculate the flux distribution and total core losses has been solved via many traditional techniques such as nonlinear programming, numerical method and …[2, 5, 7-10]. At peresent the availability of personal computers with very large memory makes it possible to predict magnetic flux distributions and loss in various transformer cores and allow one to come up with an optimum design reasonably fast. The finite element method while is based on solving the Poisson's equation of the magnetic fild problem in variational terms and minimizing the associated functional by set of trial functions [2].

Finite element method (FEM) technique are useful to obtain an accurate charaterization of the electromagnetic behavior or the magntic components, such as transformers [3].

In this paper, FEM techniques is applied to calculat the flux and loss distributions in single phase transformer using PDE toolbox of MATLAB software [4]. For our purpose, modeling of just the transformer is adequate. Therefore an appropriate model of the transformer is defined considering the construction and position of the coils and the current density of them and permeability of transformer core. Then, this model is divided into triangular elements.

By using magnetostatic analysis of the finite element method, the magnetic vector potential of three nodes of each triangular element is calculated and therefore the flux distribution over the model is obtained. Then, the flux density of each element is evaluated. Because the magnetic vector potential of each element is considered as a linear function of x and y, the flux density of each element becomes a constant value [5, 6].

In section 2, the fundumental principles of the transformer modeling using finite element method is briefly discussed. Then the detail modeling procedures introdused in section 3. In section 4, some simulation results are discussed and compared with the xperimental results. The conclutions are givn in section 5.

Principals: Finite Element Method: The finite element method is a numerical technique for obtaining

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approximation solution to boundary value problems of mathematical physics. Especially it has become a very important tool solve electromagnetic problems because of its ability to model geometrically and compositionally complex problems [7].

Using FEM to solve problems involves three stages. The consists of meshing the problem space into contiguous elements of the suitable geometry and assigning appropriate values of the material parameter - conductivity, permeability and permitivity - to each element. Secondary, the model has to be excited, so that the initial conditions are set up. Finally, the values of the potentials are suitably constrained at the limits of the problem space. The finite element method has the avantag of geomtrical flexibility. It is possible to include a greater density of elements in regions where fields and geometry vary rapidly [1, 7].

Formulation: In this section, the partial differential equation that governs calculation of the electromagnetic field inside the transformer problem is determined. The Amperes law states that:

$$\nabla \times \mathrm{H} = \mathrm{J} \tag{1}$$

Where:
H: magnetic field intensity
J: total current density

It is assumed that H is only due to the source currents i.e. no permanent magnets are present.

Linear Magneto-Static Analysis: Current density J in Equ.1 is due to the current sources, i.e. current densities of the transformer's primary and secondary windings. The following relation between the magnetic field intensity and the magnetic flux density exists:

$$\mathrm{B} = \mu.\mathrm{H} \Rightarrow \mathrm{H} = \upsilon.\mathrm{B} \tag{2}$$

The relationship between the magnetic flux density and the magnetic vector potential is:

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

Hence:

$$\nabla \times (\upsilon.\nabla \times \mathrm{A}) = \mathrm{J} \tag{4}$$

Where:
υ: is the reluctivity i.e. the inverse of the magnetic permeability (μ).
And, A: is the magnetic vector potential.

For the 2D models in x-y plane, the non-zero component of A is the z component of magnetic vector potential which is a function of x and y only. Therefore, (4) takes the following scalar form:

$$\frac{\partial}{\partial x}(\upsilon\frac{\partial A}{\partial x})+\frac{\partial}{\partial y}(\upsilon\frac{\partial A}{\partial y})=J_S \tag{5}$$

the magnetic vector potential can be obtained by Solving Equ.6 and the magnetic flux density can be calculated bysolving Equ.4. By using magneto-static analysis of PDE TOOLBOX of MATLAB software, the flux distribution for our defined model is obtained[. In 2D FEM, the flux density is given by:

$$B^2=\left(\frac{\partial A}{\partial x}\right)^2+\left(\frac{\partial A}{\partial y}\right)^2 \quad (T) \tag{6}$$

Where B is the flux density. [1, 4-7]

Transformer Models Using Fem

Transformer Parameter: Simulations were carried out based on custom-built 1KVA, 50 Hz, singl phase transformer. The design data were as follows:

- The rate voltage ratio is 220 V/ 220 V.
- The primary and secondary winding are made of copper.
- The gometriy information is shown in Fig.1.
- The depth of the transformer is 84 mm.

