MODELLING AND ANALYSING DOUBLE HELICAL WINDINGS WITH FINITE ELEMENT METHOD

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ABSTRACT

The procedure for the analysis of power distribution transformer can be used to calculate the short circuit electromagnetic forces of large power transformer also. Therefore, a 630kVA, 11/.433kV power distribution transformer has been modelled for analysing the short circuit electromagnetic forces. Windings are modelled in twenty three sections and short circuit force of each and every section of the winding is calculated using Finite Element Method of analysis. Electromagnetic forces are calculated for single helical and double helical windings of transformer. The basic principle of transformer is electromagnetic induction, which implies that electrical energy is efficiently transferred by induction from one set of coils to another by means of varying magnetic flux, provided that both sets of coils are on a common magnetic circuit. Electromotive forces are induced by change in flux linkages.

Keywords: Short Circuit Forces, Power Distribution, Windings, Finite Element Method (FEM)

1.0 INTRODUCTION

The short circuit strength of a transformer enables it to survive through fault currents due to external short circuits in a power system network; aninadequate strength may lead to a mechanical collapse of windings, deformation/damage to clamping structures, and may eventually lead to an electrical fault in the transformer itself. The internal faults initiated by the external short circuits are dangerous as they may involve blow-out of bushings, bursting of tank, fire hazard etc. The short circuit design is one of the most important and challenging aspect of the transformer design; it has been the preferential subject in many CIGRE Conferences including the recent session (year 2000)[1].

This chapter first introduces the basic theory of short circuits as applicable to transformers. The thermal capability of transformer windings under short circuit forces is also discussed. There are basically two types of forces in windings: axial and radial electromagnetic forces produced by radial and axial leakage fields respectively.[2] Analytical and numerical methods for calculation of these forces are discussed. Various failure mechanisms due to these forces are then described. It is very important to understand the dynamic response of a winding to axial electromagnetic forces. Practical difficulties encountered in the dynamic analysis and recent thinking on the whole issue of demonstration of short circuit withstand capability are enumerated.[3] Design parameters and manufacturing processes have pronounced effect on natural frequencies of winding design aspects of winding and clamping structures are elucidated. Precautions to be taken during design manufacturing of transformers for improving short circuit withstands capability are given.

1.1 SHORT CIRCUIT CURRENT

The generator step-up transformers are generally subjected to short circuit stresses lower than the interconnecting autotransformers. The higher generator impedance in series with the transformer impedance reduces the fault current magnitude for faults on the HV side of the generator transformer. [4]There is a low probability of faults on its LV side since the bus-bars of each phase are usually enclosed in a metal enclosure (bus-duct). But, since generator transformers are the most critical transformers in the whole network, it is desirable to have a higher safety factor for them. Also, the out-of-phase synchronization in generator transformers can result into currents comparable to three-phase short circuit currents. It causes saturation of the core due to which an additional magnetizing transient current gets superimposed on the fault current [5]. Considerable axial short circuit forces are generated under these conditions [6].The nature of short circuit currents can be highly asymmetrical like inrush currents. A short circuit current has the maximum value when the short circuit is performed at zero voltage instant. The asymmetrical short circuit current has two components: a unidirectional component decreasing exponentially with time and an alternating steady-state symmetrical component at fundamental frequency. The rate of decay of the exponential component is decided by X/R ratio of the transformer. The IEC 60076–5 (second edition: 2000–07) for power transformers specifies an asymmetry factor corresponding to switching at the zero voltage instant (the worst condition of switching). For the condition X/R>14, an asymmetrical factor of 1.8 is specified for transformers upto 100 MVA rating, whereas it is 1.9 for transformers above 100 MVA rating.

