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# Comprehensive Analysis and Accurate Modeling of Transformer Electromagnetic Forces

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***Abstract*—The interaction of leakage fluxes and the current flowing through power transformer windings produce electromagnetic (EM) forces. Thereby, power transformers vibrate and experience harmonic loads as a result of these forces. The ability to precisely compute EM forces is critical for transformer designers to limit the transformer vibration. In this context, it is important to study in-depth the mechanism of the generation of EM forces and to fully grasp the leakage magnetic field. This paper aims to accurately model the EM forces in power transformer windings. Due to flexibility in dealing with magnetic boundaries, this paper is mainly based on the finite element method (FEM) to study the parameters that influence the analysis of EM forces. Finally, the results of a series of FEM models and some conclusions about the behavior of the calculated EM forces are described. This paper can be used as a starting point for engineers to create comparable models of transformers to lessen the cost of field tests.**

**Keywords—*Electromagnetic forces; finite element method; magnetic flux; power transformer.***

## I. INTRODUCTION

Power transformers are the heart of high-voltage substations and play a vital role in power systems [1]. Large capacity and high voltage transformers are frequently used to transmit energy over long distances in a developing power network [2]. As a result, the load current in the electrical circuit and the EM forces generated inevitably increase. Because EM forces are proportional to the square of the load current, forces generated during a short circuit or energization process can range from hundreds to millions of newtons. The vibration response of the transformer, as well as the winding stress burden, increases considerably in these situations [3, 4]. It should also be noted that the leakage flux distribution and the amplitude of EM forces for different configurations and designs of power transformers are different [5, 6].

The purpose of this paper is to discuss the important factors and their effects on the distribution of EM forces to effectively predict them and improve the accuracy of modeling. Since the invention of transformers, there has been much discussion about the distribution of transformer leakage flux and the EM forces of windings. The initial hypotheses of EM forces modeling were based on the assumption that the leakage flux is one-way and devoid of curvatures. These procedures would result in erroneous EM force estimations, particularly in the axial direction near the winding ends [7].

In recent years, researchers have supported the FEM technique in research related to the analysis of power transformers in a variety of fields [8-10]. The FEM is a reliable method for analyzing electromagnetic fields and leakage flux distributions [11-13]. A new methodology for solving saturable magnetic field issues is described by Silvester and Chari. Based on the FEM approach, this strategy allows for a lot of flexibility in prescribing boundary forms [11]. Andersen is the first to create a FEM program for an axisymmetric field in a two-dimensional (2D) environment. Under harmonic excitations, the leakage flux density of a 2D transformer is estimated in his study [12]. Guancial and Dasgupta were pioneered to build a three-dimensional (3D) finite element tool to calculate the magnetic vector potential (MVP). Their program is evaluated discrete MVP values as unknown factors [14]. Demerdash et al. also helped to establish the 3D FE approach for formulating and solving 3D magnetic field problems. In the following work, they performed experimental verification of the FEM results and found excellent agreement with the calculated flux density [15, 16]. Kladas et al. used a three-phase shell-type transformer and expanded the 3D FEM approach to computing the short-circuit EM forces. Leakage flux measurements were used to confirm the numerical findings [17]. Models of the FEM technique are created in [18] to simulate winding forces and short circuit forces in 2D and 3D simulations. In this study, differences in modeling results are observed. However, there were no further explanations for the differences. In another study, FEM modeling is performed to simulate 2D and 3D of a small single-phase distribution transformer. The effects of magnetic shunts on EM forces have been investigated in this study [7].

To conclude the aforementioned literature review, there is a clear trend toward adopting the FEM method to calculate the leakage flux and the resulting EM forces [4, 19, 20]. Although modeling assumptions and affective factors have been investigated during the review process, the physical reasons for the differences between the various modeling and the accuracy of the modeling remain unclear and unresolved. With respect to the aforementioned points, the FEM technique is used as the major technique in this paper to investigate the influential aspects that affect force calculation in a complex ferromagnetic environment. A detailed model of a three-phase power transformer is presented first, followed by finite element analysis of several modeling and magnetic boundaries.



