Electromagnetic Forces in Power Transformers under short circuit conditions

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ABSTRACT

Power transformers are among the most expensive and key apparatuses in an electric power system. It is important thus, that they are properly protected and well-maintained. Transformers experience different stresses while in operation. The effect of electromagnetic force on transformer windings is worsened by electrical, mechanical, and thermal issues. Damage from the increase in electromagnetic force includes winding displacement, bending, and tearing. Therefore, it is essential to predict electromagnetic force when designing transformers. This paper investigated the causes and process of damage to transformer windings due to electromagnetic forces when these windings are short-circuited and recommended mitigation measures for the safer and more reliable operation of power transformers under such conditions.

Keywords: *Electromagnetic force, power transformer, short circuit current, short circuit test, windings*

INTRODUCTION

Power transformers rank among the costliest components of the electric power system network. They are necessary devices and account for a sizeable portion of the cost of the entire electrical system. Repairing a broken or failing power transformer or even replacing it can be very expensive [1]. The condition of the transformer is also a factor in the dependability and the quality of the electricity supply, and its financial worth [2]. The quality of the energy and its economic value, which are defined by the operational state of the transformer, thereby play a significant role in how dependable the electric power supply is. The electric network could suffer severe damage if a power transformer were to fail. Therefore, they must be well-maintained, adequately safeguarded, and appropriately protected. Different strains are applied on transformers while they are in use.

Different stresses are applied to transformers while they are in use. These include mechanical, electrical, and thermal failures, some of which raise the magnitude of the current and subsequently the electromagnetic stress on the windings, occasionally resulting in damage and deformation to the transformer windings and consequently a reduction in the life expectancy of the transformer. High current conditions are produced in transformer windings by short circuit occurrences. A transformer experiences excessive forces as a result of these currents. Transformer design, production, and operation all take into account electromagnetic forces.

Transformers typically have two sets of windings – the primary windings and the secondary windings over which a constant power, current and voltage are applied resulting in a significant transformation. A transformer receives primary power at its rated voltage and current during normal operation. A magnetic field created by current flowing in the primary windings will connect the secondary windings, causing a current flow and induced electromagnetic force (EMF) in the windings. It is frequently advocated to undertake an analysis of the EMF in the transformer windings using the finite element method [3] because doing short-current experiments on big power transformers is expensive and involves complex procedures.

Electromagnetic Forces in Power Transformers

Transformer functioning is intrinsically characterised by the creation of an electromagnetic field inside the transformer. The formation of forces inside the transformer windings is initiated by this electromagnetic field [4].

Normal operation keeps these forces at a manageable level, therefore the transformer design depends principally on dielectric and thermal issues—loss minimization and insulation integrity—for this situation. Extreme stresses in the transformer windings come from the current excitation increasing dramatically under short-circuit fault circumstances, possibly 8 to 10 times the nominal current [4].The thermal and mechanical performance of a transformer mostly determines its short circuit withstand capacity [4]. The major concern is mechanical, and the design interests become how to regulate the electromagnetic forces (EMFs) and avoid mechanical failure as a result of the speed at which these errors develop and are resolved [4].

Here, the fundamentals of EMFs are discussed to help the reader understand the importance of short circuit occurrences in transformer designs. The short circuit current is described first, followed by an explanation of the EMFs that are created, and finally, techniques for preventing transformer failure [4].

Power Transformer in Short Circuit Current Condition

The procedures for determining short circuit current take into account faults such as single-phase, double earth and three-phase to the ground faults. In general, symmetrical components are used to compute this current in a variety of circumstances while taking into account:

- Tapping configuration
- Fault location.
- Short circuit type; and
- Short circuit power combination

