Analysis of Magnetic Field Distribution and Core Loss under Unbalanced Load Conditions using 3D Finite Element Method for 400 kVA Transformer

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Abstract. *The finite element method is a popular methodology used to solve complex problems in engineering according to the specific model of the problem. In this paper, the finite element method was used to analyze the problem of electromagnetic field distribution of power distribution 400 kVA transformers in the form of Maxwell's equation. The distribution of the resulting magnetic field causes iron core losses and was analyzed under balanced load and unbalanced load conditions. The result analysis was developed according to the 3D finite element method and modeled by the MATLAB program. It can be seen that grain-aligned silicon steel has less loss in the steel core than M5-grad silicon steel.*

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Distribution Transformer, Magnetic field Distribution, Core loss, 3D Finite Element Method

1. Introduction

A transformer is an electrical machine capable of converting voltage from one side of a circuit to another, with the iron core as the path of magnetic field movement to achieve induction at the output coil. Transformers are important intermediaries in maintaining voltage levels that meet the standards of distribution and distribution systems, and if there is a malfunction or interruption of the distribution system, that would show a decrease in the stability and reliability of the power system. Therefore, the operation analysis of the transformer is to evaluate the efficiency of the transformer as a result of the distribution of the magnetic field. This will cause the transformer to lose energy, which is conditional on load changes in both balanced and unbalanced. The condition of the unbalanced or unbalanced load has been referred to the standard of the Provincial Electricity Authority of Thailand (PEA), where the unbalanced load condition is set at 20% of the load size between pairs of the phases.

The finite element method is a popular numerical method used in computer simulation, which has better advantages than others. An engineering application, that is, has the potential to handle non-linearity of complex geometry problems that depend on time. So this method is suitable for solving the problem of magnetic dispersion. The finite element method can evaluate solutions to Maxwell's equations governing the power transmission systems. Other methods may seem simpler but may be limited only to geometrically simple systems. Within distribution transformers, there are different material structures. The finite element method consolidates these effects by selecting material with difference magnetic permeability values. With this, FEM properties are one of the numerical simulation tools for analyzing the magnetic field problem of regional composites. To take advantage of the 3D finite element method to address the magnetic field diffusion problem. The need to develop a 3D FEM model and formulate a problem is defined in the distribution transformer magnetic field problem.

The magnetic field distribution model of the transformer is summarized in Part 2. Part 3 describes the utilization of the 3D finite element method using the Galerkin method for modeling the magnetic field, according to Details of Item 2. The domain of the 3D finite element method study can be identified using the linear tetrahedron composition. Part 4 shows the simulation results of the distribution of the transformer's magnetic field under balanced load, unbalanced load, temperature effects in the transformer and discusses the results of the changes. The resulting simulation is based on the 3D finite element methodology described in part 3. All programming instructions are encoded in the MATLAB programming environment and the last part is a summary.

2. Mathematical Modeling for Distribution Transformer

Before calculating the magnetic field consisting of the magnetic vector (**A**), field intensity (**H**) and magnetic flux density (**B**), were hypothesized as follows: the magnetic material of the core was isotropic and the displacement current was negligible due to the supply. low frequency (50 Hz), so Equation (1) describes the temporal and spatial shift values of **A** [1], [2].

$$\nabla^2 \mathrm{A} - \mu\sigma \frac{\partial}{\partial t}\mathrm{A} = -\mu \mathrm{J}_0 \qquad (1)$$

Let μ be the magnetic permeability, σ be the electrical conductivity and J_0 be the applied current density.

In the case of the problem considered, it's a system converted from the time domain to the frequency domain (time harmonic), representing a complex number. Therefore,

$$\frac{\partial \mathrm{A}}{\partial t} = j\omega A \qquad (2)$$

Let ω is the angular frequency.

Therefore, a mathematical model of the magnetic field in a distribution transformer considers the distribution transformer in 3D along the plane, which varies with time. The equation is in the form of a partial differential equation, so the equation can be expressed as Equation (3).