B. B-H curve (or loop): In transformer analysis, because of feromagnetic materials properties, usually the problems appear in nonlinear form. Magnetic permeability, $\mu = B/H$, is not constant and is a function of magnetic field in each mesh. Therefor the S matrix in Equ.1 is not constant. It is a function of Magnetic permeability or magnetic field in each mesh.

The B-H cure of a ferromagnetic core, is a hystrisys loop like Fig.2. In FEM method, for representation of magnetic curve of steel, usually the normal magnetic curve (Fig. 2) is used. The upper approximation of hystrisys loop can be used for calculation of short circuit reactance or radial and axial electromagnetic forces on the transformer coils. But for calculation of flux distributions and loss in transformer cores The B-H loop is used [5, 6].

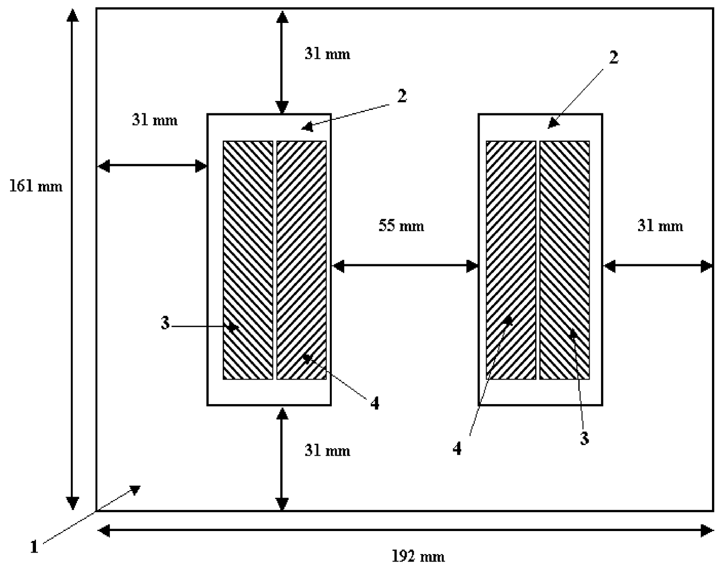

Fig. 1: The design data; 1: core; 2: window; 3: secondary winding; 4: primary winding

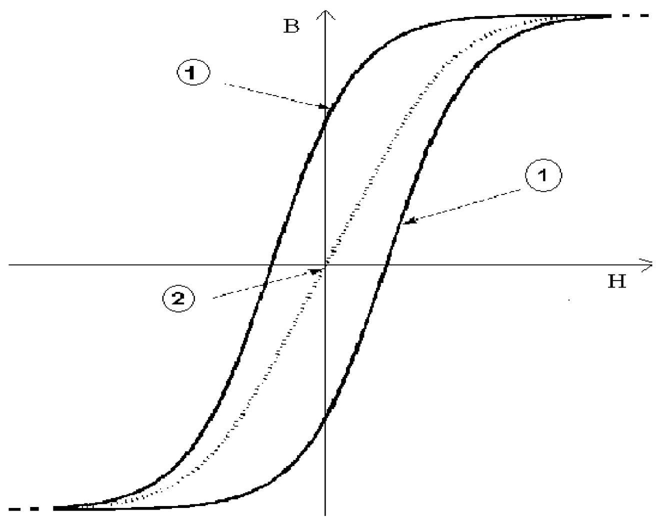

Fig. 2: (1) hystrisys loop, (2) B-H curve

For the single phase transformer(our case) in nominal circumistance, the noload current and voltage Can be measured by digital scope. Noload current and voltage are shown in Fig.3a,b.

Nominal voltage of primary winding, the valuse of B and H can be caculated from followed equations:

$$e(t) = V(t) - R i_o = N \frac{d\phi}{dt} \tag{8}$$

$$\phi = \frac{1}{N} \int e(t)\, dt \tag{9}$$

$$\phi = \frac{1}{N} \int e(t)\, dt \tag{10}$$

$$H = \frac{N i}{L} \tag{11}$$

Where

i_0 : Noload current
$V(t)$: Terminal voltage in noload circumistance
$e(t)$: Emf
ϕ : Flux
R : Risistance of winding
N : Number of turns (N = 220)
L : Mean length

