The Impact of Short-Circuit Electromagnetic Forces in a 12-pulse Converter Transformer

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Abstract

Transformers are one of the most costly, critical and major electrical components of the electric power system. Operation and stability of the electric power system mainly depend on the working of the transformer. Short-circuit forces can damage the transformer and accurate calculation of such forces is crucial for the transformer designers. Miscalculation can result in the non-optimal design. There are many different analytical methods for the calculation of the electromagnetic forces. However, these analytical methods do not consider the main factors of the transformer such as material properties of the winding and core, and complexity of the geometry. The numerical method like finite element method takes these factors into account. In this study, the 2-dimensional model is developed to calculate the short-circuit forces acting on the different parts of a 12-pulse converter transformer.

1. Introduction

In power system, transformer is one of the important and expensive components. Power quality of the power system mainly depends on the operation of the transformer. Transformers are excited 24 hours a day and variety of the mechanical stresses and faults occur during the operation. External short-circuits is one of the most common and suddenly occurred faults. Transient duration of a transformer is very short but it still damages the transformer. Resulting electromagnetic forces and thermal accumulations are main reasons for the mechanical faults in the transformers; the performance of the transformer can also be predicted from these two parameters.

This research focused on the investigation of electromagnetic forces during short-circuit and normal conditions. A short-circuit condition is a system disturbance and it produces higher current as compared to the normal conditions, the currents show nearly a tenfold increase [1]. For the safe operation, electromagnetic force due to short-circuit current must be predicted and analyzed correctly before installing a transformer at electric power system [2]. Electromagnetic forces accumulation can cause displacement in transformer windings and damage level can be increased with time, if the mechanical fault is not cleared in the earliest stage. Electromagnetic forces at over current initiate vibration and these vibrations are one of the major reasons for internal faults [3].

2. Electromagnetic Forces

The electromagnetic forces in the transformer windings are due to the interaction between magnetic field density (B) and current density (J). Force (f) can be calculated by using Eq. (1):

$$f = J \times B \tag{1}$$

These forces are exerted on the both inner and outer parts of the windings. During the normal conditions electromagnetic forces and leakage magnetic fluxes in the transformer's winding are relatively small but when external fault occurs it increases the current, which cause higher electromagnetic forces in the winding. During faulty conditions, the radial and axial components of the leakage field and electromagnetic forces must be fully considered [4]. Forces can be divided into radial and axial forces.

During the normal conditions axial component of the leakage flux density is much higher as compared to the radial components of the leakage flux density. At the top and bottom of the transformer windings radial flux is high and it is lowest in the mid of the windings. Radial force is generated by the interaction between axial flux density and current passing the windings. Radial force can be calculated as follow;

$$F_r = B_z \times J_\varphi \tag{2}$$

$$F_r = \frac{2\times\pi^2\times(NI)^2\times D_m\times 10^{-7}}{h} \tag{3}$$

where, J_φ is the current density in φ -axis direction and B_z is the magnetic flux density in the z-direction. NI is the ampere-turn of the winding, D_m is the mean diameter of the winding and h is the height of the winding. The nature of the radial force is such that the free distance between the two windings increases. Therefore, these forces act outward on the outer winding and inward on the inner winding [4,5,6].

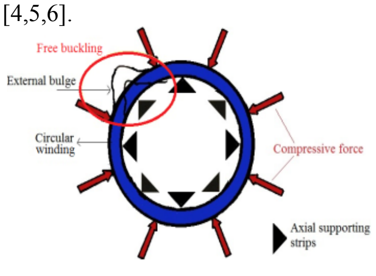

Fig. 1. Buckling of the inner winding due to the radial force [7]

Axial force is generated due to the interaction between radial component of the leakage flux and current passing through the winding. Axial force tends to compress windings conductors along the vertical axis in the middle [4, 5]. Large axial forces are mainly due to the asymmetry of LV and HV windings and these forces can cause serious risk for the transformer integrity [8]. Axial force can be calculated as follow:

$$F_a = B_r \times J_\varphi \tag{4}$$

$$F_r = \frac{2\times\pi^2\times A\times(NI)^2\times D_m\times 10^{-7}}{h_{eff}} \tag{5}$$

where A is the length of the tap section and it is expressed as a fraction of the total length of the winding, h_{eff} is the effective length of path of radial flux and value of the h_{eff} varies for each arrangement of tapping. Reference [9] can be used for the calculation of the force for different kind of tap arrangements.