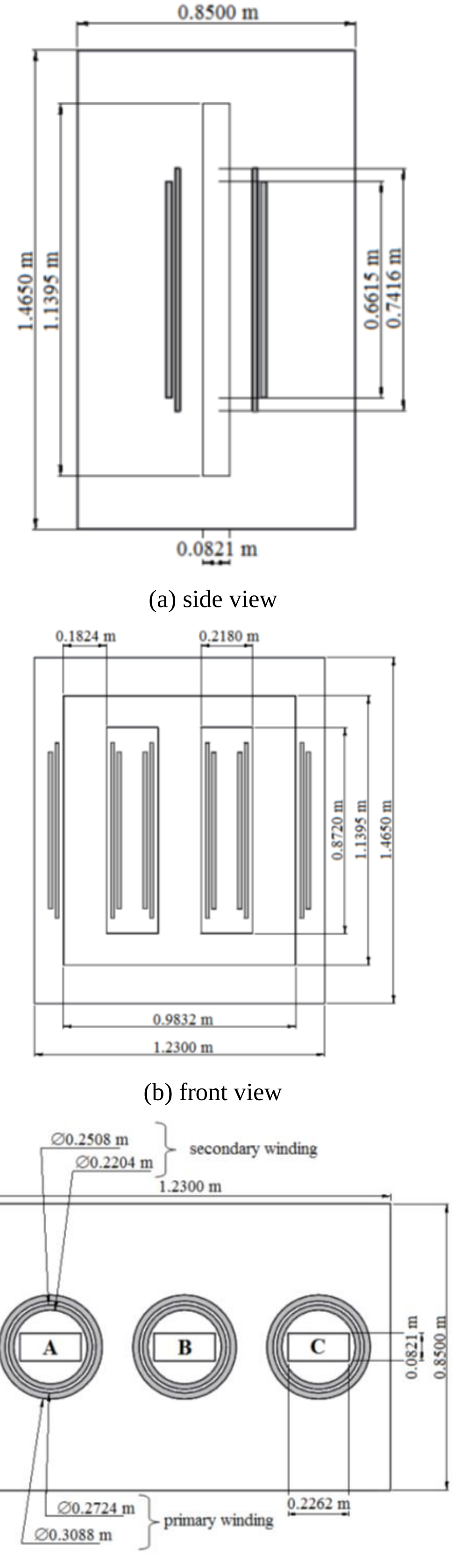
$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A}{\partial z}\right) - j\sigma\omega \mathrm{A} + J_0 = 0 \qquad (3)$$

In analyzing a problem like this, there may not be an easy way, and have a definite result. Therefore, this paper introduces the 3D finite element method, which is considered a highly efficient tool in finding the magnetic field approximate solution for the quasi-static partial differential equation as Equation (3). [4], [5]

3. 3D FEM Equations

For this article, the power loss in the iron core and the temperature of a three-phase distribution transformer, size 400 kVA, 22 kV - 400 /230 V were studied in this research in 3D format, i.e. a simulation of the shape problem, having depth or thickness. The design of a small or large grid varied according to the need to analyze areas of interest within different parts of the system.

Grid design was Elements are implemented using a package called Solid Work. The number of elements and nodes used internally in the distribution transformer was 140,448 elements and 24,469 nodes respectively. Fig.1 shows detail of distribution transformer while Fig. 2 show 3D mesh of distribution transformer.



(a) side view

(b) front view

(c) top view

Fig. 1 Detail of distribution transformer

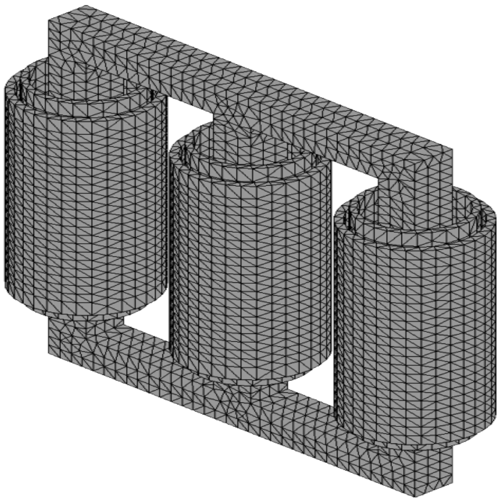


Fig. 2 3D mesh of distribution transformer

This procedure uses the 3D element interpolation function assuming a linear distribution of the solution on the element, so

$$A(x,y,z) = A_1N_1 + A_2N_2 + A_3N_3 + A_4N_4 \tag{4}$$

Let $N_n, n = 1\ 2\ 3\ 4$ is the interpolation function within the element and $A_n, n = 1\ 2\ 3\ 4$ is the result of the magnetic vector potential in each node of elements which, in the case of four-pointed tetrahedron elements, have

