Analysis of Short Circuit Electromagnetic Forces in Transformer with Asymmetrically Placed Windings Using Finite Element Method

Anupam Sinha,
Department of Electrical and Electronics Engineering,
UIET, Panjab University,
Chandigarh, India
sinha.90@gmail.com

Sarpreet Kaur,
Department of Electrical and Electronics Engineering,
UIET, Panjab University,
Chandigarh, India
sarpreetdua@yahoo.co.in

***Abstract*—Short circuit electromagnetic (EM) forces are considered as important factor and should be taken care of while designing a transformer. The effect of forces is more important in case of large transformers, but the procedure of analysis of forces is same for both power transformers and power distribution transformers. Therefore, a 630kVA, 11/.433kV power distribution transformer has been modeled for analyzing the forces using Finite Element Method (FEM). Windings are modeled into twenty three sections and short circuit EM force of each and every section of the winding is calculated. The forces are calculated under worst fault condition of three phase symmetrical short circuit current. In practical transformer, there is some axial asymmetry between the windings. Net axial force experienced by the windings because of absence of symmetry is calculated and effect of tapping on short circuit EM forces is also included in this study.**

Keywords-Finite Element Method; Power Distribution transformer; Short Circui; Tapping; asymmetry

I. Introduction

When a transformer is made, it has to gone through some of the testing process. If it passes the test, then it is installed at the substation. There are several tests which a transformer has to undergone before putting it in use like oil test, short circuit test, overload heat test, etc. When short circuit tests are performed on the transformers, it has been found that out of every hundred transformers around thirty transformers could not pass the test [1, 2]. This is causing huge loss of money and resources.

The transformer should have adequate strength so that it can survive even under severe conditions. If the strength is not adequate, then it may cause damage to the clamping or it can also cause mechanical deformation of the windings. Sometimes the tank of transformer can explode also. Work has been done in past to study the effects caused by short circuit current in transformer [3-6]. Consequently, efforts are made to improve the design of transformer.

The mathematical tool used in this work is Finite Element Method (FEM). Literature survey tells that the results obtained by FEM are correct and almost same as experimental values.

Sometimes the nature of inner or low voltage (LV) winding of transformer is helical and causes an axial asymmetry with respect to the outer or high voltage (HV) winding, if it is of cross-over type. Axial force is exerted on the windings because of this asymmetry. Other reasons for this asymmetry are: due to inaccuracy while manufacturing the transformer, variation of ampere-turns between the windings, etc. Presence of tapping can also cause vertical displacement between the windings which breaks the symmetry [1].

In this research, short circuit EM forces for a power distribution transformer are computed when there is axial asymmetry between the windings of transformer. The same analysis has been done by applying approximately 13% tapping on the middle of HV winding.

II. Forces In Windings

Short circuit EM Force is exerted on the windings because of the current which flows in it under the condition of short circuit. Short circuit current which flows in the windings is calculated as per [7]. For easy understanding, the forces are separated into two components namely radial force and axial force. To find the value of force, Lorentz Force, F_w is computed. It is defined as the vector product of current density in the winding, J_w, and leakage flux density in that region, B_w, The expression of F_w is given in (1).

$$\vec{F}_w = \vec{J}_w \times \vec{B}_w \quad (1)$$

Fig. 1 shown the diagram which indicates different components of EM force experienced by the winding under ideal conditions. Ideal condition means there is no vertical displacement between the LV and HV winding. Under ideal conditions, the net force in the windings in the direction of Y-axis (axial) is zero. If there is some vertical displacement between the windings then there exists an axial asymmetry between the windings and a net force is experienced on the winding in the direction of Y-axis. The direction of force is shown in Fig. 2.

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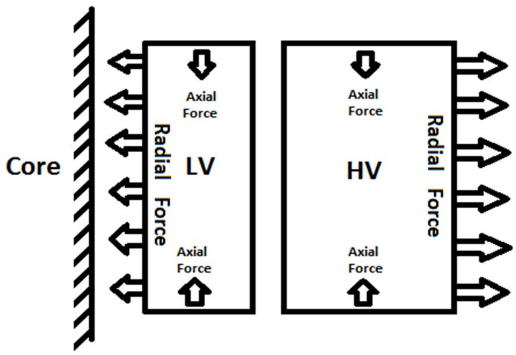

