Journal of Engineering and Sustainable Development
https://jeasd.uomustansiriyah.edu.iq/index.php
https://doi.org/10.31272/ jeasd.26.3.6

Vol. 26, No. 03, May 2022
ISSN 2520-0917

FINITE-ELEMENT CALCULATION OF ELECTROMAGNETIC FORCES IN THE DEFERENT SHAPES OF DISTRIBUTION TRANSFORMERS WINDING UNDER SHORT CIRCUIT CONDITION

*Weeam J. Hussein Kassim R. Hameed

Electrical Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq

Published 17/11/2021 ***Accepted in revised form 17/12/2021*** ***Received 1/5/2022***

Abstract: This paper is concerned with calculating the electromagnetic forces in the windings of distribution transformers with different shapes of coils. The electromagnetic forces as well as the magnetic flux density and their distribution were analyzed and calculated using Finite Element Method (FEM). The Finite Element models of the distribution transformers with non-linear magnetic characteristics for the iron core are built using FEM software "ANSYS". In this paper, the static analysis method is based on two-dimensional models, and these models have been solved by using the formula for the magnetic vector voltage (A). Three types of three-phase distribution transformers were adopted, each with a capacity of 250 kVA and a voltage ratio is 11 / 0.416 kV. These types of transformers with different shapes of coils are stack core transformer with oval coil, wound core transformer with rectangular coil, and stack core transformer with cylindrical coil. The results obtained from the FEM analysis agreed with the design calculations which depend on the conventional design formulas. The most important contributions of this study are to building two-dimensional models for different types of distribution transformers. Calculating electromagnetic forces in transformers winding during short circuit conditions in different coil shapes. Studding the effect of the shape of the coils on the calculation of the electromagnetic forces in them. This work can save time, effort, and cost for transformer manufacturers in calculating the electromagnetic forces, also using this model for the virtual test leads to avoid the risk, and efforts spent to do the real short-circuit test on the transformer before manufacturing.

Keywords: *2D models, short circuit forces, distribution transformers.*

1. Introduction

The distribution transformer is an important component of electric power systems since that failure results in expensive repairs or replacement, as well as a significant loss of power at a high cost [1]. When a short circuit occurs in the winding of the transformer, the electromagnetic force acting on the winding is proportional to the square of the current. The high pressure and eventual deformation of the winding is caused by radially and axially stress. As a result, the transformer must be strong enough to endure extreme conditions and must undergo certain testing procedures [2].

The percentages of the various faults in distribution transformers are shown in figure (1). It should be noted that (33%) of failures are due to the winding faults [3].

*Corresponding Author: eema2026@uomustansiriyah.edu.iq

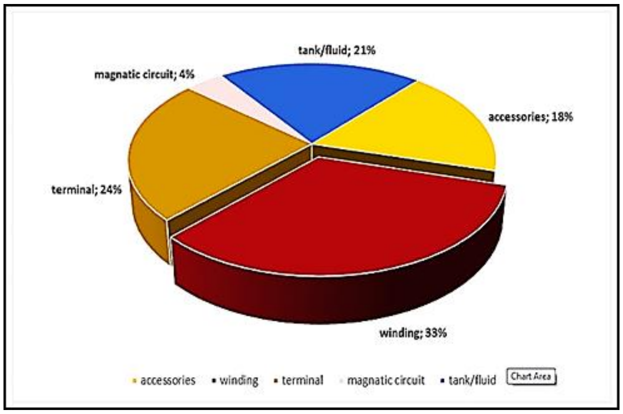


Figure 1. Typical failure distribution for transformers [3]

The short circuit capability of a transformer is mostly determined by its withstand thermal and mechanical. A large current flowing in a transformer winding at the time of a short circuit increases its temperature. Because of the fact that its duration is usually very short, the temperature rise is not appreciable to cause any damage to the transformer [4]. As a result, we are concerned with the withstand mechanical, which requires studying the distribution of forces and their computation in order to ensure proper performance and reliability during the transformer's lifetime. An example of mechanical failures is shown in figure (2).

Figure 2. Destructed windings after short circuit current

In this paper, 2-D finite element methods based on vector potential formulation have been used to model and investigation of leakage flux and electromagnetic forces. Given the importance of examining the short circuit of distribution transformers as one of the special choices, and that this test is not available in most transformer laboratories except in special sites, including KEMA and KDf. Because the cost of these laboratories is high and the transformer factories in Iraq need this test, the researcher used numerical methods to calculate electromagnetic forces, and one of these methods adopted by the researcher is the FEM method using the ANSYS program.

2. Electromagnetic Force

The work of the transformer is based on the principle of electromagnetic induction. This electromagnetic field generated the electromagnetic forces within the transformer windings, according to the laws of Faraday's law of induction and Lorenz law of electromagnetic energy. As a consequence, the first peak of currents at the short circuit is regarded as critical and may damage the transformer windings [5].

In the two-dimensional model, magnetic flux density (B) consists of two components, radial flux density (Br) and axial flux density (Ba). The direction of the force generated can be determined using the left-hand rule. As shown in Figure (3).

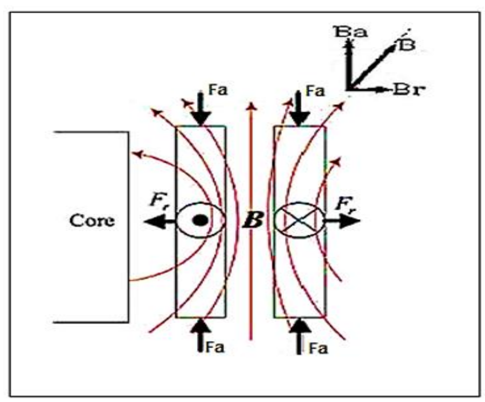


Figure 3. Electromagnetic force and leakage flux distribution in windings [1]

2.1. Radial Force (F_r)

In general, the current through the concentric windings produces magnetic flux. The axial flux

(Ba) interacts with the winding current and produces a radial force (Fr). Low voltage (LV) and high voltage (HV) windings carry currents in opposite directions, there is a large radial repulsive force between them, thus resulting in an outward pressure on the outer winding (HV) and pressure towards the axis of the limb on the inner winding (LV). The figure 4 shows the typical behavior of radial force in windings at short-circuit conditions [6 - 8].

Radial forces can cause a variety of deformations on the inner winding, including free buckling and forced buckling, as well as hoop stress on the outer winding [9]. As shown in Figure (5).

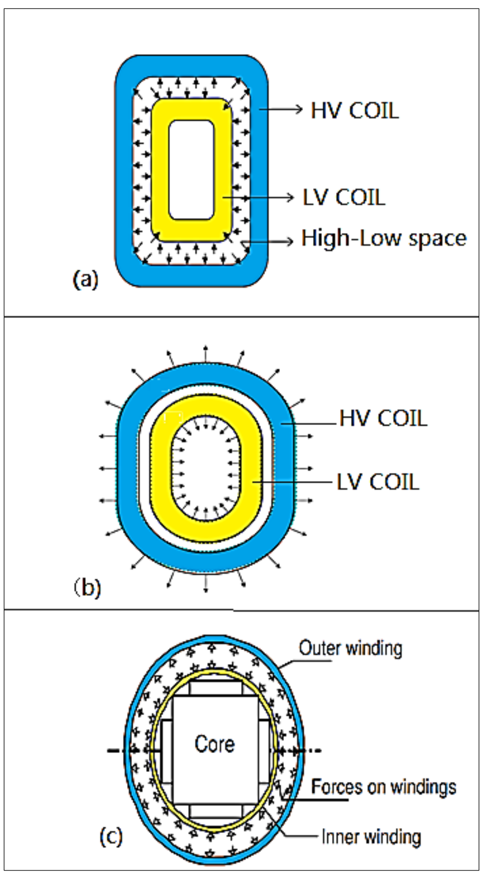


Figure 4. Fundamental force between winding (a) Rectangle winding [6]. (b) Oval winding [7]. (c) Cylinder winding [8]

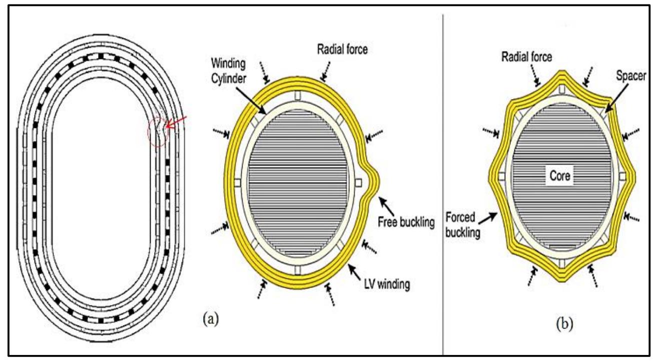


Figure 5. Winding deformation buckling model (a) free buckling**.** (b) Forced buckling [7, 9].

2.2 Axial Force (F_a)

The axial force is produced when the radial flux (Br) interacts with the current in the windings. This force has greater values at the top and bottom ends of the windings because in these regions, the radial leakage flux in windings is maximum.

For this reason, the designers of transformers aim to achieve as close balance as possible between the primary and secondary windings to limit this axial force. Tapings should be placed on a separate layer to avoid gaps in the main body of the HV.