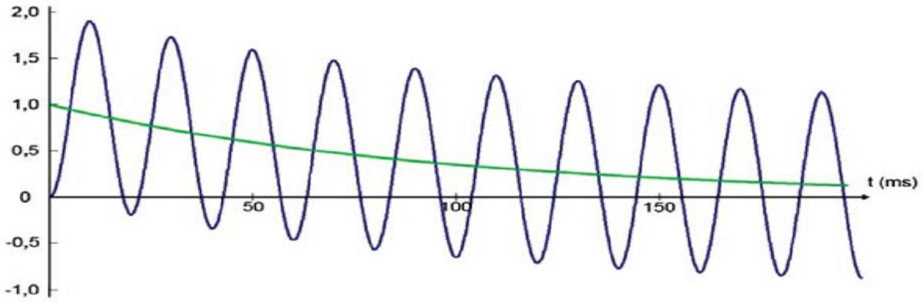

Fig. 1: *Short circuit current [4,5].*

As seen in Fig. 1, the short circuit current is described by equation (1):

$$i(t) = I_p\left[\sin(\omega t+\alpha-\varphi) - e^{-\left(\frac{t}{\tau}\right)\sin(\alpha-\varphi)}\right] \tag{1}$$

where:
i (t) = instantaneous short circuit current
Ip = peak short circuit current
ω = angular frequency in rad/s
α = voltage angle at which a short circuit occurs
φ = impedance phase angle

The force is at 90° to the bending of the flux lines and follows that pattern when looking at the transformer in cross-section (Figure 2) and assuming that the current's direction is constant. This causes an axial force to pull onto the windings at the ends of the windings and a radial force to push outward in the centre of the windings.

By using the corresponding axial and radial modes of failure, EMFs can be further split into axial and radial forces [4]. The direction of axial forces is parallel to the winding height while the radial forces developed is at 90° to it. Despite having a shared origin, axial and radial forces can generally be thought of as opposing modes [5].

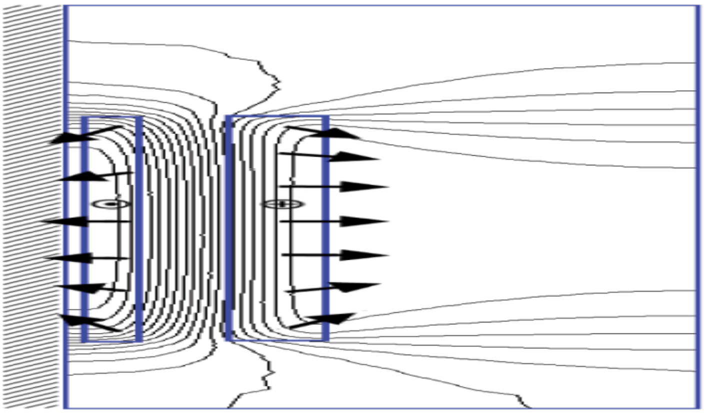

Fig. 2: *Magnetic field and associated force directions [4].*

Computation of the Electromagnetic Forces

Two methods used in the computation of electromagnetic forces are the numerical method and the analytical method.

1) In the numerical method, the power transformer's local magnetic flux density is used to compute the electromagnetic forces. The governing equation of the magnetic field when current enters the transformer windings is given by [1,6] as:

$$\nabla\times\frac{1}{\mu}(\nabla\times A) = J_s - \sigma\frac{\partial A}{\partial t} \tag{2}$$

$$B = \nabla\times A \tag{3}$$

In equation (2), μ = magnetic permeability;
A = magnetic vector potential,
σ = conductivity and in equation (3),
B = the flux density.

From the Lorentz law, the EMF becomes [1]:

$$df = idl \times B \tag{4}$$

Resolving the magnetic flux density into its components yields [6]:

$$B_r = -\sigma \frac{\partial A_\phi}{\partial z}$$

$$B_\phi = 0 \tag{5}$$

$$B_z = \frac{1}{r}\sigma \frac{\partial A_\phi}{\partial r}$$

Where B_r, B_ϕ, and B_z are the flux density's directional components in the cylindrical coordinate. Therefore, using [6], it is possible to determine the EMFs for both the radial and the axial directions:

$$F = \int_Y J_\phi \times \left(B_r\hat{r} + B_z\hat{z}\right)dv = F_r\hat{r} + F_z\hat{z}$$

$$F_r = B_z \times J_\phi \tag{6}$$

$$F_z = B_r \times J_\phi$$

Concerning equation (6), the interaction between the axial leakage flux density B_z and the current flowing through the windings produces a radial force F_r. Similarly, the winding current interacts with the radial component of the leakage flux B_r and produces axial forces F_z.

