Assessment of the use of FEM for computation of Electromagnetic Forces, Losses and Design of Transformers

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Abstract. This paper reviews the published work on power transformers for assessment of the electrical, magnetic losses, and electromagnetic forces produced during normal and short circuit conditions. The different methods used are analytical method, integral equation method, boundary element method, and finite element method (FEM). The copper losses and eddy currents within the copper conductors/windings need to be assessed to estimate the heat generate and compute the efficiency. The knowledge of the eddy current losses in the core and stray losses in each component of the transformer can help in the design improvement. Earlier 2D FEM and now 3D FEM has been used to evaluate the electromagnetic flux under normal conditions, the effect of the in-rush phenomenon, assessment of mechanical strength of windings, insulation, computation of short circuit forces and need of the mechanical support components during fault conditions. This paper gives an overview of the work done on the computation of electromagnetic forces, losses, and design of transformers using FEM to assess the scope for further work.

Keywords: Electromagnetic forces, Finite element method, Losses, Short circuit current, Transformers

1. Introduction

In a power system for transmission and also for distribution, transformers are used for stepping up and stepping down the voltage. Transformers are important components that make large power systems possible. These are electrical devices that transform need-based voltage level and current value between two electrical circuits linked with a common magnetic circuit. They transform the power from one circuit to another by electromagnetic induction without a change in frequency and have no internal moving parts. The types of transformer are classified according to their purpose, rating, use, and construction. Proper design of the transformer is essential for the reliability of the power system where it is installed. It has three main parts: namely, the primary winding which produces magnetic flux, secondary winding that gives output power at a required voltage level and a magnetic core and alternating voltage is applied to the primary winding. In this process, the power transferred between the circuits remains constant and comparatively small losses occur. The transformer losses are the iron or core loss which comprise of hysteresis loss and eddy current loss, the copper loss or ohmic loss in the windings, along with these there are also present the stray loss and dielectric loss. Since the transformer works on the principle of electromagnetic induction, electromagnetic forces are present. These forces are of very small magnitude during normal operation but have tremendous magnitude during faults due to the magnitude of the current in the windings.

This paper assesses the different technical publications on transformers based on the parts and types of construction and losses. This review aims to recognize the use of 2D and 3D FEM for assessing the different types of transformers with different ratings, different types of windings, the losses in
component, within windings, transposition of winding conductors, electromagnetic forces and design of the transformer. Also, it is intended to assess the use of the FEM results for improvement of design by reduction of stray losses and thermal analysis for the effect of overheating: its analysis to decrease hot spot, core losses, the safety factor for of axial and radial forces. This paper intends to assess the scope of future work on transformer electromagnetic forces, losses, and design improvement using FEM.

2. Method of Transformer Performance Analysis

The methods that are used for transformer analysis transformer performance are FEM, the integral equation method (IEM) and the boundary element method (BEM). FEM has been used for the analysis of different types, various parts, analysis of electromagnetic forces, and thermal analysis of transformers [1-16]. The integral equations have been used to analyze stray losses and leak magnetic flux [4, 17], and the boundary element method has been used for the design of insulation [18]. The reactance model of the transformer can be developed using FEM [19].

The finite element method is a way of solving complex problems like structure analysis, heat-transfer, and electromagnetic field. Any physical problem can be expressed by the governing equation and boundary conditions in the same partial differential equation. The partial differential equation is difficult to solve, FEM converts the partial equations into the algebraic equation by raking approximation that is easy to solve. FEM convert the domain into number of finite element and then convert the partial differential equation into the algebraic equation and give result by taking into consideration of the algebraic equation. FEM subdivides the structure on which analysis is to be carried out into subdomains or small elements. The small elements are represented by a mesh. The mesh created for a section of a three-phase transformer for 3D and 2D analysis is shown in figure 1 (a) and (b) respectively.

Both 2D and 3D FEM simulation methods have been extensively used for the study of electromagnetic forces, losses, circulating currents, and design of transformers [1,2,4,6-10,17-26]. 2D FEM analysis [12-14,27,28] and 3D FEM analysis of transformers has been done [5,15,6,29-44]. Comparison of the 2D and 3D results has also been done [38,41,45] and both are found to give results that are close to those obtained by the conventional analytical method [44] and those found by experiments [59].

![2D Mesh](image1.png) ![3D Mesh](image2.png)

**Figure 1. Mesh created by finite element method**

3. Transformer Type and Rating

FEM has been used for the study of both single-phase transformer transformers [8, 34, 36, 44, 46] and three-phase transformers [40,48]. Power transformers [4, 30-32, 35, 48-50] and distribution transformer [51-53] have been analyzed using FEM. The ratings of power transformers considered in different publications are 10 MVA [27], 28.333 MVA [44], 38 MVA [46], 40 MVA [47], 50 MVA [55], 200 MVA [30], 240 MVA [48], 315 MVA [34] 360 MVA [56] and 420 MVA [32] and rating of distribution transformers are 630 kVA [54], 1000 kVA [16], 2000 kVA [57]. Most of the work on power and distribution transformer is for low frequency 50 Hz or 60 Hz [41, 54, 58], work has also been done on medium frequency transformer [42] and high frequency [1]. Analysis of the shell type [15] and core type [59] has also been carried out. Performance of dry type transformer [51], current transformer [24], isolating transformer [60] has been assessed using FEM. The FEM results give a good performance for both distribution and power transformers along with special purpose transformers.

