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Realization of 3D Electromagnetic and Thermal Analyzes of the Autotransformer by Finite Elements Method

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Abstract:
The aim of this work is to verify a three-phase autotransformer by reviewing it magnetically and thermally with modern software using the finite element method. For this, Ansys software uses two modules combined with Ansys Maxwell-3D and Ansys Mechanical's Ansys Workbench in the same environment. As a result of analysis, 3D magnetic nonlinear behavior of this three-phase autotransformer and thermal effects of ferromagnetic core can be seen. In addition, the magnitude of the magnetic field was calculated, problematic regions were determined, and total core losses for different stress levels of the same transformer were obtained.

Keywords: Msxwell-3D, finite element method, transformer, magnetic field, thermal analysis**.**

1. Introduction

Transformers designers have only used their mathematical models as their theoretical basis. Over time, it has been understood that only theoretical results are sufficient for design [1]. Soon after, analytical software capable of performing multiple calculations was developed. At this point, an optimized transformer, minimum material, minimum cost and short calculation time have been started to be realized.

Another problem faced by the designers was that they could not see how the new transformer that was connected to the network worked without prototyping. At this stage, high-performance interactive software developed using the finite element method has begun to be used. Ansys Maxwell-3D, a high-performance interactive software package, uses the finite element method (FEM) to solve transient, AC electromagnetic, magnetostatic, electrostatic, eddy current and electrode transient problems. It also solves force, torque, capacitance, inductance, resistance and impedance, as well as state-space models [2].

Maxwell-3D solves the electromagnetic field problems with the user-defined initial conditions of the Maxwell equations at the end with appropriate boundary conditions.

The autotransformer used in the study was designed, but the electromagnetic field and thermal analysis were not done before with a software program that uses the finite element method. For this reason, a transient analysis was performed in this study and the magnetic field amplitude B, core losses and peak temperature at the core were determined for each case.

2. Ansys Electronic

Some application areas of Ansys packaged software are; motors, generators, linear or rotary actuators, relays, sensors, coils, permanent magnets, transformers, converters, barriers, IGBTs etc.

ANSYS software uses this module to solve all problems, Maxwell equations:

- Faraday's induction law:
  $\nabla x E = -\dot{B}$ (1)
- Gauss's magnetic law:
  $\nabla . B = 0$ (2)
- Apere's current law:
  $\nabla x H = j + \dot{D}$ (3)
- Gauss's electric law:
  $\nabla . D = \rho$ (4)

From these general equations, the equations will automatically change on the back of the software after you select the solvent method for the user problem. For spatial decomposition, Maxwell-3D uses quadruplets that work best for quadratic interpolation between second-order nodes.

$$A_z(x,y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^3 \quad (5)$$

3. Design Parameters of Autoransformer

The The transformer used in simulation is a three-phase, magnetic core, laminated steel, 30 step, 5 step elevated insulated and 9 winding autotransformer.

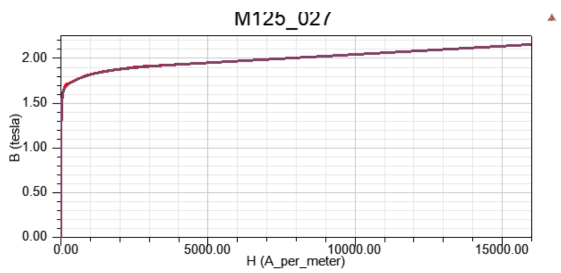

Figure 1: B-H curve for transformer core material

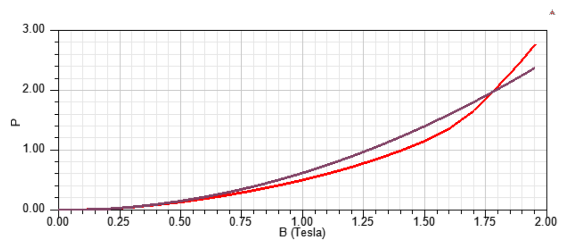

Figure 2: B-P curve for transformer core material

The connection type of this transformer is YNd11 and the transformer frequency is 50 Hz. Another feature of the transformer is the following and the above cutouts for each step. Here, it is aimed to reduce the amount of metal used in the nucleus, to lower the nucleus losses and to make it easier to carry.

