Chapter 1

Introduction

1.1 General

The basic function of a transformer is to transfer the energy from one electrical circuit to another by providing electrical isolation and changing the supply voltage level keeping the frequency unchanged. The law of Electromagnetic Induction developed by Sir Michael Faraday in 1831 has opened all the doors for electricity generation and transfer. However it took around 50 years since then to have the first commercial dry type electrical transformer. The first toroidal core dry type transformer was developed by OttÓ Bláthy, Miksa Déri and Károly Zipernowsky in the year 1985 and named it as “ZBD Transformer”. William Stanley then developed a more versatile commercially usable transformer with E-I core. The basic use of transformer at that time was to illuminate the arc lights, incandescent lights and power a railway line.

With increasing demand of the electricity, it had become necessary to transfer high amount of electricity (electrical energy) over a long distance.

The transmission of electrical energy (electrical power) over a long distance at low voltage demanded conductors with higher cross section area as the power distribution system had to handle a large amount of current. This had provided an opportunity to the scientist / engineers to develop a transformer which can step up the voltage at sending end and step down the voltage at receiving end. Handling high voltages on either end of a transformer was too difficult in those days due to non availability of insulating material with higher dielectric strength. The availability of petroleum based oil was there in early 1890s and the first oil cooled, oil insulated transformer was developed in early 1900s by William Stanley for the voltage level of 800 V to 11 kV and then up to 60 kV. The AC Power was transmitted over 22 miles using these transformers. Since the petroleum based oils were highly flammable, in early 1940s, the mineral oil (Askarels) had come into the use as an insulating as well as cooling media in a transformer. Later on in early 1970s the silicon oil and in 1990s the synthetic oils have come into the market but mineral oil is still in use due to cost effectiveness and ease of availability.

1.2 Technology Comparision – Oil Cooled vs Dry Type

The mineral oil (which will be hence forth referred to as oil or transformer oil), serves dual purpose in transformer, one as insulating media and second as cooling media. It has got numerous advantages and disadvantages in terms of dielectric strength, temperature rise and life expectancy of the transformer.

The use of oil in a transformer helps in improving the dielectric strength of the transformer winding. The craft paper being used to insulated the winding, easily absorbs the oil which then increases its dielectric strength considerably ultimately reducing the requirement of maintaining the clearances between high voltage winding and core (earth). The dielectric strength of oil is around 30 kV / mm which can further be enhanced to 60 kV / mm or even more if it is purified / filtered. The same for dry type transformer is mainly governed by the air which is around 3 kV/mm if it is dry and having normal temperature and pressure. At elevated temperature and pressure it reduces abruptly.

The other governing parameter that affects the transformer design is its temperature rise. The use of oil not only serves the purpose of insulation but it also acts as cooling media. The use of radiator with the main tank of oil insulated transformer helps in cooling down the oil and thereby cooling down the transformer considerably. This allows to design the transformer winding even with a current density of 4 to 5 A / sq.mm. Both of these advantages of oil i.e. higher dielectric strength and use as a cooling media helps in reducing the size and cost of the transformer considerably.

In spite of having above narrated advantages, the oil has got certain limitations such as low value of decomposition temperature, gasification, formation of sludge inside the oil etc. The increase in the oil temperature beyond 105 $^{\circ}C$ starts decomposition of oil which at first instant starts the gasification and ultimately leads to the sludge (carbon) formation. Also to allow the expansion and contraction of oil due to temperature variation in day to day life, transformer is being provided with conservator which has a breather with silica gel to allow the dry air to move in and out of the conservator. The life of silica gel is around 3 to 6 months depending upon the weather condition of the place where a transformer has been installed. It is to be replaced immediately on expiry of its life (it give change in color at the end of its life), however due to human negligence, often it is forgotten and this allows the moisture penetration inside the oil. This contaminates the oil and helps in creating the sludge in the oil there by reduces the life of oil.

The sludge is a good conductor of electricity. Circulation of sludge takes place during the contraction and expansion cycle of the oil which gradually bridges the gap between winding and core (earth) of the transformer leading to a phase to ground failure or phase to phase or inter-turn or inter-layer failure.

In large oil cooled transformers (power ratings in terms of few tens of MVA), it is possible to go for online DGA (Dissolved Gas Analysis or Chromatography) to monitor the status of the oil, but for small transformer it is quite a costly affair. In small transformer one can only do the dielectric testing of the oil which may or may not give the correct information about the contamination of the oil. Also contaminated oil can be filtered and reused, however this has too got a limitation. After certain nos. of filtrations (around 6 to 8 filtrations), the oil required to be changed completely as it loses its properties considerably. This demands a temporary outage of the transformer from the service which is only possible by having a same capacity spare transformer. Apart from all these problems, oil spillage, oil leakages, handling of oil, oil filtration, continuous checking of the healthiness of oil, maintaining the oil level inside the transformer, etc. are the peripheral issues related to the maintenance of the oil cooled transformers.

With the advent of technologies in last 50 years, it has become possible to have a dry type transformer in a range up to 10 MVA (higher MVA ratings are under development stage) with a voltage level up to 33 kV. This provides an alternative mean to oil cooled transformer especially in distribution network. The higher grade insulating materials having dielectric strength of the order of 3 kV / mm to 12 kV / mm or even more helps in having the optimum air clearance there by attaining the good level of dielectric strength (of course up to 33 kV level only) and at the same time allows designing the transformer with higher temperature levels. The availability of insulating material of higher temperature class – up to class C or class R which can withstand temperature of the order of 200 or 220 $^{\circ}C$, makes it possible to have compact and cost effective transformers with complete customization.