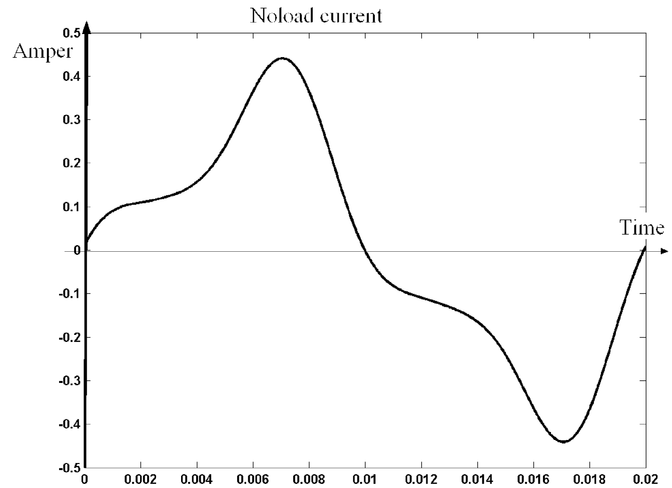

Fig. 3a: Experiment noload current

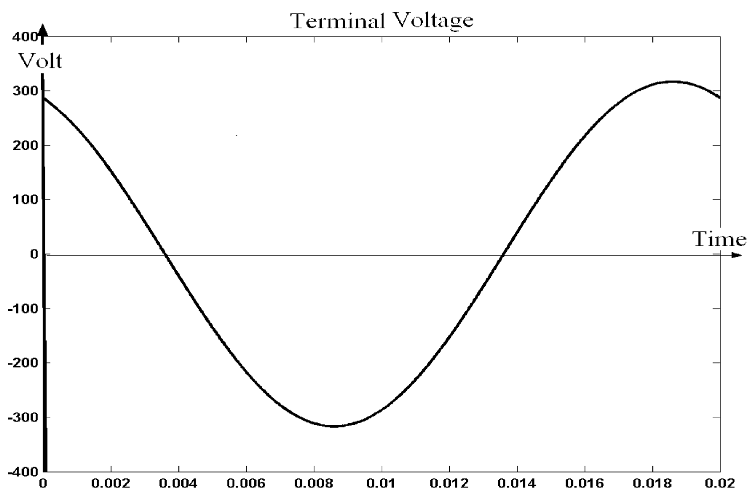

Fig. 3.b: Experiment terminal voltage

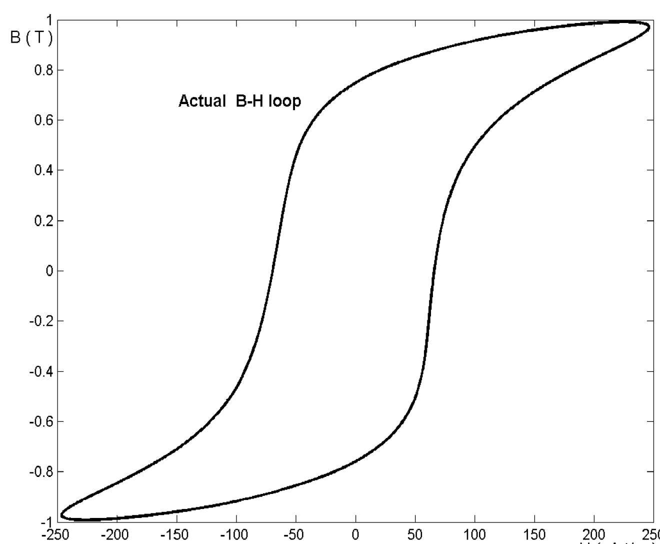

Fig. 4: Actual B-H loop

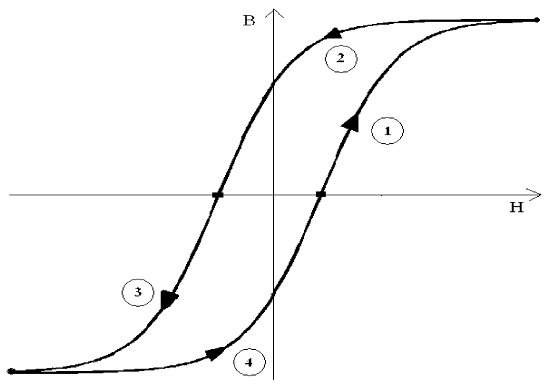

Fig. 5: Four part of B-H loop

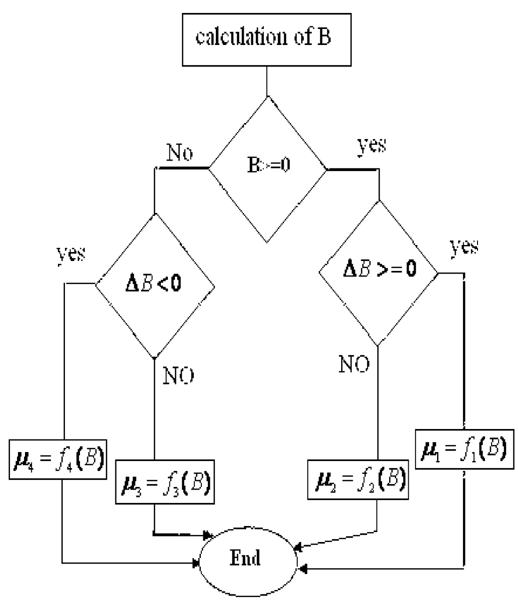

Fig. 6: algoritm of hystrisyse loop

By useing of this equations, actual B-H loop of core is obtained which is shown in Fig.4.

B-H loop model: The principal procedure in transformer analysis in FEM method, is selection of a proper model for hystrisys loop. In this paper, to model the B-H loop, actual loop is devided into four part (Fig.5)and according to the data which is reached in measuring and fitting of each part with third order equation, the seperated third order equation for each part is accessed.

The actual B-H loop of transformer core, which I accessed from experiment is used. Simulation algoritm of hystrisyse loop in this paper is like below flowchart Fig.6 using these third order equation, permeability of each part can be calculatd as a function of B ($\mu = f(B)$). for example: the third order equation for parts 1,2 is:

$$Part1: H = 151.7B^3 + 39.45B + 67.98 \tag{12}$$

$$\mu_1 = \frac{dB}{dH} = \frac{0.0253}{11.536B^2 + 1} \tag{13}$$

$$Part2: H = 338.88B^3 + 25.11B - 81.75 \tag{14}$$

$$\mu_2 = \frac{dB}{dH} = \frac{0.0398}{40.48B^2 + 1} \tag{15}$$

Simulation and Results

Transformer Model: Calculation of the Flux distribution and core losse in transformer is presented in this paper. As shown in Fig.7. the complete single phase transformer

