Analysis of Short - Circuit withstand Capability of Distribution Transformer

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Abstract: - A significant characteristic of the transformers is the capability to withstand a short circuit. During the operation of the Transformer, it experiences a range of electrical, mechanical, and thermal stresses. A significant factor contributing to these stresses is external short circuits, which create large currents in the windings, resulting in considerable inter turn forces that potential risk to its operational integrity. As a result, the ability to withstand short circuit currents is considered a key characteristic of transformers. This paper analyzes various common instances of failures in Distribution Transformers upto 630kVA during short circuit withstand tests conducted at CPRI, Bhopal. The analysis is conducted in accordance with IS 2026 standards, and the findings are summarized to highlight the causes and potential remedial actions to prevent transformer failures.

Key words: Transformers, Short circuits, Radial forces, axial forces and Mechanical stresses.

I. INTRODUCTION

The typical lifespan of a Transformer is around twenty-five years [1]. However, during their operational lifetime, they may experience external fault that can lead to short circuits. Additionally, the increasing demand for power has necessitated enhancements in generating capacity and interconnections within power systems, which has increased the grid's short circuit potential and increased the importance of transformer's short circuit capability. External short circuits produce abnormal fault currents that significantly exceed normal service currents, resulting in destructive forces. A number of variables, such as transformer's short circuit impedance and the system impedance, determine the amount of short circuit current [1].

System disruptions known as short circuit events typically result in high magnitude currents. single phase to earth, double phase, double phase to earth, three phases and three phases to earth short circuits are among the different types of short circuits. The symmetrical three phase fault is the fault configuration that typically results in the highest through currents in any transformer's secondary or primary windings. Thus, the transformer's primary design criterion is a three phase short circuit fault [2]. The repercussions of a short circuit are able to range from minor malfunctions to catastrophic failures, depending on the system's capacity to handle current during a short circuit event and the duration for which the current can flow without causing damage to the connected equipment [3].

A short circuit in the network could expose the transformer to excessive currents. The windings and their supports will experience a significant mechanical force during these currents. Furthermore, the high current density in the windings will cause the winding temperature to rise rapidly. Transformers are designed to endure short circuit currents for limited duration and the protective relays should disconnect the transformer from power sources during such events [4]. Transformer failure is typically caused by short circuit currents. Short circuit test setup on transformer is depicted in Figure 1.

Figure1. Short circuit Test Setup for Transformer

The Laboratory's test setup consists of 100MVA system of system MVA, 12kV of applied voltage, 0.76Ω of system impedance and fault duration of two seconds. A Short circuit could occur on the transformer's primary or secondary side. However, the secondary short circuiting method is recommended because it closely resembles the fault situation during faults [5]. To obtain the test current and maintain the transformer terminal voltage during testing, the supply voltage may be higher than the rated voltage of the windings being supplied. Supply voltage should not be greater than 1.10 times the rated voltage of the winding when short circuiting occurs after the application of the supply voltage [6]. In transformers containing single concentric windings, it is generally advisable to connect the winding that is located farthest from the core to the power supply prior to the application of the supply voltage, particularly in cases where the winding experiences a short circuit (preset method). This method reduces the magnetizing current that could superimpose on the short circuit current during the initial cycles and helps avoid possible core saturation.

The relationship between short circuit current and full load current can be expressed using equation (1), representing the correlation between short-circuit current and impedance voltage.

$$I_{SC} = (I_{FL} / \%Z) \text{ ------- } (1)$$

Where,
I_{SC} = secondary or primary short-circuit current
I_{FL} = secondary or primary full-load current
%Z = percentage short circuit impedance voltage

II. ELECTROMAGNETIC FORCES

When an electrical network experiences the short circuit fault, the symmetrical currents can reach to the levels 20 to 25 times the normal operating currents, while peak asymmetric currents can reach to the levels 50 to 60 times the normal operating currents [7].

$$F_{em} = J \times B \text{ ------ } (2)$$

The Lorentz equation (2) calculates the electromagnetic forces (F_{em}) in the transformer winding as a result of the interaction between the flux density (B) vector and the current density (J) vector. Short circuit currents in the windings of transformers react with the leakage flux field between the concentric windings [8]. Axial leakage flux is the main component, when it interacts with the circumferential winding currents, radial forces are created that act inward on the inner winding and outward on the outer winding [9].In layer type winding, the maximum radial force acting on a winding turn often occurs halfway along the winding height, where the total leakage flux is axial [4]. A radial flux component is created when the leakage flux bends in the direction of core leg, shortening its return path close to the ends of the windings. The axial forces produced by the interaction of this radial flux component with the circumferential winding currents tend to compress the winding conductors along the vertical axis. Axial forces are generally increased by any imbalances in the distribution of ampere turns between the inner and outer windings along the winding's axial length. A misalignment of magnetic centers between two windings has the greatest impact on radial flux and axial force [10]. Even a slight misalignment produces significant axial forces.

