Short Circuit Stress Analysis Using FEM in Power Transformer on H-V Winding Displaced Vertically & Horizontally

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Abstract The aim of this work was to work out the mechanical stresses within transformer resulting from the extreme short-circuit currents. The forces and stresses set up in transformer windings as the result of exterior or interior short-circuits or of switching operations, are measured in detail. A variety of arrangements of windings in large power transformers are described. Points at which mostly high mechanical stresses take place in concentric windings are discussed in detail. Analytical and FEM calculations for individual short circuit forces, axial and radial have been discussed. The result was then compared with actual measurements on a prototype 20 MVA 132/11.5 kV power transformer [15]. Various failure mechanisms due to these forces have been discussed. Design parameters are also discussed, whose values determine the maximum stresses which may occur in any part of the transformer. Effects of irregularity in various parts and various properties of materials have been studied and the usage of appropriate material for withstanding the dynamic effects of SC is discussed. Effect of workmanship errors on short circuit withstand capability has also elucidated. Finally, a complete model is developed.

1. Introduction

Nowadays transformer failures are increasing day by day which is a serious problem for a country like Pakistan facing the energy crisis. The major cause of transformer failure in power system is short circuit faults. Most of the transformers fail during the short circuit test which has become a major concern for the manufacturers.

Power transformers are critical and expensive components of the energy transmission and distribution process for electric utilities. It may be noted that about 33% of failures are due to the windings faults.

Power transformers are one of the main devices in found power systems. Reliability, power quality and economic cost are affected by the transformer’s health conditions. Catastrophic failures of power transformers may have a serious environmental impact, such as fire and transformer oil spill.
Therefore, the failures of power transformers are of much concern and are investigated extensively [1,2].

Lack of strengthening of transformers (for short-circuit proofness) by manufacturers can cause severe damages to the transformer as well as the system, prominent of which are as follows:

- Deformation of LV and HV windings.
- Broken pressure plates on windings.
- Bending of clamping structure.
- Bulging of tank body.
- Collapse of bushings.
- Short-Circuited tapping leads.

As a result, development of condition monitoring systems for the winding of power transformers holds promise toward cost reduction throughout power transformers' life cycle and toward an increase in the availability and reliability of power transformers.

In this paper, some basic theoretical backgrounds of short-circuit’s stresses are given, especially with respect to power transformers. The three different types of mechanical forces that arise in the windings during short-circuit are evaluated mainly the Axial Forces, Radial Forces and the combination of (axial and radial) stresses at the winding ends.

Calculation of these forces using the Finite Element Method was performed. Design parameters are discussed, whose values determine the maximum stresses which may occur in any part of the transformer. Effects of asymmetry in various parts are also studied. Different properties of materials are studied and the usage of proper material for withstanding the dynamic effect of short-circuits is studied too. Effect of workmanship errors on short-circuit withstand capability is also elucidated. Finally, a complete model for the study of dynamic effects of short-circuits in a power transformer is developed.

2. Short circuit currents

Almost all types of faults cause the sudden rise of current in power system which results in malfunction and inconsistent operation of installed equipment along with severe effect on transformer insulation. Usually, the three-phase faults are the most severe of all; hence, the transformer should be designed to withstand the effects of symmetrical three phase faults. It must be mentioned here that in some cases (where a tertiary connected winding is present), the single-phase to ground fault on those windings, since it is related to very special cases, emphasis is made on symmetrical three-phase faults.

2.1. Value of symmetrical short-circuit current

For three-phase transformers with two separate windings, the r.m.s. value of the symmetrical short-circuits current “I” shall be calculated as in Eq. (i) [4].

\[ I = \frac{U}{\sqrt{3} \times (Z_t + Z_s)} \]  

where

- \( U \): is the rated voltage of the winding under consideration, in kilovolts,
- \( Z_t \): is the short-circuit impedance of the transformer referred to the winding under consideration, in ohms per phase,
- \( Z_s \): is the short-circuit impedance of the system, in ohms per phase.

As mentioned above, due to addition of more and more generating stations within an interconnected system, the source impedance \( Z_s \) is very small and generally neglected for calculations purpose.