2) The analytical procedure for calculating electromagnetic forces is entirely linear and adheres to the ideal situation. In the transformer's normal state, a minimal axial field density (B_a) is observed on the internal and external surfaces of the LV and HV windings between the two windings such that the radial force F_r (per unit of length) remains practically the same along the length of the windings and can be determined with a high level of accuracy. The radial component of the force produced when the instantaneous ampere-turns in each winding (NI) interacts with the leakage field density, can be ascertained from equations (7) and (8):

$$B_a = \frac{4\pi(NI)}{10^4}[T] \tag{7}$$

$$F_r = \frac{2\pi(NI)^2 D_m}{h\times 10^7}[N] \tag{8}$$

Where:
N = the number of turns,
h = the length of the winding,
D_m = the mean diameter of the winding, and
I = the current flowing in the transformer winding.

The procedures involved in the determination of the axial force by the analytical approach are more cumbersome than that used in computing the radial force.

As a result, the residual Ampere-turns method is a widely used method for the computation above. This approach allows for the computation of axial force to be carried out as follows [6]:

$$B_r = \frac{4\pi}{10^4}\times\frac{a(NI)}{2h_{eff}}[T] \tag{9}$$

$$F_a = \frac{2\pi a(NI)^2}{10^7}\times\frac{\pi D_m}{h_{eff}}[N] \tag{10}$$

Where:
a = the fractional difference in winding heights, and
h_{eff} = the effective length of the path of the radial fluxes depending on the arrangement of tapings [6].

WINDING DEFORMATION

In general, transformer windings deform, shift, or sustain damage due to mechanical and electrical faults resulting from a variety of causes, such as excessive mechanical force during a short circuit fault, the inter-turns short circuit as a result of lightning strikes, due to paper ageing, the insulation shrinks and the clamping pressure might be lost, dipping its voltage withstand strength, and vibration all through transportation.

The study focuses only on winding displacement/deformation resulting from short circuit current. The combined presence of the axial and radial forces causes the transformer winding to undergo deformation as of displacements in both the radial and axial directions.

Radial Deformation

There are two ways that radial deformation occurs. One is forced buckling, which happens when the stress value surpasses the material's elastic limit as shown in Figure 3 and hoop buckling, in which one or more radial locations of the winding experience deformation of the conductor.

As shown in Figure 4, the axial leakage field's radial forces act outwardly on the outer winding, tending to stretch the winding conductor and creating tensile stress (also known as hoop stress). Radial forces develop perpendicular to the height of the winding.