1.2 THERMAL CAPABILITY OF SHORT CIRCUIT

A large current flowing in transformer windings at the time of a short circuit results in temperature rise in them. Because of the fact that the duration of short circuit is usually very short, the temperature rise is not appreciable to cause any damage to the transformer. While arriving at these expressions, an assumption is made that the entire heat developed during the short circuit is retained in the winding itself raising its temperature.[7] This assumption is justified because the thermal time constant of a winding in oil-immersed transformers is very high as compared to the duration of the short circuit, which allows us to neglect the heat flow from windings to the surrounding oil. The maximum allowed temperature for oil-immersed Transformers with the insulation system temperature of 105°C (thermal class A) is250°C for a copper conductor whereas the same is 200°C for an aluminum conductor. Let us calculate the temperature attained by a winding with the rate current density of 3.5 A/mm2. If the transformer short circuit impedance is 10%, the current density under short circuit will be 35 A/mm2 (corresponding to the symmetrical short circuit current).[8] Assuming the initial winding temperature as105°C (worst case condition), the highest temperature attained by the winding made of copper conductor at the end of the short circuit lasting for 2 seconds (worst case duration) is about 121°C, which is much below the limit of 250°C[9] Hence, the thermal withstand capability of a transformer under the short circuit conditions is usually not a serious design issue.

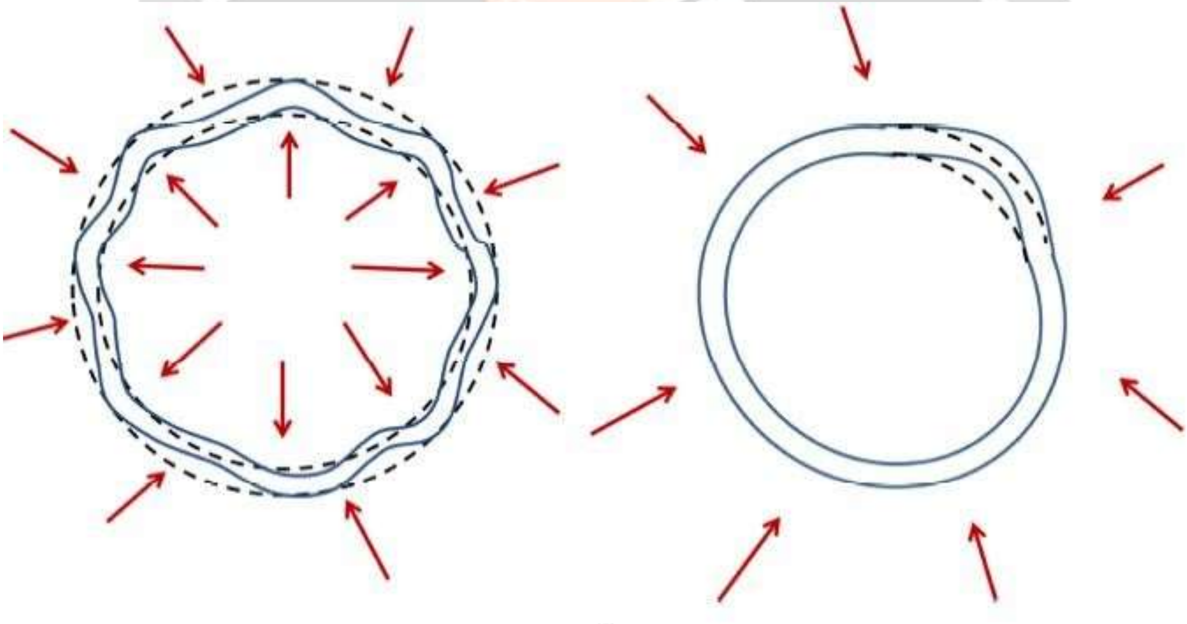

Figure 1: Forced Buckling & Free Buckling

2.0 LITERATURE REVIEW

Transformers are major parts of the power distribution network, used to step up and step down voltages for transmission between power stations and electricity consumers. Transformers are prone to failure due to external damage or general ageing of parts, which can lead to high replacement costs. Transformer failure not only interrupts the supply of electricity; it can also cause explosion and fire, threatening lives and property, and potentially disabling the power network. Several researchers have contributed in the study of short circuit forces in transformer by using Finite Element Analysis.

