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ESTIMATION OF ZERO SEQUENCE IMPEDANCE IN POWER TRANSFORMERS USING 2D AND 3D FEM

SUMMARY

This paper describes calculation of zero sequence impedance in three phase, three leg core type power transformers using 2D and 3D finite element method (FEM) calculation on example of 100 MVA power transformer. Paper also describes how winding connection and arrangement affects the size and calculation of zero sequence impedance.

Key words: zero sequence impedance, zero sequence reactance, power transformer, finite element method, FEM

1. INTRODUCTION

In power system analysis power transformer is represented by three sets of impedances. Like other symmetrical static machines, transformers have equal positive and negative sequence impedance ($Z=Z_d=Z_i$), but zero sequence impedance (Z_0) value depends on geometry of active part and connection of windings.

The positive phase sequence impedance (Z_d short circuit impedance) allows flow of balanced symmetrical three phase positive sequence set of currents and the negative sequence impedance (Z_i) allows flow of balanced symmetrical three phase negative sequence set of currents. The zero sequence impedance (Z_0) allows flow of zero sequence set of currents that are equal to and in phase with each other in all three lines, and their sum is not zero like positive (negative) phase sequence currents, pushing the magnetic flux path outside the core in three leg core type transformers.

The positive sequence impedance of power transformer is relatively easily calculated, but its zero sequence impedance is not, and is usually estimated as 0,8÷0,95 Z_d for three leg core type transformers.

Single phase transformers, shell type and five leg core type transformers have return magnetic paths, thus their zero phase impedance is nearly equal to positive and negative.

To allow the flow of set of zero phase sequence currents in three phase transformers winding arrangement is also important. Only grounded star (YN) or zig-zag connected (ZN) windings can be energized with set of zero phase sequence currents. Depending on connection of secondary winding zero sequence impedance has short circuit impedance or magnetizing impedance characteristic. For example in YNd three phase, three leg core type transformer, star connected winding energized with set of zero phase sequence currents will induce circulating current flowing in delta connected winding resulting with short circuit character impedance when viewed from primary side (YN). Since delta connected windings do not allow flow of zero phase set of currents, when viewed from secondary side transformer will have infinitely large impedance.

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2. TRANSFORMER AND FEM MODELS

2.1. Transformer

In this paper all calculations and models are based on data from KPT manufactured, three phase, three leg core network transformer, 100 MVA rating, 225/13,8 kV, 50 Hz, connection symbol YNd11.