Permissible axial forces are limited by the mechanical strength of the winding end supports. Another factor that makes complete magnetic balance is the dimensional accuracy and stability of the materials used. Figure (6) shows a schematic representation of the axial force distribution in a typical transformer winding [6, 10].

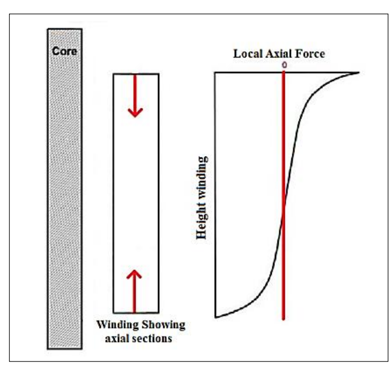


Figure 6. Axial force distribution [10].

If the transformer has two concentric windings without axial displacement, and they have a uniform distribution of turns, in this case, then the upper part of windings produces a force downward, towards the center of the windings equal to and approximately opposite to the force produced in the lower part of the windings upward towards the center of the windings. This means that the sum of the axial forces in the middle of the winding height will be zero.

In fact, if a small axial displacement is created between the magnetic centers of gravity of two windings, the equilibrium is unstable; a total axial force is generated on each winding, which tends to increase the displacement [6]. As shown in Figure (7).

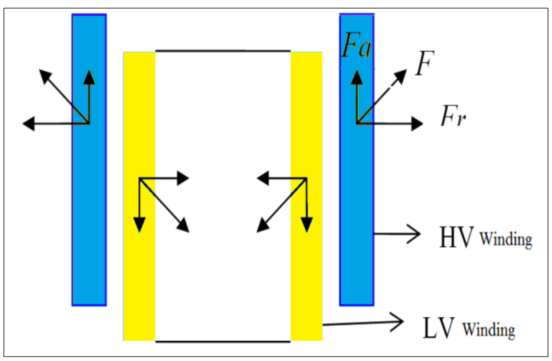


Figure 7. Axial forces when the windings are axially Non-symmetrical [6]

3. Method of Electromagnetic Forces

In this section, two methods are presented for the calculation of the electromagnetic forces: calculation method and numerical method (FEM).

3.1. Analytical Method

The calculation method for electromagnetic force is not linear, and follows the ideal condition. Imposes that the short circuit of three-phase occurs simultaneously in order to calculate the electromagnetic force because the electromagnetic force in the windings is greatest in the case of three-phase faults, especially when the two concentric winding are with axial displacement and asymmetry for the yokes and have non-uniformly. The force can be calculated in the case of axial asymmetry of the coil by calculating the asymmetry factor (k) as shown in the equation below [6] :

$$k = 1 + \frac{\sin\emptyset . e^{-\left(\frac{R}{X}\right)\left(\frac{\pi}{2}+\emptyset\right)}}{1-\left(\frac{R}{X}\right).\cos\emptyset . e^{-\left(\frac{R}{X}\right)\left(\frac{\pi}{2}+\emptyset\right)}} \qquad (1)$$

$$\text{Where: } \emptyset = \tan^{-1}\frac{R}{X} \qquad (2)$$

(R/X) ratio resistance to reactance

The value of (k) can be determining from the relationship between (k) and (R/X), as shown in fig (8):

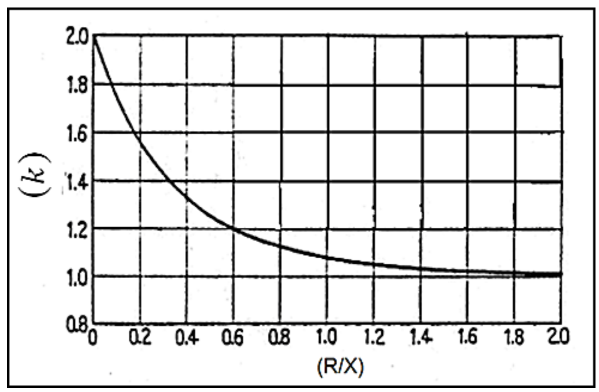


Figure 8. Relationship between (R /X) and (*k*) [6].

When a short-circuit occurs on the transformer, the current flowing through the transformer coil is calculated, and determined the peak value short-circuits current (I_{pk}) for the two-coil transformer is as follows [11, 12]:

$$I_{pk} = \frac{\sqrt{2}\times I_{rated}}{Z} \times k \quad [A] \qquad (3)$$

Where I_{rated} : rated full load current (A)

Z: Percentage impedance of the transformer

The radial component of the force (F_r) can be calculated as Eqs. (4):

$$B_a = \mu_0 \times (\frac{I_{pk}.N}{h}) \quad (T) \quad (4)$$

$$F_r = 2\pi \times (N.I_{pk})^2 \times \frac{U_m}{h} \times 10^{-7} \quad (N) \quad (5)$$

Where N is the number of turns, h is the height of the winding (mm), U_m is the mean turn of winding (mm). If the winding is rectangular or oval:

$$U_m = \frac{(L+W)_{outer} \times 2 + (L+W)_{inner} \times 2}{2} \quad (mm) \quad (6)$$

Where: (L) length, (W) width, (D) diameter of windings. If the winding is circular [13]:

$$U_m = \frac{\pi(U_{outer} + U_{inner})}{2} \quad (mm) \quad (7)$$

The analytical calculation of the axial force is not as simple as the radial force calculations. Because the flux lines are influenced by the core limbs, yokes, and all other magnetic structures within the tank, and follow quite complex paths for closure. An exact evaluation of the effective length of path is extremely difficult, if not impossible; calculation of axial force can be performed as follow [6, 12]:

$$F_a = 2\pi(N.I_{pk})^2 \times \frac{U_m}{h} \times \frac{a}{l_{eff}} \times 10^{-7} \quad (N) \quad (8)$$

$$l_{eff} = 1.3(a_1 + d + a_2) \quad (mm) \quad (9)$$

l_{eff}: is the equivalent leakage magnetic path length (mm).

a: is the difference in height between the inner and outer windings (mm)

a_1: is the width of inner winding (mm)

a_2: is the width of outer winding (mm)

d: is the gap between inner and outer windings (mm)

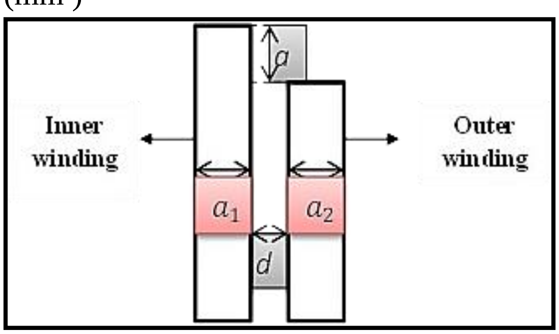


Figure 9. Illustrates the dimensions (a, a1, a2, d)

The radial leakage field makes calculating axial forces in windings complicated. The results can be erroneous if assumptions are applied to simplify calculations. As a result, we resorted to using FEM to compute axial force.

3.2. Numerical Method

A transformer is one of the electromagnetic devices whose Field equations can be used to explain its behavior, when current flows into the windings of the transformer; the governing equation of the magnetic field is expressed as [13]:

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (10)$$

$$\mathbf{J} = \nabla \times \mathbf{H} \quad (11)$$

By combining (10) and (11), we have:

$$\frac{1}{\mu} . \nabla \times (\nabla \times \mathbf{A}) = \mathbf{J} \quad (12)$$

Where (B) is magnetic flux density, (H) is magnetic field intensity, μ is magnetic permeability (H/m), (A) is magnetic vector potential (Wb/m), J current density (A/m^2).

Electromagnetic forces ($\vec{F}$) are generated in the transformer as a result of interaction between the current density vector (J), and the leakage flux density vector (B) in the winding regions according to Lorentz force, which is calculated as follows:

$$\vec{F} = \vec{J} \times \vec{B} \quad (13)$$

The electromagnetic forces for the radial (F_x) and axial (F_y) directions are given by the following equations [14]:

$$F = \int_v (J \times B) \, dv \quad (14)$$

$$F_x = J_z \times B_y \quad (15)$$

$$F_y = J_z \times B_x \quad (16)$$

In the 2D analysis of forces with taking current density in z-axis, at any point leakage flux density (B) can be resolved. Thus the interaction of axial leakage flux density (B_y) with current density (J) will generate radial force (F_x) and the interaction of radial leakage flux density (B_x) with current density (J) will generate axial force (F_y).

4. Transformer Model using FEM

Finite Element modeling is a common computational method for analyzing physical phenomena that are often represented by partial differential equations (PDEs), and it is a highly accurate method of computing the transformer parameters.

For this paper work, the Finite Element models for three types of three-phase distribution transformers (11 / 0.416 kV, 250 KVA), with non-linear magnetic characteristics for the iron core are built using FEM software "ANSYS". The (M5) type silicon alloy steel laminations with (0.30-mm) thickness are used. Table (1) shows the common specifications of the three types of distribution transformer models.