In 1980, Yasuro Hori developed, two methods of calculation of axial vibration of transformer in windings. In one method, the difference between the electromagnetic forces inside and those outside a core window, and the dimensions of the upper and lower insulators inside and those outside a core window, are considered. And, in the other method, variations in electromagnetic forces, which are expressed with Chebyschev's polynomial, are considered. It was also found that if each winding is regarded as a mass, then the vibration of winding can be expressed approximately by Mathieu's differential equation and Finally, a more precise analysis of the vibration of windings than was possible before was obtained with the above new methods of calculation [10]. Comparison of Assumptions in Computation of Short Circuit Forces in Transformers is done by Sheppard Salon et al. in[11]. The research describes the modeling of shell type distribution transformers with varying degrees of complexity. Results from several types of studies are reported and used to evaluate the effectiveness of FEA methods for resolving the forces exerted on the coils of a single- phase shell form transformer. The sensitivity of these methods to the very small changes in configuration due to manufacturing tolerances or operation was investigated. Several types of analysis were performed and compared to determine the best approach for design or failure analysis. It was found that Finite element methodology is appropriate for computing the winding forces in a distribution transformer. Skin effect and proximity effect may be significant as far as the force distribution is concerned but have no significant effect on the total force.

The Impact of Inrush Currents on the Mechanical Stress of High Voltage Power Transformer Coils was studied by Michael Steurer in 2002. From failure experience on power transformers, it was very often suspected that inrush currents, occurring when energizing unloaded transformers, were reason for damage. In this paper, it was investigated how mechanical forces within the transformer coils build up under inrush compared to those occurring at short circuit. Two-dimensional and three-dimensional computer modeling for a real 268 MVA, 525/17.75 kV three-legged step up transformer was employed. The results show that inrush current peaks of 70% of the rated short circuit current cause local forces in the same order of magnitude as those at short circuit. The resulting force summed up over the high voltage coil is even three times higher. Although inrush currents normally are smaller, the forces can have similar amplitudes as those at short circuit however with longer exposure time. Therefore, care has to be taken to avoid such high inrush currents. Today controlled switching offers an elegant and practical solution [12].

Calculation of Short Circuit Reactance and Electromagnetic Forces in Three Phase Transformer by Finite Element Method is done by S. Jamali. In the research a new and simple procedure for determination of leakage reactance and analysis of electromagnetic forces that acting upon the transformer coils is presented in this paper. Before manufacturing and within the design process, it is required that we model the transformer and analyze the transformer condition using this model. The analysis of electromagnetic forces is essential for mechanical considerations. This study is accomplished by using two dimensional planar models utilizing the finite element method. Just by modelling the transformer window and using FEM, the magnetic vector potential is calculated over each node. Then by using three post processing procedures, the leakage reactance of transformer coils is calculated and the results are verified by comparison with experimental result. The radial and axial electromagnetic forces are calculated over the transformer coils and the effect of asymmetrical of winding is analyzed[4].Effect of Asymmetrical Dimensions in Short Circuit Forces of Power Transformers is also find out by M Allahbakshi . Results of FEM show that type of short circuit forces in LV and HV are different. It seems that to prevent deformation of windings due to short circuit forces, more spacers should be provided between dishes which are affected by higher stresses. Misalignment of windings centers has serious effect on short circuit forces severity and their resultant. So by monitoring of such a displacement and 120 increasing of its amount before short circuit occurrence we can solve this defect [13]. Solving Electromagnetic Problems Using a Novel Symmetric FEM-BEM Approach is carried out by Keshong Zhao. A new hybrid FEM-BEM was proposed based on the Robin-to- Robin map. The method leads to symmetric systems, free of internal resonances and allows for non conformal meshes on either side of the truncation boundary. The BEM computations were accelerated with the ACA algorithm. The method was found very accurate and efficient for scattering and radiation problems [14]. In 2006 a research was done for calculations of transient Eddy Current Field and Dynamic Short Circuit Forces in a Large Power Transformer by S.L Ho et al. In this paper, the T-Ω finite element method (FEM) is proposed to study the three dimensional (3D) transient eddy current field and electromagnetic forces acting upon the coils in power transformers. The radial press stress on the coil sections is included in the computation. The axial vibration, displacement and dynamic force of the coil sections are analyzed by modeling the coil as a mass-spring [15].

