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Physics of Winding Deformation in Power Transformer

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Abstract —Power transformers are the most expensive and critical component of our power system. Its failure would be a costly event. Winding deformation is caused mainly due to short circuit events, other reasons may be ageing of insulation, and mechanical stresses developed due to transportation. Although, deformation may not result in immediate failure, however the dielectric strength of the winding is greatly reduced. And a further untoward short circuit faults may result in complete rupture of insulation which will result in complete damage of the winding. To prevent permanent damage of the transformers, a routine diagnosis is necessary for detection of winding deformation.

Keywords: FRA test, FEM network, physics of winding, forces, fault analysis

I. INTRODUCTION

The occurrence of short circuit faults is a major cause behind the winding deformation in the transformers. The short circuit current is 5 to 10 times higher than the normal current flowing in the windings. As the forces developed due to short circuit current are proportional to the square of the current, it will be very high. These forces cause the winding to deform radially or axially depending on the type of force acting on them. The computation of these forces is necessary to decide the short circuits withstand capability and to take necessary precautions to prevent the damage of transformers. Analytical approaches were found to be complicated when complex geometry was involved. Hence numerical modeling technique like finite element method approach (FEM) is found to give solution for computing forces, losses, and other required parameters, even for complex geometry. In this chapter, the short circuit forces and their effects along with an example of computing forces developed in transformer winding due to an axial asymmetry by using Finite element method (FEM).

II. SHORT CIRCUIT FORCES

Short circuit events generate large magnitude of current in the transformer winding. The interaction of the current and leakage flux density result in extreme electromagnetic forces to act on the winding. The basic equation for the calculation of electromagnetic forces is,

$$F = L \, I \times B \qquad (1)$$

Where B is leakage flux density vector, I is current vector and L is winding length. There are basically two categories of short circuit forces involved in the deformation action on the transformer windings, which are axial force defined by expression in (2) and radial force defined by expression given in (3). In Fig. 1 (a) & (b), the resolution of forces and leakage flux density in radial and axial direction is shown. The leakage flux density can be resolved into two components, one in the radial direction, (Bx) and the other in the axial direction, (By). The action of radial leakage flux density with the current density *(J)* results in axial force (Fy).

$$Fy = \iint (J \times Bx) \, dx \, dy \qquad (2)$$

Similarly, the interaction of axial leakage flux density with the current density results in radial force (Fx).

$$Fx = \iint (J \times By) \, dx \, dy \qquad (3)$$

The direction of forces is apparent from Fleming's left hand rule. Forces experienced by a winding are proportional to the square of the short circuit current and are unidirectional and pulsating in nature. It is required to resolve the short circuit forces into radial and axial forces to study their influence on the winding structure due to various failure modes.

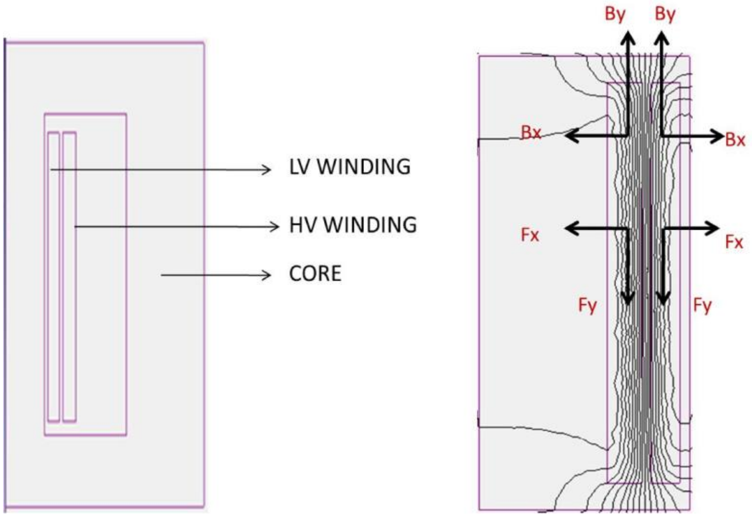

Fig. 1(a): Cross sectional view of the core and the windings of a 66/11 KV,40 MVA transformer. Fig. 1(b) Flux and forces distribution of 40MVA transformer simulated using FEM (finite element method)

2.1 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 (4).

$$Bgp = \sqrt{2}\ NI\ \pi_o / Hw \tag{4}$$

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 winding (in meters) can be calculated as,

$$Fx = [\ \tfrac{1}{2} \times \sqrt{2}\ NI\ \pi_o / Hw] \times \sqrt{2}\ NI \times \mu Dm \tag{5}$$

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 Fig. 2(a) and (b) respectively.