$$N_n = \frac{1}{6V}\left(a_n + b_n x + c_n y + d_n z\right) \tag{5}$$

and

$$a_1 = x_4\left(y_2z_3 - y_3z_2\right) + x_3\left(y_4z_2 - y_2z_4\right) + x_2\left(y_3z_4 - y_4z_3\right)$$
$$a_2 = x_4\left(y_3z_1 - y_1z_3\right) + x_3\left(y_1z_4 - y_4z_1\right) + x_1\left(y_4z_3 - y_3z_4\right)$$
$$a_3 = x_4\left(y_1z_2 - y_2z_1\right) + x_2\left(y_4z_1 - y_1z_4\right) + x_1\left(y_2z_4 - y_4z_2\right)$$
$$a_4 = x_3\left(y_2z_1 - y_1z_2\right) + x_2\left(y_1z_3 - y_3z_1\right) + x_1\left(y_3z_2 - y_2z_3\right)$$

$$b_1 = y_4\left(z_3 - z_2\right) + y_3\left(z_2 - z_4\right) + y_2\left(z_4 - z_3\right)$$
$$b_2 = y_4\left(z_1 - z_3\right) + y_1\left(z_3 - z_4\right) + y_3\left(z_4 - z_1\right)$$
$$b_3 = y_4\left(z_1 - z_2\right) + y_2\left(z_1 - z_4\right) + y_1\left(z_4 - z_2\right)$$
$$b_4 = y_3\left(z_1 - z_2\right) + y_1\left(z_2 - z_3\right) + y_2\left(z_3 - z_1\right)$$

$$c_1 = x_4\left(z_2 - z_3\right) + x_2\left(z_3 - z_4\right) + x_3\left(z_4 - z_2\right)$$
$$c_2 = x_4\left(z_3 - z_1\right) + x_3\left(z_1 - z_4\right) + x_1\left(z_4 - z_3\right)$$
$$c_3 = x_4\left(z_1 - z_2\right) + x_1\left(z_2 - z_4\right) + x_2\left(z_4 - z_1\right)$$
$$c_4 = x_3\left(z_2 - z_1\right) + x_2\left(z_1 - z_3\right) + x_1\left(z_3 - z_2\right)$$

$$d_1 = x_4\left(y_3 - y_2\right) + x_3\left(y_2 - y_4\right) + x_2\left(y_4 - y_3\right)$$
$$d_2 = x_4\left(y_1 - y_3\right) + x_1\left(y_3 - y_4\right) + x_3\left(y_4 - y_1\right)$$
$$d_3 = x_4\left(y_2 - y_1\right) + x_2\left(y_1 - y_4\right) + x_1\left(y_4 - y_2\right)$$
$$d_4 = x_3\left(y_1 - y_2\right) + x_1\left(y_2 - y_3\right) + x_2\left(y_3 - y_1\right)$$

Therefore, the volume of each element (V) can be obtained from the determinant of the coefficient as follows:

$$V = \frac{1}{6}\begin{bmatrix} 1 & x_1 & y_1 & z_1 \\ 1 & x_2 & y_2 & z_2 \\ 1 & x_3 & y_3 & z_3 \\ 1 & x_4 & y_4 & z_4 \end{bmatrix} \tag{6}$$

For the 3D finite element method, the Galerkin method of residual weighting was applied by integrating around the volume instead, as shown by the equation (3). When considering the problem in 3D, the residue is obtained as the equation (7).

$$R = \frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial z}\right) - j\sigma\omega\mathrm{A} + J_0 \tag{7}$$

Tetrahedron element There are 4 unknown points, which are the four connections. Therefore, 4 equations are needed to solve for unknown points. That means in $\int_v W_n R dV = 0$ there must be a value $n = 1, 2, 3, 4$ and it is usually selected. Therefore, when substituting the value from Equation 3.19 into Equation (7), we get elements.

$$\int_v N_n\left(\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial \mathrm{A}}{\partial z}\right)\right)dV - \int_v N_n\left(j\sigma\omega\mathrm{A}\right)dV + \int_v\left(N_nJ_0\right)dV = 0 \tag{8}$$

Or write the finite element equations for each element in matrix form.