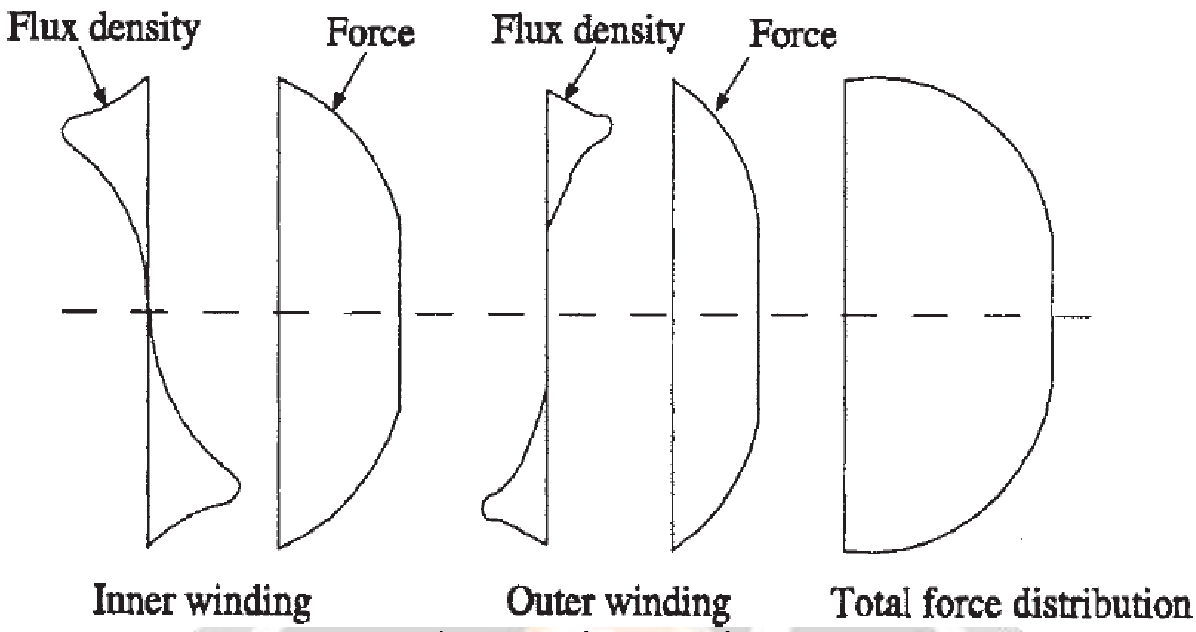

Figure 2: Axial Force Distribution

3.0 METHODOLOGY

The directions of forces are readily apparent from the Fleming's left hand rule also, which says that when the middle finger is in the direction of current and the second finger in the direction of field, the thumb points in the direction of force (all these three fingers being perpendicular to each other).It is known that the leakage field can be expressed in terms of the winding current. Hence, forces experienced by a winding are proportional to the square of the short circuit current, and are unidirectional and pulsating in nature. With the short circuit current having a steady state alternating component at fundamental frequency and an exponentially decaying component, the force has four components: two alternating components (one at fundamental frequency decreasing with time and other at double the fundamental frequency with a constant but smaller value) and two unidirectional components (one constant component and other decreasing with time). The typical waveforms of the short circuit current and force. Thus, with a fully offset current the fundamental frequency component of the force is dominant during the initial.

Radial Forces

The forces generated by the action of axial leakage field and perpendicular to the direction winding height are called the radial forces. The axial field is maximum at the middle part, in the air gap between the two windings. Hence the radial force will be maximum at that portion too. The forces acting on the inner winding produces a compressive stress and that acting on the outer winding produces a tensile stress. Let us consider an outer winding, which is subjected to hoop stresses. The value of the leakage field increases from zero at the outside diameter to a maximum at the inside diameter (at the gap between the two windings). The peak value of flux density in the gap is given in Equation 3.1 below

$$B_{gp} = \frac{\sqrt{2}\ NI\mu_o}{H_w} \qquad \textbf{(3.1)}$$

Where NI is the R.M.S value of winding ampere-turns and is winding height in meters. The whole winding is in the average value of flux density of half the gap value. The total radial force acting on the winding having a mean diameter of (in meters) can be calculated as [16]:

$$F_x = \left[\frac{1}{2}\ \frac{\sqrt{2}\ NI\mu_o}{H_w} \right] \times \sqrt{2}\, NI \times \pi D_m \qquad \textbf{(3.2)}$$

For the outer winding, the conductors close to gap (at the inside diameter) experience higher forces as compared to those near the outside diameter (force reduces linearly from a maximum value at the gap to zero at the outside diameter). The effects of radial forces are the tensile stress on the winding resulting in forced buckling and free buckling as shown in Figure2.

