Electromagnetic Field Analysis on Asymmetrical Three Phase Transformer

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***Abstract*— This study deals with the effect of core lamination thickness on asymmetrical three-phase transformer to hysteresis curve. The asymmetrical three-phase transformer is a transformer that has different leg-length. The used transformer in this research has 5-kVA rating, and E-I core-cutting topology, and a larger leg size on center compared to the the side-legs of the transformer. Research on the effect of transformer core lamination thickness was done using finite-element method (FEM) to find out the magnetic field density (B) distribution and magnetic field intensity (H) at some points which the flux distribution flows. Variables of thicknesses used in the study were either intact or non-laminated-core transformer, 2.5 cm-laminated transformer core, and 0.03 cm-laminated transformer core. Each transformer has 39 monitor points to obtain the maximum value of B and H. Based on the simulation results, the highest magnetic field density value is in the transformer with 0.03 cm-laminated core, which is 2.174 Vs/m2 and the magnetic field density with the highest absolute average is in a transformer with a non-laminated-core, which is 1.837 Vs/m2. At the branching point of the core-cutting of the transformer with 0.03 cm-laminated transformer core have the highest magnetic field intensity value compared to the non-laminated-core transformer and 2.5 cm-laminated.**

Keywords—asymmetrical leg, electromagnetic field, finite element method, hysteresis curve, three phase transformer.

I. INTRODUCTION

Transformer is one of the the static electricity machine device used in electricity distribution in transmission and distribution systems. The function of transformer is to increase the level of voltage (step-up) generated by the power generation system, so that it can be transmitted at a predetermined distance. Besides being able to increase the voltage level, the transformer can also function to reduce the level of voltage (step-down) of the transmission system to the distribution system so that the transmitted power can be used by electrical loads in offices, housing and industrial sectors according to their needs [1] . Simply put, the transformer consists of a primary coil, a secondary coil, and a transformer core.

There have been significant advances in computer modeling or simulation in the past few decades, but the three phase transformer modeling technique has not developed as well as a single phase transformer [2]. Constraints faced vary, such as the various three-phase transformer topologies and the determination of more complex non-linear parameters [3]. There have been many modeling of three phase and one phase transformers [4] - [7]. Modeling of three phase transformers with one core is considered to be more complicated due to the existence of interrelated fluxes between windings and the number of negligible parameters, such as iron core losses [8]. Therefore, it is necessary to analyze the distribution and flux density at the core. The size of the flux distribution is obtained from a simulation based on Finite-Element Method (FEM).

The level of accuracy of the modeling of the operation of the transformer has been deemed lacking [9]. Thus, the latest modeling requires the integration of hysteresis phenomena which have become one of the important research subjects. Several variations of good hysteresis modeling are available in the Jiles-Arthon (J-A) literature, Preisach, Bouch-Wen, Tellinen, Stoner-Wohlfarth, with each of its disadvantages and advantages. Research in the past few years has tried to obtain a hysteresis curve from a ferromagnetic core from a symmetrical and asymmetrical modeling of three phase transformers [10]. Transformer modeling is important, especially for the equipment manufacturing company as it does the determination of specifications, dimensions, mechanical characteristics, thermal characteristics, and electromagnetic fields.

In this study, a simulation of three phase transformers with customization of the shape of the leg is called an asymmetrical three phase transformer due to the long differences in the legs based on FEM. The expected results from the modeling are the shape of the hysteresis curve on each leg. The hysteresis curve in question is the ratio of curve B (magnetic field density) to the H curve (magnetic field intensity). Analysis of the B-H curve on three phase transformers is a challenge because its electromagnetic behavior when transient and steady-state conditions differ significantly from one-phase transformers. Specifically, magnetic coupling and more flux pathways in three-phase transformers show different behavior than one-phase transformers [11]. The air gap between the core of the transformer and the connection between the core parts also affects the magnitude of the magnetic saturation point in the transformer [12].

