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Analysis of Short-Circuit Electromagnetic Forces in Distribution Transformer Windings with Axial Asymmetry Using the Finite Element Method

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Abstract
Short-circuit faults subject transformer windings to severe electromagnetic (Lorentz) forces that can cause radial buckling, axial collapse, and permanent deformation of the winding structure. Conventional design calculations often assume that the low-voltage (LV) and high-voltage (HV) windings are of identical effective height, i.e., are axially symmetric. In practice, however, the LV winding of a distribution transformer is commonly wound as a single-layer helical winding, which introduces an axial asymmetry with respect to the HV winding. This paper presents a two-dimensional finite element method (FEM) study, carried out in FEMM 4.2, of the short-circuit electromagnetic forces developed in the windings of a 630 kVA, 11000/433 V, three-phase, three-limb distribution transformer under (a) an idealized, axially symmetric winding arrangement and (b) the actual, axially asymmetric arrangement. Radial force, axial force, and axial compressive force are computed cell-by-cell for both windings under the worst-case three-phase symmetrical short-circuit condition. The results show that while the total radial force is only marginally affected by axial asymmetry, the axial force distribution changes fundamentally: it is identically zero for a symmetric winding pair but rises to 125.6 kN (LV) and 145.5 kN (HV) once asymmetry is introduced, with the two halves of the winding experiencing oppositely directed forces. The location of maximum axial compressive force also shifts from the winding centre (symmetric case) toward the winding ends (asymmetric case). These findings indicate that neglecting axial asymmetry in short-circuit strength calculations can significantly underestimate the mechanical duty imposed on distribution transformer windings.
Keywords— Distribution transformer, short-circuit forces, axial asymmetry, finite element method, FEMM, Lorentz force, radial force, axial compressive force.

I. INTRODUCTION

The transformer is the single most critical, and most costly, piece of apparatus in a power system, and it is also one of the most vulnerable during a fault on the network to which it is connected. When a short circuit occurs, the fault current in the windings can reach ten to twenty times the rated current, and, because the mechanical force between two current-carrying conductors is proportional to the square of the current, the resulting electromagnetic forces can be two to four hundred times the forces experienced in normal service. Field experience shows that roughly one transformer in four fails the routine short-circuit withstand test specified by IEC 60076-5, and the failure rate increases with the power rating of the unit. It is therefore essential that the radial and axial forces developed in the windings under short-circuit conditions be estimated accurately at the design stage.

For a two-winding transformer of conventional concentric construction, the short-circuit force is usually resolved into a radial component, which tends to burst the outer (HV) winding outward and crush the inner (LV) winding inward, and an axial component, which arises from the radial leakage flux at the ends of the windings. Classical analytical treatments of this problem generally assume that the LV and HV windings have identical effective (electrical) height. Under this idealised assumption, the net axial force integrated over the whole winding height is zero, because the axial force distribution is anti-symmetric about the winding mid-plane. In an actual distribution transformer, however, the LV winding is frequently constructed as a single-layer (or double-layer) helical winding, whose electrical mid-plane does not coincide exactly with that of the HV cross-over winding once end-insulation, lead take-off arrangements and manufacturing tolerances are accounted for. This mismatch, referred to here as axial asymmetry between the LV and HV windings, breaks the anti-symmetry of the axial force distribution and gives rise to a net, unbalanced axial force on each winding — a phenomenon that is not captured by the idealised symmetric analysis.

The finite element method (FEM) is well suited to this problem because it can accommodate the actual, non-ideal winding geometry without the simplifying assumptions that are unavoidable in closed-form analytical methods. This paper uses two-dimensional FEM, implemented in the open-source package Finite Element Method Magnetics (FEMM) 4.2, to quantify the change in short-circuit force distribution that results when axial asymmetry between the LV and HV windings of a distribution transformer is taken into account.

II. SHORT-CIRCUIT CURRENT AND ELECTROMAGNETIC FORCE

A. Worst-Case Short-Circuit Current

Among the fault types that can occur on a power network — line-to-ground, line-to-line, double line-to-ground, and three-phase symmetrical faults — the three-phase symmetrical fault, occurring sufficiently far from the generating source, produces the highest fault current at the transformer terminals and is therefore adopted as the design condition for short-circuit strength. For a two-winding transformer, the symmetrical rms short-circuit current is obtained from the rated current and the per-unit impedance of the transformer and source, in accordance with IEC 60076-5.

