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THERMAL ANALYSIS OF POWER TRANSFORMER USING FEM

A Technological Reveiw

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Abstract — *This paper is intended to review the significant development in thermal modelling & analysis of Power transformer in last decade. Contents in this review paper starts with introduction of Power transformer and its role in the power system and industry. Different analysis methods which can be used to get best suited method of analysis of power transformer to achieve the thermal analysis of transformers are discussed. Circuit based Modelling and Finite Element Method (FEM) are the two latest methods developed in last decade based on computer simulations. This paper reviews this two methods for obtaining thermal analysis of Power transformer.*

Keywords- *thermal analysis; power transformer; FEM; ANSYS; Field analysis; hotspot.*

I. INTRODUCTION

In an interconnected power system, transformer is the main and important device. For the reliability of power supply it is compulsory that power transformer used is 'fit' for work. Hot-spot is the major culprit of internal faults in power transformer. So, in system for preventing the transformer from any possible causality due to Hot-Spot, this technique is used. This technique is useful for Design and Condition Monitoring. Many modern procedures are used to find Hot-Spot in the transformer. The objective of these techniques is to find and analyze Hot-Spot in such a manner that the requirement of 'Prototype' of a transformer is vanished. The study is mainly carried out to focus on obtaining the Hot-spot in power transformer using Finite Element Method of numerical methods through simulation on the ANSYS platform.

II. THERMAL ANALYSIS OVERVEIW.

2.1. What is Thermal Analysis?

Thermal analysis is the branch of material science in which the effect of temperature to the machine is carried out. There is two type of Thermal Behavioral Analysis: Thermal Structural Analysis, and Thermal Fluid Analysis.In Thermal Structural Analysis, the thermal behavior of Structure of machine is carried out. In Thermal Fluid Analysis, the thermal behavior of Fluid of machine is carried out.

2.2. Need of Thermal Analysis for electrical Machines.

The Electrical machines are subjected to several losses. i.e. Copper losses, Iron losses, Stray losses etc. Heat is produced due to these losses and the machine is subjected to heating. Due to this, machine will have gone under severe threat of internal contingencies. To prevent the machine from heating we have to analyze the effect of temperature on the machine in various environments.

2.3. Need of Field Analysis & Thermal Analysis for Power Transformer.

- Power transformer is subjected to internal faults due to excessive heating in the winding and the core. We have to find B (flux density) to know the scenario of losses in the transformer due to the fact that Iron losses (Hysteresis and Eddy current losses) and Copper losses (Winding losses) are directly proportional to B. These losses are the main producers of Heat in the transformer.
- Field analysis consists of Electro Magnetic plots like Flux density, Core losses, Flux lines, Current density, Ohmic loss, and various voltages and currents.
- For obtaining the effect of temperature (measure of Heat) we need Thermal Analysis of power transformer.
- Thermal Analysis consists of temperature profile, temperature distribution, change in temperature, HST (Hot-spot temperature is the highest value of the temperature), thermal flux, thermal gradient.

2.4. Need of Field Analysis & Thermal Analysis for Power Transformer.

The hottest spot is at some point inside the coil having the longest thermal paths to the outside air. This hot-spot temperature differential is controlled by the producer on model units; it is generally communicated as a temperature increment over the normal temperature.

2.4.1. Significance of Hot-spot temperature.

Hot Spots are the source of High frequency waves harmonics. When these waves pile up at a location, they will cause the equipment damage by Resonance Phenomenon. Hot spots are indicators of impending failure of the equipment. Hot spots are the primary cause for a major explosion of electrical equipment. It is one of the main reasons for failure of current transformer especially in HV circuits.

2.4.2. Significance of Hot-spot temperature.

The HST is checked with the warm furthest reaches of the transformer to check whether the specific stacking condition is ok for the transformer.

Types of Techniques:

1. IEEE Formulae for Calculating Hotspot Temperatures,
2. Fiber Optic Sensors for Temperature Measurements,
3. Thermal Models to Calculate Hotspot Temperatures,
4. Techniques Based on Computer Based Simulations.

Nowadays the last two are the most popular techniques used to determine HST.

2.4.2.1. Circuit based technique

This method is the totally analytical method where the thermal circuit of the system is made. Then after this it is one model represents the winding to oil heat transfer and the other represents oil to external air heat transfer.

All the heat generated inside the transformer due to the losses is represented by current sources and all the heat storage inside the transformer is represented by a single capacitance, claiming that the single capacitance as a lump represents the total heat storage inside the transformer. The resistance connected in each of the models represents the heat dissipation from winding to oil or oil to external ambient as the case may be. This resistance is modelled to be non-linear because of the fact that heat transfer from the winding to transformer oil as well as from the transformer oil to external ambient depends upon whether the transformer oil is directed (or forced) or natural and whether the external air is natural or forced respectively.