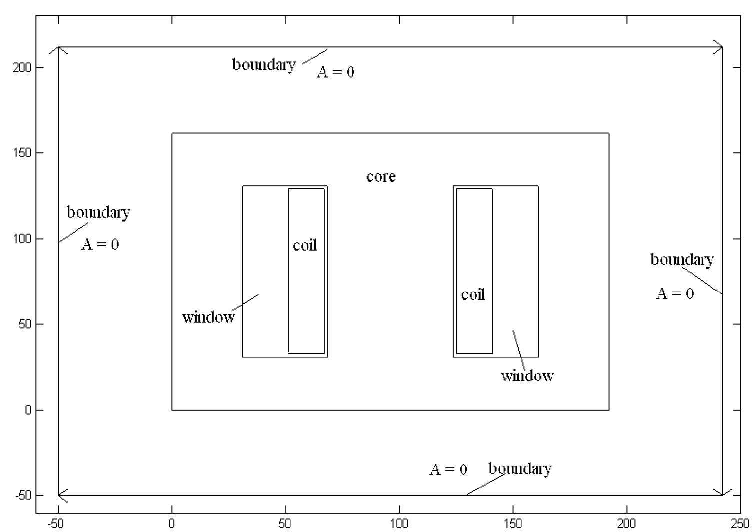

Fig. 7: Single phase transformer model

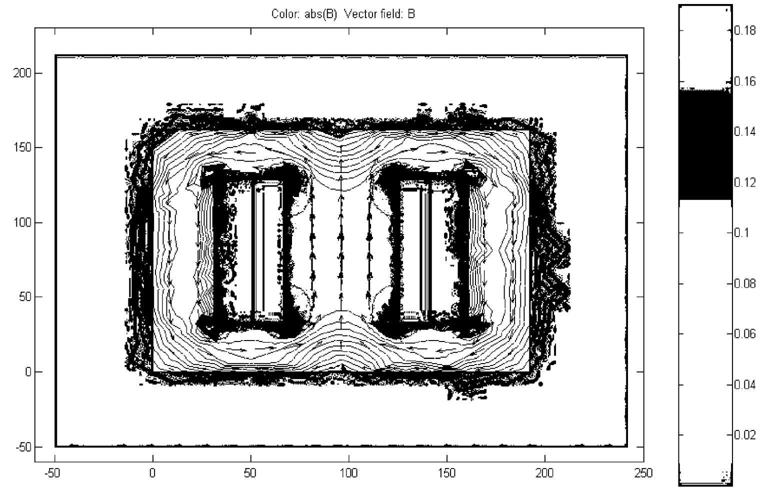

Fig. 8a: Flux distribution over the model defined for the transformer

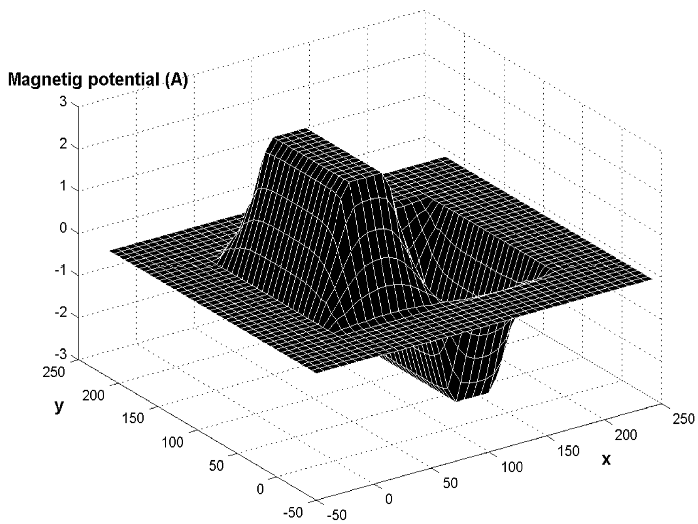

Fig. 8b: Magnetic vector potential distribution.

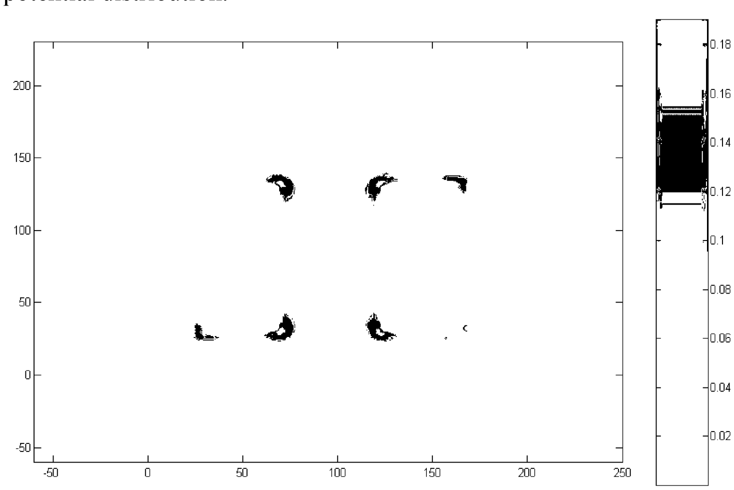