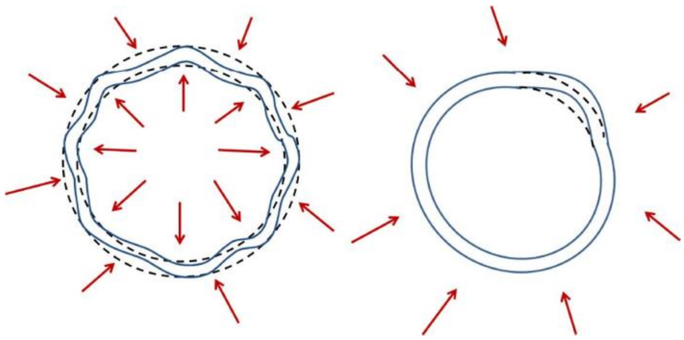

Fig. 2(a): Forced Buckling Fig. 2(b): Free Buckling

The failure modes for radial forces include

- Forced mode Buckling
- Free mode buckling
- Stretching of outer windings and spiraling of end turns in helical windings

2.2 Axial forces

The forces generated by the action of radial leakage field and acts in a direction parallel to the winding height are called as axial forces. The influence of axial forces will be maximum at the winding ends causing maximum bending of the conductors. The forces produce compressive stress on the winding conductors which acts towards the center of the winding. The axial forces are maximum at the ends of the winding as the radial leakage field between the two windings is maximum at the ends. While the axial forces will be minimum at the center as the axial leakage field is maximum between the air gap of the two windings.

For an asymmetry factor of 1.8, the total axial compressive force acting on the inner and outer windings taken together is given by the following expression:

$$F_y = [50.8 \times S] / [Z_{pu} \times H_w \times f] \quad (6)$$

Where S is rated power per limb in KVA, Hw is winding height in meters, Zpu is per-unit impedance, and f is frequency in Hz. The inner winding being closer to the limb, by virtue of higher radial flux, experiences higher compressive force as compared to the outer winding. In the absence of detailed analysis, it can be assumed that 25 to 33% of force is taken by the outer winding, and the remaining 75% to 67% is taken by the inner winding.

The reasons for a higher value of radial field and consequent axial forces are: mismatch of ampere-turn distribution between LV and HV windings, tapping in the winding, unaccounted shrinkage of insulation during drying and impregnation processes, etc.

The failure modes for axial forces include:

- Conductor tilting
- Conductor axial bending between spacers
- Displacement of the complete winding
- Axial overlap of conductors

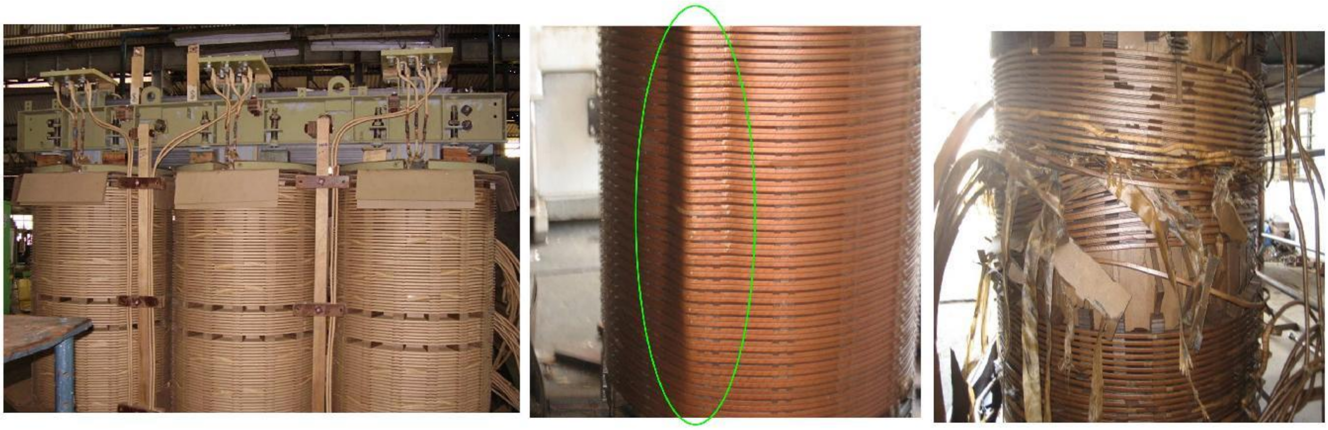

Fig. 3 (a) : 100 MVA power transformer without any deformation

Fig. 3 (b) : Free mode buckling

Fig. 3 (c): Axial deformation

III. FINITE ELEMENT METHOD (FEM) MODELING OF A TRANSFORMER

In FEM approach, the problem geometry is divided into small elements of triangular or tetrahedral shape within which the flux density is assumed constant so that the magnetic vector potential varies linearly within each element. This numerical modeling technique is a highly recommended method for analyzing any heterogeneous complicated geometry.