Table1. Common specifications of the three type's transformers

Specification Value	Value
Phase	three-phase
Frequency [Hz]	50
rated power	250 kVA
primary / secondary voltage	11000 / 416 V
Inter Phase Connection	Delta / Star
primary / secondary current	(13.1 / 347) A
Winding type	Concentric winding

4.1. Building the Transformer Model Stack Core Type with Oval Coil

The main parameters of the three-phase transformer were taken from design documents of the (The General Company for Electrical and Electronic Industries/ Alwazeria); as shown in Table (2). The actual dimension of cross-section for HV coil is (0.03×0.201) m², while the cross section of the LV coil is (0.025×0.24) m². Figure10 a & b shows the 2-D model and the mesh pattern respectively for the oval coil and stack core type transformer.

Table2. Specifications of the oval coil and stack core type transformer

Parameters	Value
Nominal Flux Density	1.71 T
No. of primary winding turns	1443
No. of secondary winding turns	30
primary-Coil Materials	Cu. Wire φ 1.9 mm
secondary -Coil Materials	Cu.Strip(0.58×240)mm
Primary winding resistance	9.6245Ω
Secondary winding resistance	0.002952Ω
Short Circuit Voltage	4.43%

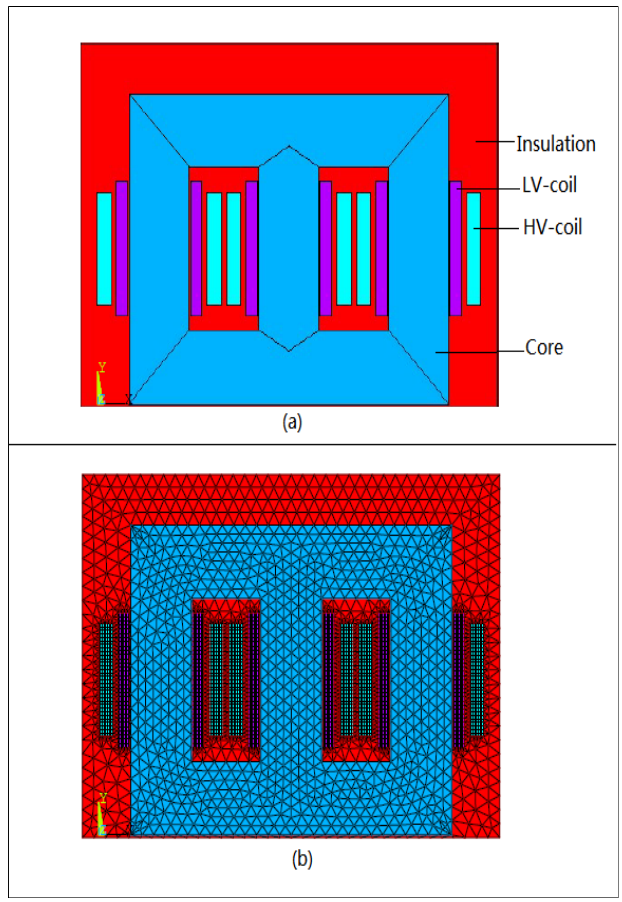


Figure 10. (a) 2-D model of the oval coil and stack core. (b) Mesh model.

4.2. Building the Transformer Model Stack Core Type with Cylindrical Coil

The main dimension of the transformer studied was taken from Factory's design documents of

(Altahady Company),as shown in Table (3). The actual dimension of cross-section for HV coil (0.0455×0.278) m², and the actual dimension of cross section for LV coil modeling (0.025×0.29) m². Figure (11) a & b shows the 2-D model and the mesh pattern respectively for cylindrical coil and stack core type transformer.

Table3. Specifications of the cylindrical coil and stack core type transformer

Parameters	Value
Nominal Flux Density	1.73 T
No. of primary winding turns	1587
No. of secondary winding turns	33
primary -Coil Materials	Cu.Wire φ 2.2 mm
secondary -Coil Materials	Cu.Strip(0.4×290)mm
Primary winding resistance	5.974Ω
Secondary winding resistance	0.00488Ω
Short Circuit Voltage	4%

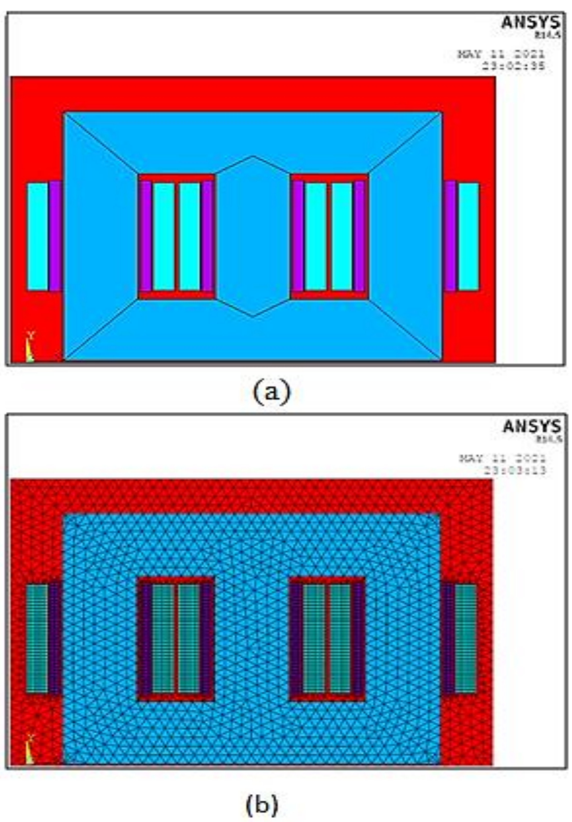


Figure 11. (a) 2-D model of the stack core with cylindrical coil. (b) Mesh model.

4.3. Building the Transformer Model Wound Core Type with Rectangular Coil

The main parameters of dimension for the transformer studied were taken from Factory's design documents of (Diyala Company/ Factory of Distribution Transformers); design parameters of the considered transformer are presented in Table 4.The actual dimension of cross-section for HV coil (0.0321×0.1872) m², and the actual dimension cross-section for LV coil modeling (0.0243×0.21) m². Figure (12) a & b shows the 2-D model and the mesh pattern respectively for rectangular coil and wound-core type transformer.

Table4. Specifications of the rectangular coil and wound-core type transformer

Parameters	Value
Nominal Flux Density	1.77 T
No. of primary winding turns	1155
No. of secondary winding turns	24
primary -Coil Materials	Cu .Wire φ 2 mm
secondary -Coil Materials	Cu.Strip(0.6×210)mm
Primary winding resistance	7.7819Ω
Secondary winding resistance	0.003584Ω
Short Circuit Voltage	4.13%

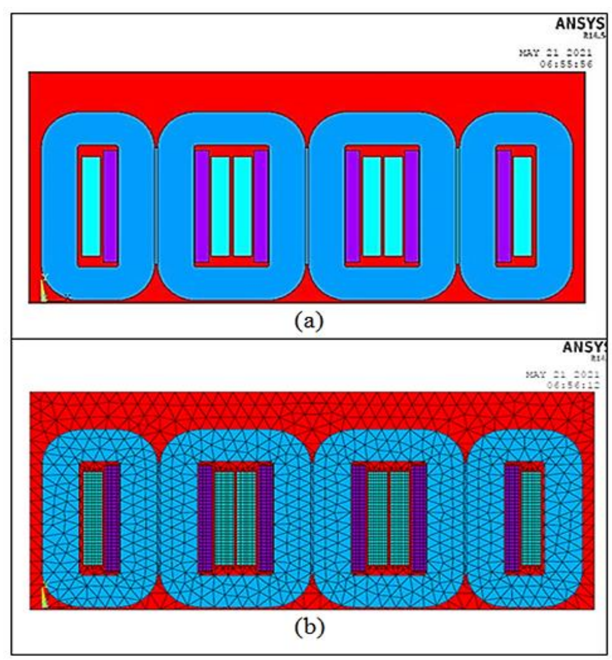


Figure 12. (a) 2-D model of rectangular coil and wound-core type (b) Mesh model.

5. Simulation and Discussion of Result

After validating the models for the three transformers, the two-dimensional static analysis method was used. To calculate the electromagnetic force and its distribution in LV and HV windings, it can apply maximum at short circuit current density (J_s) see table 5, and comparison of the FEM results with the calculation of the analytical values was also performed.

Table5. Maximum applied short circuit current density on LV and HV coils at three shapes of windings

Shape of windings	Maximum current density (J_s) A/m^2	
	HV	LV
Cylindrical	42156059.77	73487978.98
Oval	78252238.8	78578478.5
Rectangle	69387031.71	81728610.93

The FE computation of leakage flux and electromagnetic force for different shapes of winding, which is situated in detail below:

5.1. Result of Leakage Flux Density

In order to study the magnetic flux distribution in transformer models at symmetrical three phase fault, this is carried out by applying the following steps: First, calculate the short circuit current from the relation (3) then by imposing the peak current density (J_s) to each winding in order to compute the magnetic flux density with Maxwell equations. The magnetic flux density vectors for three type shapes of winding are shown in figures (13) to (15). It can be noticed that the leakage flux density concentrated in the inner side of HV-coil and outer of LV-coil. The reason for the difference between field vectors direction in the primary and secondary winding is the opposite current directions in two winding.