$$\left[M + K\right]_{4\times1}\left\{\mathrm{A}\right\}_{4\times1} = \left\{F\right\}_{4\times1} \tag{9}$$

where

$$\left[M\right]_{4\times4} = j\omega\sigma\int N_n N_m dxdydz$$

$$\left[M\right]_{4\times4} = \frac{j\omega\sigma V}{20}\begin{bmatrix} 2 & 1 & 1 & 1 \\ 1 & 2 & 1 & 1 \\ 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 2 \end{bmatrix} \tag{10}$$

and

$$\{F\}_{4\times1} = \int_v [N]_{4\times1} J_0 dV = \frac{J_0 V}{4}\begin{bmatrix}1\\1\\1\\1\end{bmatrix} \qquad (11)$$

matrix $[K]_{4\times4}$

$$[K]_{4\times4} = \frac{1}{36\mu V}\begin{bmatrix} b_1b_1+c_1c_1+d_1d_1 & b_1b_2+c_1c_2+d_1d_2 & b_1b_3+c_1c_3+d_1d_3 & b_1b_4+c_1c_4+d_1d_4 \\ & b_2b_2+c_2c_2+d_2d_2 & b_2b_3+c_2c_3+d_2d_3 & b_2b_4+c_2c_4+d_2d_4 \\ & & b_3b_3+c_3c_3+d_3d_3 & b_3b_4+c_3c_4+d_3d_4 \\ Sym & & & b_4b_4+c_4c_4+d_4d_4 \end{bmatrix} \qquad (12)$$

4. Result and Discussion

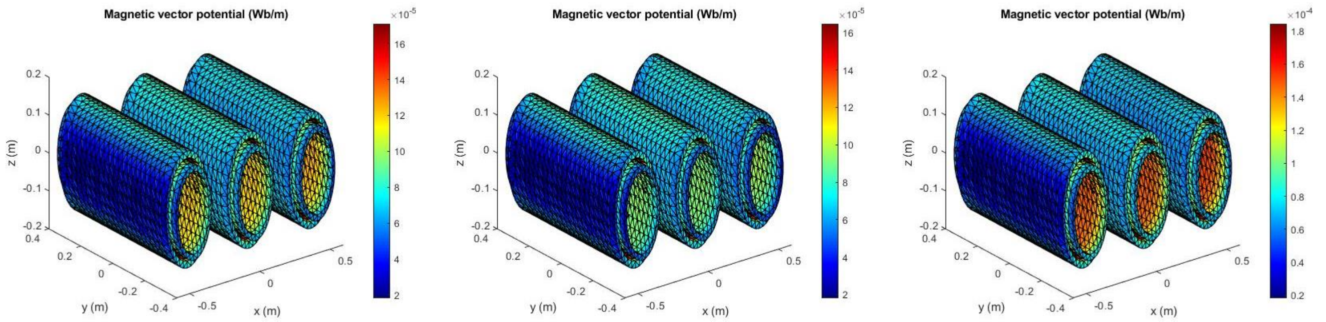
Distribution transformer of 400 kVA, parameters used in the simulation have been mentioned, and comparative simulations of both types of steel cores, namely M5-grade silicon steel cores and grain-aligned silicon steel cores, have been conducted. In the comparative simulation, two cases are analyzed, i.e., when the transformer has a balanced load supply condition and an unbalanced load supply condition. Therefore, in this simulation result, it shows the simulation results of magnetic field distribution and temperature distribution inside the distribution transformer by a simulation program according to the 3D finite element method using the MATLAB program, including the calculated energy loss in the steel core.

Part	Materails	Permeability(μ_r)	Conductivity (σ)
Core	Non-grain aligned silicon steel	4,000	2×10^6 s/m
Winding	Coper	1	5.8×10^7 s/m
Oil	oil	0.05	1.08 s/m

Table 1 Parameters of a 400 kVA distribution transformer using M5 grade silicon steel core