Table 1: Design specifications

Winding	Inner radius mm	Outer radius mm	Height mm	Turns	Rated Current(A)
LV winding	306.5	388	1136	200	2100
HV winding	413	510.5	1136	1200	350

A transformer of 40 MVA rating is designed with specifications as given in Table 1 and Fig. 4 shows the coordinates of the required design. Using these data in Table I and design coordinates of Fig.; model is designed in FEM based software MAGNET as shown in Fig 5. The material used for core is silicon steel, copper for the transformer windings and the whole model is enclosed in an airbox which acts as boundary. At normal operating conditions and identical winding symmetry, rated current will flow through the primary and secondary windings. However, if the any asymmetry arises due to shortening of height of one of the windings, the forces developed in such case is very high resulting in unequal end thrust at the ends of the windings. The reason behind this is large magnitude of current in the winding resulting in large forces top act on them.

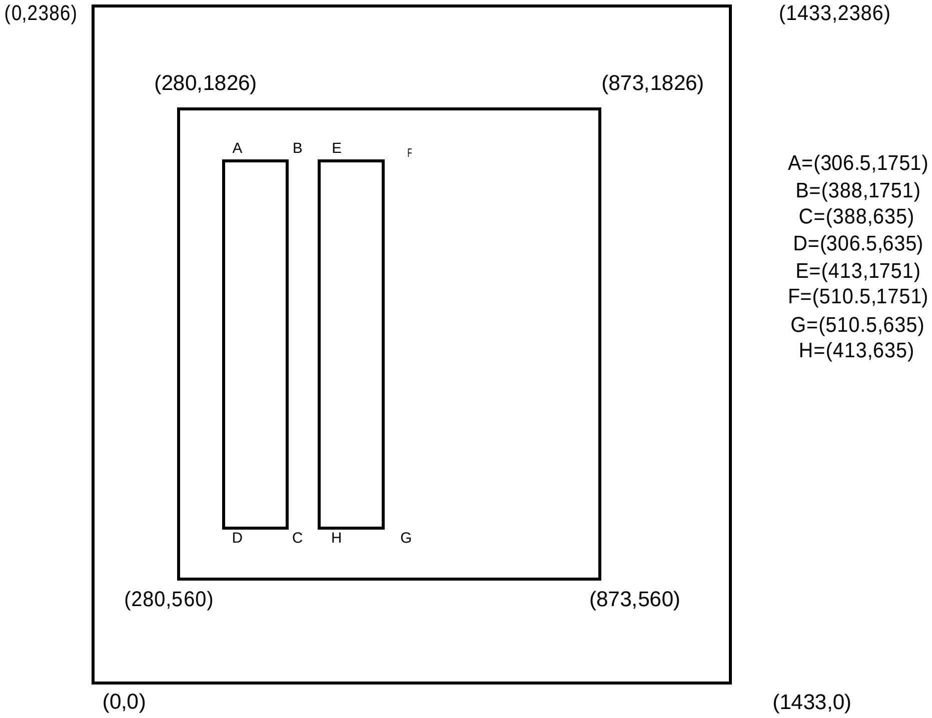

Fig. 4: geometry coordinates of transformer

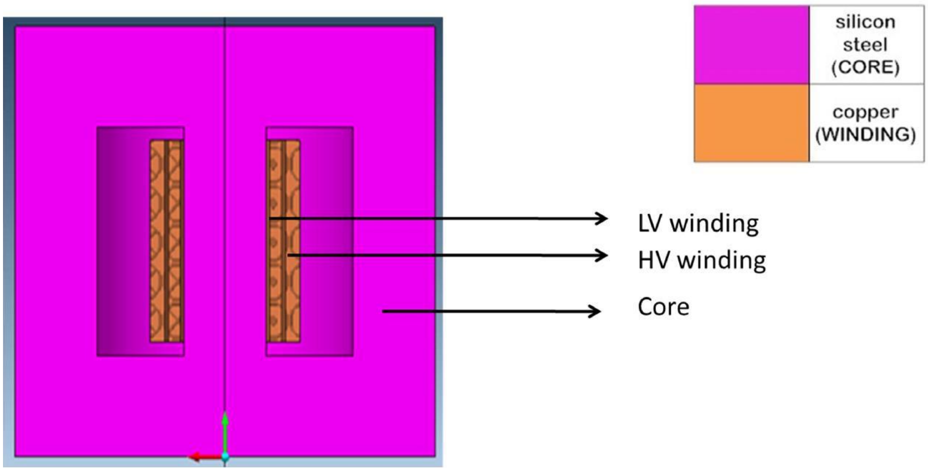

Fig. 5 Cross-sectional view of the FEM modeled transformer

Rated current flows through the primary and secondary windings of the transformer during normal operating conditions. The current in the LV and HV windings are calculated as given in (6) and (7).