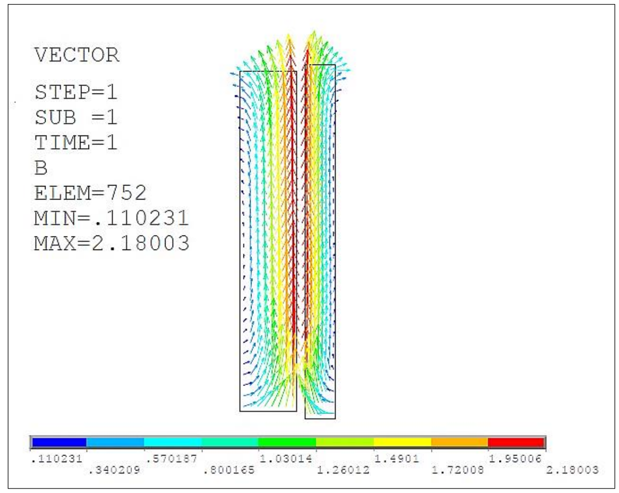


Figure 13. Vectors plot flux density distribution on cylindrical coils.

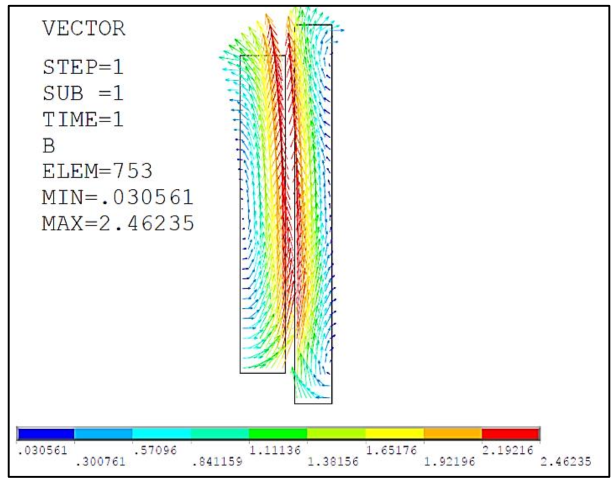


Figure 14. Vectors plot Flux density distribution on oval coils.

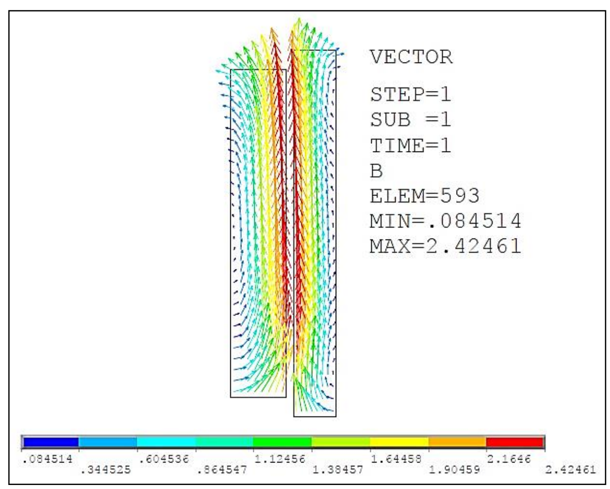


Figure 15. Vectors plot Flux density distribution on rectangular coils.

The computation result show that along height of coil (y-direction), the axial flux density (Ba) or

(By) gradually decreases from middle to the end of coil. Along coil width (x-direction) the axial flux density decreases from the inner side to outer side of the HV coil and decreases from the outer side to inner side of LV coil as seen in fig (16) to fig (18).

The results also show that the (Ba) value in cylindrical coils (2.32 T) is lower than the other coils. Because the length of the height for cylindrical coil is more than in the other two types in spite of the number turn of HV coil for cylindrical is more than other, also the Ba value of oval the (Ba) value in oval coil (2.63 T) was slightly larger than in rectangular coil (2.59 T).

The results also show that the axial flux values in the FEA are greater than the value of conventional calculations according to equation (4), because the results of FE solutions depend on the distribution of flux in all directions, while in the conventional calculations the direction of flux is assumed to be parallel to height of the coil only.

Table 6. Axial flux density in the HV and LV coils.

	Maximum axial flux density (T)	
	Analytical method	FE analysis
Cylinder coil	2.2	2.32
Oval coil	2.5	2.63
Rectangular coil	2.4	2.59

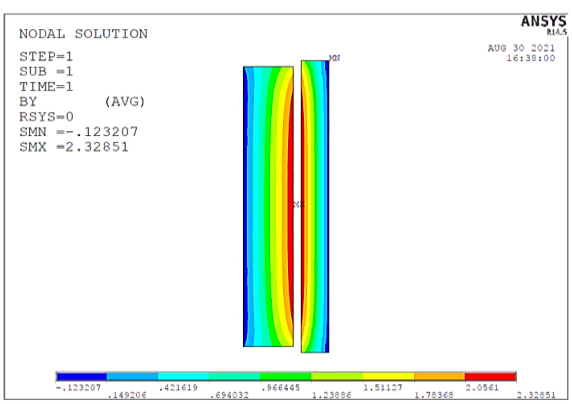


Figure 16. Axial flux density distribution on HV and LV of cylindrical winding.

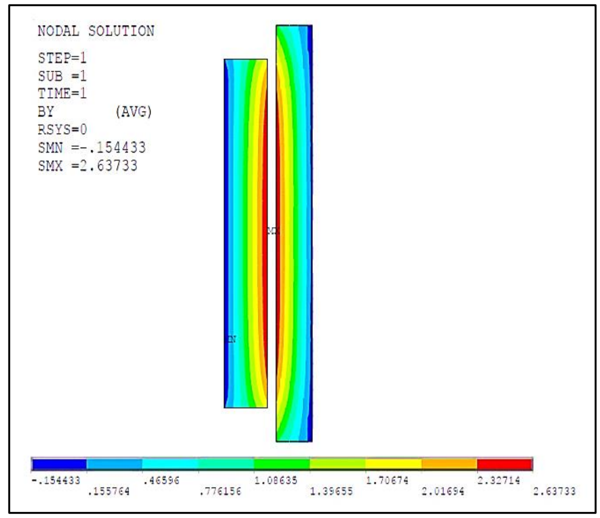


Figure 17. Axial flux density distribution on HV and LV of oval winding.

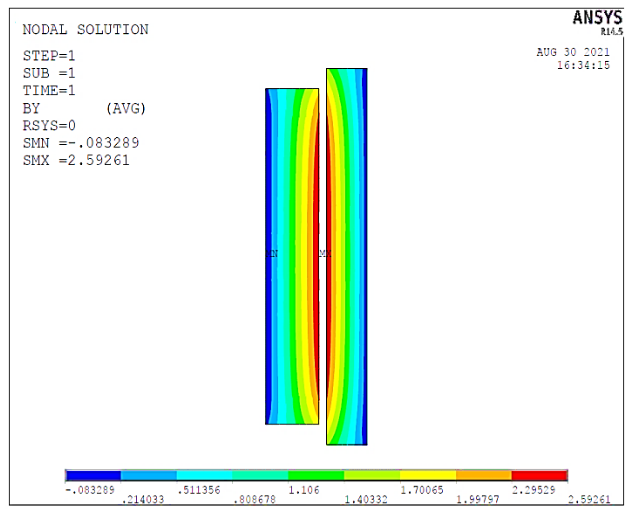
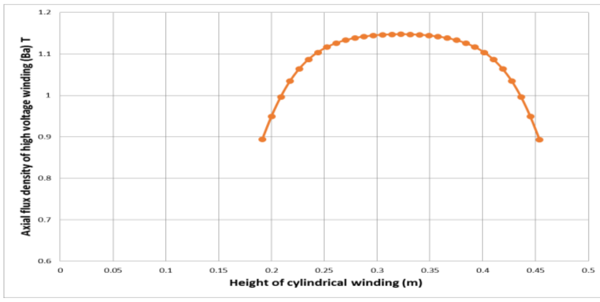
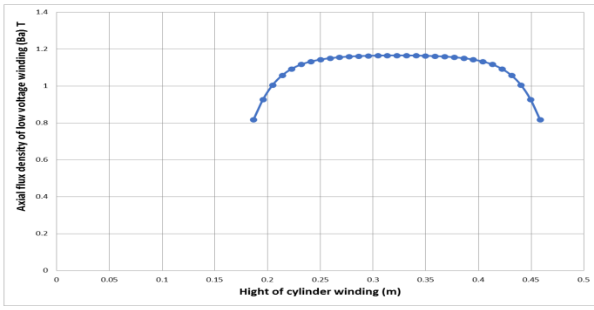


Figure 18. Axial flux density distribution on HV and LV of rectangular winding.

In order to study the distribution of flux density along the height of the coils, a center line was chosen along the height of coil in the middle of the coil width. The distribution of the (Ba) along the height of the coils can be seen the figures (19) to (21), where the values of (Ba) appear in the lowest value in the regions at the two ends of the coil and highest value in the middle region of the coil.