2.2. Nature of short-circuit current

Consider the circuit given alternate voltage source. Assuming that the below with an switch is closed at \( t = 0 \) instant, which simulates the short-circuit, the expression for the current \( i(t) \) can be written as follows (see Fig. 1):

\[ i(t) = I_{\text{max}}[\sin(\omega t - \theta)] \]  

where

- \( I_{\text{max}} \): maximum value of the current \( i \),
- \( t \): time, in seconds,
- \( \theta \): phase angle of the circuit impedance \([\tan^{-1}(\varphi L/R)],\)
- \( r \): time constant \([L/R]\).

The plot of this current expression with respect to time is as shown in Fig. 2. The mechanical strength of the transformer windings should be such that it shall withstand the highest short-circuit forces generated which correspond to the first current peak in the figure above, since this current peak has the highest magnitude due to the presence of DC component in the current pattern [8,9].

3. Short-circuit forces

When a current carrying conductor lies in a magnetic field, a force is produced upon that current carrying conductor, whose magnitude is given by Eq. (iii).

\[ F = B \cdot I \cdot L \cdot \sin \alpha \]  

where

Figure 1 A sinusoidal voltage source switched on to an RL network.
3.1. Electromagnetic forces

In transformers, electromagnetic forces may have three components if we model it in 3D cylindrical coordinates.

- r-component.
- z-component.
- φ-component.

The r-component of the electromagnetic forces results in the radial forces that act on the windings [8]. The z-component is the originator of the axial forces that act on the windings. Finally, the φ-component can cause twisting motion of the windings, but it is never present because of the other. The conventional way to calculate the short-circuit forces is by solving Eq. (iii), using data of the transformer from the design calculation sheets. This calculation, however, assumes a lot of data which can sometimes result in a very safe calculation and, otherwise, could result in unsafe margins during calculations [3].

4. Center axis of the windings is always coinciding with each finite element modeling

4.1. Introduction to finite element method

Finite element method (FEM) is a numerical method mainly used for solving Differential and Integral equations. Essence of this method is to divide the application domain in very small sub domain elements called as finite elements. Problem is subdivided into Finite size sub problems and is independently dealt to find complete problem solution.

There are many software commercially available incorporating the Finite Element Method Solution. In this paper, a software tool titled meshing and finite element solver has been used [1]. The model has been drawn using MATLAB with complete computation of leakage flux and therefore short-circuit forces.

4.2. Finite element method in transformer

In transformers, finite element method can be used to calculate the following quantities:

- Eddy currents and winding stray losses.
- Electric field analysis.
- Temperature gradient calculations.
- Short-circuit stresses.
- Stress-strain analysis of the clamping structure.

4.3. Steps of finite element modeling

Finite Element modeling is a highly accurate method of calculating the transformer parameters. The FEM formation makes use of the fact that Poisson’s partial-differential equation is satisfied when total magnetic energy function is a minimum [4,5].

1. The geometry to solve (which is basically the core and set of transformer windings represented simple as rectangular blocks) can be drawn using most CAD programs. In this work, Auto Cad 2010 is used to draw the geometry in .dxf format (see Fig. 3).
2. Once the geometry is ready, it is then divided into finite elements i.e. small elements. The smaller the size of each mesh or element, the higher will be the accuracy of the results can be obtained if problem is divided into number of small problems. Different models and geometries of transformer for the application and calculations are given in Figs. 4–
7, while Figs. 8 and 9 show flux plots of transformer which are important to obtain while calculating short circuit effect on power transformer windings.

3. The properties of each of the blocks drawn, are then assigned along with the boundary conditions. Since core has a very high relative permeability value, it will not store any appreciable energy. Hence, it doesn’t matter whether core is given a relative permeability of 10,000 or 100,000. When assigning the properties to the windings, it must be made sure that the ampere-turns of all the winding regimes must be equal and opposite, so that no mutual component of flux in the core should exist.

4. The space filled with oil is assigned a relative permeability of 1, including the windings.

5. The geometry is solved in the FEM solver and the flux leakage plot obtained.

5. Analysis on stresses based on vertical movement

Analysis of HV winding in vertical of power transformer was performed.

The winding rotation steps were chosen arbitrary as per design approach. The movement step is 0-mm, 2-mm, 5-mm, 10-mm, 15-mm is chosen for vertical respectively.

The results and geometry model for these movements are given in Fig. 6.