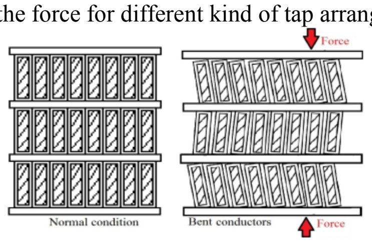

Fig. 2. Effects of the axial force [7]

Calculation of the axial force and radial leakage field density is not easy and accurate as compared to radial force and axial leakage field intensity. However residual ampere-turn method is well known approach for the calculation of the axial force and radial leakage field density. In this method winding is split into two groups having same ampere-turns. The radial field is produced by one part and another part produces axial field [9]. Compression and expansion of the windings are mainly due to the axial force [10].

3. Finite Element Method

Finite element method is a numerical method for solving integral and differential equations such as electromagnetic, magnetostatic and thermal conductivity [11]. FEM divide the geometry in small sub domain elements which is known as finite element. In FEM complex problems are represented as differential equation form, the solution of the FEM is limitless for the engineering design problems in physical science.

In this study 25 kVA, Dd0y11 connected three-phase multi-winding 12-pulse transformer is used. Main parameters, figure and dimensions of the transformer is given in Table 1, Fig. 3 and Fig. 4 respectively.

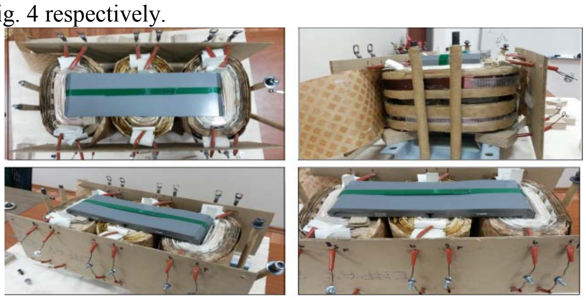

Fig. 3. 500/55 V, 25 kVA prototype transformer

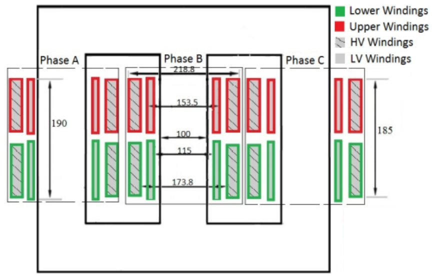

Fig. 4. Dimensions of the multi-winding transformer

Magnetic flux density distributions, obtained from 3-D and 2-D analyses, are shown in Fig. 5 and Fig. 6 respectively.

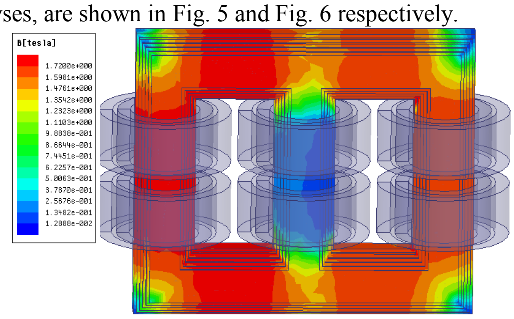

Fig. 5. Magnetic flux density distribution in 3-D model

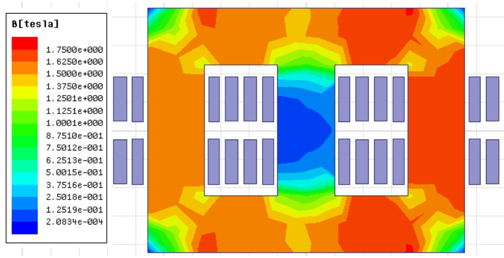

Fig. 6. Magnetic flux density distribution in 2-D model

Table 1. Transformer data

Rating	Power (kVA)	High voltage (V)	Low voltage (V)
	25	500	55
Core	Core Material	Flux Density(T)	No-load losses (W)
	M5	1.71	157
Winding	Number of turns of HV winding	Number of turns of upper LV winding	Number of turns of lower LV winding
	173	19	11

