A Comprehensive Study on Transformer Design Using Numerical Techniques

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Abstract- The aim of this study was to review the application of finite element techniques for solving complex transformer structures using modern software. The Finite Element Method (FEM), developed over the past 70 years to address intricate problems in civil and aeronautical engineering, has since found valuable applications in electrical engineering for solving complex design challenges. This paper explores the use of FEM in transformer design, highlighting its effectiveness as a numerical tool for simulating structural components, optimizing materials, enhancing reliability, performing failure analysis, taking corrective actions, and verifying new designs under various loading conditions. The study concludes that FEM is a highly efficient approach for transformer design and analysis.

Keywords- Numerical Techniques, Finite Element Method, Transformer Design.

1. Introduction

Transformers are essential, dynamic components within energy systems, and while they are highly efficient, optimizing their design can help reduce energy losses. Once installed and energized, a transformer operates continuously, consuming energy even when the connected load is inactive. These devices are complex, three-dimensional assemblies that consist of the core, windings, insulation, tank, and various accessories. In addition to the electric and magnetic fields, transformers also involve physical fields such as thermal, liquid, and mechanical. Each component must be carefully evaluated to ensure the transformer's reliability and the longevity of the entire system.

Transformers operate based on electromagnetic induction, transferring power between circuits. Despite being stationary, they face numerous challenges that can affect performance. According to data from the High Voltage Testing Research Centre, one in five transformer failures is attributed to weak insulation, which must withstand short-circuit currents. Poor-quality insulation, often the result of cost-cutting by manufacturers, can lead to disruptionsof transformer.

Design challenges in transformers can be addressed using analytical, numerical, or experimental methods. However, experimental approaches are often costly and time-consuming. Traditionally, analytical methods were employed for transformer design and performance analysis, but these methods have limitations, particularly when dealing with complex geometries. In such cases, engineers rely on numerical methods to provide accurate and reliable solutions. The Finite Element Method (FEM) is a powerful numerical tool used to simulate mechanical components under various loads, enabling material optimization, consistency evaluation, failure analysis, corrective actions, and validation of new designs. FEM, particularly magneto-static FE techniques, has been widely adopted by researchers to analyze transformer performance and address failure modes.

Today, computer simulations have revolutionized transformer design, allowing engineers to optimize parameters like flux density, core diameter, and current density in just minutes. Over time, numerous performance criteria have been developed, and this review provides a thorough examination of recent studies on transformer performance and improvement strategies. Key areas of transformer performance analysis include:

- **Assessing short-circuit strength using FEM** to evaluate the transformer’s ability to withstand short-circuit conditions.
- **Studying transformer behavior under short-circuit forces** through a combination of numerical simulations and experimental methods.
- **Analyzing the effects of inrush currents** on high-voltage transformer coils to understand their impact on performance and potential damage.
- **Optimizing low- and high-voltage windings and transformer tanks** through FEM to enhance efficiency and durability.
- **Calculating short-circuit forces within transformers** using FEM to accurately predict the forces that occur during fault conditions.
- **Developing alternative methods for high-current estimation**, utilizing piezoelectric transducers and validating the results with MATLAB/SIMULINK simulations.
- **Investigating the impact of hot-spot temperatures** on transformer components to identify potential areas of concern for overheating and degradation.
- **Applying nonlinear buckling analysis** to assess winding deformation under short-circuit conditions and simulate the cumulative effects over time.

2. Design Related Problems with Transformers

2.1 Magnetic Circuit (Core)

In transformer design, the magnetic circuit is a crucial element. This circuit includes a laminated iron core that facilitates the transfer of flux between the windings. The extent of flux linkage between the windings plays a significant role in determining the transformer's performance. To ensure efficient flux transfer, the transformer core must offer a low-reluctance magnetic path. However, the core faces challenges primarily due to hysteresis and eddy current losses. Hysteresis losses are largely influenced by the core material. Initially, standard steel laminations were used, but by adding 4-5% silicon to the steel, both eddy current and hysteresis losses have been significantly reduced, resulting in improved transformer performance and overall efficiency.