In the recent past, some work has been done in using the computer simulations and FEM packages in the transformer analysis and are presented in [25] – [28]. Ref. [25] describes a computer model, which can predict hot-spot temperatures for different types of cooling regimes and transformer winding geometries coded using ANSYS.

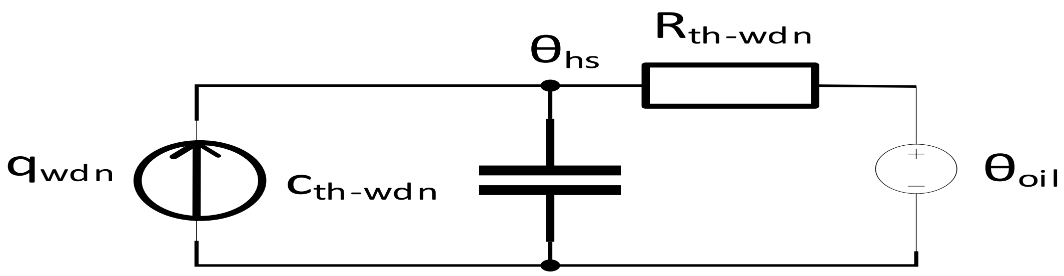


Figure 1. Circuit based technique

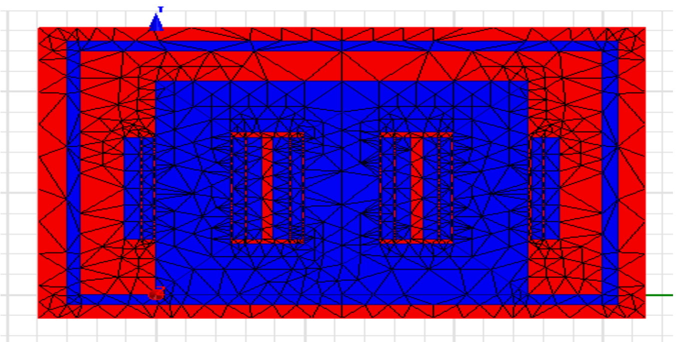


Figure 2. Model based technique

For calculating cost and time, the main step is the use of an effective simulator.

In most applications, once a right model representation is complete and implemented, an optimization procedure frequently includes the calculation of objective function several times, frequently thousands and even millions of configurations. Such calculations frequently include the use of general computational tools such as a computational fluid dynamics simulator or a finite element solver. This step is very time consuming and it takes 50% to 90% of the total calculating time.

III. Finite element method (FEM)

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It is also referred to as finite element analysis (FEA). It subdivides an extensive issue into littler, more straightforward parts that are called limited components.

FEM is a numerical method for solving a system of governing equations over the domain of a continuous physical system, which is discretized into simple geometric shapes called finite element.

A finite component strategy (abridged as FEM) is a numerical method to get an estimated answer for a class of issues represented by elliptic incomplete differential conditions.Such problems are called as boundary value problems as they consist of a partial differential equation and the boundary conditions.

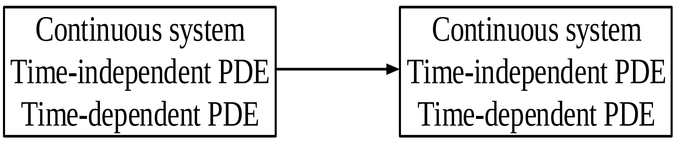
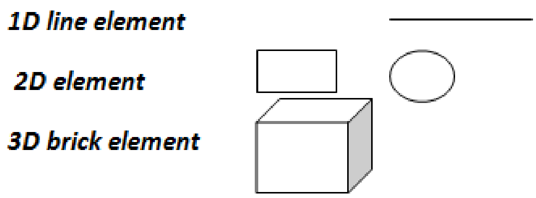


Figure 3. Finite Element method

3.1. Discretize and select the element types and the mesh making by using FEM.

The basic elements form the whole objects in multi-dimensions.

a) Element type



b) Total number of element (mesh)

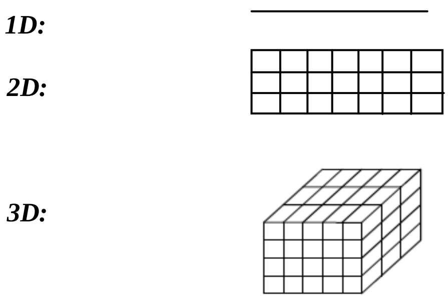


Figure 4. Finite element and meshing of the multi-dimentional objects (a) element type (b) total number of element (mesh).