Fig.1 Different Components of Short Circuit Force

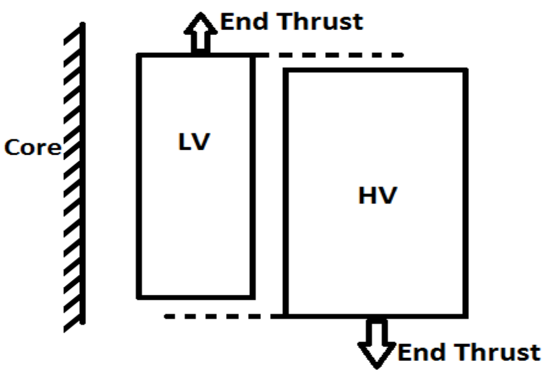

Fig.2 Net Axial Force Because of Axial Asymmetry

III. Modelling And Simulation

A. Modelling

A three phase, three legged power distribution transformer is used for modeling. The transformer is modeled in two dimensional planes as per guidelines given in [8, 9]. Practical transformer is three dimensional in nature so; per unit depth is taken in the direction of Z-axis. Core of transformer is made from M4 steel. Specifications and ratings of the transformer used in this model are shown in table I.

Analysis of force is done by breaking the winding into cells. Each cell will be composed of turns of coil. Cell number one denotes the bottom of the winding and cell number twenty three denotes the top of the winding.

B. Simulation

Finite Element Method Magnetics (FEMM) 4.2 by D. Meeker is used for computer simulation [10]. To solve a FEM problem boundary condition has to be applied so, Dirichlet boundary condition is used. Currents entered in the simulation are of peak value. The Core of the model transformer is assumed to be circular. Lorentz force is calculated for windings present on the central limb because it usually experiences higher force. The magnetic density plot for untapped winding and tapped winding is shown in Fig. 3 and Fig. 4 respectively. The tapping is applied at the middle of HV winding and approximately 13% of the winding is tapped.

To validate the result obtained from simulation, radial force is calculated for both the winding with zero axial asymmetry. The value of radial force obtained from simulation and the value obtained by analytical method are almost of same value. The slight difference in the results is present because the windings are assumed to be rectangular in the simulation. The simulation result and result obtained by analytical method is shown in table II. In this way the model is verified. The same model is used for further simulation.

TABLE I. Specifications of Transformer used

Parameters	Inner Winding (LV)	Outer Winding (HV)
Type of Coil	Cross-Over	Helical
Number of Coils Per Phase	2	1
Number of Turns Per Phase	1062	23
Conductor Size (mm)	2.85	6.70 X 4.25 X 10
Conductor Placement	-	2W X 5D
Number of Turns Per Coil	531	23
Number of Layer	9	1
Number of Turns Per Layer	59	23
Voltage (V)	11000	433
Yoke Clearance	21	11
Inter Phase Connection	Delta	Star

TABLE II. SIMULATION AND ANALYTICAL RESULT

Classification of Winding	Analytical Result (kN)	Simulation Result (kN)
Inner Winding (LV)	815.58	773.84
Outer Winding (HV)	1137.93	1020.95

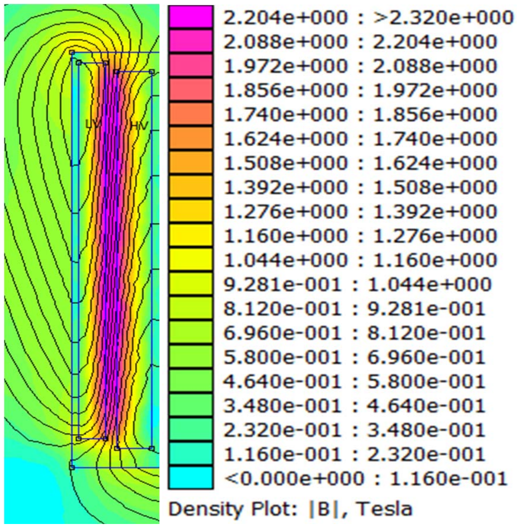

Fig.3 Magnetic Density for Winding when Tapping is Not Applied

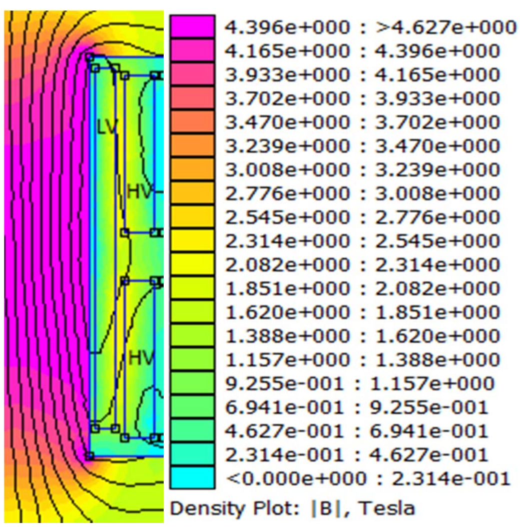

Fig 4 Magnetic Density for Winding when 13% Middle Tapping is Applied on HV Winding

IV. LORENTZ FORCE

Lorentz force, when the windings are displaced vertically (not axially symmetrical) is calculated along with its direction. The direction of forces when no tapping is applied on HV winding and when tapping is applied on HV winding is shown in Fig. 5 and Fig. 6 respectively. Table III shows the value of components of Lorentz force for windings under two cases: Case (i) No tapping applied in HV winding and Case (ii) Tapping applied on HV winding. The trend of radial and axial force of each cell throughout the winding under case (i) is shown in Fig. 7 and Fig. 8 respectively. The same trend for case (ii) is shown in Fig. 9 and Fig. 10 respectively.