3.1. Electromagnetic Forces Calculation using FEM

Table 2 shows the radial forces acting on the LV and HV windings during the normal operating condition. By using ANSYS Maxwell electromagnetic analysis software, we get the distributed radial force (F_{r-d}) along the winding, which can be calculated using equation (6) [12],

$$F_{r-d} = \frac{2\times\pi\times(NI)^2\times 10^{-7}}{h} \tag{6}$$

Table 2. Radial forces acting on the multi-winding transformer

Winding	Analytical (N)		FEM (N)		Error%
	$F_{r\text{-}d}$	Total Force	$F_{r\text{-}d}$	Total Force	
Upper HV	58.03	32.53	51.50	28.87	11.25
Lower HV	58.03	32.53	51.30	28.75	11.60
Upper LV	57.45	24.26	50.50	21.33	12.10
Lower LV	57.98	24.48	50.70	21.41	12.55

Axial forces are small and negligible in the magnetostatic analysis during the normal operating condition. Axial forces acting on the LV and HV windings are between 0 to 2 N.

3.2. Short-Circuit Test

During short-circuit test, multi-winding transformer has been analyzed under three different conditions. In condition I all the phases of the LV wye windings (lower LV winding) are short circuited and delta connections of LV (upper LV winding) remain open circuited during the short-circuit test. During the condition I lower windings have higher current. Fig. 7 and Fig. 8 show current in the lower windings.

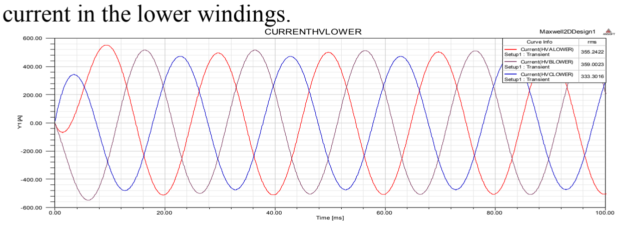

Fig. 7. Current in HV lower windings (Condition I)

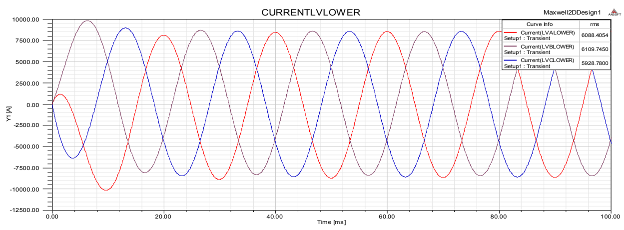

Fig. 8. Current in LV lower windings (Condition I)

During the short circuit test of the multi-winding transformer, in first few cycles, the forces along the windings are different due to the inrush current. However, after few cycles, inrush current becomes zero which resulted in the same ampere-turn in the lower LV and HV windings, which resulted in approximately same distributed radial forces along the windings. Forces of the phase A lower windings are shown in Fig.9, to fig. 12.

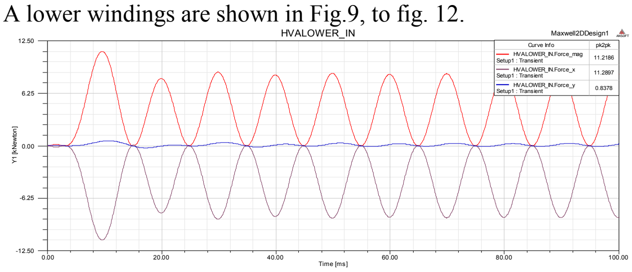

Fig. 9 Forces in HVA lower inner winding (Condition I)

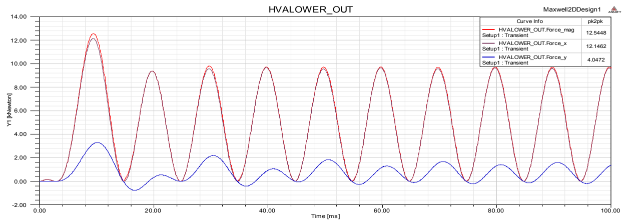

Fig. 10 Forces in HVA lower outer winding (Condition I)

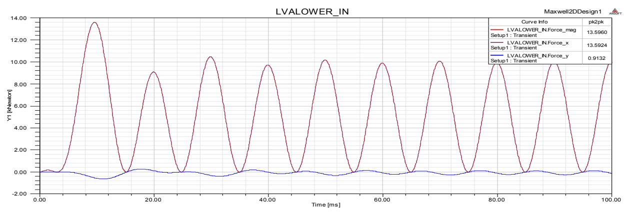

Fig. 11 Forces in LVA lower inner winding (Condition I)