IV. Electromagnetic Analysis

Electromagnetic analysis is the best method to find electromagnetic behavior with respect to time. This analysis gives us several electrical characteristics like voltages, currents, current density, ohmic loss, core loss, energy and magnetic characteristics like flux lines, field density, field intensity. From this we can obtain all the required analysis for condition monitoring of transformer.

This analysis can be achieved by the software like NASTRAN, ABAQUS, ANSYS, FEMM, JMAG, etc.

Now the classification of Electromagnetic analysis is given in following figure.

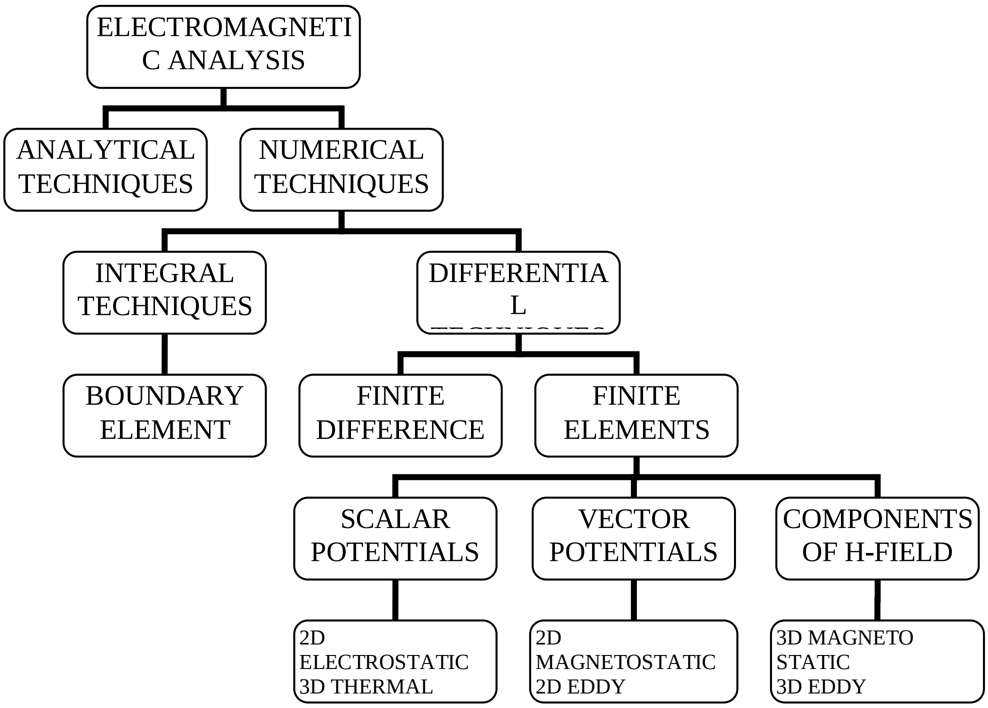


Figure 5.1. Classification of Electromagnetic analysis in ANSYS Maxwell.

VI. USE OF FEM FOR THERMAL ANALYSIS

The finite element method is mainly known as finite element analysis (FEA) in industry all over the world. It is one of the best practice to obtain thermal analysis nowadays. FEM give us accurate approximation for the solution of number of partial differential equations of the system.

- The simulation variations for electrical and mechanical characteristics of the transformer internal components without the need to construct prototypes.
- Thus, it is possible to properly design the equipment while still in the project stage.
- It is also possible to verify the influence of different materials that can be used on the construction.
- The discretization of the space with different levels of detailing, depending on the part of the transformer to be analyzed.
- This simulation is on the time domain.
- With the computer advances and their increase on storage and processing capacity there is great interest in solving engineering problems by the use of the FEM.

Thermal analysis can be obtained by more than one software interactions. In India, we have many software but among that ANSYS is the best suitable software. The electromagnetic analysis can be obtained by ANSYS MAXWELL and the thermal analysis can be obtained by ANSYS MECHANICAL. The interface between this two is provided by ANSYS WORKBENCH.

V. ANSYS MAXWELL

Ansys Maxwell is the best suited software for doing electrical analysis. It gives us ease and reliable solution procedures that can gives us more accurate approximation of the desired quantity. Ansys Maxwell works on the Maxwell's equations which is used for Electro-magnetic analysis.

In the differential form of Maxwell's equation is given in the following table 5.1.

