Synopsis

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The economic and social growth of any country depends on the power generation and its efficient utilization. It is really a challenging task for any authority to cater to the need of a customer which is ever increasing both in nos. and KVA requirements. In today's competitive environment, an authority needs to adhere to the new technology which is cost effective, efficient and hassle free.

A dry type transformer (available in a range up to few tens of MVA) provides an alternative mean to oil cooled transformer especially in distribution network. The oil cooled transformers not only present the maintenance problems but also limits the working of the transformer under over load condition. The dry transformers present high resistance to short circuit currents, surge voltages and humidity effects. Also they present reduced noise levels and supports the high temperature levels which make them compact compared to oil cooled transformers. Whereas the oil deterioration in oil cooled transformers reduces their life and at the same time the authority needs to keep 100% availability of spare transformer during the time of oil replacement to avoid the power interruption.

The concept of dry type transformer is not new, however the enormous use of different types of insulating material in dry type distribution and power transformer makes it necessary to carry out the complete analysis of the transformer at the design stage to avoid probable failure in the field and consequently the power interruption and also to increase the cost effectiveness.

Finite Element Analysis (FEA) using Finite Element Method (FEM) was developed over 70 years to solve the complex elasticity and structural analysis problem in civil and aeronautical engineering. Application of FEA is being expanded to simulation in electrical engineering also to solve the complex design problems. The circuit theory models for designing transformers are not much accurate in determining the transformer parameters such as winding impedance, leakage inductance, hot spot temperature etc. The physical realization of these parameters is needed on a prototype unit. The finite element method can play a vital role in deriving these parameters without any physical verification. An effort has been made in this thesis to show the effectiveness of finite element method in determining the above said parameters while designing the transformers - for power and distribution sectors.

The finite element method (FEM) rapidly grew as the most useful numerical analysis tool for engineers and applied mathematicians because of its natural benefits over prior approaches. The main advantages of FEM are, it can be applied to arbitrary shapes in any number of dimensions, the material properties can be non-homogeneous (depend on location) and/or anisotropic (depend on direction). The way that the shape is supported (also called fixtures or restraints) can be quite general, as can be the applied sources (forces, pressures, heat, flux, etc.). The FEM provides a standard process for converting the governing energy principles or governing differential equations in to a system of matrix equations to be solved for an approximate solution. For linear problems such solutions can be very accurate and quickly obtainable.

Various papers have been reviewed that show the use and effectiveness of finite element method in designing the power transformer such as Power transformer design using magnetic circuit theory and finite element analysis – A Comparison of Techniques [2], internal winding fault detection and analysis [4, 5], a three dimensional finite element analysis of electric fields at winding ends of dry type transformer [15], hot spot and life evaluation of power transformer [8, 20], leakage inductance calculations [10] and transformer over heating under non linear load conditions [11] etc. With development of the electronic equipments such as Computers, UPS, and High Frequency Drives for motor loads, arc furnaces, Electronic Ballasts, Compact Fluorescent Lamps, etc. the harmonic content in the power distribution network has increased tremendously. These highly non linear loads are present not only in the industrial sectors but also in the commercial sector and the first victim to any such load is always a transformer feeding them. These non linear loads result into the overheating of the transformers. The non linearity of the loads is best judged by the K factor [1] and accordingly the transformer required is being designated as K-rated transformer. The K-rated transformer does not mitigate the harmonic but is capable enough to sustain the overheating due to such non linear loads. The design and application considerations along with testing approach based on UL, NEMA and IEEE standard C57.110-1986 are best described by L. W. Pierce, member IEEE [6].

A three dimensional finite element method using a magnetic scalar potential formulation is applied [11] to compute the magnetic field in free and iron spaces. The calculation is then combined with a mixed analytical and numerical form of the electrical circuit equation to take into account the skin and proximity effects in the rectangular windings in dry type transformers under non linear load conditions.

The hot spot in any electrical machine is due to losses in it. The hot spot temperature is to be determined for estimating the life of insulating material and consequently that of a machine. In a transformer the heat flow is through core and through winding and insulation. It mainly depends on its geometry and type of construction.

In a dry type transformer the construction is critical for maintaining the thermal capacity. Thermal capacity is defined by its ability to supply the rated load within predefined temperature rise limit in connection with the temperature rise limits of the insulating materials used. The parameters governing the temperature rise are no load losses, load losses and the space between core and winding. The volume of core and winding plays a vital role in heat dissipation.

The another major problem observed during the design stage is the estimation of impedance value and short circuit forces in a transformer during dead short circuit on the load side of a transformer. The finite element analysis is to be done in determining such forces and also the impedance values to the close proximity there by reducing the design efforts.

The other type of short circuit in transformer is turn to turn, disk to disk or turn/disk to earth short circuit. This occurs mainly because of the aging of the insulation. This leads to the overheating of the transformer and finally results into the transformer failure. Study shows that around 70-80% of the transformer failures are due to the short circuit between turns. Considering this damage occurring in the transformer and time and cost involved in rectifying the same, it seems that simulation involving modeling of the transformer is the most economical and convenient way. One of such methods of modeling distribution transformer with internal short circuit faults using Finite Element Analysis (FEA) is presented in [5]. The electromagnetic quasi-static finite element approach [4] describes the detection of winding short circuit faults with the help of frequency response analysis. In [8], a temperature calculation method for oil cooled transformers to identify the hottest spots with consideration of stray losses has been evaluated using finite element method. The same approach may be extended to dry type transformers also.