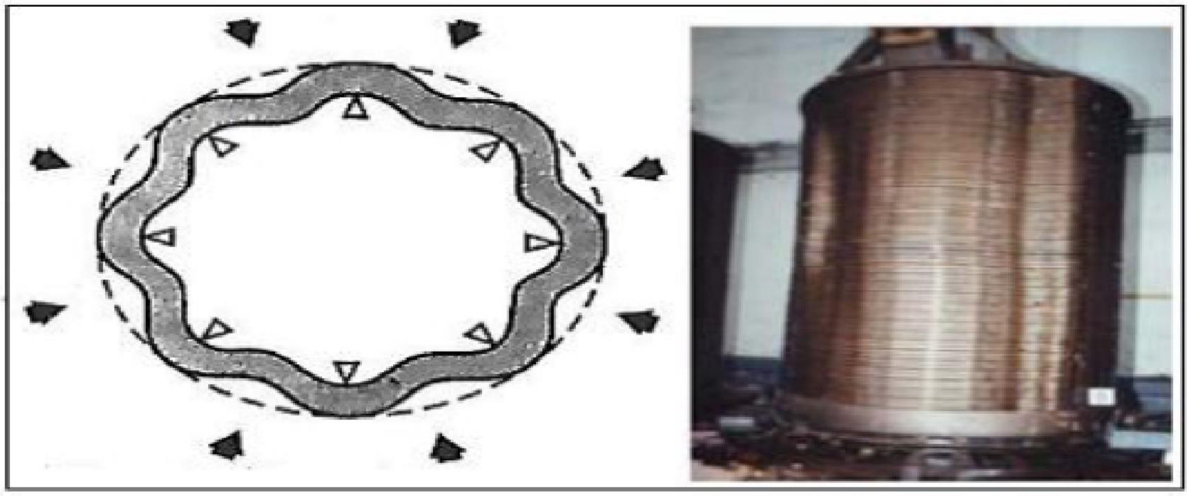

Fig. 3: *Forced buckling [7].*

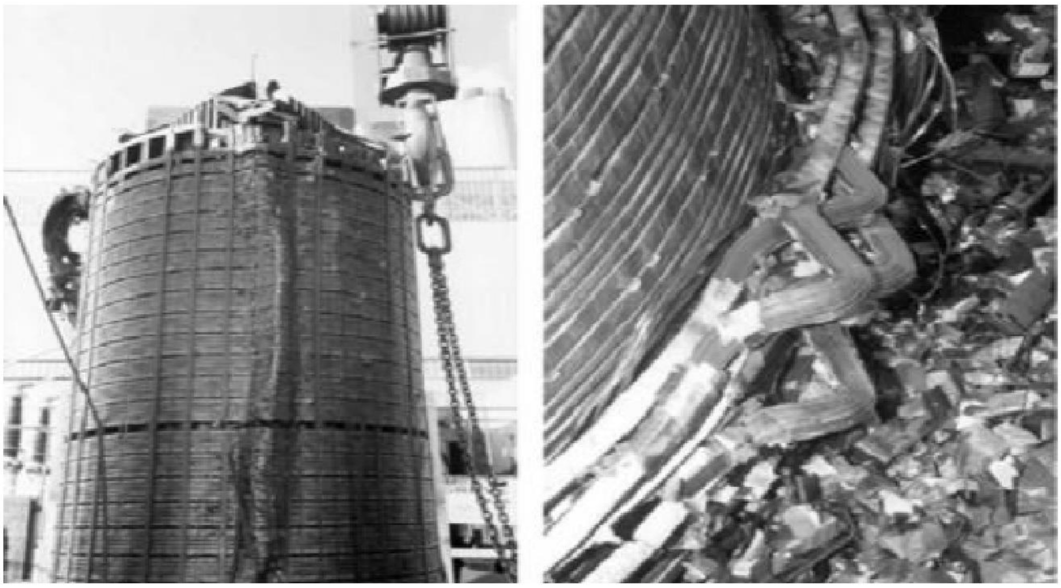

Fig. 4: *Hoop buckling in the outer winding [7].*

Axial Deformation

The direction of axial forces is parallel to the winding height. An axial force is primarily focused towards the middle of the winding and away from its ends. Thus, the centre of each winding has the most compression. Figure 5 depicts how windings can flex between supporting columns, which can lead to the breaking of the conductor insulation.