TABLE 5.1. Maxwell's equation in differential and integral

Name of Equations	Differential Form	Integration Form
Gauss's law of Electricity	$\nabla E = \frac{\rho}{\varepsilon_0}$	$\oiint_{\partial V} E \cdot dA = \frac{Q(V)}{\varepsilon_0}$
Gauss's law of Magnetism	$\nabla \cdot B = 0$	$\oiint_{\partial V} B \cdot dA = 0$
Maxwell-Feradey Equation (Feradey's law of EMI)	$\nabla \times E = -\frac{\partial B}{\partial t}$	$\oint_{\partial V} E \cdot dl = \frac{\partial \Phi_{B,S}}{\partial t}$
Ampere's circuital law (with Maxwell's correction)	$\nabla \times B = \mu_0 \cdot J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$	$\oint_{\partial V} E \cdot dl = \mu_0 I_S + \mu_0 \varepsilon_0 \frac{\partial \Phi_{E,S}}{\partial t}$

The ANSYS Maxwell is the platform where we can easily obtain the Electrical as well as Magnetic Characteristics in different environment. It will give us Flux lines, Flux density, Flux intensity (vector & scaler), Energy, Co-energy, Ohmic loss, and Core loss.

ANSYS Maxwell do the simulations using FEM and adaptive meshing is shown in figure.

Also the solution process is carried out by ANSYS Maxwell is as shown in figure 5.2.

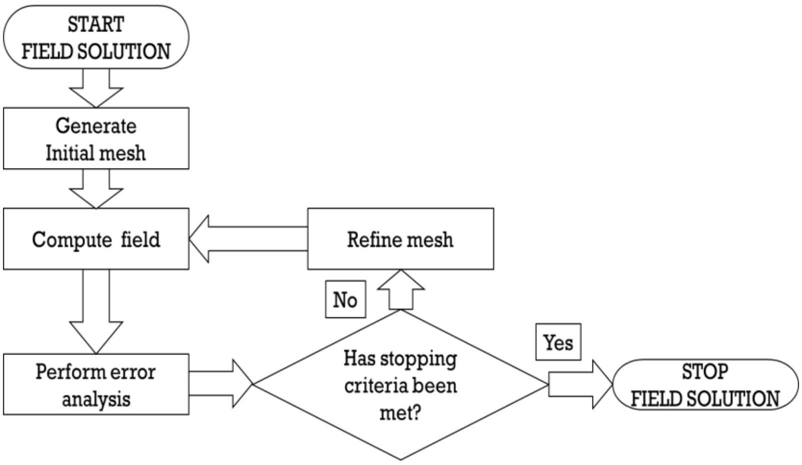


Figure 5.1. FEM and Adaptive Meshing used in ANSYS Maxwell

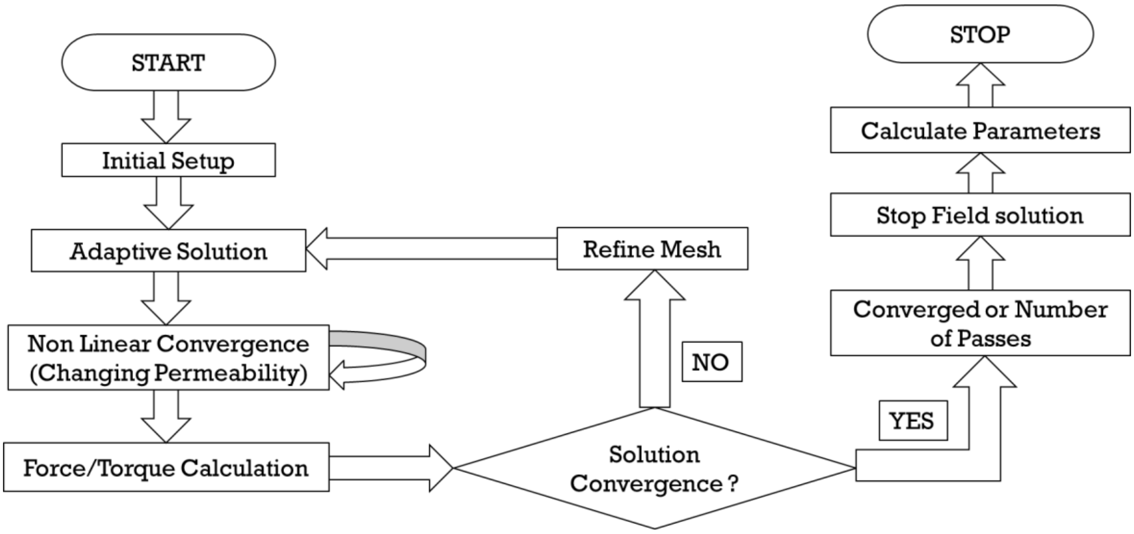


Figure 5.2. Solution Setup in ANSYS Maxwell.