$$I_p = \frac{P \times 1000}{\sqrt{3} \times V\,line} = \frac{40 \times 1000}{\sqrt{3} \times 66} = 349.90\ AMP \qquad (7)$$

$$I_s = \frac{P \times 1000}{\sqrt{3} \times V\,line'} = \frac{40 \times 1000}{\sqrt{3} \times 11} = 2099.45\ AMP \qquad (8)$$

Where, P is MVA rating of the transformer,
Ihv and Ilv are current in the hv or primary winding, and lv or secondary winding respectively,
Vline and Vline' is the line voltage across primary winding and secondary winding respectively.

And N1/N2 = V1/V2 = I2/ I1 = 6

After simulation using FEM, the flux pattern and shaded plot of magnetic flux density can be observed as shown in Fig. 6 (a) and (b). Maximum flux density exists between the HV and LV winding which is 0.468 T. The main reason behind the low value of flux density is the area of the 2D transformer model which is very less as compared to the actual transformer.

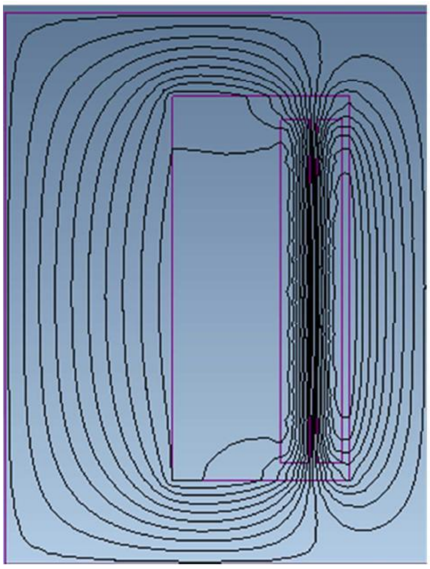

Fig. 6 (a) Flux pattern

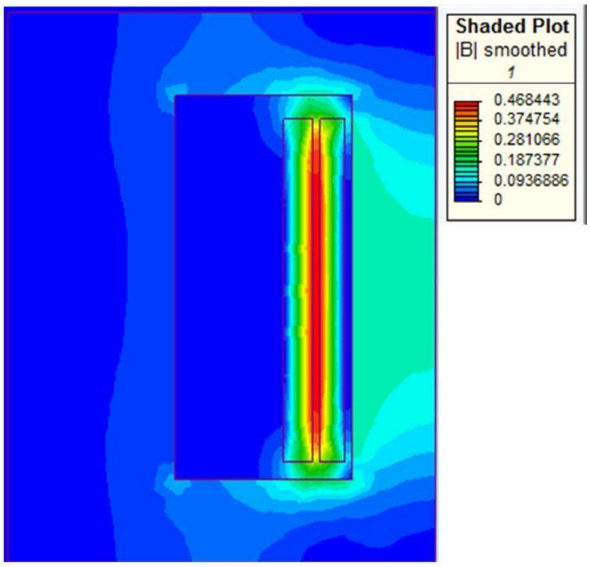

Fig. 6 (b) Shaded plot of magnetic flux density

IV. AN EXAMPLE OF STUDY OF AXIAL DEFORMATION THROUGH FEM MODELING

Any kind of asymmetry between the height of the two windings, mismatch of ampere turns, which may result due to shortening of the height of one of the windings, is capable of creating large axial force. Now, let the height of the HV winding be reduced to 1% of the original height. The forces obtained are much greater than that in normal case as the short circuit current results to flow in the windings which are assumed to be 8 times than that of the normal rated current. To calculate and compare the forces developed due to the described situation is analyzed using finite element method (FEM).