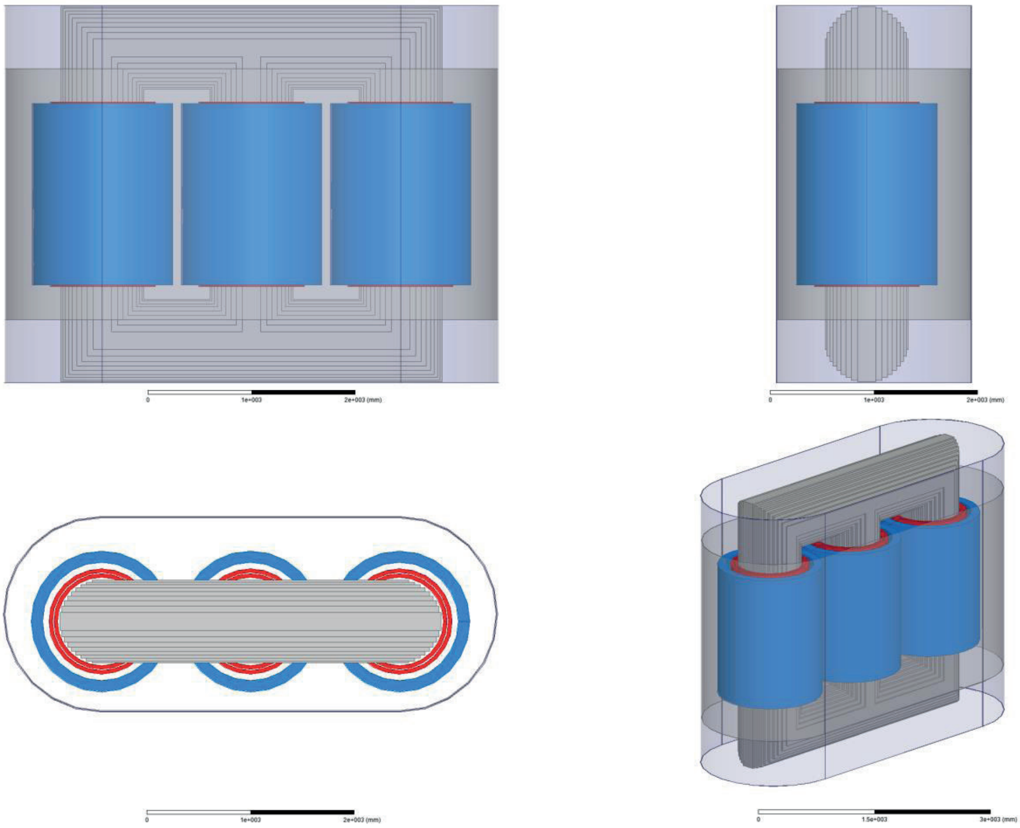

Figure 1 - Three dimensional model of example transformer

2.2. FEM models

For the purpose of zero sequence impedance finite element method calculation only the inner geometry of the transformer is important

2.2.1. 2D

Since set of zero sequence currents are equal and in phase and induced magnetic flux closes thru oil and tank, three phase transformer can be broken down in three independent single phase transformers without return limb and core yokes for purpose of calculation.

For two dimensional calculation transformer is presented with simplified axi-symmetric single phase geometry that consist of core leg, HV and LV windings and tertiary winding that represents a tank. In calculation with magnetic shield it is added in front of tank. Since the distance from windings to tank (shield) is not the same on HV and LV sides, tank is modeled on the mean distance from windings.

2.2.2. 3D

With three dimensional geometry full complexity of problem can be stressed with little simplification. For calculation of zero sequence impedance three dimensional geometry (figure 1) of transformer consists of three limb core, all windings and simplified tank and magnetic shield (if used in calculation).

2.2.3. Materials

Since resistivity is negligible compared to reactance in large power transformers only imaginary part of zero sequence impedance is calculated. Thus only important material characteristic for zero sequence reactance calculation is relative magnetic permeability. Materials used in FEM calculation are high permeability magnetic steel for core and shield, construction steel for tank and cooper for windings.

3. CALCULATION

3.1. Current distribution problem

Magnetic flux that is pushed outside transformer core seeks lower reluctance path. In three phase Dyn transformers outer delta connected winding act as shield when inner star connected winding is energized with zero phase current, thus both windings have equal absolute ampere-turns. Otherwise in YNd transformers, where outer winding is star connected HV winding, when HV winding is energized with zero sequence current, tank acts like tertiary delta connected winding representing lower reluctance path for magnetic flux.

For calculating share of ampere-turns in secondary winding and tank (tertiary winding) expression for calculating reactive power of a system of windings can be used [1]. Primary winding (HV) is labeled with index 1, secondary winding (LV) with index 2, and tank with index 3.

$$Q = -\frac{1}{2}\sum_{k=1}^{n}\sum_{j=1}^{n} X_{jk} I_j I_k \tag{1}$$

$$Q = -\frac{1}{2}[2X_{12}I_1(-I_2) + 2X_{23}(-I_2)(-I_3) + 2X_{13}I_1(-I_3)] \tag{2}$$

Where: Q is reactive power,
X_{jk} is mutual reactance of pair of windings,
I_j and I_k are winding peak currents

Secondary and tank currents have negative value compared to primary current. If magnetizing current is neglected it can be stated:

$$I_1 = I_2 + I_3 \tag{3}$$

Since rated current flows in primary winding it has value of 1 per-unit ($I_1 = I_n \Rightarrow i_1 = 1\ p.u.$)

$$i_3 = 1 - i_2 \tag{4}$$

$$q = x_{12}i_2 - x_{23}i_2(1 - i_2) + x_{13}(1 - i_2) \tag{5}$$

The currents get distributed in the windings in such a way that the total energy is minimized. Hence, differentiating q with respect to current i_2 and equating it to zero results with:

$$\frac{dq}{di_2} = x_{12} - x_{23} + 2x_{23}i_2 - x_{13} = 0 \tag{6}$$

$$i_2 = \frac{x_{13}+x_{23}-x_{12}}{2x_{23}} \tag{7}$$

$$i_3 = \frac{x_{23}+x_{12}-x_{13}}{2x_{23}} \tag{8}$$

When reverted back to absolute value from per-unit value and reactance substituted with energy, since it is proportional, expressions become:

$$I_2 = \frac{W_{13}+W_{23}-W_{12}}{2W_{23}} I_1 \tag{9}$$

$$I_3 = \frac{W_{23}+W_{12}-W_{13}}{2W_{23}} I_1 \tag{10}$$

Where: W_{jk} denotes energy between winding pairs calculated with FEM

For calculation of rectance (in this case energy) for first pair of windings (HV and LV) excitation is defined as rated ampere-turns in HV and LV windings. Value is the same but directions are different. Procedure for the rest pairs is analog. In three dimensional calculations excitation in tank is three times greater due to the influence of all three phases. With calculated energy between pair of windings ampereturn distribution for zero sequence FEM model can be calculated using expressions 9 and 10. All calculations are done with the same geometry and in all calculations sum of ampere-turns must be zero. Magnetic shield represents lower reluctance path than oil and tank since it is made from high permeability magnetic steel and rises zero sequence impedance. In model it is represented with open circuit fourth winding that lowers induced current in tank [2]. Calculation of current distribution is same as described, only the fourth winding without any excitation is added in geometry for FEM.

3.2. Zero sequence impedance calculation

Finally zero sequence impedance can be calculated from obtained energy using expressions:

$$L_0 = \frac{2W_0}{I_1^2} \tag{11}$$

$$X_0 = 2\pi f L_0 \tag{12}$$

$$u_{0\%} = 100\frac{S_n \cdot 2\pi f L_0}{U_n^2} \tag{13}$$

Where: W_0 denotes zero sequence energy calculated with FEM,
L_0 is zero sequence inductance,
S_n is rated power,
f is frequency,
X_0 is zero sequence reactance (impedance)
$u_{0\%}$ is percent zero sequence impedance

Defined procedures can be used to calculate zero sequence impedance of any power transformer or autotransformer.

4. RESULTS

All calculations were made using commercial Ansoft Maxwell v15 software for finite element method calculations on a two and three-dimensional computer model as magnetostatic problem. Four sets of calculations were done. Two dimensional calculations with and without magnetic shield, and three dimensional calculations with and without magnetic shield. Results obtained in calculations without magnetic shield on tank, regardless two or three dimensional method differ less than 2% from measured zero sequence impedance, while results obtained from calculation with magnetic shield are approximately 5% greater than measured ones.

Table 1 - measured and calculated values of zero sequence impedance

Zero sequence impedance	X_0 [Ω]	u_0 [%]
Measured	49,61	9,80
2D	48,95	9,66
3D	50,59	9,99
2D with magnetic shield	52,20	10,31
3D with magnetic shield	52,22	10,32