The effect of laminate thickness on the transformer core on the magnitude of the magnetic saturation point on the transformer and the comparison of the shape of the hysterical curve on each leg with variations in the thickness of the laminate has been discused in this study. Whereas, it is simulated asymmetrical leg three-phase transformer and thickness variation of the transformer core lamination, ie without lamination or intact form, 2.5 cm laminate thickness, and actual transformer laminate thickness of 0.03 cm, core pieces of E-I, the material used is ST-37, and the observation location based on point (point).

II. Transformer Principle

A. *Construction of Transformer*

Transformer has two types of construction that are commonly used, namely the core type (core-form) and shell type (shell-form). The core type has a type of transformer with a primary coil and the secondary coil is on a different side of the arm. Whereas the shell type illustrates that the primary coil and secondary coil are stacked together. Stacking here can be interpreted mounted up-down or inside-out.

B. *Non Ideal Transformer*

Practically, transformers in the world have parameters that cannot be ignored even though they are only have little value. For example, the transformer winding has a winding resistance value even though the value can be categorized as small. Turn resistance can result in flux leakage. Flux leakage is the flux that comes out through the air around the winding. Flux leakage produced by the primary coil and secondary coil can cause a joint flux. The flux does not flow in the air, but flows into the transformer core.

In addition, in the world, transformers cannot convert power perfectly like ideal transformers. There are several factors that can cause these conditions, including the effect of winding resistance, flux leakage, and excitation currents due to limited core permeability. Another factor is the presence of power losses, such as core losses that are influenced by core resistance and magnetic reactance that occur in the transformer core. Limited magnetic circuit permeability can affect the amount of current needed to produce magnetic forces to maintain the flux needed by the transformer to keep working. The magnetic force and the required current are directly proportional to the flux density or magnetic field density (**B**) obtained from the following formula:

$$\mathbf{B} = \phi / A \qquad (1)$$

Where, **B** is the magnetic field density (Wb/m2), ϕ is the magnetic flux (Wb), and A is the ferromagnetic core surface area (m2). The magnetic field density illustrates the strength of the field which is influenced by the magnetic field intensity and the permeability of magnetic material that can be written in the equation as follows:

$$\mathbf{B} = \mu \times \mathbf{H} \qquad (1)$$

Where, μ is the material permeability constant (H / m) and **H** is the magnetic field intensity (A / m)..

C. *Equivalent Circuit of Transformer*

In real conditions or in conditions that are not ideal, modeling the circuit approaching the transformer needs to pay attention to various parameters which will make the modeling of equivalent circuits more complex. This equivalent circuit is used to analyze the work of the transformer in accordance with real conditions by considering losses of winding and core material components, such as magnetization reactance and core resistance.

D. *Magnetization Curve of Transformer*

The magnetization curve or can be called a hysteresis curve or also known as a **B**-**H** curve is a curve that describes the relationship between magnetic field density (**B**) and magnetic field intensity (**H**). This curve shows the effect of magnetic field density that occurs in the transformer core due to an increase in magnetic field intensity. The transformer magnetization curve also shows that there is nonlinearity in the transformer core.

III. Simulation and Experiment Setup

A. *Spesification of the Asymmetrical Three Phase Transformer*

This study modelling 5-kVA three phase transformers as research objects with different transformer leg topologies. Different transformer leg topology is the difference length in the middle leg of the transformer compared to the left and right transformer leg. This type of transformer in the world of research is often referred to as an asymmetrical leg three phase transformer as depicted on Fig. 1. Transformer spesification has been shown in Table I and Table II.

TABLE I. Asymmetrical three phase transformer specifications

Transformer Specifications	
Phase	3 Phase
Construction Type	*Core-form*
Power Capacity	5-kVA
Primary Voltage	380 Volt
Secondary Voltage	380 Volt
Winding	$Y - \Delta$
Number of Primary Turns	255
Number of Secondary Turns	255
Right Leg Winding Resistance	1,48 Ω / phase
Middle Leg Winding Resistance	0,89 Ω / phase
Left Leg Winding Resistance	1,48 Ω / phase
Frequency	50 Hz

B. *Dimension of The Asymmetrical Three Phase Transformer Core*

The asymmetric three phase transformer used in this research has parameters consisting of dimensional specifications, core cut shapes, and laminate thickness. Dimension specifications and shape of core pieces are obtained through physical measurements of transformer objects. The dimension of middle leg of the transformer has twice as long as the two legs on the side. This transformer used the E-I cutting method as depicted on Fig. 2.