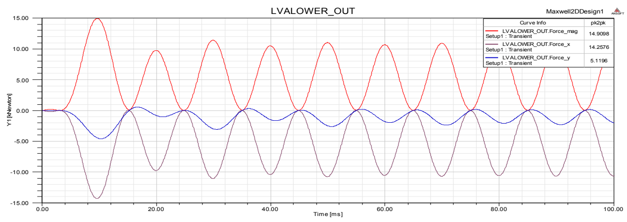

Fig. 12 Forces in LVA lower outer winding (Condition I)

During the Condition I lower windings of phase B and C also have higher current and forces. Upper windings of the transformer have less current as compared to the lower windings which resulted in the fewer forces.

In Condition II all the phases of LV delta windings are short-circuited and wye connections of LV remain open circuited.

During the Condition II upper windings have higher current. Current of the upper windings are shown in Fig. 13 and Fig. 14.

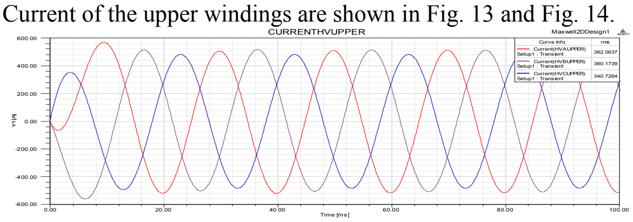

Fig. 13. Current in HV upper windings (Condition II)

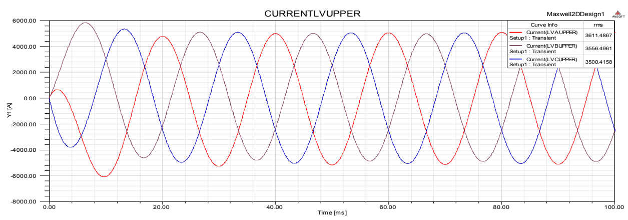

Fig. 14 Current in LV upper windings (Condition II)

Due to the higher current in upper windings, forces of the upper windings are also high. For the first few cycles, forces are even higher than the normal short-circuit conditions due to the inrush current. However, after few cycles, minimization in the inrush current resulted in the approximately same distributed radial force along the windings. Forces of the phase A upper windings are shown in Fig. 15 to Fig. 18.

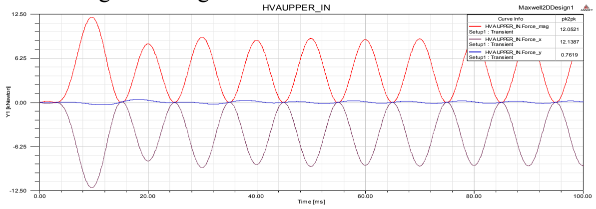

Fig. 15. Forces in HVA UPPER inner winding (Condition II)

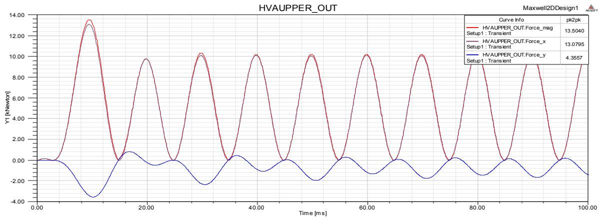

Fig. 16. Forces in HVA upper outer winding (Condition II)

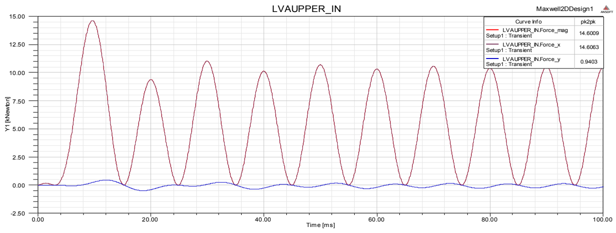

Fig. 17. Forces in LVA upper inner winding (Condition II)

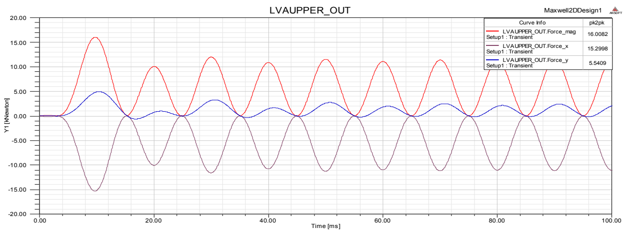

Fig. 18. Forces in LVA upper outer winding (Condition II)

During the Condition II upper windings of phase B and C also have higher current and forces. Lower windings of the transformer carry less current as compared to the upper windings which resulted in the fewer forces.