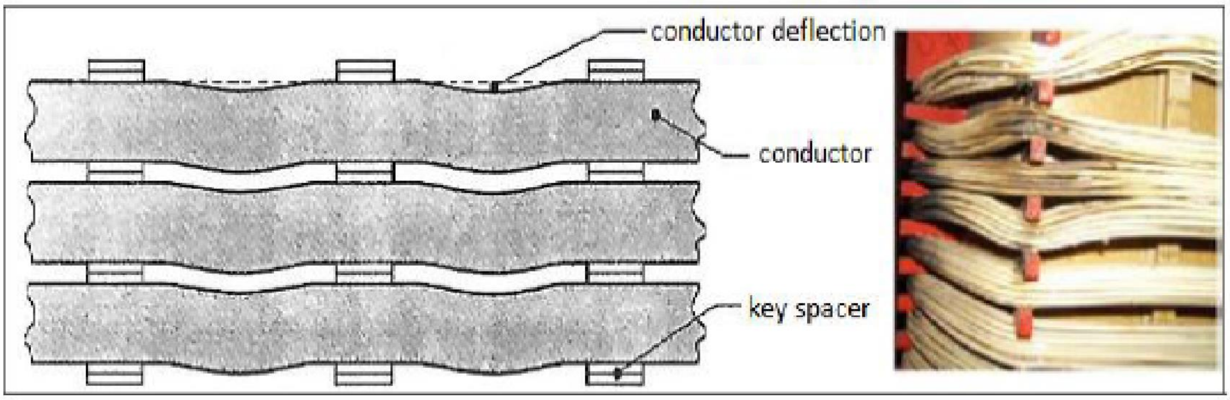

Fig. 5: *Axial bending of conductor between radial spacers [7].*

Figure 6 illustrates how conductors might tilt in a zigzag pattern when these axial forces exceed a specific threshold, leading to failure. The conductor cross-section turns around the perpendicular axis of symmetry in this mode of failure.

Fig. 6: *Tilting under an axial load [7].*

The EMFs in the transformer are classifiable into Axial forces and Radial forces [8].

Axial forces

These are produced in the transformer winding as the radial component of the leakage flux interacts with the current flowing through the windings.

In the middle of the transformer winding, the larger axial force can compress the winding conductors along the vertical axis [8,9].

Higher axial forces may be caused by the lack of balance between the transformer's low-voltage and high-voltage windings. The disparity in the ampere-turns of the high-voltage and low-voltage windings is another factor contributing to the larger axial force. Higher axial forces pose a major threat to the integrity of transformers [8,10].

An axial force is computed as follows:

$$F_a = B_r \times J_\varphi \tag{11}$$

$$F_a = \frac{2 \times \pi^2 \times A \times (NI)^2 \times D_m \times (10)^{-7}}{h_{eff}} \tag{12}$$

The radial leakage field density, B_r, can be determined using equation (13):

$$B_r = \frac{4\pi}{10^4} \times \frac{A(NI)}{2h_{eff}} \tag{13}$$

Where:

A = the length of the tap section expressed as a fraction of the total length of the winding,

h_{eff} = the effective length of the path of radial flux and the value of the h_{eff} varies for each arrangement of tapping.

The computation of the axial force for various tap layouts can be done using reference [11]. Figure 7 depicts the conductor bending as a result of the increased axial force caused by the short-circuit conditions [12].