Fig. 8c: Magnetic flux density distribution (Tesla).

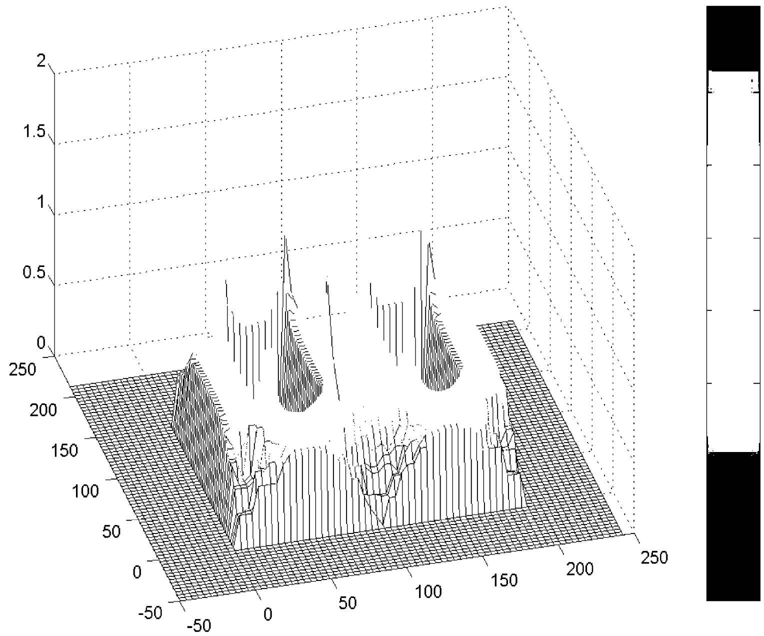

Fig. 9: Absolute magnetic flux density distribution (Tesla)

is modeled. For transformer simulation, the transforer is first divided into 1056 meshes and is set as A=0. the boundary condition over the rectangle that enclosed the single phase transformer model.