C. Determining Monitor Locations and Mesh Compilers

Asymmetrical three phase transformer modeling using the help of Computer Simulation Technology (CST) Studio software. The first step in modeling is to describe the design of a three-dimensional transformer construction. The description of transformer construction in the form of core pieces of E-I begins by entering the coordinates of each transformer vertex that has been adjusted to the real scale of the transformer object. There are sixteen observation points as depicted on Fig. 3. The core material used is ST-37 steel with variations in laminate thickness parameters. The following are ST-37 steel specifications, coordinate material forms, and FEM-based transformer modeling images. Before the simulation is run, CST Studio software will separate the transformer structure that has been formed into elements that are interconnected between points called mesh. In FEM, this process is called discretization..

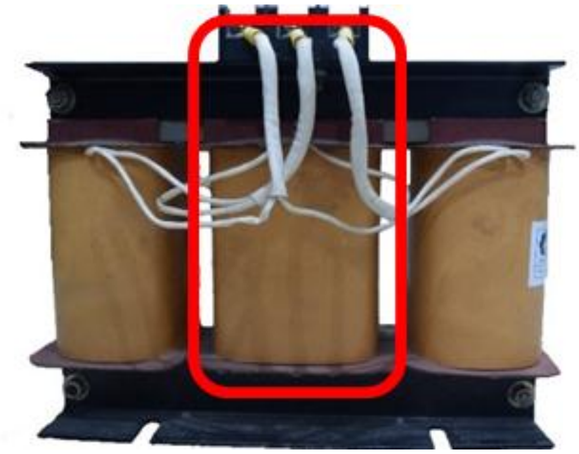


Fig. 1. Asymmetrical three phase transformer

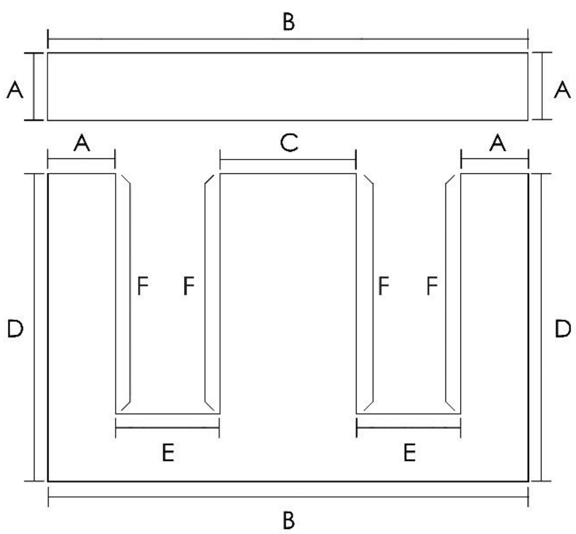


Fig. 2. Transformer Design Spesification

TABLE II. SPECIFICATION OF CUTTING TRANSFORMER DIMENSIONS

Transformer Dimension	Size
A	4 cm
B	28 cm
C	8 cm
D	18 cm
E	6 cm
F	14 cm
Total Height	22 cm
Thickness	10 cm
Lamination Thickness	0,03 cm

D. Magnetization Curve of ST-37 Steel Material

ST-37 steel material is steel with a tensile strength of 37 MPa (Mega Pascal) or equivalent to 37 kg / mm2. The greater the magnetic field intensity is, the denser the field will be before it reach its saturation point. It can be seen that the ST-37 material has saturation point when the magnetic field intensity is 7.235.44 A / m and the magnetic field density is 1.79786 T as depicted on Fig. 4.

E. Data Acquisition of Magnetic Field Density and Magnetic Field Intensity

After the simulation has finished, data acquisition of magnetic field density and magnetic field intensity will be carried out against the time at each monitor point as depicted on Fig. 5 and Fig. 6. Then, the second data plot is plotted into one form of hysteresis curve, where the magnetic field density becomes the value on the y axis and the magnetic field intensity becomes the value on the x axis.