4. Transformer Losses
4.1 Copper Loss

Ohmic resistance of the winding of the transformer produces copper losses. For the primary and secondary losses, the copper losses are I₁²R₁, I₂²R₂, where I₁ and I₂ are the currents in the primary and secondary winding and R₁ and R₂ are the resistance of the primary winding. Copper losses vary with the load of the transformer. Total copper losses in the transformer are the sum of the losses in the primary and secondary. Calculation and simulation of copper losses [41, 59] have been done as well.

4.2 Stray Loss

Analysis of stray losses [4, 6, 16, 22, 32, 33, 35, 37, 41, 42, 48, 57, 63, 64, 65]. Three-phase transformer [29], and single-phase transformer [44] losses have been assessed. Stray losses have been analyzed for power transformers [4, 33, 64] and distribution transformers [16, 44, 52, 57]. The stray loss occurred in metal structures and their values have been computed oil tank [18, 19, 31, 32, 34, 35, 64, 66] upper/bottom frame [6], tie-plate [6, 64], bushings [66], flanges [64]. For minimization of losses and accurate calculations relating to absolute values, the most effective position of clamps and crossbars are detected. [31] Transformer tank walls and fitting may be modeled accurately for the justification of skin effect [67]. The computation of stray losses using FEM can be used to improve the transformer efficiency by making changes in the design.

4.3 Eddy Current Loss

Eddy current losses caused by varying magnetic field inducing eddy currents in the lamination and thus generating heat. Eddy current generates resistive losses that transform energy into heat. The eddy current losses (Pₑ) are equal to KₑBₘ²t²fν. Where K is co-efficient of eddy current, Bₘ is a maximum value of density (wb/m²), t is the thickness of lamination (m), f is the supply frequency (hertz) and ν is the volume of magnetic material (m³). Eddy currents also occur within winding conductors as well as in other metallic parts where they create losses.

Different techniques like non-linear surface impedance methods [40], FEM [3, 13, 26, 38, 39] are used for computation of circulating currents. Circulating current is calculated by the inductance matrix [25]. Calculation of circulating current losses using the analytical formulation has constraints, there has been calculated using 2D FEM [13] and 3D FEM [39]. In transformer eddy current in clamping [39, 68] clamping frame [39] clamp plates [40] have been computed. Circulating current in a stranded conductor depends upon the relative location of strands throughout the winding [69]. Circulating current losses create proximity losses in the stator winding [43, 70]. Eddy currents in the coaxial winding have been calculated using FEM [58]. Core losses at different excitation frequencies have been found [68]. Eddy current losses have been investigated in power transformer [56], three-phase transformer [72]. These have been found for round conductors [26] and stranded winding [69]. FEM can compute these losses in the metallic parts and the windings as well. Eddy currents are also referred to as circulating currents in literature. Transformer losses are assessed as no-load and load loss [71]. A comprehensive analysis of the transformer losses is not available.

5. Transformer Windings

The transformer’s windings are generally of three types; namely layer type, disc type or spiral or helical type. Transformer helical winding single layer/I-type [73-75] and double-layer/U-type [5, 12, 75-77] U-type for low voltage winding [9, 79], high voltage [27, 42] and both low voltage and high voltage winding [11, 24, 73] have been analysed FEM. Analysis of asymmetric winding [78] stranded winding [69] has been carried out using FEM. To reduce proximity losses effectively transposition is done. Study of the effect of transposition [43] and transposition optimized design is done [13, 79]. Ideal transposition has been proposed [80], also transposition design has been done using a genetic algorithm [73, 79]. Analysis of disc type transformer windings is not available.

6. Analysis of Electromagnetic Forces, Field Distribution, and Design

6.1 Electromagnetic Forces
Leakage flux density (B) and current interact to produce electromagnetic forces of a very large magnitude. The leakage flux density is resolved by radial direction (Br) and axial direction (Ba). With the current density, the action of radial leakage flux results in axial forces (Fa) and the axial leakage flux density results in radial force (Fr). The forces and flux density in the HV winding of a transformer are shown in figure 2. To study the deformation action on transformer winding the values of axial forces and radial forces are used. In a power transformer, the analysis of electromagnetic field distribution is based on electromagnetic theory [81], the eddy current losses are obtained [23, 82], electromagnetic forces were investigated over the windings and inside the operating transformer using FEM [8, 42]. By the method of finite element analysis, the electromagnetic forces have been evaluated. The effect of tappings on transformer symmetry has been analyzed [82, 83]. The FEM successfully computes the electromagnetic forces in low-frequency devices.

6.2 Short Circuit Forces and Design

In the power lines, the different phase comes in contact with each other, then a large current flow in the circuit. The effect of impedance in the circuit may reduce the short circuit current as of the current rises in the circuit. Because of the short circuit current, equipment will overheat and the production of forces of the electrodynamic interaction may destroy the equipment. During the short circuit current, the transient phenomenon observed because of current undergoes a continuous change.

