FEM based Reactance Computation for Transformer Winding Deformation Detection

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ABSTRACT
Leakage reactance is one of the most important specifications in transformer that has significant impact on its overall design. Variation in leakage reactance serves as a diagnostic measure to indicate mechanical integrity of power transformers before and after a short circuit test that demonstrates mechanical strength of transformer windings. This paper presents an approach for leakage reactance computation through finite element method (FEM) and subsequent analysis of winding deformation due to a short circuit. A concentric two winding transformer is considered and reactance computation is made using FEM package. The results of computation are compared against classical method. It is observed that the method can provide sufficient theoretical basis for improving the design.

Keywords
Transformer,reactance calculation,FEM, mechanical strength, axial deformation, radial deformation.

1. INTRODUCTION
Power transformer is highly expensive equipment in a power system network that requires continuous, reliable and stable operation. Short circuits occurring within and external to the transformer may cause heavy damage and hence needs to be specified for their short circuit with stand capability [1]. Adequate short circuit strength is essential for the safe operation and any inadequacy may cause winding deformation due to short circuit that leads to complete collapse of the winding structure [2].

Devising a transformer model is essential to make improvements in the design [3]. Therefore better methods for the design of transformers with sufficient short circuit strength are necessary [4]. As reactance is one of the most important design specifications, recent researchers focus their attention towards various computational methods for reactance calculation. During the past calculation of reactance were based on classical methods that have considered simplified configurations along with certain assumptions [5]. These methods are simple but not suited for special types of transformers having complicated structures.

Numerical method of reactance computation may provide accurate results and FEM is one such method [6]. It is a discretization method of solving nonlinear partial differential equations numerically. With the advancements in computational facilities it is possible to model complex structured transformers accurately and is the reason for the choice of FEM based approach for solving problems of this type [7-10]. This paper proposes a FEM based reactance calculation that is suitable even for non standard winding configurations. Axial and radial winding deformation analysis based on reactance computation is presented through a simulation work.

2. PROBLEM FORMULATION
The transformer considered for the proposed method of reactance computation is a two winding concentric fictitious transformer with specifications as mentioned in [11]. The specifications of the transformer is chosen as 31.5MVA, 132/33 kV, 50Hz.The low voltage (LV) winding is adjacent to core and it is the inner winding and the outer winding is high voltage (HV) winding. Both LV and HV windings have equal ampere turns. Two dimensional axisymmetric model of the fictitious transformer (variant 120) with all dimensions in mm as shown in Fig. 1 is the device under study (DUS) for which FEM based reactance computation is required. The problem is formulated using two dimensional magneto static solver of FEM package that solves for magnetic vector potential.

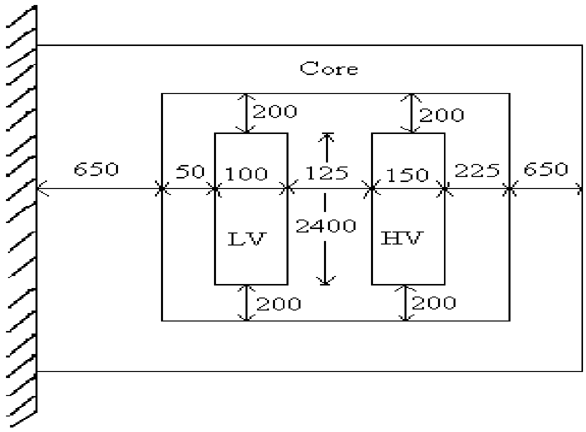

Figure 1: Dimensions of fictitious transformer variant 120

3. FINITE ELEMENT MODEL OF DEVICE UNDER TEST
Finite Element model of thedevice under study with dimensions as in Fig. 1 is developed using the FEM package and is shown in Fig. 2. The number of turns,volts per turn and current through HV winding are 500, 152.42 and 137.78A respectively. The ampere turns of the LV winding has been chosen similar to that of HV winding. The materialwith permeability 1000 is chosen to define the core.