Fig. 7 shows mesh model in these cases would be displaced in vertically as shown below.

The geometries are solved in the FEM solver software and the flux leakage plots obtained as in Fig. 8.

Following is the comprehensive simulation results of fluxes obtained from FEM measured forces obtained from FEMM by setting properties of core, oil, LV, HV windings, etc. It also includes comparison plots of forces obtained by MATLAB.

There are number of findings from the simulation results of FEMM.

- The direction of short-circuit flux (arrows in the figure).
- Total effect of the forces appears to cancel out.
- Forces at the winding center are purely radial.
- Inner winding is subject to buckling effect.
- Outer winding tends to stretch out.
- Forces at the winding ends have both axial and radial directions [7,11].

The flux simulation results at vertical movement are given below which are extracted from [6,7]. The minimum flux density is shown with light color while maximum flux density is present at top middle and bottom turns of winding. Different colors show the level of flux produced in windings followed by measurement of H.V and L.V forces at bottom and in different positions in windings with the help of FEM. Results are concluded by comparing the results of FEMM and measurements made mathematically. In given below flux density plots as in Fig. 9, various levels of flux densities are presented by different colors [13].

6. Vertical winding forces

The comparison plot of LV forces in windings at different displacements is given in Fig. 10.

From the above plot in Fig. 10, it is clear that in early turns the negative forces are dominant and in middle of the turns the forces approach to zero because of cancelation of effect of the negative and positive forces. This force applied on winding pattern is same for the displacements of 0-mm, 2-mm, 4-mm,
Figure 6  Geometrical model.

Figure 7  Mesh model.

Figure 8  Flux plot.
5-mm, 6-mm, 8-mm, 10-mm and 15-mm. The only difference is the windings having less displacement have tendency of negative forces to approach from negative to zero more quickly and forces approach from zero to positive more slowly and vice versa. The comparison plot of HV forces in windings at different displacements is given in Fig. 11.

From above plot it is clear that in early turns the negative forces are dominant and in middle of the turns the forces approach to zero because of cancelation of effect of the negative and positive forces. This force applied on winding pattern is same for the displacements of 0-mm, 2-mm, 4-mm, 5-mm, 6-mm, 8-mm, 10-mm and 15-mm. The only difference is the windings having less displacement have tendency of negative forces to approach from negative to zero more quickly and forces approach from zero to positive more slowly and vice versa. Figs. 10 and 11 show the complete comparison plots of LV and HV forces in windings at different displacements. Figs. 12 and 13 show the individual plots of forces in winding at different displacements 0-mm, 2-mm, 4-mm, 5-mm, 6-mm, 8-mm, 10-mm and 15-mm respectively.

6.1. x-axis forces at winding

The comparison plot of LV forces at bottom of windings at different displacements is given in Fig. 14.

From the above plot it is clear that accumulated forces are minimal in upper and bottom turns, whereas accumulated force is maximum at middle turns of windings. The accumulated force increases from zero to a constant maximum value earlier at winding having less displacement and decreases from maximum value to zero late in bottom turns and vice versa for windings with more displacement. This force applied on winding pattern is same for the displacements of 0-mm, 2-mm, 4-mm, 5-mm, 6-mm, 8-mm, 10-mm and 15-mm. The comparison plot of HV forces at bottom of windings at different displacements is given in Fig. 15.
From the above plot it is clear that accumulated forces are minimal in upper and bottom turns, whereas accumulated force is maximum at middle turns of windings. The accumulated force increases from zero to a constant maximum value earlier at winding having less displacement and decreases from maximum value to zero late in bottom turns and vice versa for windings with more displacement. This force applied on winding pattern is same for the displacements of 0-mm, 2-mm, 4-mm, 5-mm, 6-mm, 8-mm, 10-mm and 15-mm. Figs. 16 and 17 show the individual plots of forces at winding on different displacements 0-mm, 2-mm, 4-mm, 5-mm, 6-mm, 8-mm, 10-mm and 15-mm.