![Figure 2: Direction of radial and axial forces and flux density in HV winding of a Transformer](image)

In the transformer windings during the short circuit, a large magnitude of current flows. When a transformer is submitted to a short circuit condition the electromagnetic forces that arise in the transformer are exerted on the windings. Figure 3 shows the short circuit current and forces in the transformer winding. The short circuit current has a steady-state alternating component at fundamental the frequency and an exponentially decaying current. The force experienced by a winding is proportional to the square of the short circuit current. The force has four components, there are two alternating components and two unidirectional currents. One of alternating component is at the fundamental frequency, and the other at double the fundamental frequency, the double frequency component of current is of a constant but smaller value. The other two components of force are unidirectional; one is constant and the other is decreasing with time. With a fully offset current, the fundamental frequency component of force is dominant during the initial cycles.

FEM has been used to analyze electromagnetic forces [5, 8, 11, 27, 53, 54, 76, 80, 82-84]. 3D FEM analysis of electromagnetic forces in the transformer winding is compared with that done by numerical analysis. The calculated values of the axial and radial force of the transformer by 3D FEM are comparable with the numerical values [5].

![Figure 3: Short circuit current and forces](image)
50MVA one-phase transformer subjected to inflow (inrush) current was analyzed by FEM to investigate electromagnetic forces at the time of faults [8]. FEM has been used to analyze the short-circuit current in transformers [83-90]. Force calculated in power transformer along the HV and LV winding defined with the help of FEM and this approach helped in the designing process [11]. The asymmetrical form of excitation and the effect of some of the factors were calculated in 10MVA power transformer 2D model developed and short circuit forces over distinct transformer parts were computed [27]. In a distribution transformer effect of harmonics caused by non-linear load was analyzed. It was used to separate the no-load hysteresis loss and no-load eddy current loss. The two-frequency method was applied and it was observed that the core loss increases with an increase in applied voltage [53]. In a 360 MVA power transformer, the computation of 3D FEM was used for the evaluation of eddy current fields. In this case the tank wall with a magnetic shunt, aluminum screen was analyzed [75]. By using FEM, the design of the window of transformer and magnetically built vector potential was evaluated. The axial and radial FEM’s were evaluated on the coil of the transformer and the asymmetrical form of windings effect was analyzed [80]. To calculate the value of radial and axial force the FEM method is used [85]. FEA method used to calculate resolving the forces exerted on the coil of the single-phase shell-type distribution transformer [83]. During short circuit condition, Short circuit forces have been computed for a different type of transformers dry type transformer [9], 3-phase transformer [84] and transformer under load [86]. Calculation and comparison of Short circuit forces in power transformer has been undertaken and the forces are calculated by 3D FEM [2, 38]. The effect of inrash current on electromagnetic forces has also been assessed [55]. Voltage harmonics have been analyzed [53]. Performance analysis has been carried out for the dry type transformer [9]. The deformation of windings due to electromagnetic forces has been analyzed [9] winding asymmetries have also been analyses using FEM [5, 87]. Winding height has been optimized for the least stresses [53]. Transposing of the winding for design improvement has been undertaken [13, 40, 79, 80]. 3D FEM has been used to study shielding [6,33], and insulation design [40]. The short circuit forces produced during inter-turn faults have been evaluated [88]. Based on the forces the mechanical characters of the transformer have been analyzed [89]. Extensive work has been done regarding electromagnetic forces, winding design, evaluation of losses, however, the complete comprehensive analysis of a designed transformer is not available.

Assessment of use of FEM for computation of losses, and electromagnetic forces during short-circuit conditions in the publications referred to in this work are given in table 1.

| Parameter assessed    | Total number of Publications | Last publication Year | Number |
|-----------------------|------------------------------|-----------------------|--------|
| Copper Loss           | 16                           | 2017                  | 4      |
| Eddy Current loss     | 15                           | 2016                  | 1      |
| Stray Loss            | 17                           | 2017                  | 2      |
| Short circuit Forces  | 25                           | 2019                  | 4      |

The finite element method has gained popularity for the assessment of short circuit forces in transformers in the current year.

7. Conclusion

A review of published work for the analysis of the different loss and electromagnetic forces in transformers found that 2D and 3D FEM, integral equation method (IEM) and boundary element method (BEM) have been used. The results of 2D and 3D FEM have been found to match with analytical values. The 3D FEM for transformer performance under normal and fault conditions, for different types of transformers, ratings, and design has found extensive popularity in the recent past. FEM is a reliable method for analysis of losses, transposition, control, and elimination of hot-spot in the transformer. Much work has been done on power transformer short-circuit withstand capacity and losses that occur in different parts of transformers. Analysis of transposing of windings has been done. Helical windings have been analyzed. It is found that there is scope for analyzing forces, and losses in transformers having disc-type windings using FEM. There is no work available on the disc type
windings. The analysis of short circuit forces and losses due to the field created by disc type windings that find much use in power transformers.

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