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## II. CALCULATION OF ELECTROMAGNETIC FORCES

The local magnetic flux density in the power transformers is used to compute the electromagnetic forces. When current flows through the transformer's windings, the magnetic field governing equation is [21, 22]:

$$\nabla \times \frac{1}{\mu}(\nabla \times A) = J_s - \sigma \frac{\partial A}{\partial t} \text{ , } B = \nabla \times A \quad (1)$$

where $\mu$ is magnetic permeability, $A$ is magnetic vector potential, $J_s$ is the current density, $\sigma$ is the conductivity and $B$ is the flux density. The electromagnetic force, according to Lorentz law, is:

$$df = idl \times B \quad (2)$$

The magnetic flux density's radial and axial components are as follows:

$$B_r = -\sigma \frac{\partial A_\phi}{\partial z} \text{ , } B_\phi = 0 \text{ , } B_a = \frac{1}{r} \sigma \frac{\partial A_\phi}{\partial r} \quad (3)$$

where $B_r$, $B_\phi$, and $B_a$ are the flux density directional components in cylindrical coordinate. As a result, the EM forces in the radial and axial directions can be determined using the following equation:

$$F = \int_V J_\phi \times \left(B_r \hat{r} + B_a \hat{z}\right) dv = F_r \hat{r} + F_a \hat{z} \quad (4)$$

$$F_r = B_a \times J_\phi \text{ , } F_a = B_r \times J_\phi \quad (5)$$

The current flowing through the windings interacts with the axial leakage flux density $B_a$, generating the radial force $F_r$. As well, axial forces $F_a$ are generated by the interaction between the winding current and the radial component of the leakage flux $B_r$, as shown in Fig. 1.

## III. MODEL DESCRIPTION

The 8 MVA dry-type transformer is utilized to model EM forces in this paper. Table I summarizes the most important technical parameters. A series of FEM models are created and examined based on the main structure of the model power transformer, including:

- 2D FEM model.
- 3D FEM model with symmetrical magnetic boundaries.
- 3D FEM model with asymmetric boundary condition.
- 3D FEM model within a metal enclosure.

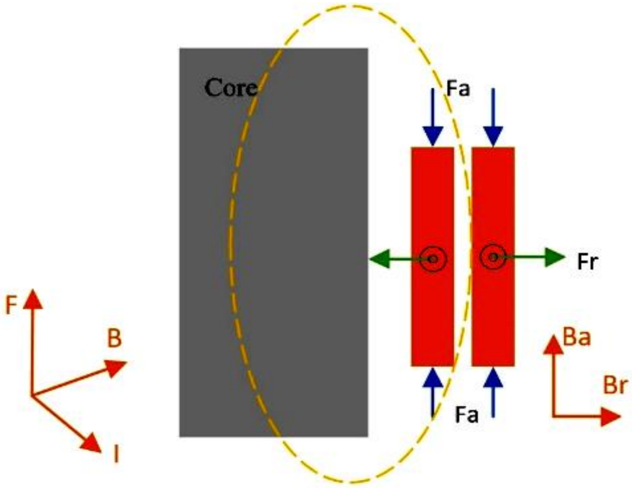


Fig. 1. Distribution of EM force in two directions of radial and axial.

Fig. 2 shows the 2D and 3D models of magnetic boundaries with various arrangements. Fig. 2(a) depicts the 2D model of the transformer winding and the core. Fig. 2(b) shows an axial symmetric model with a winding assembly and a surrounding core around the middle phase that creates a symmetrical magnetic flux route in space. Due to the high permeability of the transformer core, the Neumann boundary condition is naturally satisfied. Fig. 2(c) shows a 3D model with asymmetric boundary conditions for core and windings. The magnetic path axial symmetry is lost in this configuration. Fig. 2(d) represents the 3D model inside a metal housing that resembles a real transformer. In this model, the metal tank can act as a specific magnetic flux shunt. Its impact on the EM force of the transformer will be explored in the rest of this paper.

Table I. MAIN TECHNICAL PARAMETERS OF THE TEST TRANSFORMER.

| Main Technical Indicators | Parameter |
|---|---|
| Phase number | Three-phase |
| Rated power | 8 MVA |
| HV rated voltage/current | 20 kV/230.9 A |
| LV rated voltage/current | 11 kV/419.9 A |
| Turns ratio | 510/162 |
| Connection mode | Dyn |
| Height (cm) | 100.4 |
| Inner/Outer diameter of LV winding (mm) | 200/146 |
| Inner/Outer diameter of HV winding (mm) | 285/215 |