2.2 Inrush Current Phenomenon

When a transformer is switched off, a residual flux remains in the core, typically ranging from 50% to 90% of the full operational flux, depending on the core material and type. The flux generated by the applied source voltage adds to this residual flux within the core. If the transformer draws more current than its rated full-load current, the flux level can remain saturated. The magnitude of the inrush current can vary, ranging from 3.5 to 40 times the rated full-load current, depending on the transformer's design. While the inrush current waveform generally resembles a sine wave, it is significantly distorted in both the positive and negative directions. Factors related to transformer design and installation play a key role in influencing the magnitude of inrush current, making it crucial to accurately calculate both its value and the contributing factors.

2.3 Overfluxing

Transformers are designed to keep the magnetizing flux below saturation under normal operating conditions. However, over fluxing can occur due to factors overvoltage and low frequency. Transformers are intended to operate at or below a maximum flux density in the core to minimize eddy current losses. The magnetic flux in the core is directly proportional to the voltage applied to the winding and inversely proportional to the winding's impedance, meaning that flux increases with higher voltage or lower frequency. When the transformer becomes overexcited, it enters a non-linear magnetic state, generating harmonic components in the excitation current. A key indicator of over excitation is an increase in current at the fifth harmonic. To prevent these undesirable effects, it is essential to carefully consider over fluxing parameters during transformer design.

2.4 Impedance Characteristics

The leakage impedance of a transformer is a critical specification that plays a significant role in its design. Each transformer is designed with a specific leakage impedance level, and deviating from this specified range can lead to substantial costs. To accurately determine the leakage impedance, both analytical and numerical methods are available for calculation.

2.5 Stray Losses

Stray losses arise from the leakage field around transformer windings, affecting both the windings and structural components like the frame, tank, and bushings. Accurate estimation of all stray loss components is crucial for effective transformer design. Stray loss calculations rely on principles of eddy currents originating from electromagnetic fields.

2.6 Short-Circuit Stresses

Short-circuit events are a major cause of transformer failure. Under normal conditions, the windings are surrounded by magnetic flux, which creates electromagnetic forces that induce mechanical stress on the transformer structure. During a short circuit, these forces intensify and can deform the transformer.

3. Numerical and Analytical Techniques for Transformer Design

Extensive research has been conducted on various aspects of transformer design, modeling, protection, and analysis. Numerical and computational methods are employed to evaluate transformer performance and accurately predict characteristics. Transformer parameters such as load losses and short-circuit impedance are intrinsic to operations and are optimized throughout the design process. These parameters are influenced by leakage flux between windings, which generates eddy current losses in conductive structures such as windings, core laminations, clamping structures, and tank walls. Researchers have investigated flux distribution and its impact on transformer losses.

Both numerical and analytical methods have been proposed for transformer design, with experimental methods often supplementing these approaches to produce accurate transformer models. Improved efficiency is achieved by reducing no-load and load losses, which, though typically less than 0.5% in large power transformers, can cause localized heating. Accurate calculation of these losses is essential for effective transformer design and reliability improvements.

3.1 Core Design

To minimize core losses, researchers have examined core materials, types, and characteristics. Studies, such as those by Swift G.W., investigated core loss factors including frequency effects and air gaps. Valkovic Z. analyzed different core configurations and the impact of joint design on flux distribution, while Loffler et al. showed that multistep-lap (MSL) joints reduce power losses compared to single-step-lap (SSL) joints. Research has also explored various stacking patterns of C.R.G.O. silicon steel laminations to reduce core losses in power transformers.

Core losses and eddy current losses both significantly impact overall transformer losses. Krawczyk and Turowski demonstrated the importance of analyzing eddy currents in electric devices, while other researchers have used simulations to study electromagnetic fields and current distribution in transformer windings. Kulkarni and Khaparde focused on accurately estimating and controlling stray losses, and Olivares et al. reviewed transformer loss issues related to core joints and stray losses.

3.2 Short-Circuit Forces

Short-circuit forces, including axial and radial forces, build up in transformer windings during a short-circuit event. Modeling transformers in 3D cylindrical coordinates allows analysis of electromagnetic forces, which can include radial, axial, and twisting components. Recent research, such as the work by Ashfaq Ahmad et al., aims to guide transformer manufacturers in designing transformers that withstand dynamic short-circuit stresses.