During the Condition III, all of the low voltage windings are short-circuited which resulted in the higher current in all of the windings. Current of the high and low voltage windings are shown in Fig. 19 to Fig. 22.

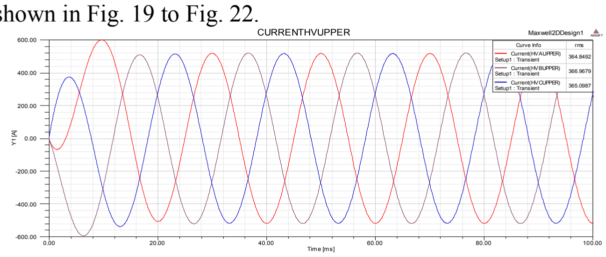

Fig. 19. Current in HV upper windings (Condition III)

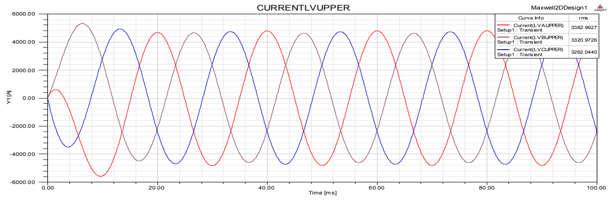

Fig. 20. Current in LV upper windings (Condition III)

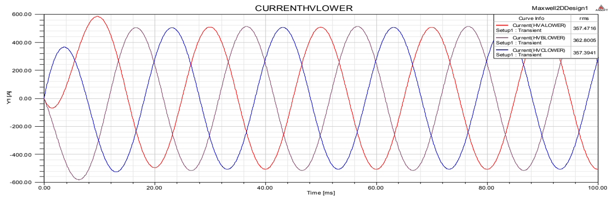

Fig. 21. Current in HV lower windings (Condition III)

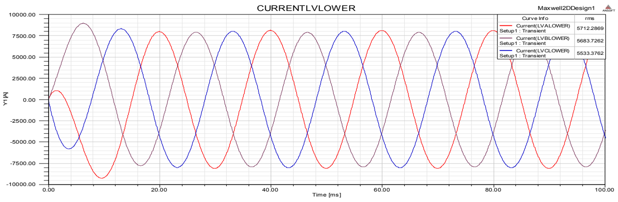

Fig. 22. Current in LV lower windings (Condition III)

During Condition III after first few cycles, distributed radial forces become approximately same for all of the windings. The forces of the phase A windings are shown in Fig.23 to Fig. 30.

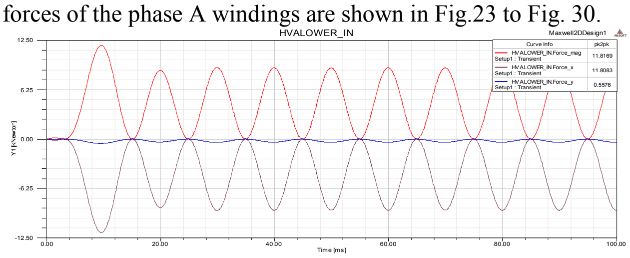

Fig. 23. Forces in HVA lower inner winding (Condition III)

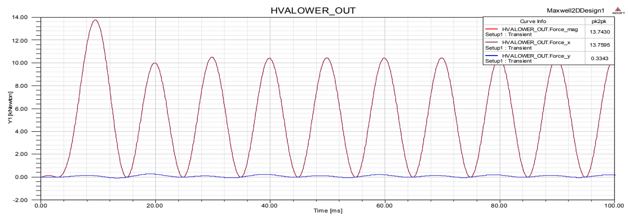

Fig.24. Forces in HVA lower outer winding (Condition III)

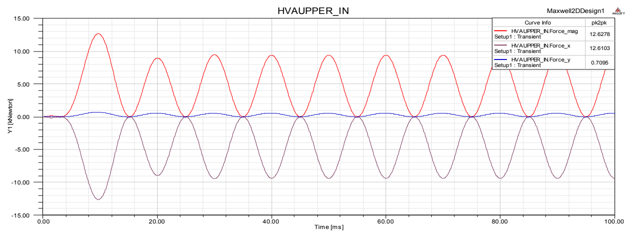

Fig. 25. Forces in HVA upper inner winding (Condition III)