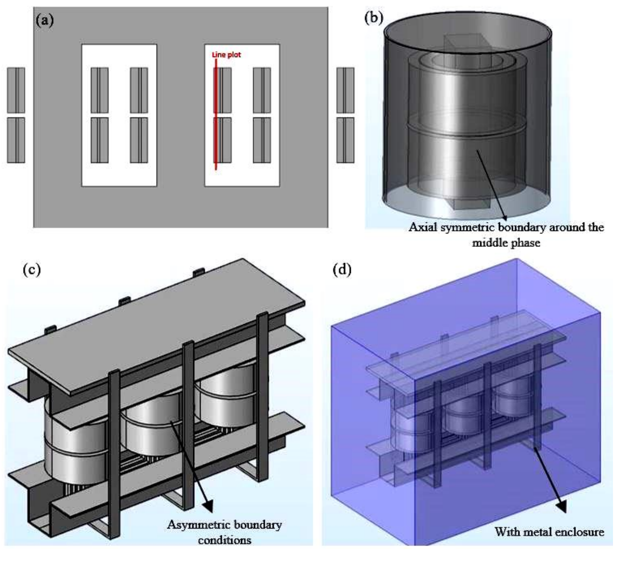


Fig. 2. 2D and 3D models of 8MVA dry-type transformer: (a) 2D model, (b) 3D axial symmetric model, (c) 3D asymmetric model, (d) 3D model with metal tank.

## IV. RESULTS AND DISCUSSIONS

The magnetic field distribution of the axial flux in the 2D model is represented in Fig. 3. As shown in Fig. 3(a), the axial leakage flux is largely concentrated between the HV and LV windings, where the maximum field strength is reached at mid-height along the winding. Fig. 3(b, c) shows the calculated radial and axial magnetic flux densities along the red line plot shown in Fig. 2(a). According to (2), axial flux distribution between two windings generates EM forces in the radial direction. As a result, because the line current of



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each turn is equal, the maximum radial EM force is expected in the mid-height along the windings.

### *A. Comparing the 3D axial symmetric model with the 2D model*

Verification of the 3D FEM calculation technique is required before discussing the factors affecting EM forces. In this study, a 3D symmetrical model is used, as illustrated in Fig. 2(b). The winding assembly and the encircling core form the axially symmetric model, which creates a symmetrical magnetic boundary in the space. In the axial symmetric model, a layer of the ferromagnetic core is placed around the middle phase winding in a cylindrical manner, which models the permeability of the core as in the 2D model, Fig. 2(b). In Fig. 4, the calculated EM forces in the middle phase are compared along the red line plot. Both radial and axial EM forces in the LV winding show good agreement with each other. The HV windings and the other two phases show a similar agreement, which is not shown here for the sake of brevity.

These findings show that when the magnetic boundaries are treated as axially symmetric, the 2D model of EM force is equivalent to the 3D model. It can be concluded that a 3D axial symmetric model does not have added value compared with the 2D model. On the other hand, the 2D model requires much less computational power and, therefore, is preferred to the 3D model. In the following studies, however, more complex situations with asymmetric boundaries are introduced to the 3D FEM model to show that the 2D model (or the 3D axial symmetric model) has some shortcomings.

### *B. Influential factors in modeling transformer EM forces*

In this subsection, the influential factors are investigated by presenting and comparing the results of the 3D asymmetric model. Practical transformers normally include windings, a core assembly, insulation, cooling elements, and other accessories. Insulation and cooling components are typically composed of non-magnetic materials and so have no much impact on the leakage flux distribution between the windings. The transformer core and metal tanks, on the other hand, are usually made of ferromagnetic materials. They have effects on the distribution of the leakage flux and, as a result, on EM forces.

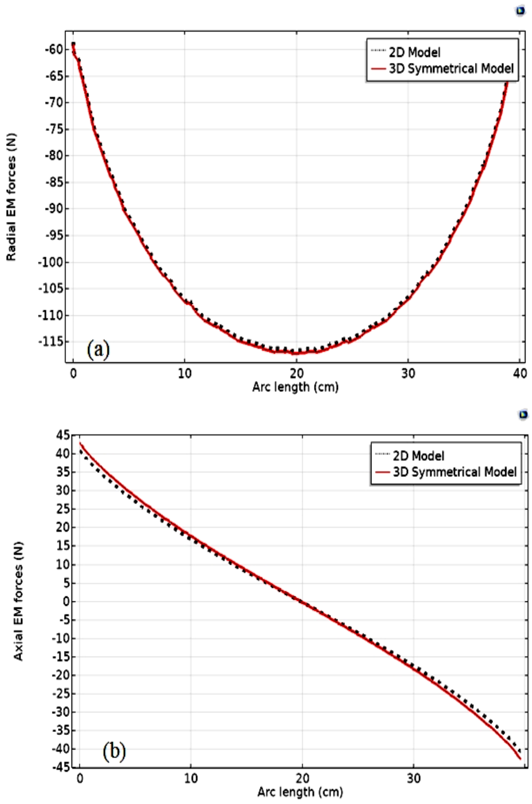


Fig. 4. Comparing the EM forces distribution in the (a) radial, and (b) axial directions between the 3D axial symmetric model and the 2D model.