Because the fault can be initiated at any point on the voltage waveform, the short-circuit current in general contains a decaying unidirectional (DC) component superimposed on the steady-state AC component. The instant of switching that produces the maximum possible peak current (zero-voltage switching) is taken as the design case, and the corresponding asymmetry factor, which depends on the winding reactance-to-resistance ratio (X/R), is applied to the symmetrical current to obtain the peak short-circuit current used in the force calculation.

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B. Radial and Axial Force Components

The local electromagnetic force density on a current-carrying conductor in a magnetic field is given by the Lorentz force law, $F = J \times B$, where J is the local current density and B is the local flux density. In a two-winding transformer, the leakage flux has a predominantly axial (vertical) component within the winding window and a radial (horizontal) component that becomes significant near the winding ends. The interaction of the winding current with the axial flux component produces the radial force, which pushes the LV winding toward the core and the HV winding away from the core (a bursting force on the outer winding and a crushing force on the inner winding). The interaction of the winding current with the radial flux component at the winding ends produces the axial force, which, for windings of equal effective height, is directed toward the winding mid-plane from both ends and integrates to zero over the full winding height.

III. FINITE ELEMENT MODELLING PROCEDURE

A. Reduction to a Two-Dimensional Problem

The core-type distribution transformer considered in this study has a high degree of rotational symmetry about its central limb, and edge effects associated with the finite axial length of the winding are neglected. The three-dimensional field problem is therefore reduced to a planar, two-dimensional problem in the (x, y) plane normal to the winding axis, with the model given a unit depth. Under planar symmetry the current density and the magnetic vector potential each have only a z-directed component, and the field is governed by the Poisson equation

$$\nabla^2 Az = -\mu\, Jz$$

where Az is the z-component of the magnetic vector potential, Jz is the source current density, and μ is the magnetic permeability of the region.

B. Boundary Conditions

A homogeneous Dirichlet boundary condition ($Az = 0$) is applied on the outer boundary of the solution domain, consistent with the assumption that the leakage flux is confined within the transformer core and winding window and does not cross the chosen outer boundary. This condition is standard practice for core-type transformer geometries in which the flux path is well contained by the surrounding core material.

C. Force Computation — Lorentz Force

Once the field solution (the distribution of Az, and hence of the flux density B, over the solved domain) is obtained, the force on each current-carrying region is computed directly from the Lorentz force integral

$$F = \iint (J \times B)\, dS \quad \text{(per unit axial length)}$$

The Lorentz force method was preferred over the Maxwell stress tensor and virtual-work methods for this study because, for a region containing materials of unit relative permeability (i.e., the copper conductors themselves), it gives an accurate force estimate without the sensitivity to the choice of integration contour that affects the Maxwell stress tensor method, and without requiring the solution of two separate field problems as required by the virtual-work method.

To obtain the force distribution along the height of the winding, each winding is divided into 23 cells, numbered 1 (bottom) to 23 (top). The radial and axial force on the current contained in each cell is computed separately, allowing the force distribution along the winding height, and the cumulative axial compressive force at any section, to be evaluated.

IV. TRANSFORMER MODEL UNDER STUDY

The transformer used for this study is a 630 kVA, 11000/433 V, three-phase, three-limb, oil-immersed distribution transformer, with the HV winding delta-connected and the LV winding star-connected. The LV winding is of single-layer helical construction and the HV winding is of cross-over construction. The rated specifications of the windings and the core are summarised in Table I and Table II. The winding on the central limb, which experiences the highest short-circuit force in a three-limb core-type transformer, is chosen for the analysis.

TABLE I. WINDING SPECIFICATIONS OF THE 630 kVA, 11000/433 V TRANSFORMER

Parameter	HV Winding	LV Winding (single-layer helical)
Number of coils per phase	2	1
Number of turns per phase	1062	23
Bare conductor size (mm)	Dia. 2.850	6.70 × 4.25 × 10
Covered conductor size (mm)	3.150	7.10 × 4.65
Inner diameter of coil (mm)	275.5	207
Axial length of coil (mm)	398	398
Outside diameter of coil (mm)	339.5	254.5
Rated voltage (V)	11000	433
Yoke clearance (mm)	21	11
Winding connection	Delta	Star

TABLE II. CORE SPECIFICATIONS

Parameter	Value
Core material	M4 CRGO silicon steel
Maximum flux density (T)	1.68
Stacking factor	0.97
Window height (mm)	440
Leg centre distance (mm)	350
Core diameter (mm)	200
Yoke height (mm)	195

Two magnetostatic FEM models of the winding cross-section were built: (i) an idealised model in which the LV and HV windings are assigned equal effective (electrical) height, representing the classical symmetric assumption, and (ii) a realistic model that reproduces the actual axial offset between the LV single-layer helical winding and the HV cross-over winding. Peak short-circuit current values, computed from the transformer impedance and the IEC 60076-5 asymmetry factor, are applied as the excitation in both models.