For a 3D transformer model, a simplified physical model geometry can be used to find the total core losses and electromagnetic behavior by removing the connecting bars, the transformer tank and other components.

The transformer design uses copper for the windings, magnetic characteristic B-H for the core, and laminar steel, shown in Figure 1 above, in the BP curve.

The design of the designed transformer is shown in Figure 3 below.

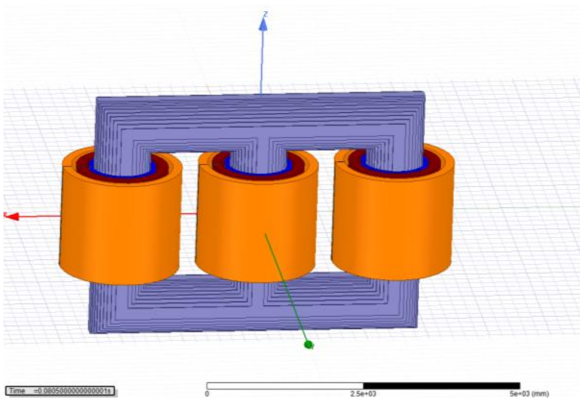

Figure 3: Basic design and winding arrangement for a 300 MVA transformer (brown - LV winding, blue - delta winding, orange - HV winding, gray - core).

Table 1: Parameter of autotransformer

	300MVA Ototransformatör		
	HV winding	*LV winding*	*Delta winding*
Connecting type	YNd11		
Rated power	300MVA		
Cooling system	ONAN/ONAF/ONAF		
Rated voltage	345kV	120kV	13.8kV
Frequency	50hz		
Number of turn	461.5	246	49
Core material	M125-027S, M530-50A lamination steel		
Thickness of laminations	0.27mm, 0.3mm		
Stacking factor	0.95		

4. Autotransformer Modeling in Maxwell-3D

For the 3D analysis of the transformer, some simplifications have been made in the designed models. This is done by taking into consideration the distance between the isolated magnetic core, the coil array and the array stages. In all 3D models there are two types of geometric shapes, Maxwell extraction function and box and cylinder.

All simulations for this study were performed in the time domain (Transient). For each winding, excitation sections were created and Terminal Coil was selected for the drive and the winding numbers were introduced here. "Coreloss" is set for the transformer core and the "edd current effect" for the windings is neglected.

After this process all the terminals are assigned to the bandage they belong to. By giving the excitation voltage, the stranded structure was chosen for the account of windings and resistances.

$$R = \frac{\rho.l}{s}\Omega \qquad (6)$$

Resistance values in no-load condition;

$R_{HV} = 1meohm$

$R_{LV} = 1meohm$

$R_D = 15.2mohm$

Olarak seçilmiştir.

Excitation voltage values due to phase angle difference;

$V_{peak}.(1 - \exp(1 - 50.time).\cos(2.pi.50.time)$ (7)

$V_{peak}.(1 - \exp(1 - 50.time).\cos\left(2.pi.50.time + (\frac{2}{3}.pi)\right)$ (8)

$V_{peak}.(1 - \exp(1 - 50.time).\cos\left(2.pi.50.time + (\frac{4}{3}.pi)\right)$ (9)

It is defined as.

Where, V_{peak} value can be changed depending on voltage level.

Mesh for all types of geometry and inner parts of the parts is set with a length of tetrahedron depending on the length.

For Analysis Setup, the time interval of 0-0.1s is selected in steps of 0.0005s. The time interval from 0.08 s to 0.1 s, the most significant period of time, in which the voltage reached the peak at a nonlinear peak, was selected as the recording range for the Analysis Setup.