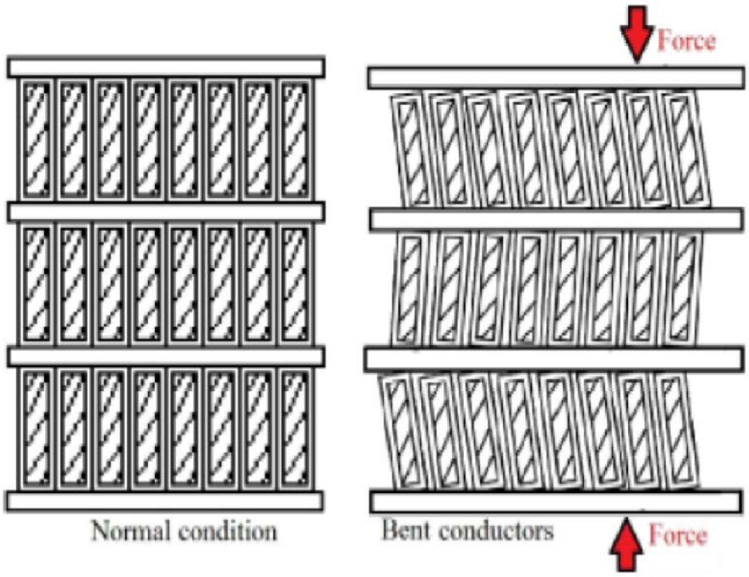

Fig. 7: *Effects of the axial force on the windings of the transformer [8].*

It is often more cumbersome to calculate the radial leakage field density and the axial force than to compute the axial leakage field intensity and the radial forces. However, the axial forces can be calculated using the residual ampere-turn approach. The computation of the radial leakage field density and the axial force is commonly done using this method. This technique divides the winding into two groups with equal ampere-turns. One component creates the axial field, while another component creates the radial field [11]. The three-phase transformer EMFs under normal and short-circuit situations are determined using the Ansys Maxwell software. The forces on the transformer winding's radial axis are calculated as follows [8]:

$$F_{rad-dist} = \frac{2\pi\left(NI\right)^2}{h} \times 10^{-7} \qquad (14)$$

The transformer windings may compress and expand under higher axial forces [13]. The short-circuit current is responsible for the deformation of the transformer windings [14]. Equation (15) can be used to ascertain the short-circuit current.

$$I_{sc}(t) = I_o e^{\frac{-Rt}{L}} + \frac{V_m}{\sqrt{\left(R^2 + X^2\right)}} \mathrm{Sin}(wt - \theta) \qquad (15)$$

Where I_0, V_m, R, X and L are initial current, maximum voltage, resistance, reactance, and inductance respectively.

Radial forces

Under normal circumstances, the axial component of the leakage flux density in the transformer winding is often substantially higher than the radial components of the leakage flux density. Radial flux is highest at the bottom and top of the power transformer windings and lowest in the middle of the windings [12]**.**

The axial flux density and the current flowing through the windings interact to produce the power transformer radial force [12]. It is possible to determine the radial forces in the transformer's windings using equations (16) and (17).

$$F_r = B_z \times J_\varphi \qquad (16)$$

$$F_r = \frac{2 \times \pi^2 \times \left(NI\right)^2 \times D_m \times 10^{-7}}{h} \qquad (17)$$

The axial leakage field density of the transformer can be determined using equation (18):

$$B_a = \frac{4\pi(NI)}{10^4} \qquad (18)$$

The void between the two windings grows as radial forces increases. These forces exert an inward and an outward force on the transformer's inner and outer windings, respectively [12,15]. Figure 8 depicts free buckling as a result of the inner winding's radial force.

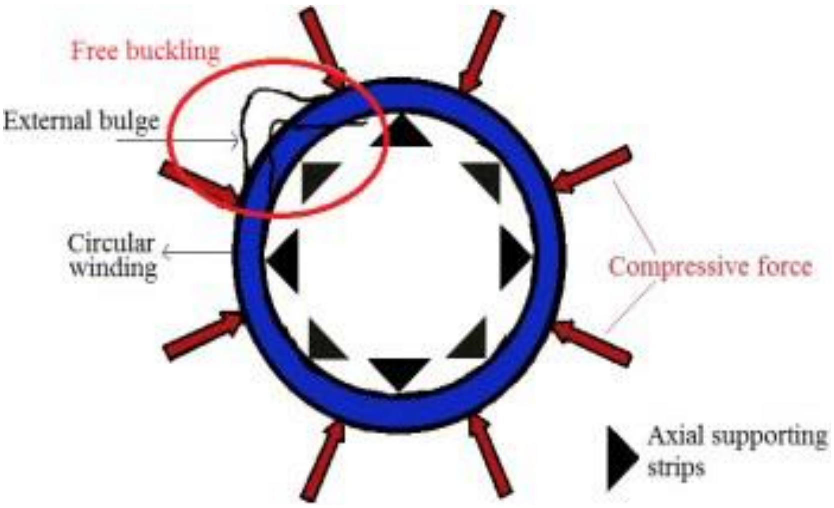

Fig. 8: *Free buckling due to the radial force for the inner winding [8].*

MITIGATION OF THE EFFECTS OF THE SHORT-CIRCUIT FORCES

There are essentially two methods for minimizing the negative consequences of short circuit forces. By making wise design decisions, transformer designers initially seek to reduce the prevailing electromagnetic forces. However, because electromagnetic forces will always exist in substantial amounts, precautions must be made to lessen their impact. While limiting the source of these forces is essentially an electrical problem with a magnetic field, measures against electromagnetic forces are primarily mechanical and involve structural countermeasures.