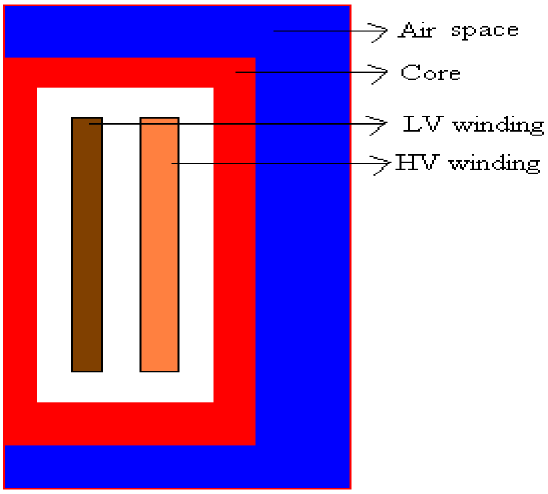

Figure2: Two dimensional axisymmetric FEM model of the fictitious transformer

4. REACTANCE COMPUTATION FOR WINDING DEFORMATION USING CLASSICAL METHOD

The reactance calculation is based on the fundamental definition of inductance in which inductance is defined as the ratio of total flux linkages to a current which they link and is given as

$$L = \frac{N\emptyset}{I} \qquad (1)$$

where N ,φ,I represents the number of turns, flux linkage and current respectively. The leakage inductance of a transformer can be written as

$$L = \frac{\mu_0 \pi N^2}{H_{eq}} \sum_{k=1}^{n} ATD \qquad (2)$$

where the equivalent height (H_{eq}) is obtained through dividing winding height (H_w) by the Rogowski factor K_R (<1.0). μ_0, ATD represents the permeability of free space and ampere turns diagram respectively [12].

$$H_{eq} = \frac{H_w}{K_R} \qquad (3)$$

The expression for the leakage reactance X is defined as

$$X = 2\pi f \frac{\mu_0 \pi N^2}{H_{eq}} \sum_{k=1}^{n} ATD \qquad (4)$$

For the base impedance of Z_b the formula for percentage reactance is

$$\%X = \frac{X}{Z_b} = \frac{IX}{V} * 100 \qquad (5)$$

$$\%X = 2\pi f \frac{\mu_0 \pi I N^2}{H_{eq} V} \sum_{k=1}^{n} ATD * 100 \qquad (6)$$

$$\%X = 2\pi f \frac{\mu_0 \pi (NI)}{H_{eq} \left(\frac{V}{N}\right)} \sum_{k=1}^{n} ATD * 100 \qquad (7)$$

where V is the rated voltage and the term (V/N) is volts/turn of the transformer. Substituting $\mu_0 = 4\pi * 10^{-7}$ and adjusting constants, so that the dimensions used in the formula are in the units of centimeters the reactance can be written as

$$\%X = 2.48 * 10^{-5} * f * \frac{(\text{Ampere Turns})}{H_{eq}\left(\frac{\text{Volts}}{\text{Turn}}\right)} \sum_{k=1}^{n} ATD * 100 \quad (8)$$

If D_1, D_g and D_2 are the mean diameters and T_1, T_g and T_2 are the radial depths of LV, gap and HV respectively. Hence

$$\sum_{k=1}^{n} ATD = \frac{1}{3}(T_1 + D_1) + (T_g + D_g) + (T_2 + D_2) \qquad (9)$$

If LV and HV windings have uniformly distributed ampere-turns the leakage field is predominantly axial, except at the winding ends. The typical leakage field pattern is shown in Fig.3. It is obvious that the concentration of leakage field is strong in the gap between the windings and fringing effect exists at the winding ends.

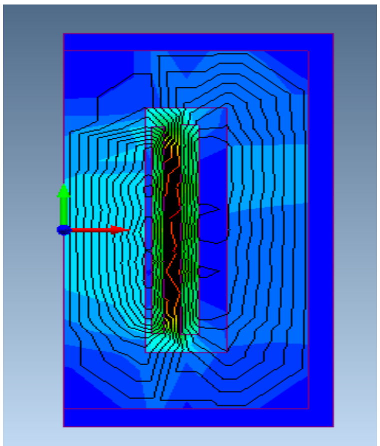

Figure3: Flux plot as computed through FEM package

5. FEM BASED REACTANCE COMPUTATION

In order to perform magneto static two dimensional simulation of the device under study, the LV and HV coil source typesare chosen as current driven with equal ampere turns defined to be 137.78 *500.In solver option, Newton Raphson method is selected and the maximum number of iterations is chosen as 20 with polynomial order 2. With the above settings, the static 2D simulation is carried out.

The magneto static solver provides the total stored energy in the windings W_m that is used to compute leakage inductance as given below.

$$L = \frac{2W_m}{I^2} \qquad (10)$$

Using the above computed inductance and the value of base impedance as given by

$$Z_b = \frac{KV^2}{MVA} \qquad (11)$$

the percentage reactance is calculated as

$$\%X_L = \frac{2\pi f L}{Z_b} * 100 \qquad (12)$$

The reactance computation is carried out with equal LV and HV height (Normal). Next the procedure is repeated with 2% and 10 % change in axial and radial dimensions and the results of reactance computation are tabulated in Table 1. The table also indicates the reactance values computed through classical method under normal, asymmetrical axial and radial dimensions as described in section 4. As per IEC standard for transformers with rating < 100 MVA a change in reactance of more than 2% is indicative of failure due to short circuit.