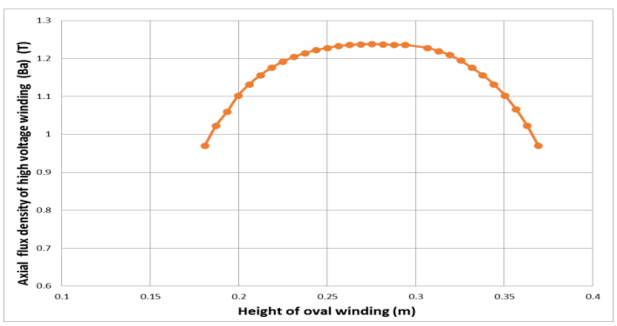


(a) Axial flux distribution along center line of HV coil.

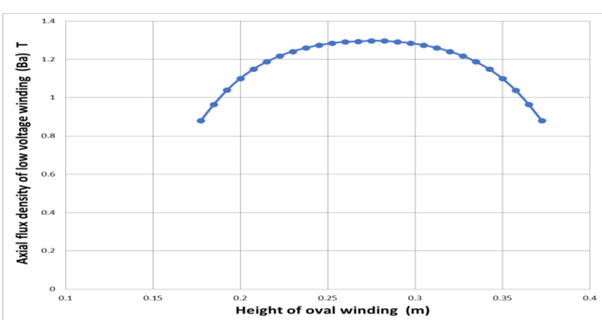


b) Axial flux distribution along center line of LV coil.

Figure 19. Axial flux distribution along center line for cylindrical windings.

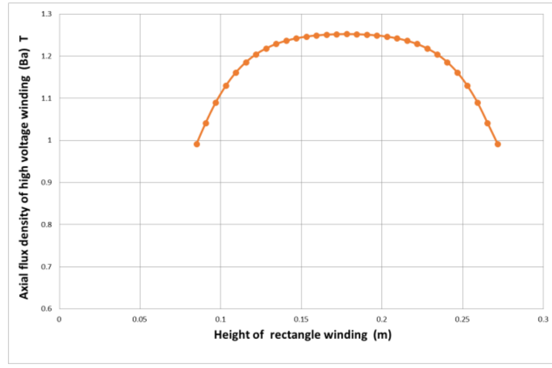


(a) Axial flux distribution along center line of HV oval coil.

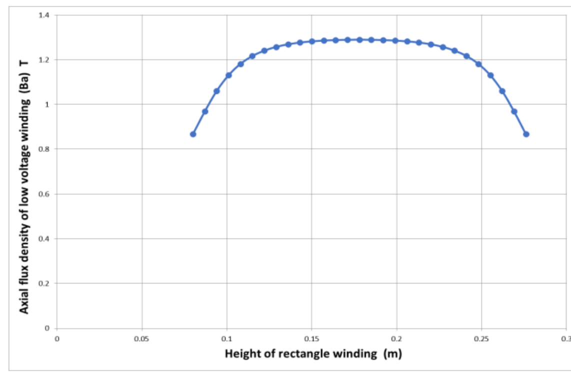


(b) Axial flux distribution along center line of LV oval coil.

Figure 20. Axial flux distribution along center line for oval windings.



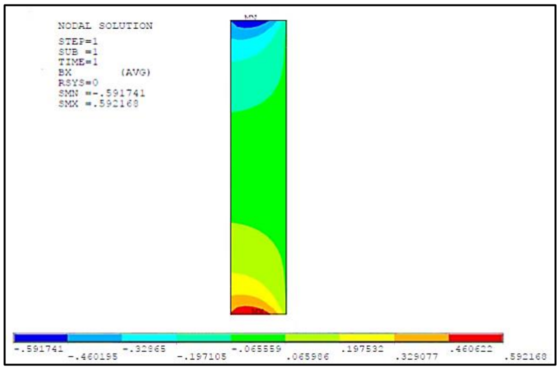
(a) Axial flux distribution along center line of HV coil.



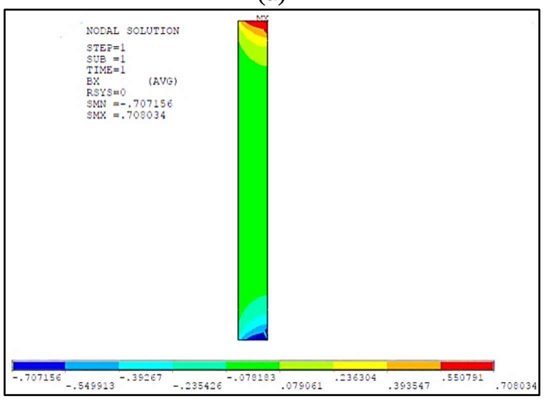
(b) Axial flux distribution along center line of LV coil

Figure 21. Axial flux distribution along center line for rectangular windings.

The results showed that the distribution of radial magnetic flux in transformer coils is mutually different in terms of location with the distribution of axial magnetic flux as shown in figure (22) to (24) where the results from figure show that the distribution of (Br) along with the height of the coil, that the highest value of the (Br) are concentrated in the region of the ends of coils, and the lowest values of the (Br) in the middle region of the coil.

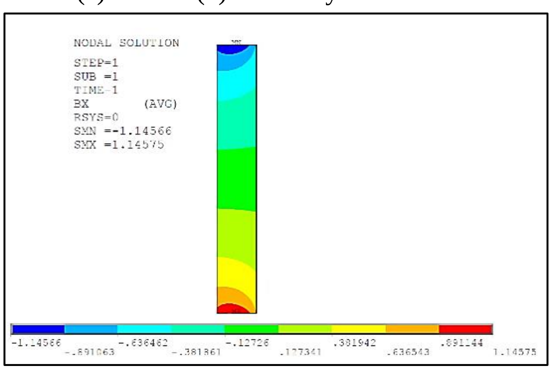


(a)

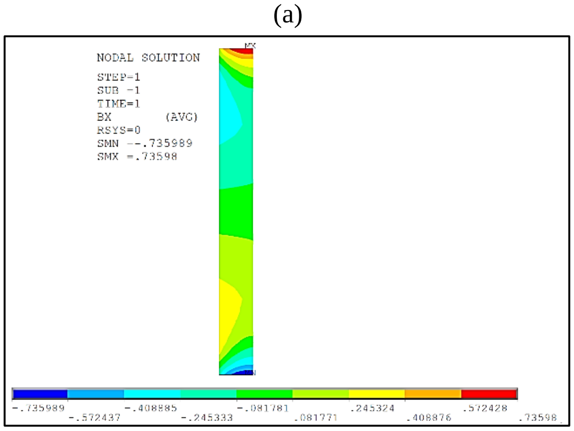


(b)

Figure 22. Radial flux density distribution on (a) HV and(b) LV for cylindrical coil.

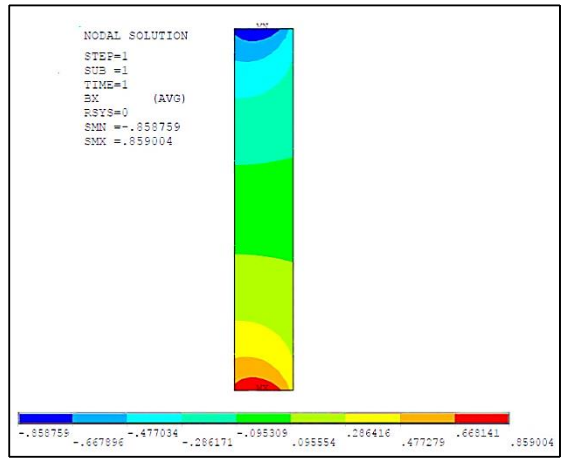


(a)

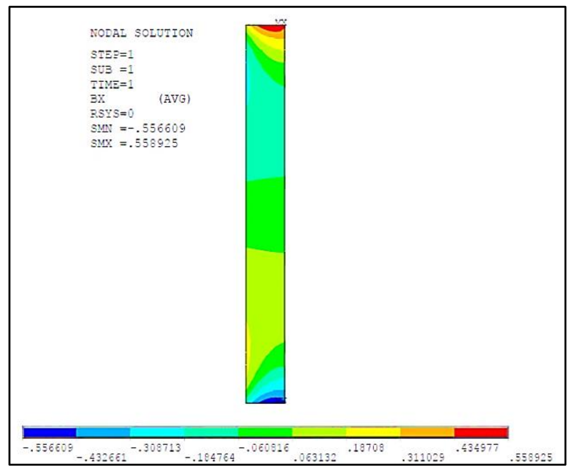


(b)

Figure 23. Radial flux density distribution on (a) HV and(b) LV for oval coil.



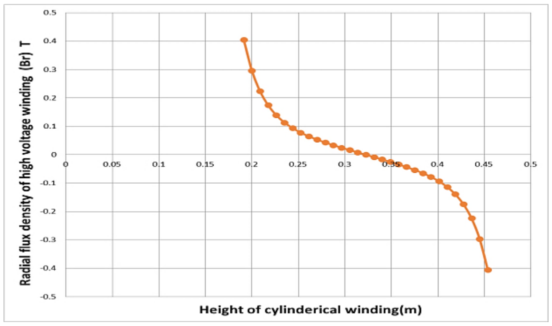
(a)



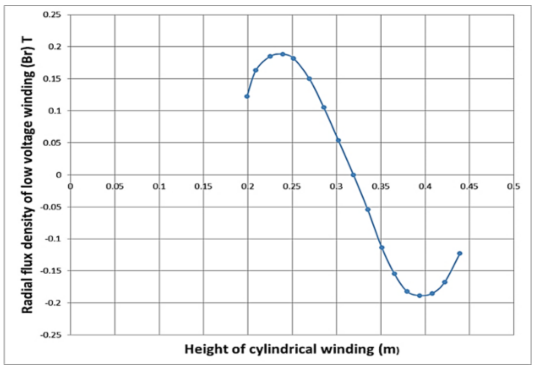
(b)

Figure 24. Radial flux density distribution on (a) HV and (b) LV for rectangular coil.