It is necessary to design end support structures that are strong enough to withstand the combined forces. Supporting components need to be properly aligned in order to maintain equal stress distributions.

III. RADIAL ELECTROMAGNETIC FORCES

A radial force is produced in transformers with concentric windings as a result of an interaction between the winding current and the axial component of leakage flux density. This interaction induces compressive stress and hoop stress in the inner winding and outer winding respectively. The standard hoop stress σ_{mean} [13] in the conductors of the external winding, occurring at the crest of the first wave of short circuit current, can be calculated by considering a peak factor of 2.55 and e_s,

$$\sigma_{mean} = 0.031 W_{cu} / h\,(e_z+e_s)^2 \text{ kN/mm}^2 \text{ ---- } (3)$$
$$e_s = MVA/S \text{ ------------ } (4)$$

Where,
e_s = Transformer's system impedance
e_z = Transformer's impedance per unit
h = Transformer's axial height of the windings in mm
$W_{cu} = I^2R_{dc}$ loss in the transformer winding in kW.
S = The Transformer's SC apparent power in MVA
MVA = Transformer rating.

The radial electromagnetic force reaches its peak in the inner conductor, and as it approaches the outermost conductor, it gradually decreases to zero. Inside a disc coil, the internal stress distribution allows for significant leveling, leading to the conclusion that the σ_{mean}, as described in equation (3), is applicable for calculations. The inner windings are easily compressed against the core, leading to the usual approach of reinforcing the winding from the core. The radial forces tend to separate the inner and outer windings. The rectangular insulating form is attempted to be crushed by the inner winding [10]. Radial force can lead to failure by increase in diameter of outer winding, Spiralling of end turns in circular winding and compression of inner winding. Untanking of 400kVA transformer is depicted in Figure 2.

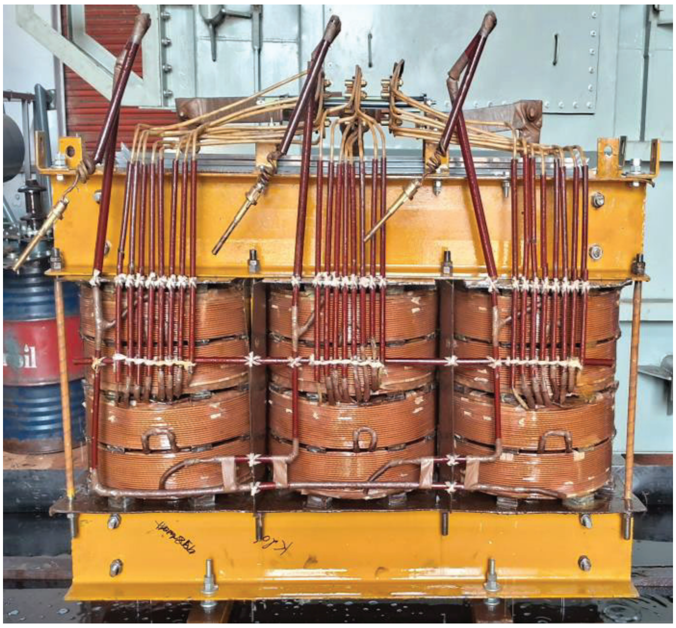

Figure 2. Untanking of 400 kVA Transformer

IV. AXIAL ELECTROMAGNETIC FORCES

When the radial flux component interacts with the winding currents, an axial force is generated that leads the winding coils to either axially expand or compress. Axial forces can lead to failure by causing the winding to collapse, Evidences of Mechanical Failure are collapse of winding end supports, Beam failure, Conductor tilting and circumferential displacement or conductors. Additionally, excessive compression of the insulation may result in slackness, potentially displacing spacers and leading to further failure. These forces Pc [12], which travel through the core to the transformer tank, cause stress on the main insulation between the winding and the core.

$$P_C = K*U / ((e_z+e_s)*f*h) \text{ in kN ------------ (5)}$$

Where,

P_C = axial compression force in kN

f = Frequency in Hertz.