References [2], [6], [15] & [23] also describe various approaches for designing transformer using FEM. FEM for calculating the leakage flux and force on a power transformer winding under short circuit condition is represented in [17].

A case study on 30 MVA, 63 KV/20 KV, Ynd1, and 50 Hz transformer has been discussed in paper [4]. The frequency response analysis in power transformer for detecting the winding short circuits due to inter-turn faults or disk to disk faults has been carried out. Parameters of transformer are estimated by means of finite element analysis and utilized in circuit based model and the input impedance is calculated in wide band frequency. In addition to classifying and analyzing main types of short circuit according to IEEE standard C57.140, frequency response of disk-disk short circuit state is also investigated in several points in the HV winding to identify the location of the short circuit fault along the winding. The results have been summarized in terms of deviation of resonance component which showed that the first resonance of the input impedance due to short circuit moves orderly giving a better idea about the location of the short in a winding.

The built-in leakage inductance of the transformer also helps in making them short circuit proof. The finite element analysis of a dry type transformer makes it possible to estimate the winding reactance and leakage reactance to the close approximation [10] thereby reducing the design efforts for estimating the impedance value and also the short circuit forces.

A short circuit analysis of a split winding transformer using coupled field circuit approach has be presented in [6]. In this study authors have estimated short circuit forces on an individual winding using FEM. However, actual deformation due to such short circuit was not estimated. These mechanical forces have been taken care of in [21] on a 50 KVA dry type transformer with experimental verification.

Apart from above sited problems, the design of air distances (insulation supports) and exact estimation of magnetizing inrush current are the major issues in oil cooled as well as dry type medium and high voltage transformers. However in oil cooled transformers the air distances are not creating havocs inside the transformer tank due to the presence of oil. But in dry type transformers this becomes a critical problem. Over dimensioning of air distances avoid the breakdown between upper high voltage side and core frame but at the same time adds to the cost and size of the transformer. A study of the parameters that affect the breakdown voltages in dry type transformers is performed in [12]. The effect of the high operational temperatures of the transformer on the voltage breakdown in the supports as well as other insulating materials is investigated and the electric field distribution on different profiles of these supports is modeled using finite element method. Based on the estimation of the electric field distribution around the support and also winding and core, the magnetizing inrush current can be computed to the closest approximation.

In this research work an effort has been made to investigate on the core areas of dry type transformers (Distribution and Power Transformers of Medium Voltage range) as listed above with the help of finite element analysis and finally an optimized design solution has been obtained by using the optimization solver.

The main objectives of this research work, "Finite Element Analysis of Dry Type Transformers" are:

- ✓ To find out the temperature rise and hot spots under linear and / or non linear load conditions (K rating of the transformer) of a transformer being operated in IP 00 conditions or within an enclosure.

- ✓ To determine the Impedance value and short circuit forces to identify the electrical stresses and weakest insulation points in a transformer or reactor winding.

- ✓ To estimate the magnetizing inrush current low and medium voltage transformers and air clearance in medium voltage transformers.

- ✓ To work out the optimized design based on the results obtained from Finite Element Analysis (FEA) of dry type transformers. A reverse design approach [20] has been adopted for this.

The thesis has been organized in following 5 chapters:

Chapter 1: It gives an introduction about the use of oil cooled and dry type transformers. The difficulties encountered in oil cooled technologies, advantages of dry type technologies and challenges in meeting the design development requirements in both oil cooled and dry type transformers. It also represents a historical development of both the technologies.

Chapter 2: An overview of Finite Element Method and Finite Element Analysis has been presented in this chapter. Various approaches that can be adopted in designing and being adopted by different research scholars have been discussed. Literature survey has been represented in this chapter along with highlights of different type of optimization techniques.

Chapter 3: In this chapter, a theoretical approach for determining various design parameters as narrated in objectives i.e. Determination of Impedance value and Short Circuit Forces, Determination of Temperature Rise and Estimation of Magnetizing Inrush Current and Air Clearance using Finite Element Analysis has been described. The results are presented and compared with the analytical results obtained by testing the respective models in third party laboratories in line with relevant reference standards.

Chapter 4: Based on the obtained designed parameter mainly impedance value and temperature rise estimation within prescribed limit of the declared insulation class/declared temperature rise limit, the design optimization has been done. A generalized approach has been presented for optimizing the transformer design for low and medium voltage transformers. A reverse design approach has been also suggested to have the optimized design without violating the limits / constraints on the design parameters.

Chapter 5: It represents the main findings of this Thesis and suggests for future scope for further research work.

List of Papers Presented/Published

1. G. H. Chitaliya and S. K. Joshi, "Finite Element Method for Designing and Analysis of the Transformer – A Retrospective", *Proceedings of International Conference on Recent Trends in Power, Control and Instrumentation Engineers, ACEEE 2013*, pp. 54-58, doi: 03.LSCS.2013.7.524
2. G. H. Chitaliya and S. K. Joshi, "Determination of Short Circuit Stresses in an Air Core Reactor using Finite Element Analysis", *International Journal of Engineering Science and Technology,* vol 7, no. 3, pp. 141-147, 2015, ISSN:2141-2839
3. G. H. Chitaliya and S. K. Joshi, "Determination of Temperature Rise in A Dry Type Transformer using Finite Element Analysis", *2016 IEEE Annual India Conference (INDICON)*, Bangalore, 2016, pp. 1-6, ISSN: 2325-9418, doi: 10.1109/ INDICON.2016.7839110

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