In order to know the distribution of the Radial flux density (Br) along the height of the coil. Figures (25) to (27) represent the Br. The obtained results show that the radial flux values are highest in the regions of the ends of the coil and gradually decrease towards the middle region of the coil, and its values are very low in the case of homogeneous distribution of MMF in the coil.

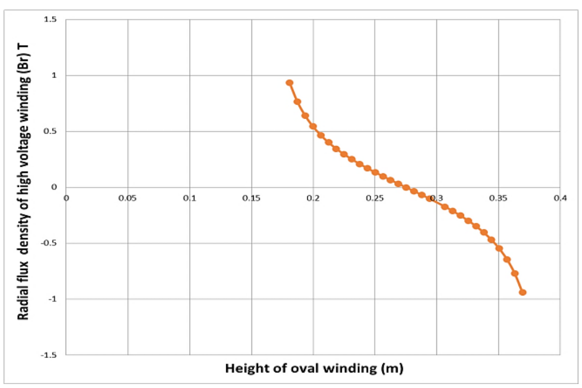


(a) Radial flux distribution in HV coil

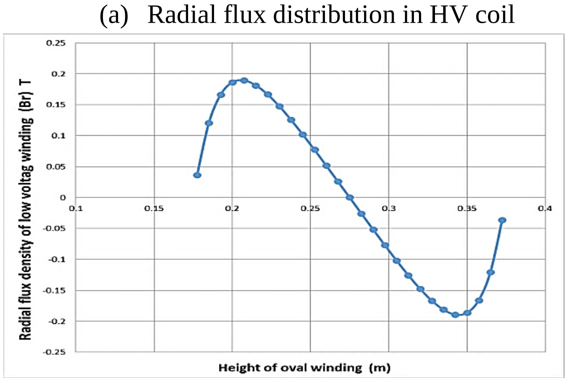


(b) Radial flux distribution in LV coil

Figure 25. Radial flux distribution along center height line for cylindrical coils.

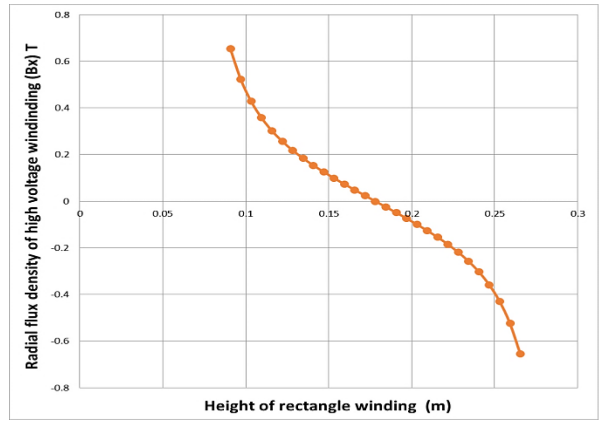


(a) Radial flux distribution in HV coil

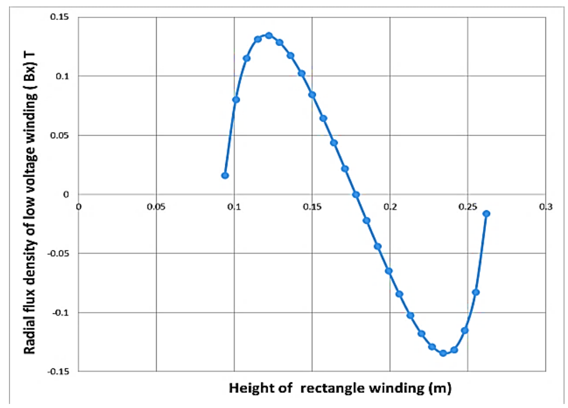


(b) Radial flux distribution in LV coil

Figure 26. Radial flux distribution along center height line for oval coils



(a) Radial flux distribution in HV coil



(b)Radial flux distribution in LV coil

Figure 27. Radial flux distribution along center height line for rectangular coils.

The results also show that the (Br) value in oval coils (1.145 T) is higher than the other coils. Whereas, the (Br) value in rectangular coil (0.858 T) was larger than in cylindrical coil (0.592T) because the displacement (a) between the LV and HV coils of the oval coil is more than in the other two types.

The results also show that the radial flow values in FEM are greater than the conventional formulated value, as shown in the table (7). Because the conventional formulated did not take equivalent leakage magnetic path length (l_{eff}) calculations along the coil area, making it difficult to obtain an exact value, but the FEM method takes the calculations along the coil region.

Table7. Radial flux density in the HV coils.

	Radial flux density HV winding(T)	
	Conventional Method	FE analysis
Cylinder coil	0.127	0.592
Oval coil	0.565	1.145
Rectangular coil	0.339	0.858

5.2. Results of Electromagnetic for at Short Circuit Condition

The calculation of electromagnetic (EM) forces in coils according to Lorenz's law (F = J×B**)** depends on the accuracy of calculating the (Ba) and (Br). The EM forces obtained from solving the 2D FE transformers models include two components, the axial force (Fa) and the radial force (Fr), where the (Fa) arises from the interaction between the (Br) with current density passing through the coil, while the (Fr) arise from the interaction of the (Ba) with current density passing through the coil.

Figure (28) to (30) show the direction of influence of EM force on the three types of coil shape. Where it can be seen that the Fr pushes the inner coil inward and pulls the outer coil outward. As for the Fa, it pushes the high coil (outer coil) vertically upward and pushes the inner coil vertically down word, and this happens in the case of a displacement between the axis of inner coil (LV) and outer coil (HV). The reason for this reversal in direction of the EM force is due to the opposite direction of the current of HV and LV coils. The results also show, that the nature of the distribution of EM force in cylindrical coils is more uniform than the distribution of EM force in rectangular and oval coils, the reason for this is that the structure of rectangular and oval coils has two regions called (side) and two regions called the (end) differ from each other in area, while the structure of cylindrical coils is the same on all sides.

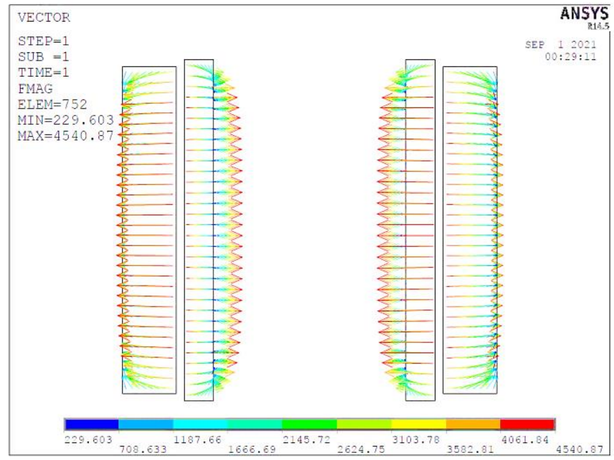


Figure 28. Force vector plot on cylinder coils area.

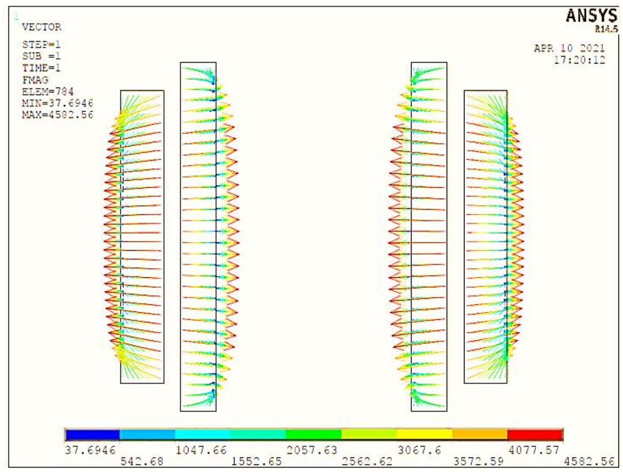


Figure 29. Force vector plot on oval coils area.