7. Short circuit forces experimental value and theoretical value with percentage error

In this paper we displaced high voltage winding of the transformer on both axes (horizontally and vertically). The displaced points are discussed above in this paper. We calculate the percentage error for all displaced transformers. Finally plot
the percentage error graph versus displaced values of transformer winding.

\[
\text{Fax} = 0.6289 \left( \frac{(N \cdot I)^2}{(H_x)^2} \right) \cdot \pi \cdot D_m \cdot \left( d + \frac{a_1 + a_2}{3} \right) \cdot (2K - 1)r^2 \cdot (K\sqrt{2})^2 \cdot 10^{-6}N
\]

\[H_x = \text{geometrical average length of windings,}\]
\[N = \text{number of turns},\]
\[I = \text{current of HV},\]
\[D_m = \text{mean diameter of the pair of windings},\]
\[d = \text{width of main duct},\]
\[a_1 \& a_2 = \text{radial width of winding \# 1 \& 2},\]
\[K = \text{Rogowski factor}.\]

For LV: \[D_m1 = \frac{\text{outer diameter} - \text{inner diameter}}{2}\]

For HV: \[D_m2 = \frac{\text{outer diameter} - \text{inner diameter}}{2}\]
\[ D_m = \frac{D_m1 + D_m2}{2}; \quad K = 1 - \frac{d + a_1 + a_2}{\pi \cdot H_w} \]

Given data:
- HV current = 1287.878788,
- Outer diameter of LV = 658 mm; inner diameter of LV = 535 mm,
- Outer diameter of HV = 946 mm; inner diameter of HV = 742 mm,
- \( N = 2067 \),
- \( r = 3.2 \text{ mm} \),
- \( d = 42 \text{ mm} \),
- \( a_1 = 61.5 \text{ mm} \),
- \( a_2 = 102 \text{ mm} \),
- \( H_w = 1324 \text{ mm} \).

0-mm:
- \[ K = 1 - \frac{42 + 61.5 + 102}{3.14 \times 1324} = 0.950 \]
- \[ D_m1 = \frac{658 - 535}{2} = 61.5; \quad D_m2 = \frac{946 - 742}{2} = 102 \]

\[ \text{Figure 15} \quad \text{Comparison of HV forces at windings.} \]

\[ \text{Figure 16} \quad \text{Individual LV forces at winding on different displacements.} \]
\[ D_m = \frac{D_m1 + D_m2}{2} = \frac{61.5 + 102}{2} = 81.75 \]

\[ r^2 = 10; \quad \sqrt{2} = 1.414 \]

\[
\text{Fax} = 0.628 \times \frac{(2067 \times 1287.878788)^2}{(324)^2} \times 3.14 \times 81.75 \\
\times \left( 42 + \frac{61.5 + 102}{3} \right) \times (2 \times 0.950 - 1) \times 10 \\
\times (0.950 \times 1.414)^2 \times 10^{-6} N
\]

\[ = 0.628 \times \frac{7.087 \times 10^{12}}{1.752} \times 256.695 \times 96.5 \times 9 \times 1.805 \times 10^{-6} \]

\[ = 0.628 \times 4042893.149 \times 256.965 \times 96.5 \times 9 \times 1.805 \times 10^{-6} \]

\[ = 1021669.773 \]

Percentage Error = \[ \frac{\text{Experimental Value} - \text{Theoretical Value}}{\text{Theoretical Value}} \times 100 \]

\[ \text{P.E.} = \frac{1100558.131 - 1021669.773}{1021669.773} \times 100 \]

\[ \text{P.E.} = 7.72\% \]

Remaining percentage error values of transformer displaced model are shown in Table 1.

**Table 1 Percentage error value.**

<table>
<thead>
<tr>
<th>Sr #</th>
<th>Displacements (mm)</th>
<th>Percentage errors (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>3.43</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>2.64</td>
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<td>10</td>
<td>-1.52</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>-5.2</td>
</tr>
</tbody>
</table>

**Figure 17** Individual HV forces at winding on different displacements.
8. Conclusions

The results of mechanical forces generated due to prolonged high currents in power transformer windings have been evaluated. High temperatures generated inside transformer may puncture the insulation which causes breakdown. As power transformer is very expensive power system apparatus is needed to be protected with first priority. That is why its failure is avoided and comprehensive analysis is done to cater all drastic situations which may cause its complete failure. This research will enable the transformer manufacturers for careful design of transformer and the power utility authorities to ensure its safe operation in power system.

References


Further reading