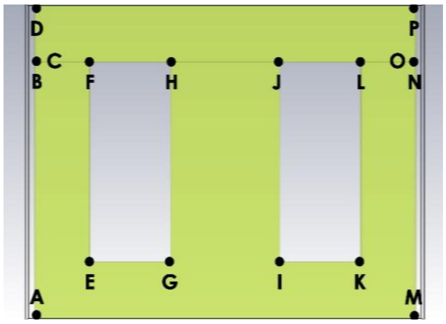


Fig. 3. Monitor locations on transformer

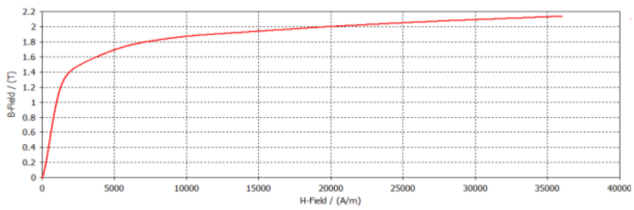


Fig. 4. Magnetization curve of ST-37 steel material

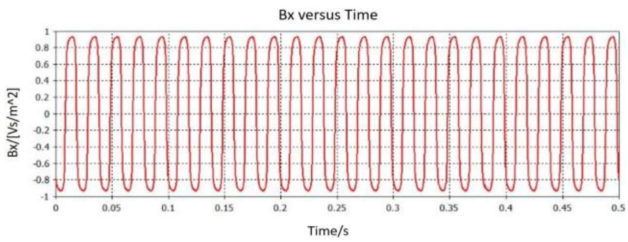


Fig. 5. Magnetic field density versus time

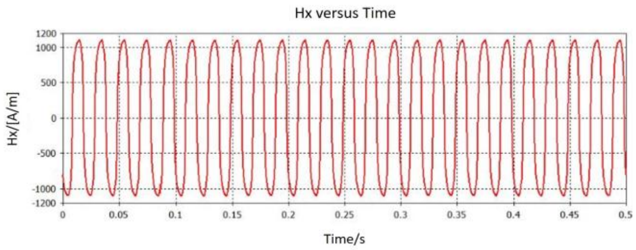


Fig. 6. Magnetic field intensity vs time

IV. Results and Analysis

A. Distribution of Magnetic Field Density and Magnetic Field Intensity

The value of magnetic field density (B) and the intensity of the magnetic field (H) are obtained through FEM simulations on the modeling of asymmetric three phase transformers. The material used, ST-37 steel is classified into the category of soft steel because there is an element of silicon and has a density (ρ) of 7.850 kg/m3. This simulation is used to obtain a comparison curve of the value of magnetic field intensity as the x axis with magnetic field density as the y axis.

At 0° phase angle the distribution of magnetic field density with the greatest value moves from the left leg to the first piece, then to the middle leg. At 60° phase angle distribution of the magnetic field density shows the average distribution and the value is equal. The magnetic field density in the middle leg spreads equally towards the left and right legs as depicted on Fig. 7.

The distribution of magnetic field intensity at phase 330° still looks evenly distributed to the entire core of the transformer. In phase 300°, the intensity distribution of the magnetic field is still in the transformer's left leg towards the middle leg passing through the I as depicted on Fig. 8.

B. Comparison of Hysteresis Curves with Lamination Thickness Variables

Monitor points in the transformer have been determined to observe the hysteresis curves that occur in each variable thickness of the transformer laminate. In each transformer simulation is carried out at 39 points. So that one variable thickness of lamination has 39 magnetization curves. The following is a comparison of the hysteresis curve with variations in the thickness of the laminate.

C. Core Saturation Analysis

From these monitor points, it can be seen that in the simulation of 0.03 cm core lamination there are several points that have exceeded the saturation limit of the transformer core material. From these points the dominant points on each leg are taken and can be related to the magnitude of the inrush current. Table III and Table IV shows magnetic field density and magnetic field intesity values at observation points.