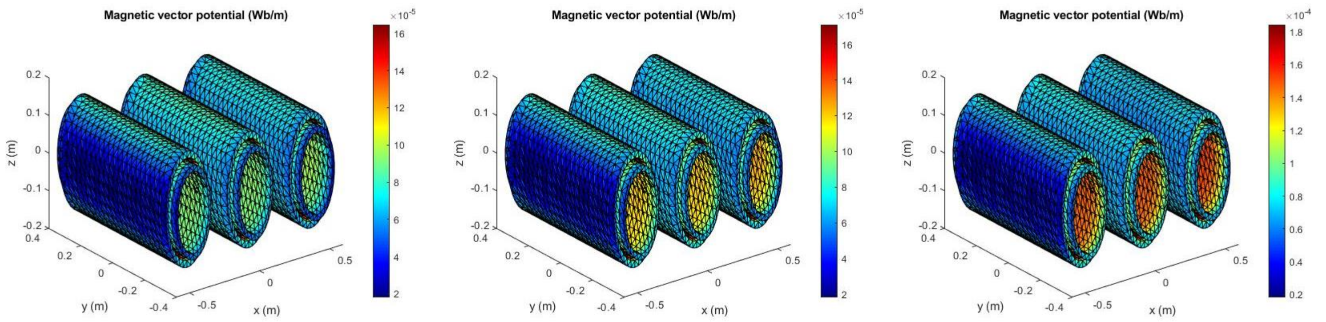
Part	Materails	Permeability(μ_r)	Conductivity (σ)
Core	Non-grain aligned silicon steel	3,000	2.08×10^6 s/m
Winding	Coper	1	5.8×10^7 s/m
Oil	oil	0.05	1.08 s/m

Table 2 Parameters of 400 kVA Distribution Transformer Using Grain Aligned Silicon Steel Core Type



60% 80% 100%

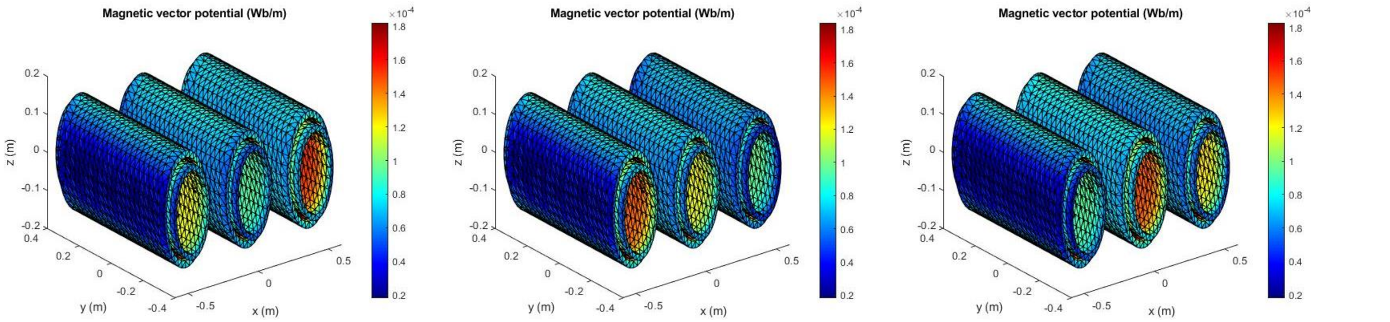
(a) M5 grade silicon steel core



60% 80% 100%

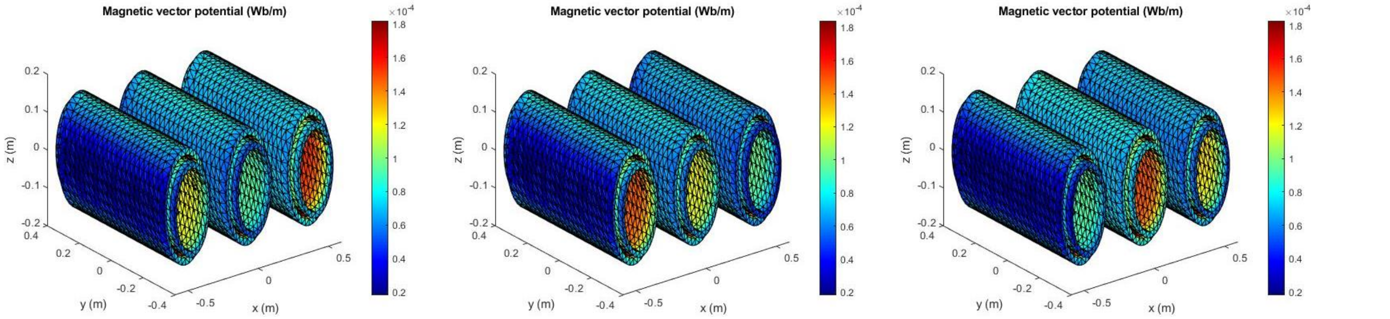
(b) Grain Aligned Silicon Steel Core

Fig. 3 Distribution of the magnetic vector potential (Wb/m) in the transformer winding for load balancing cases