The effects of asymmetric boundary conditions on the leakage flux distribution and EM forces are investigated using the two models presented in Fig. 2(c, d). The simulation results of the 3D model show that the maximum flux-leakage density of the dry-type transformer winding is 0.08 T, while the maximum flux density of the core is 1.75T, as shown in Fig. 5(b, c). In addition, adaptive refinement techniques are used to create the meshes, which are much more refined in the zones of strong variation and high intensity of the magnetic field, as shown in Fig. 5(a). The simulation results are consistent with the output parameters of the 8 MVA dry-type transformer. The results validate the model accuracy, demonstrating that it can be used to simulate a variety of factors that affect EM forces.

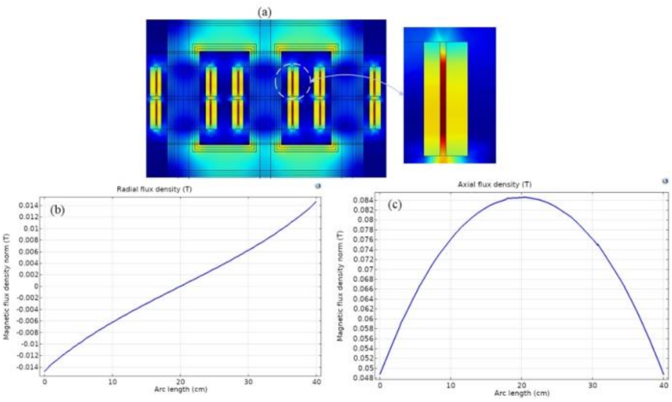


Fig. 3. (a) Axial leakage flux distribution between windings and leakage flux distribution in the (b) radial, and (c) axial directions along the red line plot.

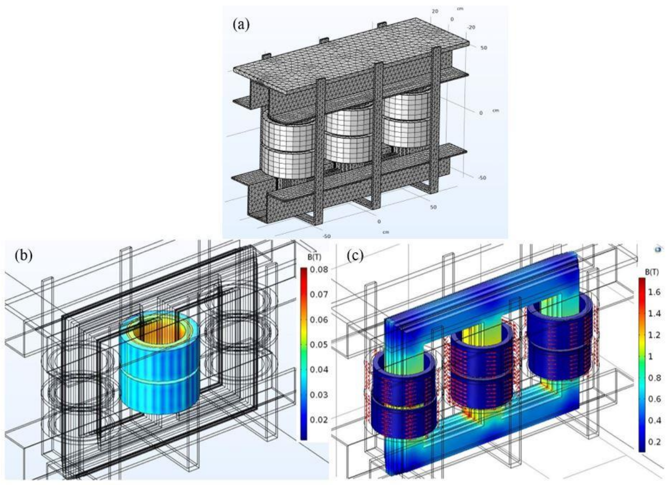


Fig.5. (a) Mesh-generation results of the 3D geometric model, (b) magnetic flux density distribution of the transformer winding, (c) magnetic flux density distribution of the transformer core.



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The calculated results from three FEM models are compared in Fig. 6. The following analysis focuses mainly on the EM forces of the LV winding. Analyzing the findings for the HV winding using the same steps leads to similar conclusions.

The results of all three modelings show a similar pattern in the distribution of EM forces in the radial and axial directions, as shown in Fig. 6. However, the main difference is in the calculated amplitude of forces. In comparison to the 3D model with asymmetric boundary conditions, the 2D model estimates axial forces less and radial forces more. Based on the results of this comparison, it can be concluded that 2D modeling can overestimate the radial force while underestimating the EM axial force. The inadequacy of the 2D model to accurately describe the non-symmetric magnetic boundary is the explanation for these results. The 3D model is better suited for complicated boundary conditions since it can effectively achieve the actual situation. Furthermore, the existence of a metallic tank lowers the axial EM force while increases the radial EM force as compared to the 3D model. The component relationship of the EM forces can be summarized as follows based on the simulation results:

$$\begin{cases} F_{z3D} \geq F_{z2D} \geq F_{z3D,\text{tank}} \\ F_{r2D} \geq F_{r3D,\text{tank}} \geq F_{r3D} \end{cases} \quad (6)$$

A detailed magnetic field study is undertaken to explain this simulation result. In this regard, Fig. 7 demonstrates only a part of the core window environment corresponding to the leakage flux distribution in the space between the two windings due to symmetry. Fig. 8 also shows one of the leakage fluxes lines above the windings.

