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ORIGINAL ARTICLE

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.

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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 line fault short-circuit current can be higher than the three-phase fault on those windings, since it is related to very special cases, emphasis is made on symmetrical three-phase faults only.

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].

$$I = \frac{U}{\sqrt{3} * (Z_t + Z_s)} \quad \text{(i)}$$

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 phases,
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):

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

where
$I_{\max}$: maximum value of the current i,
t: time, in seconds,
θ: phase angle of the circuit impedance [tan − 1(φL/R)],
τ: 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).

$$F = B \cdot I \cdot L \ \sin\alpha \quad \text{(iii)}$$

where

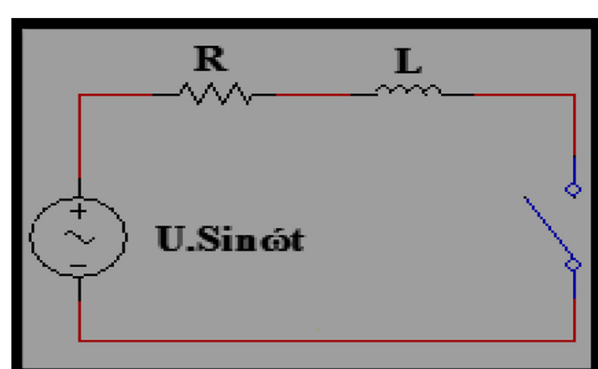

Figure 1 A sinusoidal voltage source switched on to an RL network.