In 2015, Deepika Bhalla et al. conducted a short-circuit force analysis on helical windings using the Finite Element Method (FEM) to examine axial force characteristics and identify stress-prone regions. Findings revealed that axial forces, especially at the start of the LV winding, cause conductor bending, while forces at the end of the LV winding produce vibrations that may damage insulation. In contrast, axial forces in the HV winding, secured with wire, had lesser effects. The simulation results show flux density under short-circuit conditions for transformer windings with and without tap changers, as illustrated in Fig. 1(a) and Fig. 1(b).

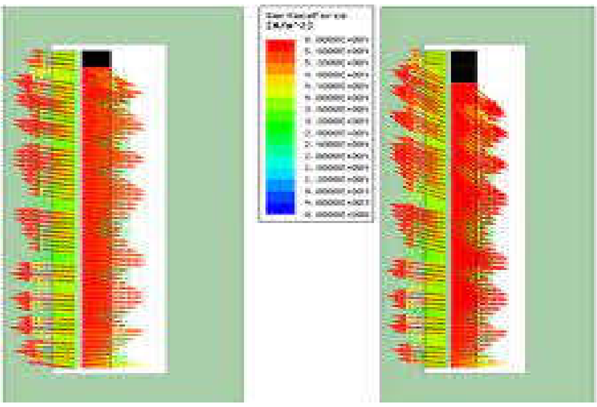

Fig. 1. *Flux density plot* ***(a)*** *without tapping,* ***(b)*** *with tapping*

Hyun-Mo Ahn et al.studied the short circuit forces utilizing numerical method suggests a Finite Element analysis of the transformer components individually by 2011 [31]. The momentary electromagnetic forces, the magnetic flux densities and the magnetic vector potential, are computed by the finite element system with 3-D representation of the transformer. axial forces respectively. A power transformer winding design is as shown in Fig. 2.

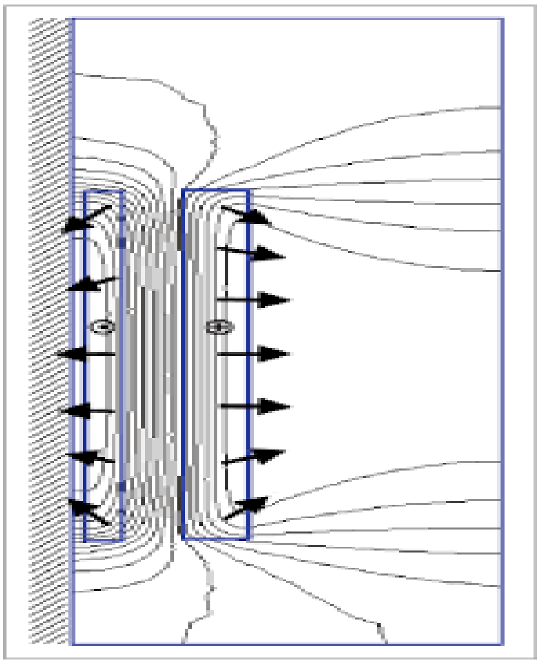

Fig. 2. *Electromagnetic force and leakage flux in concentric windings*

In 2001, H. Wang and K. L. Butler conducted a finite element (FE) analysis on internal winding faults in distribution transformers, concluding that 70–80% of modern power transformer failures result from turn-to-turn short circuits. They developed a low-cost, online diagnostic technique for detecting internal winding faults in distribution transformers by monitoring terminal behavior. For their investigation, they used the Maxwell Spice embedded tool to simulate a test structure, modeling the behavior of a defective transformer within the Maxwell software environment.

In related work from 2000, Sheppard Salon and colleagues analyzed the forces on the coils of a single-phase shell-type transformer using the FE method. They observed that, in an ideally aligned transformer, the net axial force is zero since the electrical centers of the windings are balanced. However, if the electrical centers are misaligned, opposing axial forces emerge in the low-voltage (LV) and high-voltage (HV) windings. During short-circuit conditions, these forces can become strong enough to cause axial displacement between the LV and HV windings. They compared results from 2D and 3D analyses and found good alignment between both methods. However, a 3D model was essential to capture asymmetries outside the window area, which are not possible to analyze with a 2D model.