4.0 RESULTS & DISCUSSIONS

The finite element method (FEM) is a numerical method for solving problems of engineering and mathematical physics. Typical problem areas of interest include structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential. The analytical solution of these problems generally requires the solution to boundary value problems for partial differential equations. The finite element method formulation of the problem results in a system of algebraic equations. The method approximates the unknown function over the domain. To solve the problem, it subdivides a large system into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variation methods from the calculus of variations to approximate a solution by minimizing an associated error function.

FEM is best understood from its practical application, known as finite element analysis (FEA). FEA as applied in engineering is a computational tool for performing engineering analysis. It includes the use of mesh generation techniques for dividing a complex problem into small elements, as well as the use of software program coded with FEM algorithm. In applying FEA, the complex problem is usually a physical system with the underlying physics such as the Euler Bernoulli Equation, the heat equation, expressed in either PDE or integral equation, while the divided small elements of the complex problem represent different areas in the physical system.

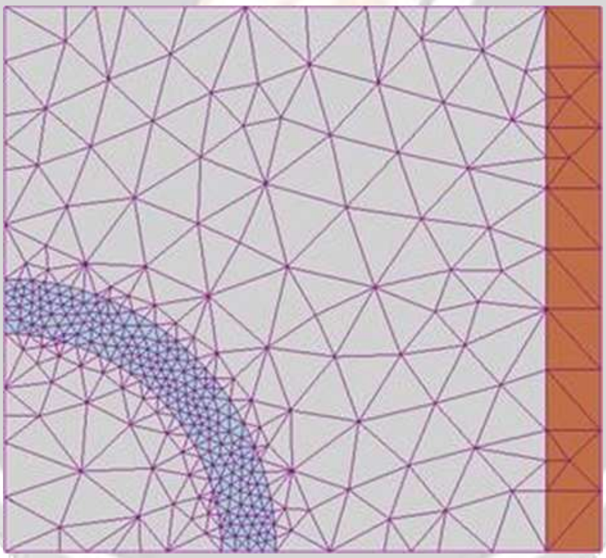