One major problem with the oil cooled transformers is its working limitation under over load or short circuit condition. The momentary overloads lasting for few minutes to the maximum couple of tens of minutes or a dead short circuit even for few milliseconds; may heat up the oil beyond 110 $^{\circ}C$ leading to the decomposition of the oil which over a period of time leads to the complete failure of the oil cooled transformer. On the contrary, a dry transformer can handle such momentary overloads or dead short circuits quite easily without permanently loosing the dielectric strength or without having appreciable deterioration in the characteristics of the insulating material. This increases the life span of a dry type transformer as compared to that of an oil cooled transformer.

The peripheral issues normally observed with oil cooled transformers are no longer there with the dry type transformer except for the regular cleaning of dust and sediments and periodic physical inspection.

This indicates that for low and medium voltage applications, dry type transformers can give a better option in comparison to an oil cooled transformer for distribution level up to 10 MVA. Also the development of compact substations for commercial applications e.g. in shopping malls, cinemas, residential enclaves etc., demands the use of dry type transformers as they are having better life span as compared to oil cooled transformers and being maintenance free or having quite low maintenance related issues

1.3 State-of-the-Art

The use of Finite Element Method (FEM) and Finite Element Analysis (FEA) in the field of electrical engineering is evident since long back by around 1960s.The finite element analysis of engineering systems governed by a non linear quasi-harmonic equation has been discussed by Lyness et.al [1]. The developments in adaptive finite element software systems have been presented in [2]. Harewood and McHugh [30] made the comparison of implicit and explicit finite element methods using crystal plasticity. J. Mackerle has presented a bibliography on parallel finite element and boundary element analysis – theory and applications [17].

Various papers have been presented describing the use of finite element method in designing the transformer. In [5], hottest spot temperatures have been identified for different type of windings of a dry type transformer and hottest spot temperature in ventilated dry type transformer too. Petkov [10] has presented his work on optimum designing of a high power, high frequency transformer. Kezunovic and Guo [16] have done modeling and simulation of power transformer. M. Rausch and et.al [20] have used the combination of finite and boundary element methods in investigation and prediction of load controlled noise of power transformers. M. K. Pradhan [28] did the assessment of the status of insulation due to thermal stresses during accelerated life test experiments on prototype transformer. In [33] and [35], object oriented knowledge based system for designing a distribution transformer and computer aided analysis and designing of power transformers have been discussed respectively. D. L. Harris [38] has discussed at length about the design and performance of circular disc, helical and layer type of windings used in power transformers. Y. Li and et.al have studied the characteristics parameters of a converter transformer for HVDC system. In [42], A. D. Theocharis and et.al have presented a three phase transformer model that included the effects of eddy currents and magnetic hysteresis. An analytical algorithm for calculating the magnetization and loss curves of a delta connected transformer has been presented by Chiesa and Hoidalen in [43].

M. Eslamian and et.al [44] proposed a method having a combination of analytical and finite element method for obtaining a high frequency model of cast-resin dry type transformer. A detailed model of the transformer has been used and parameters like Resistance (R), Inductance (L), Capacitance (C) and losses have been identified using finite element method. In [55], Metwally has discussed about the failures, monitoring and new trends in power transformers. He has mainly discussed and compared three main types of transformers namely, oil immersed, gas insulated and dry type. A current limiting or self limiting transformer design up to the rating of 100 kVA has been proposed as in [56] and test results have been also presented therein. A detailed literature survey has been presented in chapter 2 that has inspired the author for taking up this research task.

1.4 Motivation

Whether it is a dry type or oil cooled transformer certain design challenges are still accounted for. They are; determination of impedance voltage, temperature rise of the winding and oil in case of oil cooled transformer, air clearances especially in dry type transformer and estimation of magnetizing inrush currents. For impedance and temperature rise verification a prototype coils is required to be manufactured and to be tested for both the parameters. However a prototype coil does not give the exact estimation of air clearances and inrush current. Air clearances in an oil cooled transformer do not create havoc due to presence of oil inside the tank / enclosure but for dry type transformer, it's a critical issue. Over designing of air clearances do avoid the failure between high voltage winding and core / earth but at the same time it increases the size and ultimately the cost of a dry type transformer.

All these design related issues can be solved using finite element analysis. It can be used in estimating the electric field in the entire geometry of a transformer and there by identification of the impedance, air clearances and inrush current can be made possible without manufacturing any prototype winding. Also finite element analysis can be used in finding the temperature distribution in the winding as well as core ultimately eliminating the requirement of manufacturing a prototype coil. Apart from all above cited design problems, optimization of the design is the demand of present highly competitive market. During the literature survey, it has been observed that an effort is required to estimate the impedance value and thereby short circuit forces/stresses, temperature rise distribution in winding and core segments of a dry type transformer and finally to have design optimization based on achieved results. If required a reverse design approach may be adopted as in [14]. All these problems have motivated the author to take up this research work on – "Finite Element Analysis of Low and Medium Voltage Dry Type Transformers".

The main objectives of this research work 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 in a low or medium voltage transformers and air clearance in a medium voltage transformers.
- To work out the optimized design based on the results obtained from Finite Element Analysis (FEA) of a dry type transformers. A reverse design approach has been adopted for this [14].

1.5 Thesis Organization

The thesis has been organized in following 5 chapters:

Chapter 1: It has given an introduction about the use of oil cooled and dry type transformers with their historical development. 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.

Chapter 2: It gives an overview of Finite Element Method and Finite Element Analysis. Various approaches that can be adopted in designing and being adopted by different research scholars have been discussed. A 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 , Estimation of Magnetizing Inrush Current and Air Clearance using Finite Element Analysis have 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.