Solving (5), the magnetic vector potential can be obtained and solving (3), the magnetic flux density can be calculated.By using magneto-static analysis of PDE TOOLBOX of MATLAB software [6], the flux distribution for our defined model is obtained, as shown in Fig.8a-8c. Figs.9 is the three-dimensional pictures of the absolute flux density.

Core loss calculation: The magnetic vector potential of each triangular element was considered as a linear function of x and y (Equ.16). Therefore, the radial and axial components of the magnetic flux density and consequently the absolute value of B of each triangular element become fix values as shown in the following equations.

$$A = C_1 + C_2 x + C_3 y \tag{16}$$

$$B_x = \frac{\partial A}{\partial y} \tag{17}$$

$$B_y = -\frac{\partial A}{\partial x} \tag{18}$$

$$B = \sqrt{B_x^2 + B_y^2} \tag{19}$$

Where, C_1, C_2 and C_3 are constant coefficients. B_x and B_y are radial and axial components of the magnetic flux densities. After calculation of absolute value of B for each element, the magnetic energy stored in the core space can be calculated by Equ.20.

To calculate loss, we use from equation(20).

$$\mathrm{W} = \sum_{i=1}^{n} (\mathrm{Vol})_{\mathrm{i}} \int_0^T H_i \, d\mathbf{B}_i \ (j) \tag{20}$$

Where:

H_i : Magnetic field intensity in mesh (i)
B_i : Magnetic field density in mesh (i)
$(Vol)_i$: Volume mesh (i)
And n : Number of meshes (n = 1056, T = 20 ms)

Table 1 shows compare between numerical calculation and experimental value. In table(1) it is shown that As the number of meshes is increased, the numerical calculation error is decreased.

Numerical calculation shows that flux density in any points of core is different from the other one. Fig.10 shows the figuer of flux distribution in different points of core. According to this figure this is concluded that Flux at the corners of window has maximum value and these points are (called) hot spots of transformer.

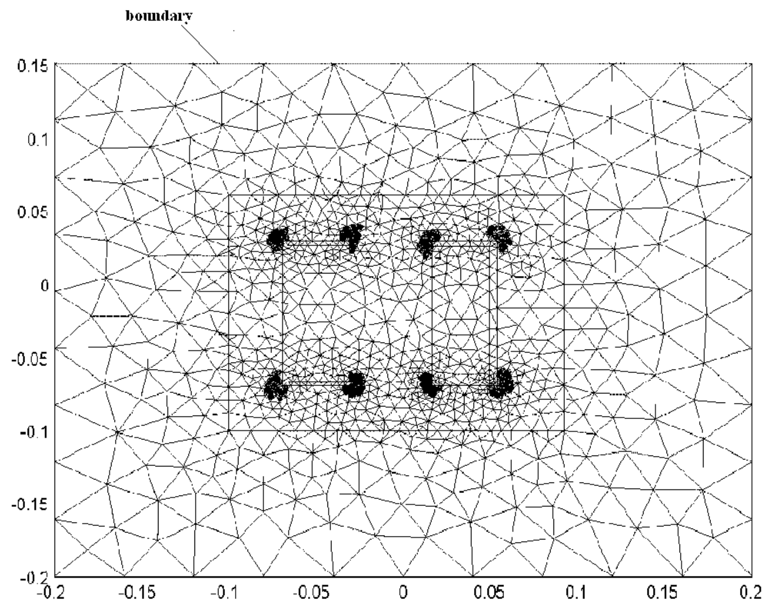

Fig. 10: flux density distribution and Hot spot points

Table 1: compare between numerical calculation and experimental value

# mesh	PRACTICAL	NUMERICAL	ERROR
1056	36.1	38.7	7.2%
4183	36.1	37.35	3.46%

CONCLUSION

Core treatment can be well predicted by using the suggested third order equation model. Calculation results accessed in FEM, shows that by the model of core presented in this paper, we can estimate core loss with high accuracy and flux distribution in the core can determined locally. We also can find hot spots inside the core. Calculation shows that: as the number of used meshes is increased, the more exact result is accessed. The modeling that is shown in this paper allows us to know the transformer behavior before manufacturing them and, thus reducing the design time and cost.

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