Figure 3: FEM mesh created to solve magnetic problems

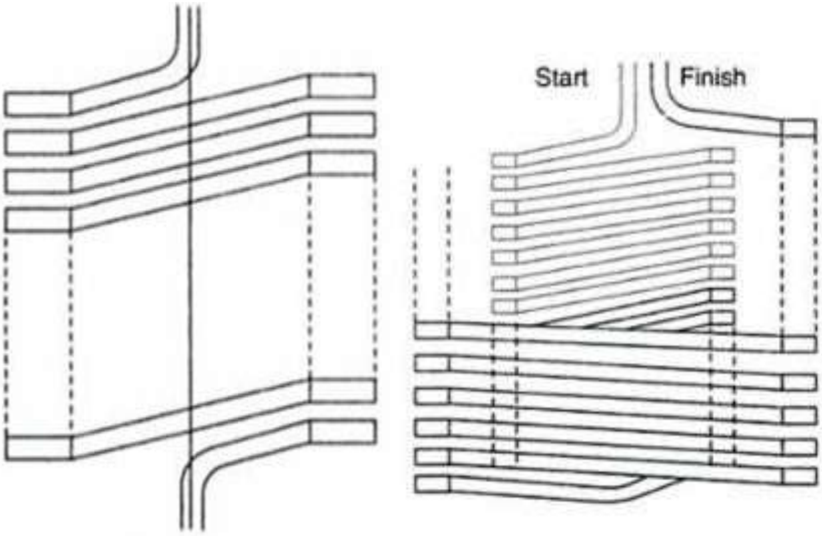

Figure 4: Single helical winding & Double helical winding

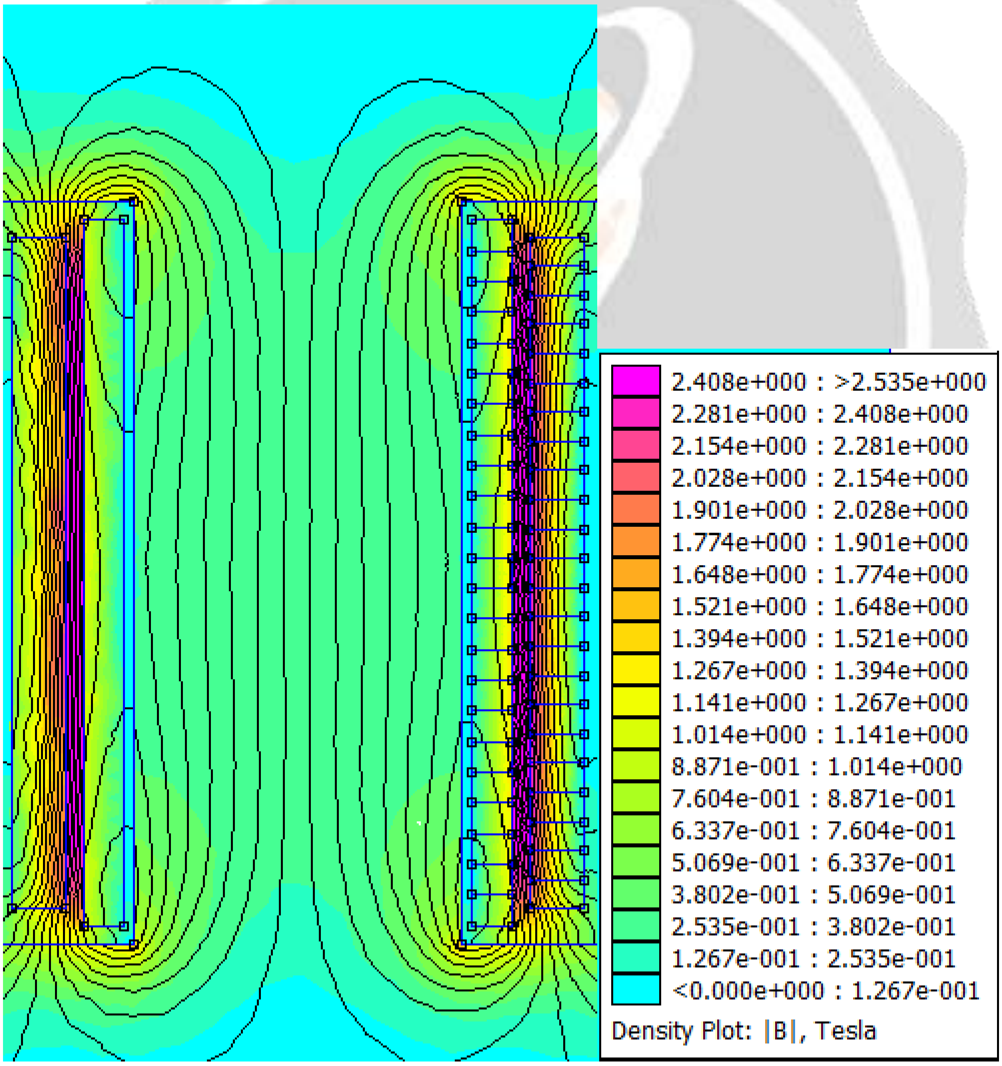

Figure 5: Magnetic density plot of double helical winding

The axial force at the turns which are at the centre of the winding is very in magnitude as compared to the axial force at the centre of the winding. Short circuit force at each cell of the winding for both LV and HV in case of single and double helical To find the axial compressive force , axial force on the first cell of the winding is added with the next cell of the winding. The axial compressive force on single and double helical windings. The maximum value of axial force is at the centre of the winding.

5.0 CONCLUSIONS

In this study ,two dimensional study is done to find out electromagnetic forces with the help of finite element method. Comparison of forces on single helical and double helical winding is done ,it is find out that forces on double helical windings are less than forces acting on single helical winding. The research analysis suggest that the transformers should be designed by keeping in mind the short circuit forces acting on them during short circuit situation. The technique used and result obtained from research may help in the design of transformer. Further work can also be extended to double helical windings with tappings..

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