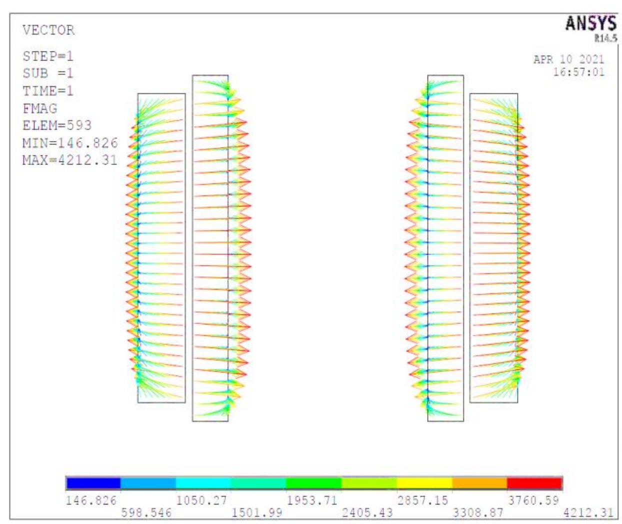
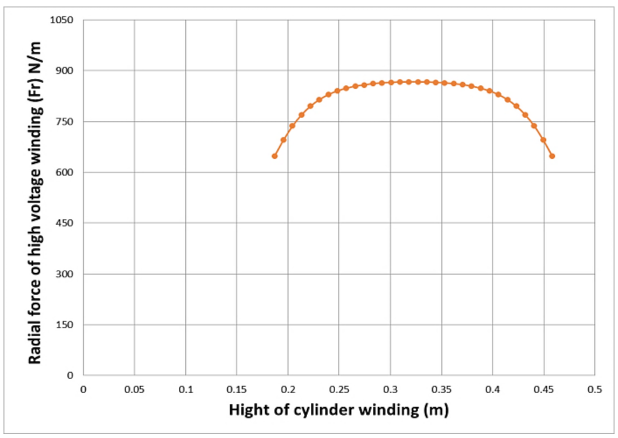


Figure 30. Force vector plot on rectangular coils area.

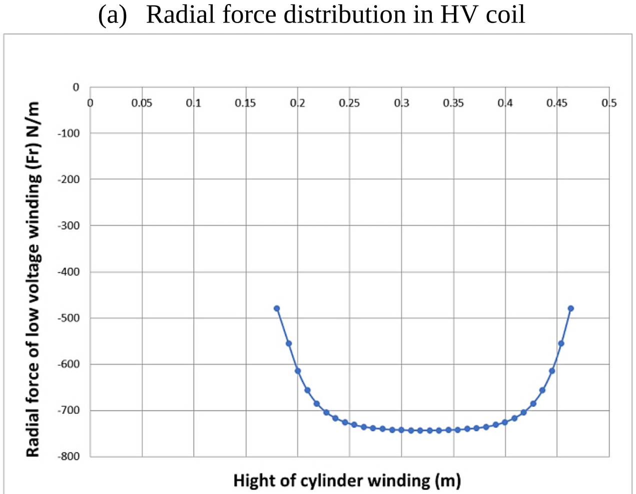
The calculation and distribution of EM force along the centerline of the coil height depends on the accuracy of the calculation and distribution of the axial and radial magnetic flux.

5.2.1 Electromagnetic Radial Forces

The calculation of the Fr and their distribution depends on the calculation of the Ba and its distribution in the coil as shown in figures (31) to (33). Where it can be noted, that the values of the radial forces are high in the middle region of the coil, while in the regions of the ends of the coil they are of low values, because the axial flux in the middle region of the coil is higher than the axial flux in the regions of the ends of the coil.

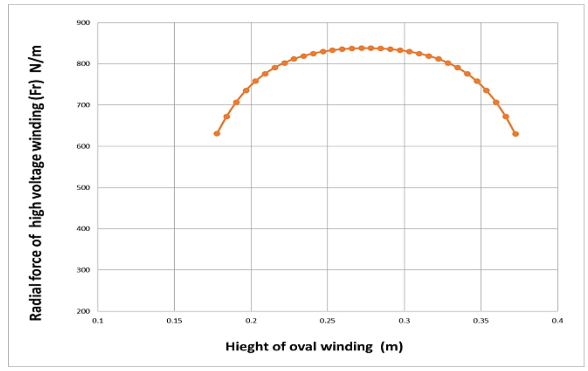


(a) Radial force distribution in HV coil

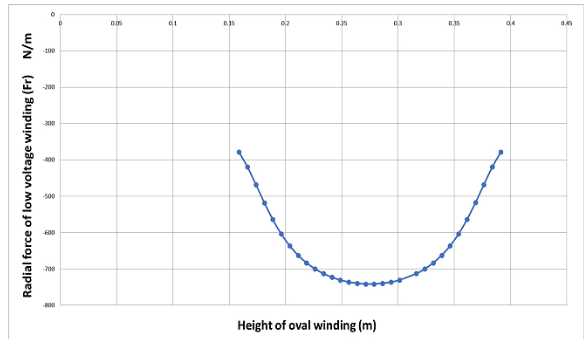


(b) Radial force distribution in LV coil

Figure 31. Radial force along center line distribution for cylinder coil.

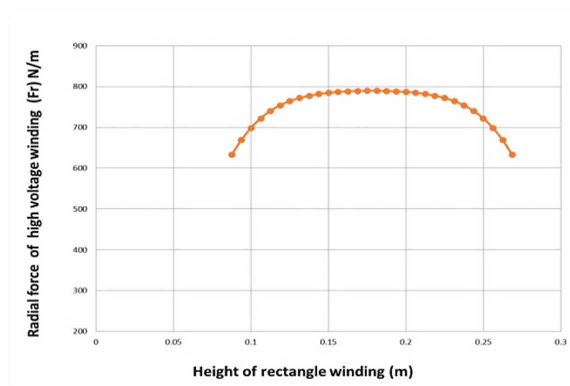


(a) Radial force distribution in HV coil

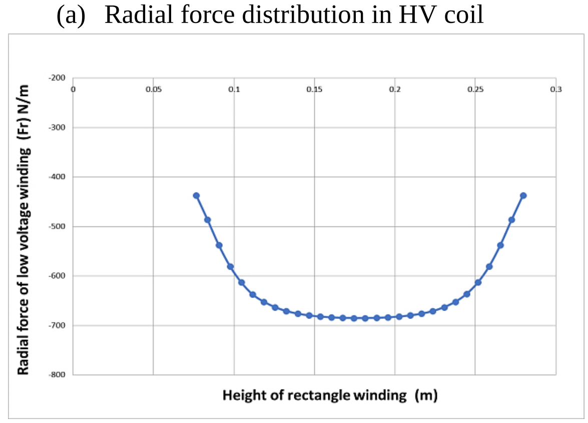


(b) Radial force distribution in LV coil

Figure 32. Radial force along center line distribution for oval coil.



(a) Radial force distribution in HV coil



(b) Radial force distribution in LV coil

Figure 33. Radial force along center line distribution for rectangle coil

Table (8) shows the results of the values of Fr obtained from solving finite element models of transformers and their comparison with the values calculated by the traditional method. It is clear from the table that the value of the Fr in the high coil of rectangular shape (498275 N/m), is less than the oval coils and cylindrical coil, and because the number of turns in the rectangular coils (1155) is less than the number of turns of the oval coil and cylindrical coil.

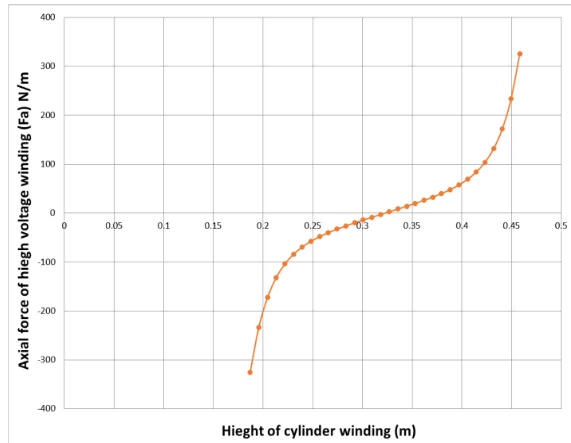
Table 8. Maximum radial force in LV and HV windings.

Radial Force (N/m)					
	Conventional Method		FEM 2D		Error %
	HV	LV	HV	LV	HV
Cylindrical coil	567948	566996.5	575026	576642	1.2
Oval coil	539180.8	538289	554525	541048	2
Rectangle coil	490506.7	490756	498275	491818	1.5

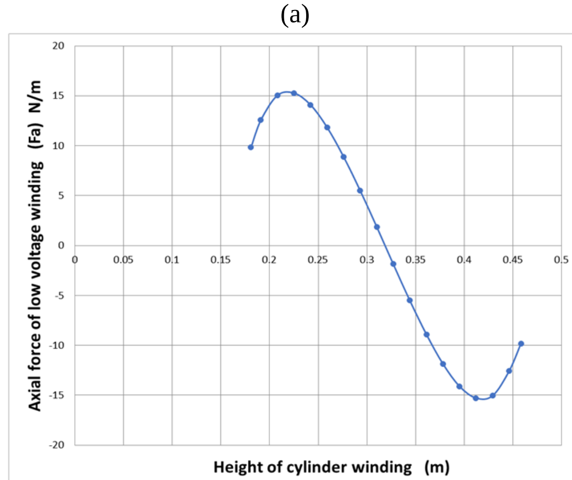
5.2.2 Electromagnetic Axial Forces

The calculation of the Fa and their distribution depends on the calculation of the Br and its distribution in the coil as shown in figures (34) to (36). As it can be seen that the values of the axial forces are high in the ends regions of the coil, and they are low in the middle region of the coil because the radial flux in the regions of the ends of the coil is higher than flux in the middle region of the coil. It can also be seen that the value of the sum of the axial forces in the HV coil or in the LV coil is small because these forces are almost equal in value and opposite in direction. This equalization of the axial forces in the coil is a result of the homogeneous distribution of the MMF.