3.3 Hot-Spot Temperatures

In 2016, Serguei Maximov et al. developed an analytical approach to derive a formula for calculating temperature distribution in transformer tanks. This formula is both effective and accurate, helping mitigate unwanted thermal issues in transformer tanks and high-temperature rise in bushing plates. It also provides a general formula to determine temperature distribution in transformer covers due to losses.

In 2015, Longnv Li et al. introduced a 3D magnetic-thermal coupling approach combined with CFD calculations to evaluate hot-spot temperature rise. The two primary factors affecting hot-spot temperature in power transformer components are electromagnetic stray losses and the mean external convection heat transfer coefficient. To accurately define stray loss density distribution, magnetic-thermal coupling is commonly used to calculate hot-spot temperature rise. Figure 3 illustrates the temperature distribution in the tank, while Figure 5 shows the temperature distribution on the yoke clamps.

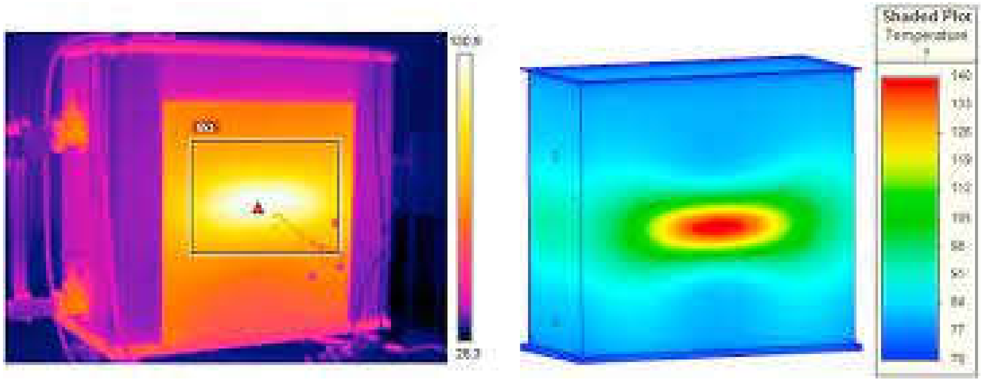

Fig. 3. *Computed temperature distribution in the tank.*

3.4 Inrush Current Phenomena

In 2014, Steven Hodder et al. explored transformer differential protection under magnetizing inrush conditions with low levels of second harmonics. They proposed a novel method for inrush current detection that greatly enhances protection security. In 2008, Jawad Faiz et al. examined the electromechanical forces on transformer windings caused by short-circuit and inrush currents using finite-element analysis. Their study found that, in certain areas, the forces on windings due to inrush currents can exceed those caused by short circuits. Figure 4 illustrates the inrush current waveform in the HV windings.

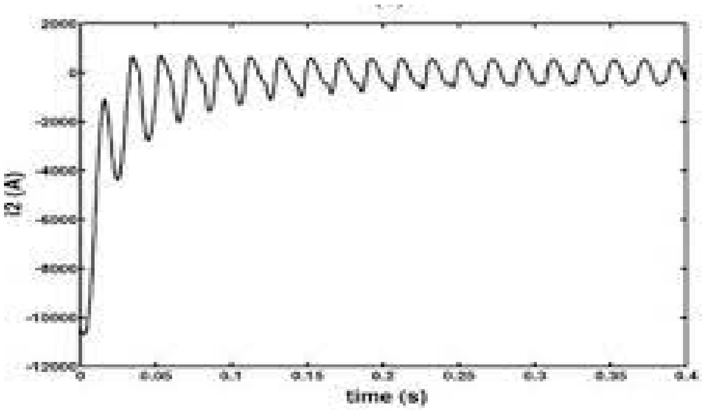

Fig. 6. *Inrush current in the HV winding*

In 2002, Michael Steurer and Klaus Fröhlich in [38] calculated the forces occur due to short circuit and compare it qualitatively. FEM model has also been arranged to verify the results obtained with the 2-D and 3-Drepresentation. The calculated forces proved that the inrush current appears to be more than 60% of the rated Short Circuit current. Inrush current is compared with short circuit current with the help of 2-D and 3-D model. The summary of various methods reviewed is mentioned in TABLE 1.

Table 1: Summary of various methods reviewed.