In general, the magnetic reluctance of the flux pathway determines the flux density amplitude. The 2D model top and bottom yokes, as well as the side limbs, make a closed route around the winding. This configuration allows for a wider magnetic path with low reluctance. As a result, the 2D model has the highest amplitude of flux density. Furthermore, the presence of a transformer metallic tank causes the flux density amplitude in the 3D model with the metallic tank to be greater than the flux density amplitude in the 3D model due to the availability of additional magnetic pathways. To make concepts clear, a vector angle α between the flux line direction and the radial direction is established, as shown in Fig. 8. To meet (6) and the previously discussed amplitude relation, the vector angle sequence in the three situations should be $\alpha_{3D} < \alpha_{3D,\text{tank}} < \alpha_{2D}$. This implies that in the 2D model, the flux lines are more likely to bend towards the top yoke than in the 3D models with asymmetric boundaries. The presence of a high magnetic yoke in the 2D model, which acts as a large magnetic path, is the physical reason for this.

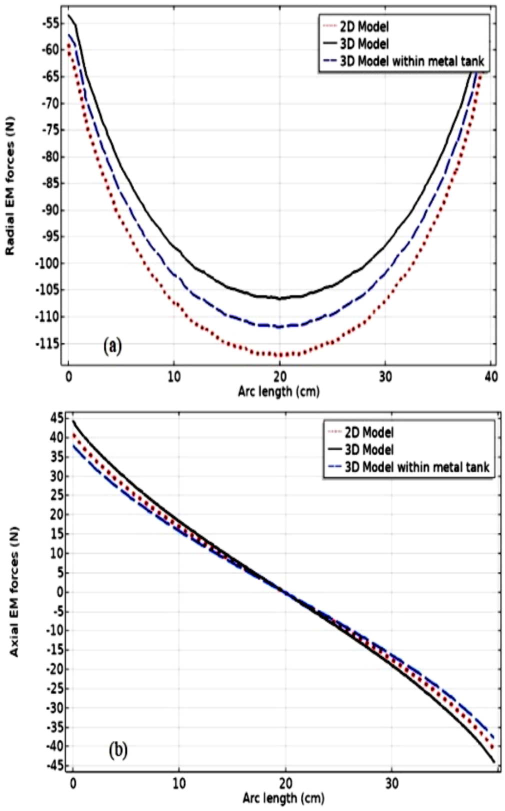


Fig. 6. Comparing the calculated EM forces in the (a) radial and (b) axial directions between the 2D model, the 3D asymmetric model, and the 3D model within a metallic tank.

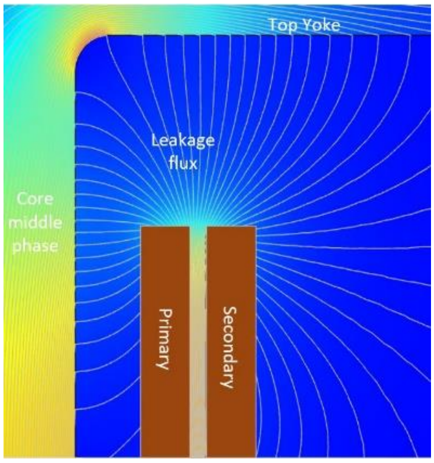


Fig. 7. Leakage flux distribution between two windings in the 2D model.

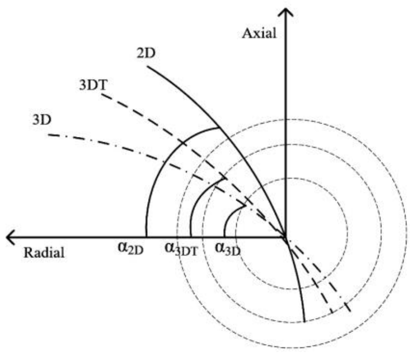


Fig. 8. One of the leakage fluxes lines in the 2D model (solid line), 3D model (dot-dashed line), and 3D model within a tank (dashed line).



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## V. CONCLUSIONS

This paper presents a comprehensive analysis and accurate modeling of power transformer EM forces. Factors such as asymmetric boundary conditions, metallic tank effect, and 2D model effects in the accuracy of leakage flux analysis and EM forces modeling are investigated in order to improve the accuracy of EM forces calculated in a power transformer. This paper showed that the 2D modeling of EM forces in practical transformers is inaccurate. In order to account for the magnetic field asymmetric boundaries and improve modeling accuracy, a 3D model is required. The results showed that the asymmetric magnetic boundaries of practical transformers such as cores and metallic tanks influence the leakage flux distribution and EM forces. This work is useful for researchers and designers who want to design windings and magnetic shunts for power transformers because it discusses the factors influencing the EM force modeling of a transformer. This paper can also be used as a foundation for engineers and researchers to create similar models.

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