Phase A Phase B Phase C

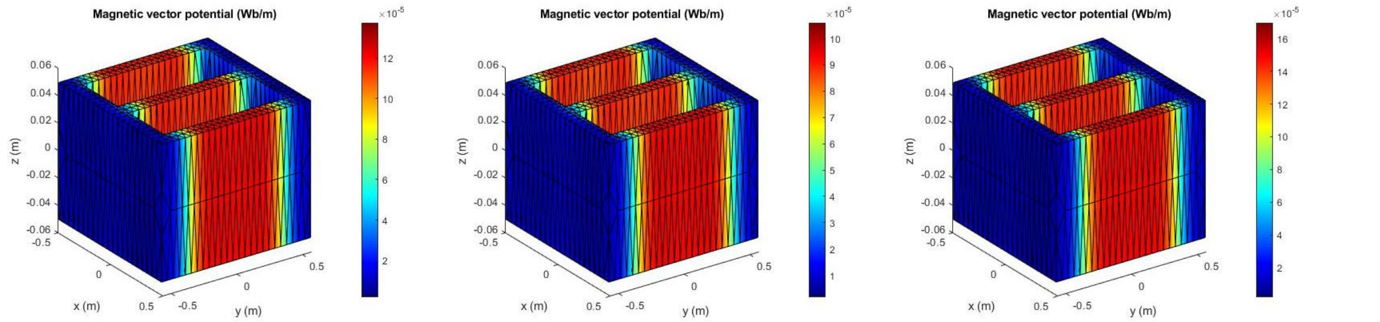
(a) M5 grade silicon steel core



Phase A Phase B Phase C

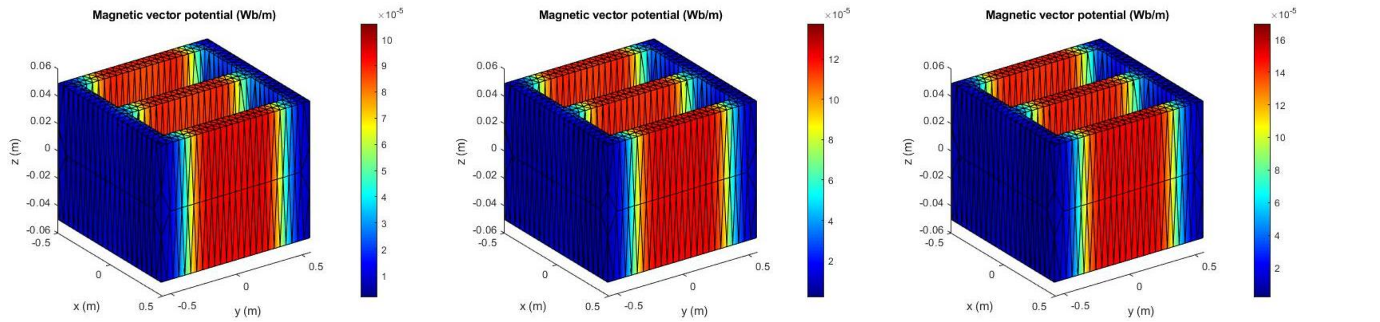
(b) Grain Aligned Silicon Steel Core

Fig. 4 Distribution of the magnetic vector potential (Wb/m) in the transformer winding for load unbalancing cases