Table 2: Comparison of forces

Element	Average Force without deformation(N)	Average Force with deformation(N)
LV winding	7.72370192	7.44×10^6 N
HV winding	0.00014233	5.25×10^6 N

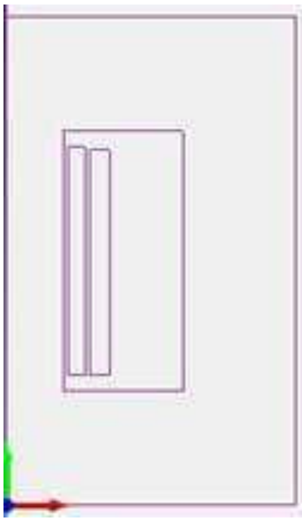

Figure 7: shortened height (1%) of the HV winding

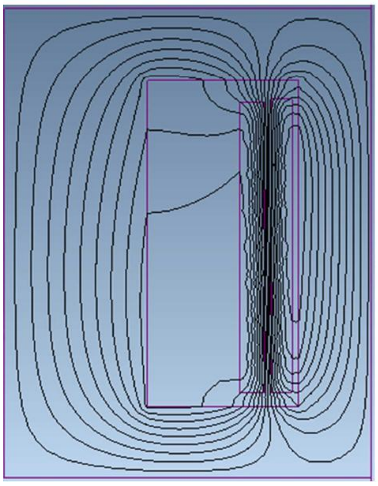

Fig. 8 (a) Flux pattern

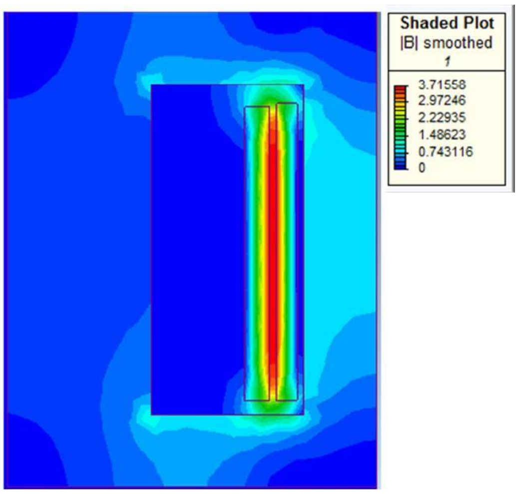

Fig. 8 (b) Shaded plot of magnetic flux density

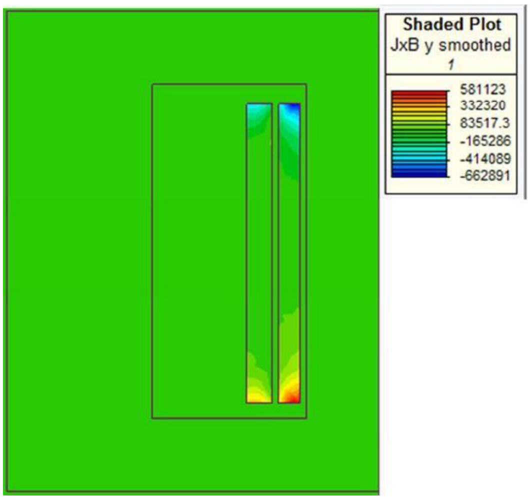

Fig. 9 (a) Axial force distribution at normal Condition

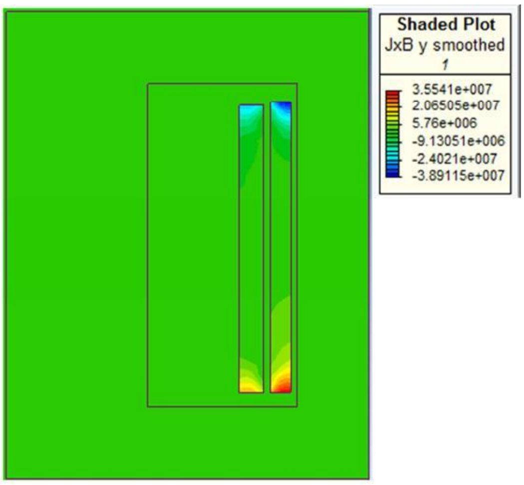

Fig. 9 (b) Axial force distribution due to asymmetry

The table clearly shows the variation of forces with change in height of one the windings. When both the windings were of same height and the electrical centers were coinciding the forces were almost nil. However when the height of one of the winding, here the HV winding was shortened, the axial force magnitude increased manifold. The end thrust will be more at the ends of the windings. Such kind of deformation will give rise to compression or expansion of the winding height.

V. CONCLUSION

The short circuit forces are the main cause of winding deformation and displacement arising in power transformers. Using numerical modeling approach like FEM, the study of winding deformation through computation of forces and other requirements can be met. Further, the method is applicable for complex geometrical structures like transformers, which is advantageous over other analytical techniques.

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BIOGRAPHIES

Sameer Patel Doing M.Tech In Electrical Engineering (Power System) At Rajasthan Institute Of Engineering And Technology, Jaipur And Also Completed Diploma & B.Tech In Electrical Engineering.