Table 1: Comparison of reactance computed by FEM and classical method and effect of asymmetrical axial and radial dimensions on reactance

Conditions	%X computed through Analytical method	FEM Computed % X	Deviation in%X
Normal	8.060	10.2301	2.1701
2% change in axial height	8.567	10.2202	1.6532
10% change in axial height	9.328	10.2214	0.8934
2% change in radial height	8.073	10.2995	2.2265
2% change in radial height	8.126	10.2876	2.1616

The variation in reactance computation between the two methods is 2% only and the results of FEM could further be improved by redefining the mesh size and boundary conditions.

6. EFFECT OF WINDING DEFORMATION ON REACTANCE

Since the inner winding experiences more short circuit forces than the outer winding to study the effect of winding deformation on reactance the LV winding is divided in to four sections as shown in Fig. 4. Each section has 600mm height. The reactance is computed by effecting changes in dimensions of axial height and radial depth of each section. Fig. 5 and Fig. 6 show respectively the variation of reactance due to changes in axial height and radial depth.

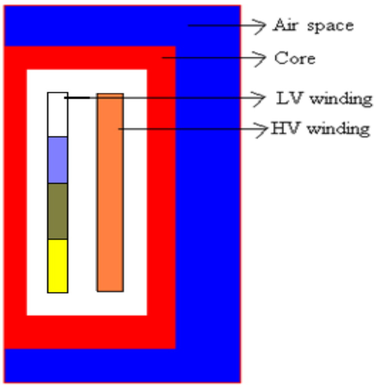

Figure4: Segmental model of fictitious transformer

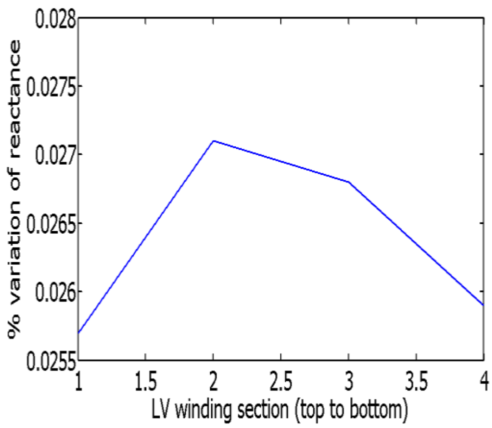

Figure5: Variation of reactance with changes in axial height

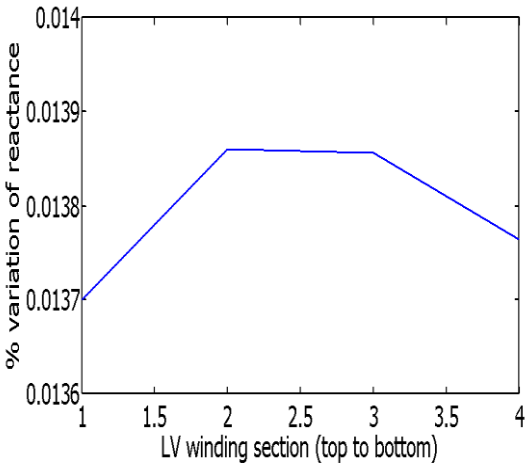

Figure6: Variation of reactance with changes in radial depth

It is observed that when there is change in axial height the variation in reactance is maximum near the winding end and when there is change in radial depth the reactance variation is maximum near the winding centre. This observation coincides with the concept that the axial deformation effect is more at the winding ends and radial deformation is more at the centre of the winding. Thus FEM approach can provide better indication of reactance variation that can serve as a tool to demonstrate mechanical integrity of windings. Further it offers a possible method for improving the design through model based approach for ascertaining the short circuit strength of power transformers.

7. CONCLUSION

Finite element method based approach for the computation of reactance of a fictitious transformer is demonstrated through a simulation study using FEM package and the results are compared with analytical method of reactance computation. It is evident that the accuracy of FEM approach can be improved by proper definition of mesh and boundary conditions. Further the effect of axial and radial deformation on reactance has been studied by defining the inner winding with number of sections. From the results, it is evident that there is close relation between the deformation of winding and the reactance variation. Hence this method can provide possible solution to short circuit strength design of power transformers.

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