U = Rated kVA of the Transformer per limb

K= Constant

The Axial compression force is directly proportional to Rated kVA of the transformer per limb and inversely proportional to transformer's axial height of the windings as expressed in an equation (5),

V. TEST RESULTS

The consequences of short circuit forces on the active components of transformers are examined. Short circuit currents generate significant axial and radial forces within transformers, resulting in core deformation that alters the reactance percentage beyond the limits established by standards. This paper presents several critical issues identified during short circuit evaluations conducted on Distribution Transformers at CPRI, illustrated through case studies.

Case Study 1: A 315 kVA, 11/0.433 kV transformer was subjected to dynamic and thermal short circuit withstand testing. During the fourth short circuit test, the current and voltage oscillogram exhibited distortion after 0.245 seconds, as depicted in Figure 2. A disturbance in the low voltage current oscillogram was also observed, accompanied by severe arcing.

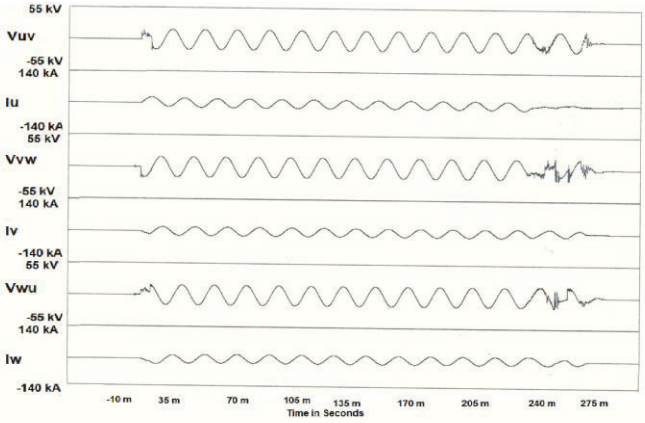

Figure 2. Oscillogram of 315 kVA Transformer

After the third short circuit, percentage change in reactance increased from 0.770% to 1.637% as depicted in Table 1. Upon untanking, the high voltage side bushing failed, outer winding diameter was enlarged and the top cover was dislodged due to the hoop stress (σ_{mean}) of radial forces as per equation (3) that the transformer could not endure.

Case Study 2: A 400 kVA, 11/0.415kV transformer was subjected to dynamic SC withstand strength testing. After the sixth short circuit, percentage change in reactance increased to 0.663% then after the ninth short circuit, percentage change in percentage reactance decreased to 0.321% as depicted in Table 2. During SC withstand test, Interturn failure occurred on transformer due to excessive radial forces and it is reflected in post routine test. Following routine testing, the no-load current measured was 95A at 60V, exceeding the standard specifications. Actual hoop stress (σ_{mean}) of radial forces is equal to or lesser than 1.1 times of Reference hoop stress (σ_{mean}) [11] as per equation (6)

$$\sigma_{mean,\ actual} \leq 1.1 * \sigma_{mean,\ reference} \text{ ----- } (6)$$

Upon untanking inspection, inter turn failure on HV winding of transformer was observed. The transformer cannot endure the actual hoop stress ($\sigma_{mean,\ actual}$) caused by radial forces during short circuit condition. Hence Interturn failure occurred on transformer.

Table 1. 400kVA Transformer Reactance measurement

Vrms in Volts	Irms In Amps	Wrms In Watts	Freq In Hz	%X	% Change in X	Remarks
420.3	15.46	6255	50.02	4.153	0.0000	Before Test
420.6	15.39	6210	50.01	4.174	0.506	After 1st SC
420.1	15.31	6125	49.99	4.185	0.770	After 2nd SC
419.8	15.22	6052	49.98	4.221	1.637	After 3rd SC

Where,
V_{avg} – Average Voltage in Volts
I_{avg} – Average Current in Amps
W_{total} – Total Power in Watts
Freq – Frequency in Hertz
%X – Percentage change in Reactance
SC – Short Circuit Test

Case Study 3: A 400 kVA, 11/0.433kV transformers was tested for dynamic SC withstands capability. After the third short circuit, percentage change in percentage reactance varied from 0.466% to -1.754% as depicted in Table 3. During the fourth short SC withstand test, the current and voltage waveform became collapsed after 70 milliseconds, as depicted in Figure 3. Oil leakage was observed from the transformer, and significant arcing was noted.