In general, radial and axial short circuit forces and the associated mechanisms of failure can be regarded as mutually exclusive, as was already mentioned. Preventative actions include managing the magnetic field and using design elements that produce a more tolerable field distribution inside the transformer.

A transformer short circuit withstand capacity is determined by its multiple structural components under real-world situations. The two types of axial allowable stress are those of the compressive forces within the windings and those of the axial thrust forces directed towards the clamping structure. After being subjected to some compressive stresses, the windings spring back into position, which causes axial thrust forces (Figure 8).

Different causes of failure are often considered, including spacers dissolving and conductors bending between them [5]. The pulsing nature of the forces is also significant since it might cause the insulating structure to deteriorate and emphasises the significance of speedy fault clearance times.

The way the windings are handled and put together directly determines how likely it is that one of these forces may lead to failure. High-quality materials, correct winding clamping, limited winding displacements, and decreased moisture content as a consequence of sufficient processing are all necessary to lower the risk of failure caused by axial stresses.

Tensile and compressive stresses produced by radial forces exhibit different mechanisms of failure. Tensile stresses result from forces pushing the windings' diameter up. If the conductor yield strength is surpassed, these forces cause the conductors to strain and possibly rupture. The conductors buckle under compressive pressures, forcing them inward and possibly bulging outwards near the elastic limit of the conductor material.

The main step in radial force mitigation is selecting the proper conductor hardness while taking cost and manufacturability into account. Additionally, the probability of radial failure is reduced by deploying sound winding design methodologies such as self-supporting windings, proper drying and processing, and the use of suitable conductors. Secondary failure that is dielectric is frequently caused by both axial and radial forces. Arc formation and dielectric breakdown result from the failure of insulation structures caused by failure mechanisms, which is widespread.

When a short circuit occurs in a network, the transformer winding may experience significant mechanical or electromagnetic forces as a result of the interplay between the magnetic field in the transformer and the current density in the transformer windings. As a result, excessive force is generated for any increase in current because the force so generated is exponentially proportional to the current. Thus, the radial and axial forces may be handled separately and, if the resist capability is exceeded, could lead to radial and axial modes of failure. Studies have revealed that by adjusting the magnetic field by modifications to the transformer shape, the strength of these forces could be minimised.

The location of the various transformer materials and mechanical resist capabilities are the major ways to make provisions for these stresses. Thermal and dielectric qualities are initially what influence a transformer's design; however, short circuit protection frequently trumps these considerations, resulting in a large cost rise. The importance of short circuit withstand capacity in any electromagnetic equipment, least of all in power transformers, should not be understated. It is a challenging interplay between electrical and mechanical engineering.

CONCLUSION

From the study, it can be concluded that:

- When single-phase and three-phase short-circuits occur on the low-voltage winding, the short-circuit current of the short-circuit phase and the short-circuit current of the zero-crossing closing phase are identical.

- The two ends of the axis winding are where the electromagnetic force is at its largest value in the high-voltage and low-voltage directions, whereas the centre of the winding has the smallest value. The centre of the winding is where the electromagnetic force is at its greatest in the radial direction, while the force on either side of the winding is the weakest.
- When the three-phase and single-phase short-circuits occur on the low-voltage winding, the electromagnetic force of the zero-crossing closing phase in the three-phase short-circuit is very close to that in the single-phase short-circuit, and the error is very small.

These conclusions are important because they highlight the need for advancements in both the power transformer's general architecture and its ability to tolerate short circuits.

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