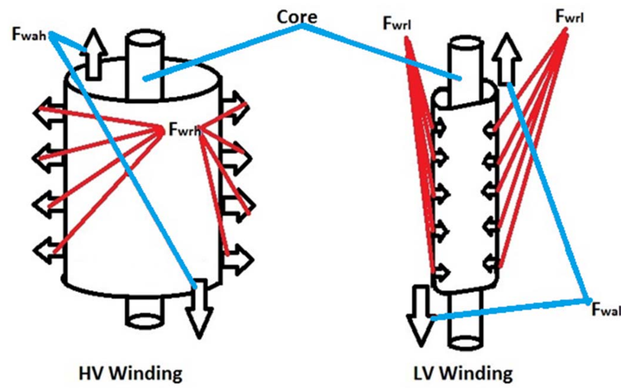

Fig.5 Lorentz Force on the Windings because of Axial Asymmetry

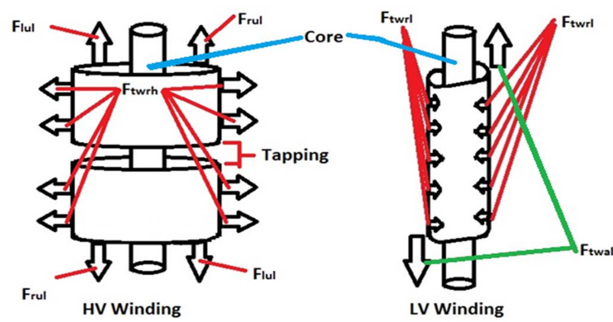

Fig. 6 Lorentz Force on Windings because of Axial Asymmetry under Tapped HV Winding

TABLE III. LORENTZ FORCE OF WINDINGS

Lorentz Force	Case (i) No Tapping on HV Winding	Case (ii) Tapping on HV Winding
Radial Force for LV Winding	F_{wrl}=778.8kN	F_{twrl}=610.7kN
Radial Force for HV Winding	F_{wrh}=1019.18kN	F_{twrh}=788kN
Axial Force for LV Winding	F_{wal}=125.6kN	F_{twal}=103.1kN
Axial Force for HV Winding	F_{wah}=145.5kN	F_{rul}=40.438, F_{lul}=149.21kN