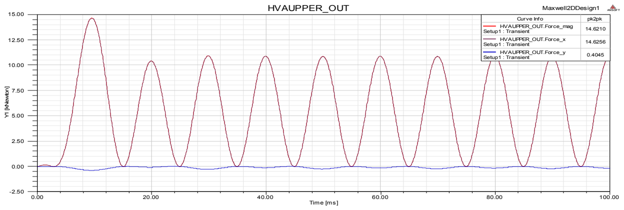

Fig. 26. Forces in HVA upper outer winding (Condition III)

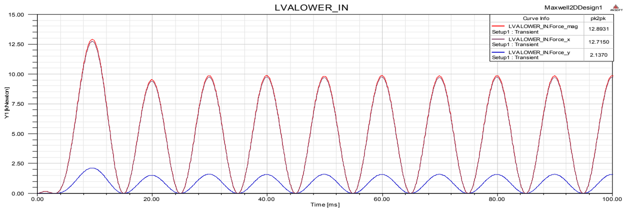

Fig. 27. Forces in LVA lower inner winding (Condition III)

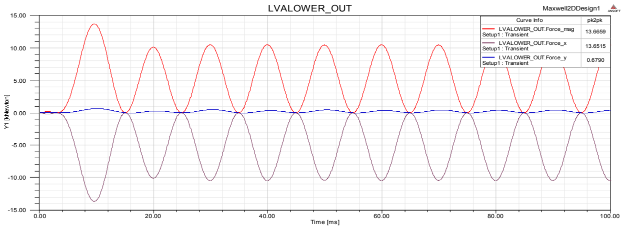

Fig. 28. Forces in LVA lower outer winding (Condition III)

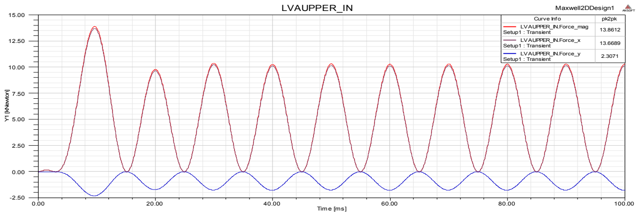

Fig. 29. Forces in LVA upper inner winding (Condition III)

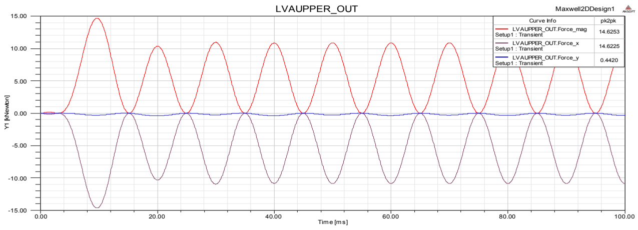

Fig. 30. Forces in LVA upper outer winding (Condition III)

It can be observed from the results that axial force is higher during the inrush current. Results also show that axial forces are higher during the condition I and II as compared to Condition III i.e. when one LV winding is short-circuited; axial forces are higher as compared to the both LV windings short-circuited. In normal conditions, the distributed radial force in LV and HV windings was less than 60 N. However, during short-circuit transient test, these forces can be increased up to 16 kN. From the results of the simulation, it can be concluded that during the short-circuit conditions, forces in the HV and LV windings can be increased more than 266 times of the normal conditions.

4. Conclusions

In this study, two dimensional finite element analysis has been used for the calculation of the magnetic flux density and short-circuit forces in a 12-pulse multi-winding converter transformer. For this multi-winding transformer, the radial and axial forces computed for three different conditions. For first two conditions single winding was short-circuited and for the third condition both windings were short-circuited. Results show that axial forces were higher during the single winding short circuit as compared to the both short circuited.

Results also show that axial forces exerted during the inrush current are larger than short-circuit forces. It is recommended that during the transformer design stage, inrush current must be considered as one of the main factors because inrush current occurs frequently and sometimes duration of the inrush current is much higher as compared to the short circuit. Due to the higher duration of inrush current, its continuous repetition can damage the transformer and which will be resulted in high financial losses.

5. References

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