After making the simulations, Maxwell-3D Ansys Mechanical is connected to a Steady State using Ansys Workbench. Three engineering materials have been used here.

Table 2: Properties of three materials

	Density	*Isotropic thermal conductivity*	*Specific temperature*
Cooper	8933 kg/m^3	400 W/m^2°C	385j/kg^2°C
Core	7650 kg/m^3	5 W/m^2°C	
Insulation material		4.5 W/m^2°C	

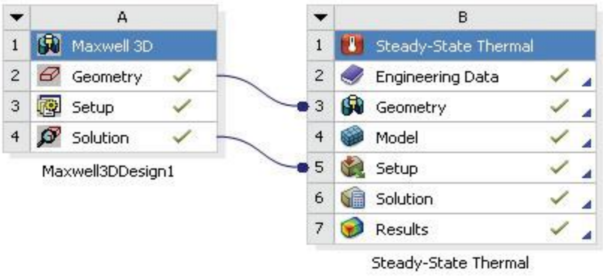

Figure 4: Ansys Workbench, imported from Maxwell-3D to Ansys Mechanical.

5. Simulation and Result

Equalize First Application: $U_{Delta} = 13.8\ kV$

In this case, the Delta coil has 49 turns. The winding counts of the LV and HV windings are the same for each case (LV = 246, HV = 461.5). The tension varies in value and resistance.

From simulation, it can be seen that the magnetic flux density from the field graph B of the nonlinear behavior of the transformer is 1.20 T minimum and 1.74 T maximum. The total core losses of the transformer increased gradually from 0 to 53.8 kW at the end of the simulation. The average of total core losses in the 0.08s-0.1s range is 42.12 kW.

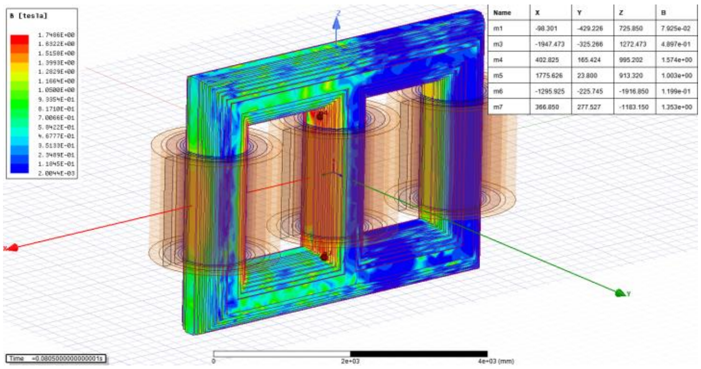

Figure 5: $for\ U_{Delta} = 13.8\ kV$ magnetic field distribution on the core

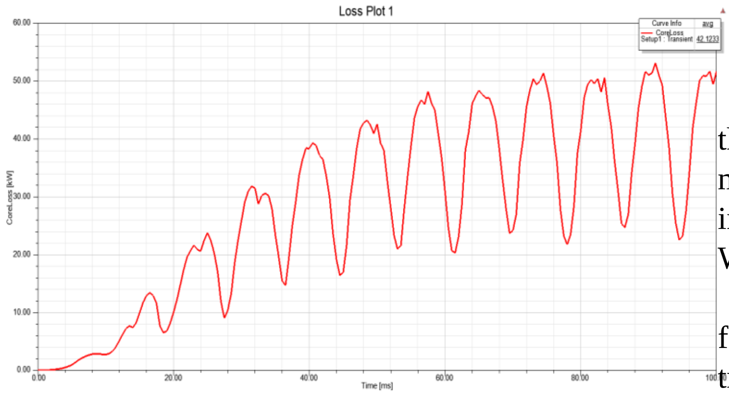

Figure 6*:* Three phase transformer core losses for 13.8 kV.