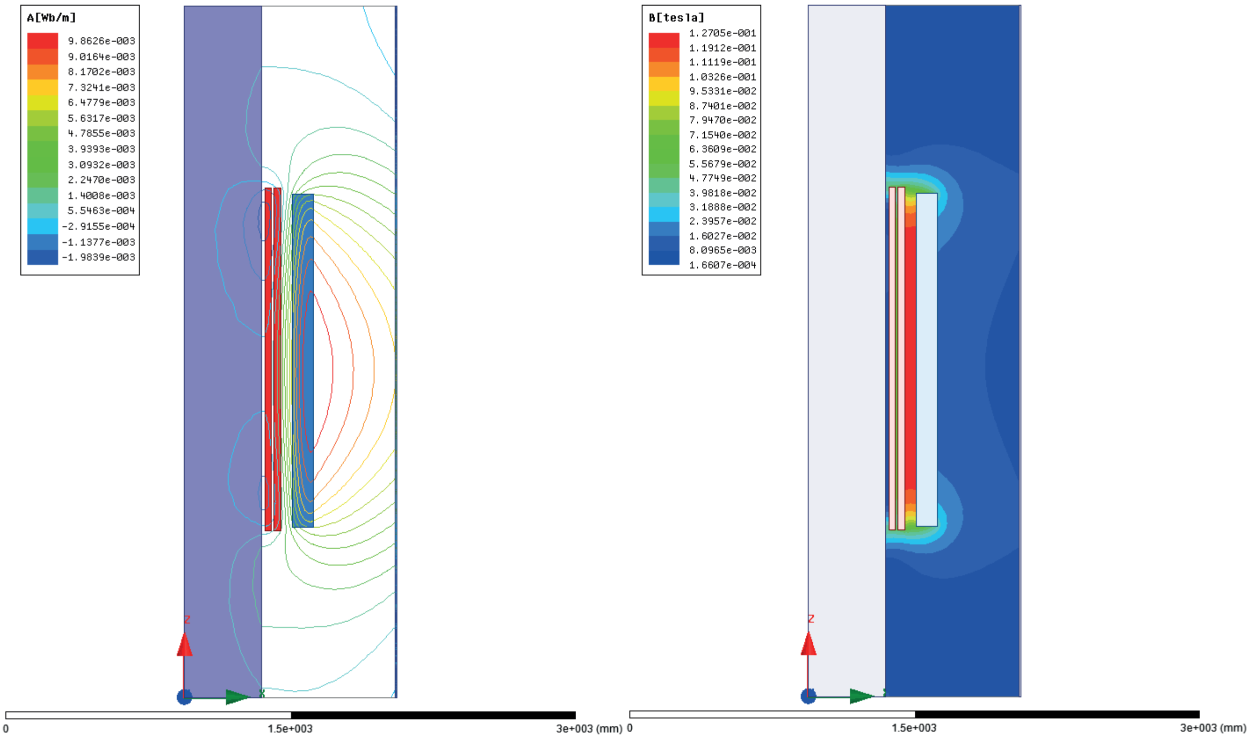

Figure 2 - magnetic flux and induction in 2D FEM model without magnetic shield

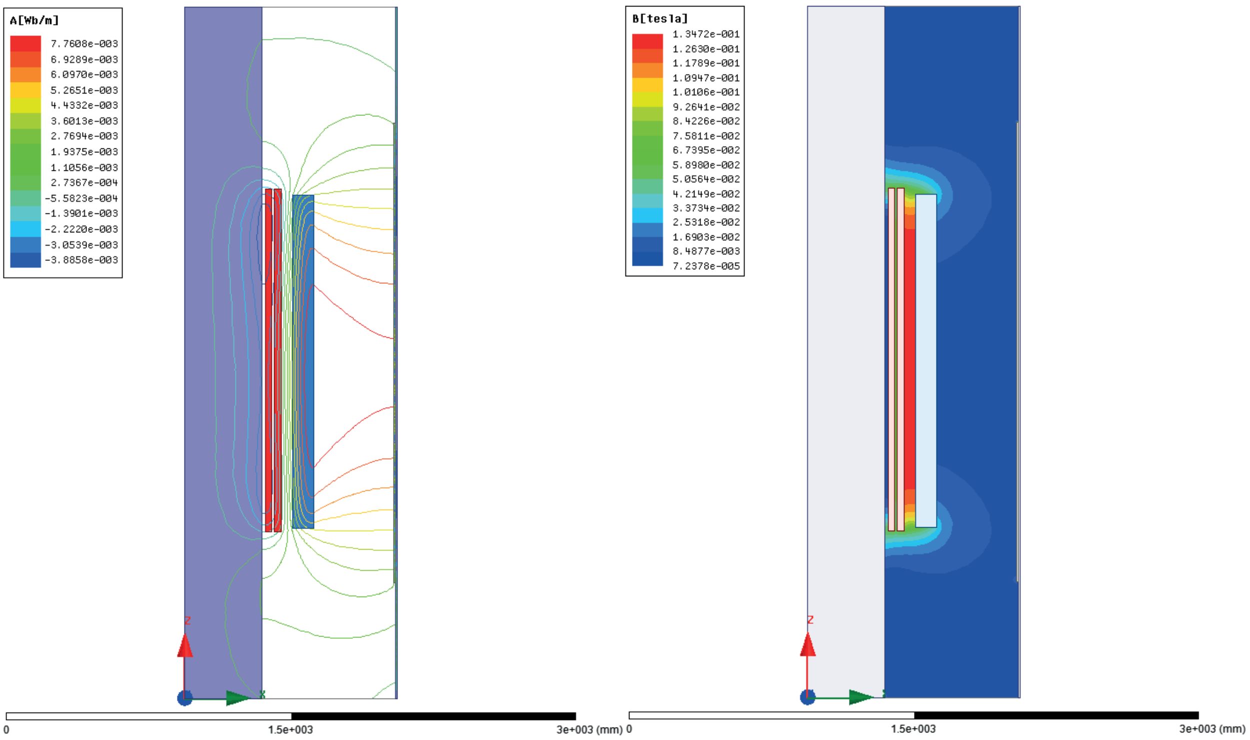

Figure 3 - magnetic flux and induction in 2D FEM model with magnetic shield

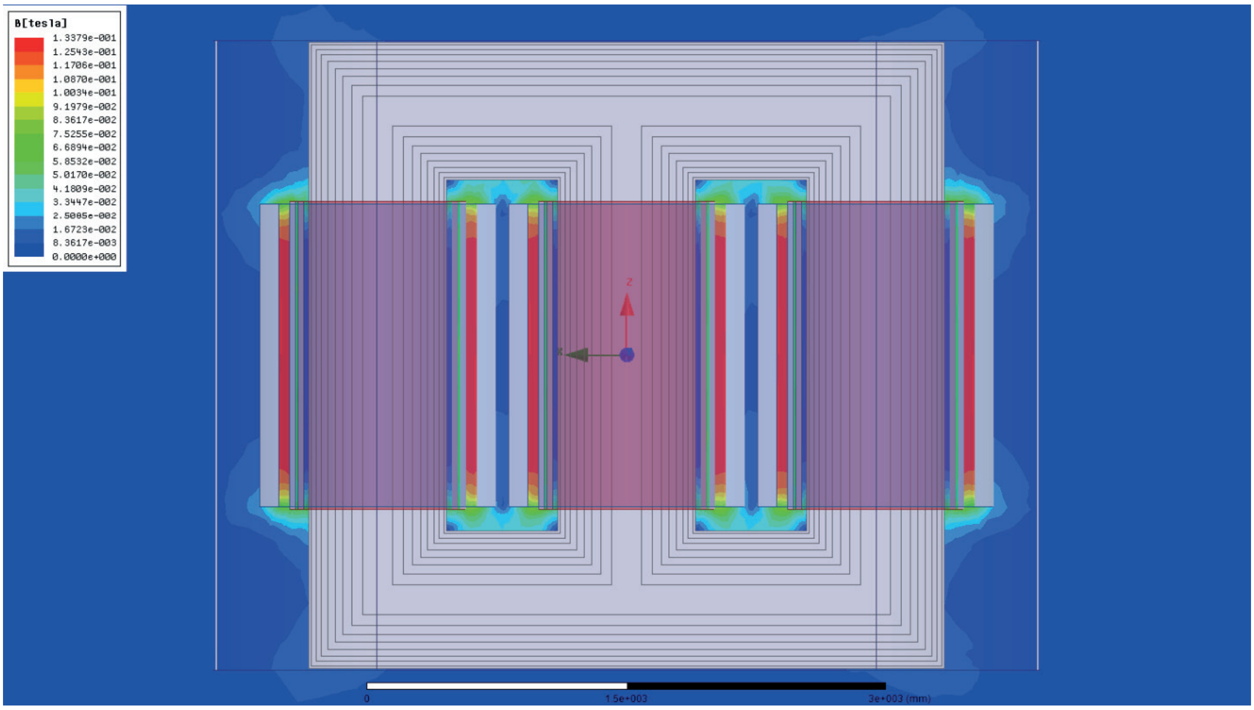

Figure 4 - magnetic induction in cross section of 3D FEM model without shield

Higher difference between measured and calculated values with magnetic shields is probably result of combination of nonlinear B-H curve and highly complex geometry of shields in real life compared to simplified geometry and material used in both 2D and 3D calculation.

5. CONCLUSION

Transformer zero sequence impedance value is important when calculating unsymmetrical short circuit currents and consequently short circuit forces especially in autotransformers. In this paper it is presented that zero sequence impedance of power transformer can be estimated using two dimensional or three dimensional finite element method calculation. Since the results in both 2D and 3D calculation are in good agreement with measured values, because of simplicity, 2D calculation without magnetic shield is recommended.

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