Ref. No	**Analysis of transformer based on**	**Techniques**	**Software**	**Effect on transformer**	**Advantage of the analysis**
[1]-[3]	SHORT CIRCUIT FORCE	Coupled electromechanical finite-element method	ANSOFT's Maxwell Software, Embedded Maxwell Spice and ANSYS 8.1.	✓ Mechanical damages of windings. ✓ Transformer may explode. ✓ Cause vibrations or instability in the system.	✓ Analysis prevents the damage of windings. ✓ Improve the efficiency of transformer.
[4]-[8]	SHORT CIRCUIT FORCE	Finite Element method and Analytical method	FEMM software.		
[9]	TEMPERATURE RISE	FEM analysis andAnalytical formula	*	✓ Causes heating and restrict the compactness. ✓ Reduce the useful life of Transformer. ✓ Increases the operating cost.	✓ Provide compact and improved design of Transformers. ✓ Protects the overall system.
[10]	TEMPERATURE RISE	Magnetic-thermal coupling 3-Dimensional analysis with CFD calculation	*		

[11]	HIGH TEMPERATURE SUPERCONDUCTORS	Circuit–Field coupled method	COMSOL	✓ Normal performance of HTS transformer gets disturbed by forces. ✓ Quench phenomenon and insulation breakdown may occur.	✓ Helps in energy saving and reduction of operating cost. ✓ High efficiency. ✓ Size could become 1/3 or 1/2 of the conventional Transformer ✓ Lower losses and less heating is produced
[12]-[14]	HIGH TEMPERATURE SUPERCONDUCTORS	Finite element method	Flux2D software		
[15]	HIGH TEMPERATURE SUPERCONDUCTORS	OLTC	*		

[16]-[17]	BUILD UP EFFECT	3-D Finite element method	Coupling of ANSYS and Maxwell software	✓ Plastic deformation causes frequent damages to the windings. ✓ Most serious problems for failure of power T/F.	✓ Accurate design of Transformer could be developed.
[18]-[21]	WINDING INTERNAL FAULTS	Artificial neural network (ANN)	MATLAB	✓ Insulation degradation is accelerated by the localized thermal overloading in the shorted region. ✓ Causes irreversible damage to the transformer.	✓ Detection of the winding inter turn fault at early stage protects the Transformer.

[22]-[24]	INRUSH CURRENT	Time-stepping finite-element method (TSFEM).	ANSOFT Maxwell software	✓ Inrush currents cause serious damage to T/F.Axial force due to inrush is larger than SC currents.	✓ Could protect from temporary shutdown of the transformer in operation
[25]	PIEZOELECTRIC MATERIAL	Piezoelectric effect	MATLAB/SIMULINK	✓ Till now also PZT can operate only at low power levels, up to few 100 watts.	✓ Miniaturization ✓ No EM noise ✓ High efficiency.
[26]	PIEZOELECTRIC MATERIAL	Finite-element method and Heat Transfer Analysis	*		

4. Results and Discussions

Earlier researchers used analytical methods for transformer design and performance analysis, but these approaches have limitations when applied to complex geometries. For issues involving intricate geometries, boundary conditions, and varied material properties, designers rely on numerical techniques like finite element analysis (FEA), which provides accurate solutions. FEA is widely used for failure analysis, enhancing reliability, optimizing materials, and validating new designs. A review of literature highlights several methods for improving transformer performance. Main findings of the study are summarized as:

1. Optimizing core material, dimensions, and permeability.
2. Modifying winding construction.
3. Reinforcing structural supports.
4. Using alternative winding materials.
5. Adopting new winding arrangements.
6. Linking electric circuits with magnetic fields.
7. Recognizing the impact of localized thermal overloads.

5. Conclusion

The primary objective of this work is to offer a thorough analysis of various performance-related parameters and methods for enhancing transformer performance, with a focus on practices implemented at a single location. This paper reviews and compares different performance analysis techniques, examining their impact on transformer functionality and the advantages of each approach. The use of ANSYS for performance enhancement is found to be on par with traditional methods, thanks to its advanced capabilities. However, there has been limited application of ANSYS in 3D, as most previous studies have utilized 2D methods, such as FEMM or other 2D software. Based on the reviewed studies, it can be concluded that the most effective method for improving the performance of power transformers is 3D finite element analysis using ANSYS.

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