60% 80% 100%

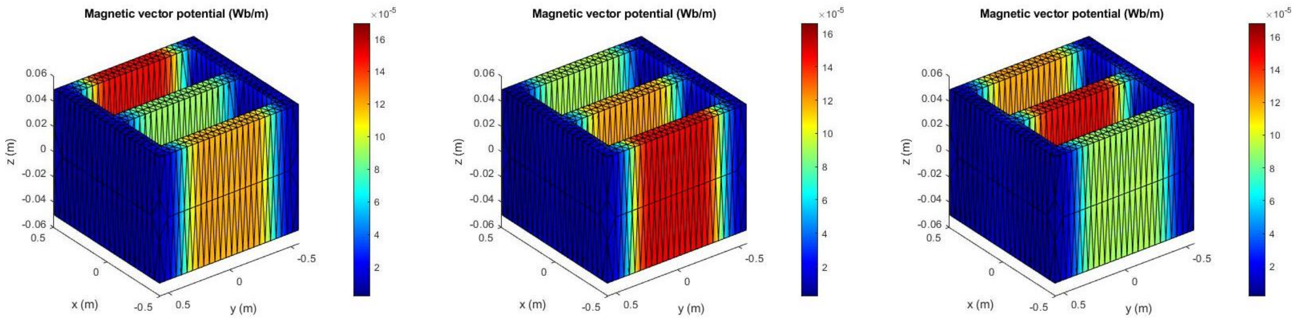
(a) M5 grade silicon steel core



60% 80% 100%

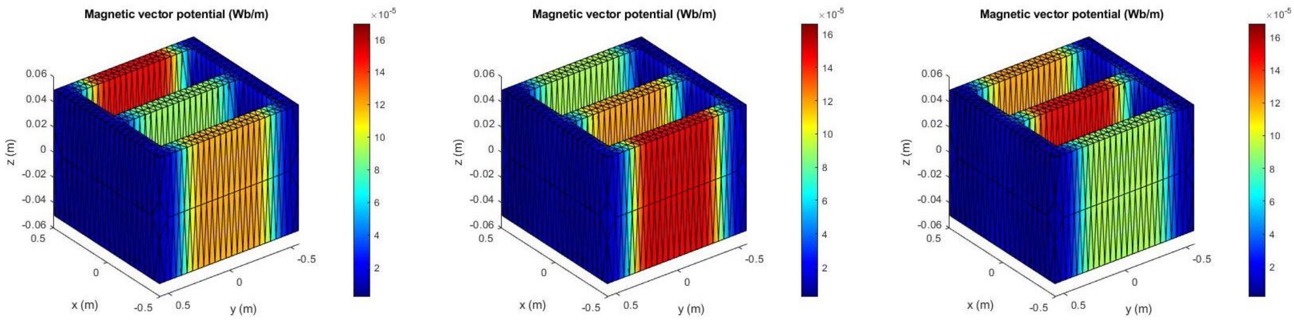
(b) Grain Aligned Silicon Steel Core

Fig. 5 The distribution of the magnetic vector potential (Wb/m) in the iron core region for load balancing cases



Phase A Phase B Phase C

(a) M5 grade silicon steel core



Phase A Phase B Phase C

(b) Grain Aligned Silicon Steel Core

Fig. 6 The distribution of the magnetic vector potential (Wb/m) in the iron core region for load unbalancing cases

From the simulation results of the distribution transformer's magnetic field distribution using the 3D finite element method, it was found that the magnetic vector potential is high in the conductor winding area. The magnetic vector potential of the coil will induce the magnetic vector potential at the iron core to be higher. From the distribution of the magnetic field at the iron core, the area that is surrounded by the conductor coil is higher than other areas, which corresponds to the magnetic vector potential, therefore calculating the power loss in the iron core of the two types of iron from the equation (12)

$$P_{core} = P_e + P_h \tag{13}$$

which can be summarized as follows,

Consider	Core loss (W)
Load balance 100%	4,197.3
Load balance 80%	4,033.3
Load balance 60%	3,880
Load unbalance phase A	4,371.2
Load unbalance phase B	4,295.5
Load unbalance phase C	5,420.5

Table 3 Power loss in the iron core of a 400 kVA distribution transformer using M5 grade silicon steel type

Consider	Core loss (W)
Load balance 100%	3,600
Load balance 80%	3,456
Load balance 60%	3,321.2
Load unbalance phase A	3,753.1
Load unbalance phase B	3,686.5
Load unbalance phase C	4,672.4

Table 4 Power loss in the iron core of a 400 kVA distribution transformer using grain aligned silicon steel

5. Conclusion

This paper has studied the magnetic field distribution in the coil and iron core of a 400 kVA transformer with a voltage rating of 22 kV to 400 /230 V. Transformers are required to use two types of iron cores: M5-grade silicon steel and grain-aligned silicon steel. By simulating the balanced and unbalanced load distribution according to the finite element method developed in MATLAB. It is evident that the power loss in the core of a 400 kVA distribution transformer with a grain-aligned silicon steel core is less than that of a silicon steel core. Gon grade M5 is about 15% Therefore, if the distribution transformer uses a grain-aligned silicon steel core, it will be better to reduce the power loss in the core, and have better performance.

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