At point C_1 (left leg) transformer with laminate thickness 0.03 cm, B_N value is 0,0177 V.s/m^2, B_R is 0,0002 V.s/m^2, and B_S is 1,133 V.s/m^2. So that the peak value of the inrush current is obtained:

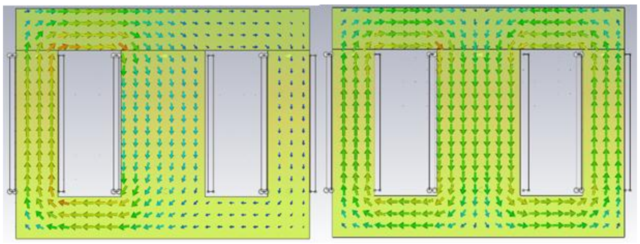
$|i_{peak}|$ = (380×2/5.905,39)(-1,097/0.0177)
$|i_{peak}|$ = 8,49 A.

At point H_1 (middle leg) transformer with laminate thickness 0.03 cm, B_N value is 0,00923 V.s/m^2, B_R is 0,0067 V.s/m^2, and B_S is 1,100 V.s/m^2. So that the peak value of the inrush current is obtained:

$|i_{peak}|$ = (380×2/5.903,99)(-1,073/0.00923)
$|i_{peak}|$ = 15,5 A.

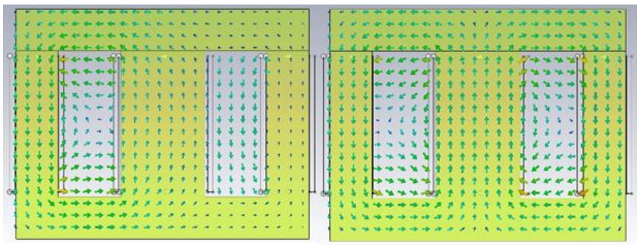
At point M_1 (right leg) transformer with laminate thickness 0.03 cm, B_N value is 0,0224 V.s/m^2, B_R is 0,00089 V.s/m^2, and B_S is 1,232 V.s/m^2. So that the peak value of the inrush current is obtained:

$|i_{peak}|$ = (380×2/5.905,39)(-1,186/0.0224)
$|i_{peak}|$ = 7,33 A.



(a) (b)

Fig. 7. Magnetic field density distribution of 0.03 cm laminated core at phase 0° (a); and 60° (b).



(a) (b)

Fig. 8. Magnetic field density distribution of 0.03 cm laminated core at phase 300° (a); and 330° (b).

TABLE III. SUMMARY THE VALUE OF B-H IN 2.5 CM LAMINATED TRANSFORMER

Titik Monitor	B_{max} (V.s/m^2)	| B_{avg} | (V.s/m^2)	H_{max} (A/m)	| H_{avg} | (A/m)
A_1	0,964	0,807	1.198,988	925,077
A_2	0,972	0,819	1.432,287	1.034,978
A_3	1,012	0,846	1.409,409	1.034,756
B_1	0,001	0,000	2,683	1,310
B_2	0,000	0,000	2,458	1,204
B_3	0,001	0,000	2,969	1,440
C_1	0,980	0,838	1.586,526	1.150,202
C_2	1,014	0,858	1.561,221	1.134,377
C_3	0,814	0,710	1.289,556	980,225
D_1	1,838	1,559	8.630,251	5.079,608
D_2	1,837	1,559	8.618,456	5.071,906
D_3	0,011	0,007	8.801,502	5.200,755
E_1	**1,838**	1,559	8.624,051	5.076,145
E_2	1,837	1,559	8.618,996	5.074,241
E_3	0,011	0,007	**8.854,797**	**5.251,631**
F_1	1,143	0,506	1.192,716	514,928
F_2	1,136	0,508	1.182,197	515,542
F_3	1,140	0,508	1.188,875	516,953
G_1	0,008	0,002	16,429	2,781
G_2	0,004	0,001	5,546	1,496
G_3	0,002	0,000	4,662	0,844
H_1	1,109	0,487	1.142,002	492,383
H_2	1,107	0,486	1.138,753	491,028
H_3	1,109	0,487	1.141,591	492,276
I_1	1,837	**1,564**	8.596,848	5.083,175
I_2	1,837	**1,564**	8.599,566	5.081,821
I_3	1,836	**1,564**	8.581,941	5.074,967
J_1	1,837	1,563	8.588,248	5.078,076
J_2	1,836	**1,564**	8.575,871	5.073,557
J_3	1,837	**1,564**	8.603,568	5.087,133
K_1	0,949	0,800	1.147,276	902,243
K_2	0,972	0,819	1.431,865	1.034,373
K_3	0,002	0,001	1.598,350	1.087,858
L_1	0,000	0,000	2,251	1,121
L_2	0,000	0,000	2,133	1,060
L_3	0,001	0,000	2,830	1,388
M_1	0,791	0,695	1.224,339	945,063
M_2	0,796	0,699	1.308,752	992,050
M_3	0,002	0,002	1.905,199	1.309,350