VI. ANSYS MECHANICAL

ANSYS Mechanical is the co-software of ANSYS Inc. software package. It will provide the aid to obtain the Mechanical characteristics and analysis. Only the ANSYS Multiphysics, ANSYS Mechanical, and ANSYS Professional programs support thermal analyses. The basis for thermal analysis in ANSYS is obtained by a heat balance equation from the principle of conservation of energy. Nodal temperatures are being calculated by the finite element solution you perform via Mechanical APDL, then uses the nodal temperatures to obtain other thermal quantities. The ANSYS program handles every one of the three essential methods of heat transfer: conduction, convection, and radiation.

6.1. Convection

You determine convection as a surface load on conducting solid elements or shell elements. You indicate the convection film coefficient and the bulk fluid temperature at a surface; ANSYS at that point ascertains the fitting heat exchanges over that surface. In the event that the film coefficient relies on temperature, you determine a table of temperatures alongside the relating estimations of film coefficient at every temperature.

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are:

- ➢ The temperature distributions.
- ➢ The amount of heat lost or gained.
- ➢ Thermal gradients.
- ➢ Thermal fluxes.

Thermal simulations play an important role in the design of many engineering applications, including internal combustion engines, turbines, heat exchangers, piping systems, and electronic components.

In many cases, engineers follow a thermal analysis with a stress analysis to calculate thermal stresses (that is, stresses caused by thermal expansions or contractions).

VII. ANSYS APDL WORK BENCH

7.1. Types of Thermal Analysis.

ANSYS supports two types of thermal analysis:

- ➢ A **steady-state thermal analysis** determines the temperature distribution and other thermal quantities under steady-state loading conditions. A steady-state loading condition is a situation where heat storage effects varying over a period of time can be ignored.
- ➢ A **transient thermal analysis** determines the temperature distribution and other thermal quantities under conditions that vary over a period of time.

7.2. Steady state Thermal Analysis

Steady-state thermal analysis is supported by The ANSYS Multiphysics, ANSYS Mechanical, and ANSYS Professional products. The effects of steady thermal loads on a system or component can be calculated by a steady-state thermal analysis. Engineer/analysts often perform a steady-state analysis before performing a transient thermal analysis, to help establish initial conditions. A steady-state analysis also can be the last step of a transient thermal analysis, performed after all transient effects have diminished.

You can use steady-state thermal analysis to determine temperatures, thermal gradients, heat flow rates, and heat fluxes in an object that are caused by thermal loads that do not vary over time. Such loads include the following:

- ➢ Convections,
- ➢ Radiation,
- ➢ Heat flow rates,
- ➢ Heat fluxes (heat flow per unit area),
- ➢ Heat generation rates (heat flow per unit volume),
- ➢ Constant temperature boundaries.

7.1.2. Transient Thermal Analysis.

The ANSYS Multiphysics, ANSYS Mechanical, and ANSYS Professional products support transient thermal analysis. Transient thermal analysis determines temperatures and other thermal quantities that vary over time.

Engineers commonly use temperatures that a transient thermal analysis calculates as input to structural analyses for thermal stress evaluations. Many heat transfer applications - heat treatment problems, nozzles, engine blocks, piping systems, pressure vessels, etc. - involve transient thermal analyses.

A transient thermal analysis follows basically the same procedures as a steady-state thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time.

To specify time-dependent loads, you can either use the Function Tool to define an equation or function describing the curve and then apply the function as a boundary condition, or you can divide the load-versus-time curve into load steps.

7.1.3. Task in a Thermal Analysis.

The procedure for performing a thermal analysis involves three main tasks:

- Build the model.
- Apply loads and obtain the solution.
- Review the results.

There are three ways to build the system model. First is by using surface-effect element, and the other is by creating model geometry. For reviewing results by two ways i.e. with the General Postprocessor, with the Time-History Postprocessor, and as a Graphics or Tables. The analysis approach has two ways to deal with i.e. Commands for building and solving the model, and by using GUI method.

VIII. CONCLUSION

The thermal analysis by using computer software ANSYS is quite easier and accurate, on the other hand it is a bit complex while establishing the interfacing between ANSYS Maxwell and ANSYS Mechanical. The introduction to ANSYS package as well as the detailed classification of electromagnetic analysis and thermal analysis is given. The clear overview of FEM technique and its importance is discussed. The foremost advantage of this review gives overall picture of thermal analysis. The paper creates an advantage to the future researchers to explore the subject extensively. This paper provides all the pre-requisite needed for thermal analysis. This paper gives more than references which is needed to explore the topic.

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