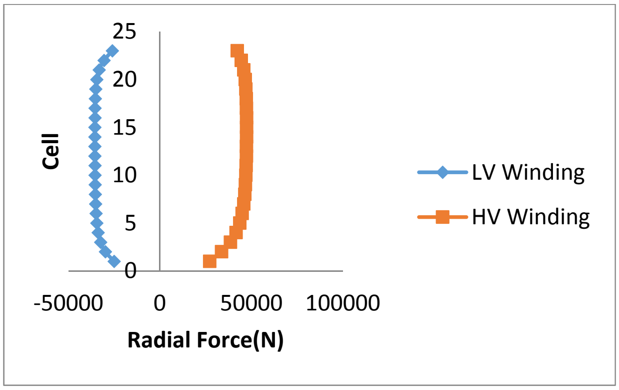

Fig.7 Radial Force of Untapped Windings

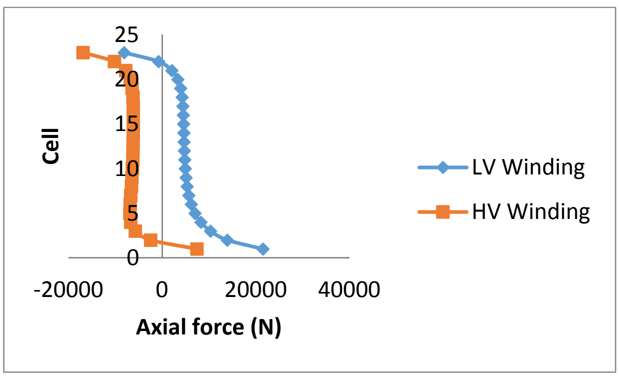

Fig. 8 Axial Force of Untapped Windings

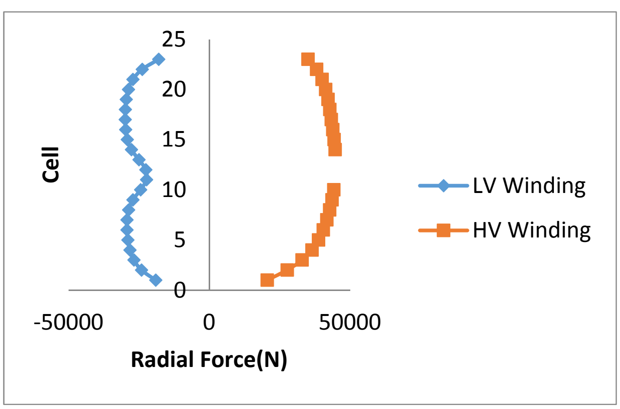

Fig. 9 Radial Force of Windings with Tapping Applied on HV Winding

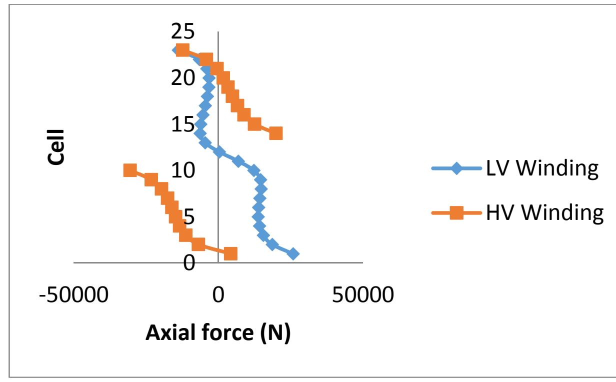

Fig. 10 Axial Force on Windings with Tapping Applied on HV Winding

Axial force exerted on each cell affects the force of next cell. So, axial compression force is calculated. Axial Compression force gives the value of axial force acting up to a particular point on the winding along its length. The pattern of axial compression force for complete winding is obtained by adding the axial force of all the cells in the winding. This pattern for case (i) and case (ii) is shown in Fig. 11 and Fig. 12 respectively. The maximum value of axial compression force in the windings under both the cases obtained from the study is written in table IV.

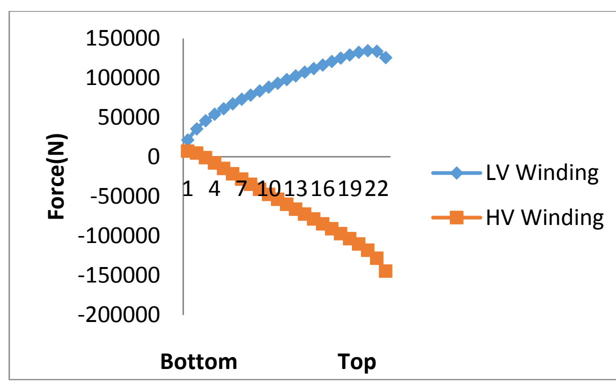

Fig. 11 Axial Compression Force of Untapped Winding

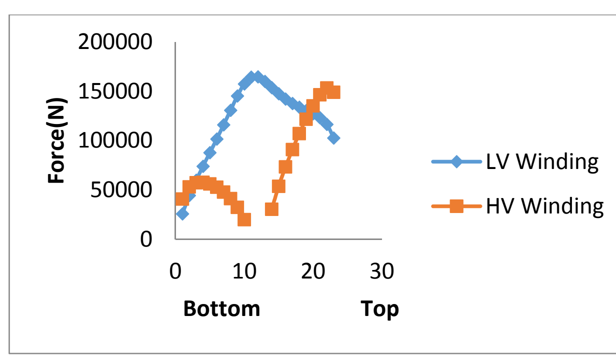

Fig. 12 Axial Compression Force of Windings with Tapping Applied on HV Winding

TABLE IV. AXIAL COMPRESSION FORCE OF WINDINGS

Condition	**Maximum Axial Compression Force of LV Winding**	**Maximum Axial Compression Force for HV Winding**
Without Tapping on HV	133.8kN	144.5kN
With Tapping on HV	164.7kN	153.4kN

V. Conclusions And Scope of Further Research

In this paper, finite element method is used to analyze the forces in transformer windings under worst condition of three phase symmetrical short circuit current. The analysis is done by assuming that the windings are not placed symmetrically. The results from the research are shown in the above section. The research also tells that if off-load tapping is applied on the HV winding then the magnitude and direction of force in the direction of Y-axis changes as compared to the case when no tapping is applied on HV winding. So, transformers should be designed by keeping in mind these effects in order to reduce the failure rate during testing and in-service time. The same research can also be done for double layer helical winding.

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