The FEM model was first validated by comparing the total radial force on each winding, obtained from the simulation, against the value obtained from the classical analytical (magnetic-field) formula for the idealised, axially symmetric case. The comparison, given in Table III, shows close agreement between the two methods, confirming the validity of the mesh, boundary conditions and post-processing procedure used for the subsequent asymmetric-winding study.

TABLE III. VALIDATION OF THE FEM MODEL — TOTAL RADIAL FORCE, IDEAL (SYMMETRIC) CONDITION

Winding	Analytical Result (kN)	FEM Simulation Result (kN)
Inner winding (LV)	815.58	773.84
Outer winding (HV)	1137.93	1020.96

V. RESULTS AND DISCUSSION

A. Radial Force

Under the idealised, axially symmetric condition, the total radial force is 773.84 kN on the LV winding, directed toward the core, and 1020.96 kN on the HV winding, directed away from the core (bursting force). When the actual axial asymmetry between the windings is introduced, the corresponding values change only marginally, to 778.8 kN (LV) and 1019.18 kN (HV). In both cases the radial force is smallest at the top and bottom cells of each winding and largest at the cells nearest the winding mid-height, reflecting the reduction of leakage flux radial spreading toward the ends of a well-contained core-type winding window. The close agreement between the symmetric and asymmetric cases confirms that the total radial force is governed primarily by the winding ampere-turns and the mean radial gap between the windings, and is not strongly sensitive to a moderate axial offset between the winding mid-planes.

B. Axial Force

The effect of axial asymmetry is most pronounced in the axial force distribution. Under the idealised symmetric condition, the axial force on each cell is anti-symmetric about the winding mid-height, is of comparatively low magnitude at the mid-height cells and rises toward the winding ends, and integrates to zero over the complete winding for both LV and HV. When axial asymmetry between the LV and HV windings is introduced, this anti-symmetry is destroyed: the net axial force on the complete LV winding becomes 125.6 kN, and on the complete HV winding, 145.5 kN. Considering the transformer model in the two-dimensional (x, y) coordinate system used for the FEM analysis, the LV winding on one side of the central limb experiences a net upward force while the LV winding on the other side experiences an equal-magnitude net downward force, and the HV winding experiences forces in the opposite sense to the corresponding LV forces. This behaviour is a direct, quantifiable consequence of the axial offset between the electrical mid-planes of the two windings and is entirely absent from the idealised symmetric analysis.

C. Axial Compressive Force

The cumulative axial compressive force, obtained by successively summing the cell-by-cell axial force from one end of the winding, provides a direct measure of the compressive duty on the winding and its supporting/clamping structure at any given section. Under the idealised symmetric condition, the axial compressive force is maximum at the winding mid-height for both windings, with peak values of approximately 34.6 kN (LV) and 14.7 kN (HV). Under the axially asymmetric condition, however, the point of maximum axial compression shifts away from the mid-height toward the extreme ends of the winding, and the peak magnitude increases substantially, to 133.8 kN for the LV winding and 144.5 kN for the HV winding, with the two windings' peak compressive forces acting in opposite directions. This shift in both the magnitude and the location of the critical section has direct implications for the design of axial clamping structures, which, if sized only on the basis of the idealised symmetric analysis, would be under-designed for the actual short-circuit duty.

VI. CONCLUSION

A two-dimensional finite element analysis, carried out in FEMM 4.2, has been used to quantify the effect of axial asymmetry between the LV and HV windings on the short-circuit electromagnetic forces in a 630 kVA distribution transformer. The results show that while axial asymmetry has only a marginal effect on the total radial force, it has a decisive effect on the axial force behaviour: a net, unbalanced axial force (125.6 kN on the LV winding and 145.5 kN on the HV winding) is developed that does not exist under the idealised symmetric assumption, and the location of maximum axial compressive force shifts from the winding mid-height to the winding ends, with the peak magnitude increasing by roughly a factor of four (LV) to ten (HV) relative to the idealised case. These findings demonstrate that the axial asymmetry inherent in the common combination of a single-layer helical LV winding with a cross-over HV winding should be explicitly represented in short-circuit strength calculations, rather than being neglected in favour of the simpler, idealised symmetric assumption. The procedure demonstrated here for a single-layer helical LV winding can be extended to double-layer helical and other winding configurations, and represents a useful, computationally economical design-verification tool for distribution and power transformer manufacturers.

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