It is difficult to accurately calculate the axial forces from the conventional calculations, because there is no possibility to calculate the radial magnetic flux due to the complexities of the distribution of the Br. As shown in table (9).

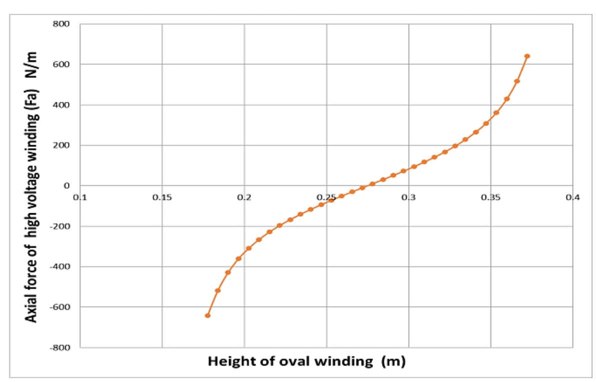


(a)

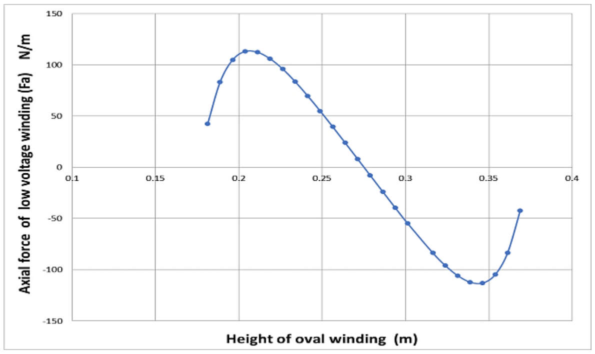


(b)

Figure 34. Axial force distribution along center line for cylinder coils (a) HV. (b) LV coils.

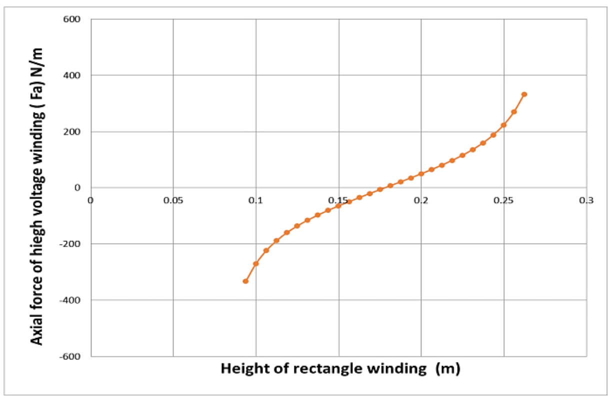


(a)

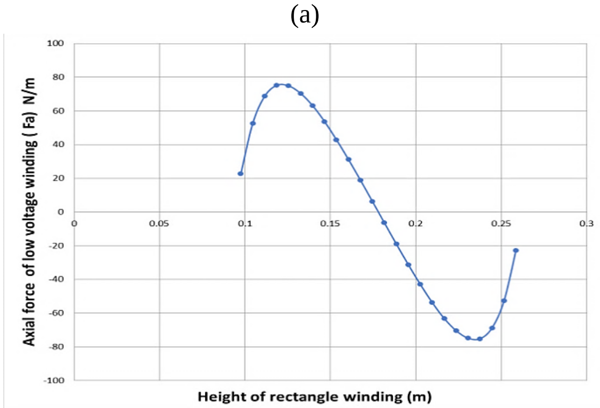


(b)

Figure 35. Axial force distribution along center line for oval coils HV. (b) LV coils.



(a)



(b)

Figure 36. Axial force distribution along center line for rectangle coils (a) HV. (b) LV coils.

Table 9. Shows the FE results of axial force in three shapes of HV coils

	Radial Force for HV Winding (N/m)	
Shape of winding	FE at real design parameter	FE at same design parameter
Rectangle	498275	498275
Oval	554525	430172
Cylindrical	575026	351505

5.2.3 Calculation of electromagnetic forces when applying the same design parameters and the same operating conditions for three types of transformers.

In order to determine the best design for the shape of the windings of distribution transformers that withstand the EM forces resulting from the passage of short current in the transformer windings, as well as to compare the behavior of the distribution of those forces. It requires that the same design parameters and operating conditions be applied to three types of transformers with different coil shapes (cylindrical, oval, rectangular) coils. The design parameters of the wound core transformer are adopted as a reference for other transformers.

In order to compare that, three types of transformers were adopted, with different coil shapes, with a capacity of 250 kVA, and rated voltage of 11 / 0.416 kV, and the same design parameters were applied such as (number of windings, short- circuit current, and number of elements in coil models) as well as applying the same operating conditions, and the results were the model solutions for transformers are shown in the table (10).

Table10. Compares the values of EM force for three coil shapes

	Axial Force HV Winding (N/m)	
	Conventional Method	FEM 2D
Cylindrical coil	67646	3.5
Oval coil	265170	4.01
Rectangle coil	141259	3.17

It is clear from the table that the value of the radial force in the high coil of cylindrical shape (351514 N/m), is less than in the oval and rectangular coil because the structure of the cylindrical coil is uniform on all its sides, and the length of the coil is (278 mm) and the width of the coil is (45.5mm) are larger than the rectangular coil and oval coil.

Conclusion

1- The results show that along height of coil, the axial flux density gradually decreases from the middle to the ends of coil. Furthermore, the radial flux density at the ends of winding is much higher than that in the middle of the winding.
2- The results showed that transformers with cylindrical coils are better than the other two types. The values of the radial electromagnetic forces and their distribution arising in the coils when a short circuit occurs in the transformer are less than the values of the radial electromagnetic forces of other transformers with rectangular and oval coils because the structure of the cylindrical coil is uniform on all its sides.
3- In transformers with rectangular coils and rectangular wound core, it has the ability to withstand mechanical tension in the event of a short circuit due to the presence of a strong iron housing and holding the active part (coils+ iron core) strongly.
4- The results obtained from the numerical method are more accurate as compared to the conventional calculation method.
5- This work offers the assistance of design engineers working in distribution transformer factories in checking the short circuit of transformers and improving the design without the need to manufacture prototypes.

Conflict of interest

The publication of this article does not cause any conflict of interest.

Abbreviations

I_{rated}	Rated full load current
k	Asymmetry factor
Z	Percentage impedance
N	Number of turn
h	Height of the winding
Um	mean turn of winding
L_{eff}	Equivalent leakage magnetic path

6. Reference

1. A. Sinha and S. Kaur. (2016)."Two dimensional finite element analysis of short crcuit forces in distribution transformer with tapping arrangement" .Int. J. Electr. Electron. Comput. Sci. Eng. Spec. Issue, pp. 39–42.
2. A.Najafi and I. Iskender. (2016). "Electromagnetic force investigation on distribution transformer under unbalanced faults based on time stepping finite element methods " .Int. J. Electr. Power Energy Syst. vol. 76, pp. 147–155.
3. S. Hajiaghasi and K. Abbaszadeh. (2013). "Analysis of electromagnetic forces in distribution transformers under various internal short circuit faults " .pp. 13–14.
4. S. V. Kulkarni and S. A. Khaparde. (2013)."Transformer Engineering - Design, Technology, and Diagnostic". CRC Press Taylor&Francis.
5. M. J. Heathcote. (2007). "The J & Transformer Book".
6. K. R. Hameed,thesis. (2007). "Analysis of Short-circuit Forces in Windings of shell-type ‘wound core’ distribution Transformer Using Finite Element Method ". pp. 1–142.
7. N. Meško, Ć. Branimir, and D. Žarko. (2017)."Short-circuit stress calculation in oval windings". vol. 00, pp. 1–8.
8. M. S. A. Minhas. (2007) ."Dynamic Behaviour of Transformer Winding under Short-Circuits".DoctorThesis, no. November, pp. 1–142.

9. S. D. Mitchell and J. S. Welsh. (2017). "Methodology to locate and quantify radial winding deformation in power transformers " .High Volt., vol. 2, no. 1, pp. 17–24.

10. N. Mahomed. (2011). "Electromagnetic Forces in Transformers Under Short Circuit Conditions. " Energize, no. March, pp. 36–40.

11. A. Sathya and U. Savadamuthu.(2019). " Electromagnetic Force and Deformation in Transformer Winding " .Int. J. Appl. Eng. Res., vol. 14, no. 3, pp. 790–796.

12. V. Behjat, A. Shams, and V. Tamjidi. (2018)."Characterization of power transformer electromagnetic forces affected by winding faults ".J. Oper. Autom. Power Eng., vol. 6, no. 1, pp. 40–49.

13. J. Pedro and N. Sadowski. (2003). "Electromagnetic Modeling by Finite Element Methods Electrical and Computer Engineering" .Book. vol. 117.

14. A. Najafi and I. Iskender. (2015). "A new approach to reduce the leakage flux and electromagnetic force on distribution transformer under unbalance faults based on finite element method" .pp. 13–14.