Table 2. 400kVA Transformer Reactance measurement

Vrms in Volts	Irms In Amps	Wrms In Watts	Freq In Hz	%X	% Change in X	Remark
489.9	19.62	9240	49.94	4.677	0.0000	Before
489.5	19.55	9240	49.96	4.691	0.299	After 1st SC
490.2	19.57	9299	49.9	4.694	0.363	After 2nd SC
490.1	19.53	9302	50.04	4.699	0.470	After 3rd SC
490.0	19.53	9263	50.02	4.696	0.406	After 4th SC
490.6	19.52	9287	50.02	4.703	0.556	After 5th SC
490.3	19.47	9210	50.04	4.708	0.663	After 6th SC
489.9	19.50	9190	50.03	4.692	0.321	After 7th SC
490.4	19.57	9302	50.00	4.687	0.214	After 8th SC
490.6	19.53	9256	50.03	4.692	0.321	After 9th SC

The high voltage side bushing was damaged. Upon untanking inspection, the outer winding diameter enlarged, the inner winding diameter was reduced, and the top cover was displaced due to the radial and axial forces, as depicted in Figure 4 and Figure 5.

The pressure (P) as per equation (7) which is higher on the areas of the overlap of the core laminations in order to hold the magnetic circuit [11]. The short circuit force exerted onto the end yoke is higher therefore supporting structure, end yoke and winding arrangements unable to withstand the pressure.

$$P = (F'*10^3) / (2*S*a*t*h) \text{ in MPa ------------- (7)}$$

Where,
F’ = The short-circuit force (peak value) exerted onto the end yoke (kN).
S = the area of the corner overlap of the core laminations (mm^2).
a = the adherence factor (p.u.).
t = the number of sheets of core laminations per unit of height (mm^-1).
h = the height of the magnetic circuit (mm).

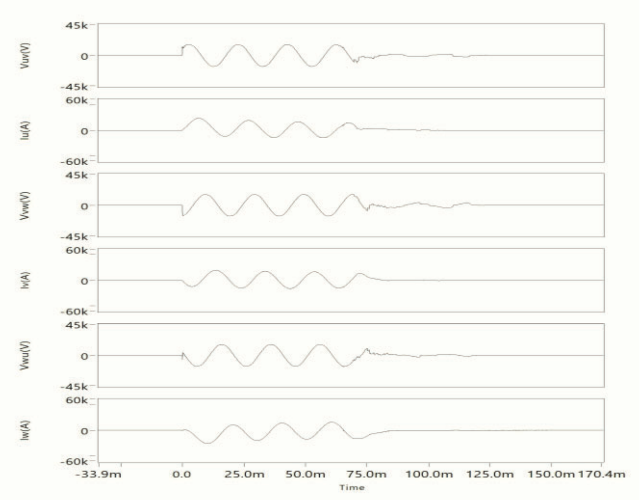

Figure 3. Oscillogram of 400 kVA Transformer

Fig 4. Distortion on HV side of 400 kVA, Transformer

Table 3. 400kVA Transformer Reactance measurement

Vrms in Volts	Irms In Amps	Wrms In Watts	Freq In Hz	%X	% Change in X	Remarks
460.3	19.16	8545	50.04	4.504	0.0000	Before Test
460.9	19.11	8542	50.06	4.530	0.5770	After 1st SC
459.7	19.10	8415	49.95	4.525	0.4660	After 2nd SC
459.6	19.46	8612	49.96	4.425	-1.7540	After 3rd SC

Figure 5. Distortion on LV side of 400 kVA, Transformer

The excessive forces encountered during short circuit conditions, which cause insulation degradation, are the causes of insulation failure in transformers. The design of the outer winding must ensure that the conductor's temporary elongation caused by the temperature fluctuations during a short circuit fault does not result in any negative consequences. Above a certain value of stress the copper will remain a permanent elongation [12]. Ensure that the supporting structure is strong enough to withstand the hoop stress due to a short circuit. These factors contribute to transformer failures as in the cases discussed.

VI. CONCLUSIONS

The short circuits withstand test serves as a crucial parameter for enhancing the reliability of transformers. When the short circuit withstand capacity is exceed, the axial and radial force can be treated separately, which may result in different radial and axial failure modes. These phenomena have been examined in detail. Improving the quality of material and strengthening to the supportive structure can prevent failure.

Best manufacturing practices and material selection play an important role in preventing a transformer failure due to a short circuit. Magnitude of fault current should also be considered during the selection of conductor. Analysis of the failure will enable to prepare an accurate scenario and develop proper recommendation to prevent a repetition. Designing, material selection, component assembly and supporting structure can prevent failure and enhance the reliability of transformer. The high failure rate of approximately 8% during testing highlights that dependence solely on calculation methods is inadequate for designing transformers that can bear the most extreme short-circuit currents.

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