TABLE IV. SUMMARY THE VALUE OF B-H ON A TRANSFORMER WITHOUT LAMINATION

Titik Monitor	B_{max} (V.s/m^2)	| B_{avg} | (V.s/m^2)	H_{max} (A/m)	| H_{avg} | (A/m)
A_1	0,932	0,790	1.099,795	879,257
A_2	0,922	0,782	1.065,137	858,274
A_3	0,002	0,002	1.942,166	1.303,675
B_1	0,001	0,000	2,948	1,417
B_2	0,000	0,000	0,133	0,052
B_3	0,002	0,002	3,170	1,518
C_1	0,973	0,840	1.962,382	1.347,105
C_2	1,146	0,945	2.045,253	1.363,651
C_3	0,931	0,816	1.761,537	1.255,874
D_1	1,836	1,558	8.571,089	5.051,644
D_2	1,835	1,558	8.530,582	5.031,084
D_3	0,011	0,007	8.767,822	5.191,361
E_1	**1,837**	1,558	8.584,717	5.054,869
E_2	1,836	1,558	8.570,289	5.051,043
E_3	**1,837**	1,558	8.594,120	5.061,135
F_1	1,147	0,506	1.199,254	515,595
F_2	1,165	0,530	1.228,597	542,969
F_3	1,135	0,501	1.180,774	509,085
G_1	0,001	0,000	2,522	0,614
G_2	0,001	0,000	1,230	0,294
G_3	0,002	0,001	3,546	1,141
H_1	1,105	0,485	1.136,731	490,716
H_2	1,161	0,519	1.221,832	530,618
H_3	1,106	0,485	1.137,507	490,198
I_1	**1,837**	**1,565**	8.591,411	5.086,487
I_2	1,836	1,564	8.557,311	5.069,384
I_3	0,011	0,006	8.596,096	5.089,211
J_1	1,836	1,564	8.577,488	5.075,506
J_2	1,836	1,564	8.564,003	5.068,930
J_3	0,011	0,007	**8.797,737**	**5.202,882**
K_1	0,935	0,790	1.107,249	879,921
K_2	0,946	0,822	1.713,222	1.220,594
K_3	0,902	0,764	1.027,062	829,965
L_1	0,001	0,000	2,991	1,445
L_2	0,000	0,000	0,323	0,185
L_3	0,001	0,000	2,647	1,291
M_1	0,936	0,818	1.732,086	1.234,610
M_2	1,073	0,894	1.672,127	1.178,008
M_3	0,002	0,002	1.878,987	1.274,900

V. CONCLUSIONS

The absolute mean of the highest density of the highest magnetic field is at points D, E, I, and J, which means that the four locations are in the branching path of the flux distribution flow. On the z = 10 axis, the value of the magnetic field density fluctuates, so the hysteresis curve is found in a form resembling a linear line. The value of the largest magnetic field density is in the transformer with 0.03 cm lamination. Magnetic field density with the highest absolute mean is in the transformer with a core without lamination. The inrush current on the middle leg of an asymmetric three phase transformer has a higher inrush current value.

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