Second application: $U_{HV} = 345\ kV$

HV winding 690 winding and high value 345 kV. Also HV winding resistance has different values.

In Figure 7, it can be seen that for a state of 345 kV, the minimum B field is 1.25 T and the maximum is 1.75 T. The total core losses of the transformer increased gradually from 0 to 230 kW at the end of the simulation. The average total loss of the core at 0.08 ÷ 0.1 is 90.3 kW.

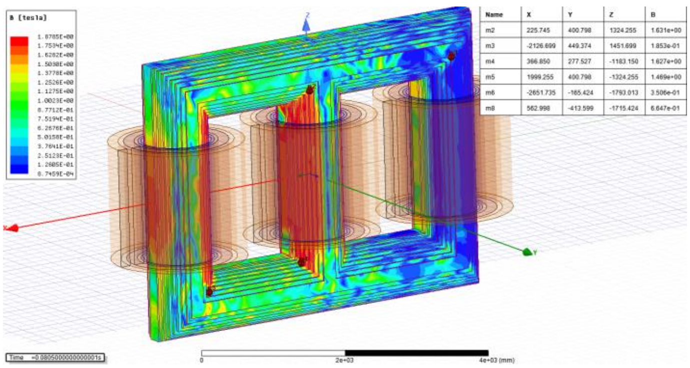

Figure 7: $for\ U_{HV} = 345\ kV$ magnetic field distribution on the core

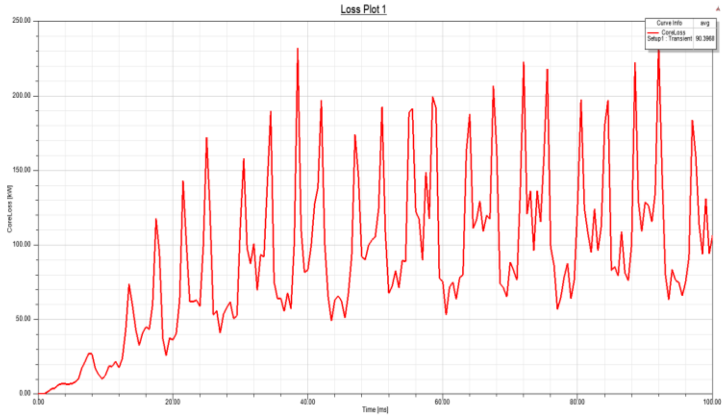

Figure 8*:* Three phase transformer core losses for 345 kV.

Ansys software has a great working environment that offers the user the possibility of combining multiple modules in a short distance and easily. This integrated working environment is called Workbench.

The thermal analysis was carried out with the oil-free, ON-AIR type cooling system to see whether the transformer is operating with this type of cooling system and whether this cooling system is also a transformer contribution in the future measurement stand.

Thermal simulation was done only for the highest B field value, so in the case of the last voltage, only the Heat Generation was taken as the mechanical parameter. The maximum temperature of the kernel is 95,255 ° C.

The simulation was performed in 3D for the ferromagnetic core. The value obtained from the simulation is less than the 98 ° C value found in the IEC standards for this type of insulation [9].

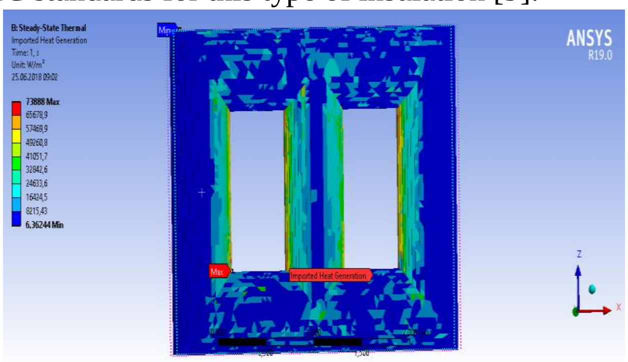

Figure 9: Heat generation on the core.

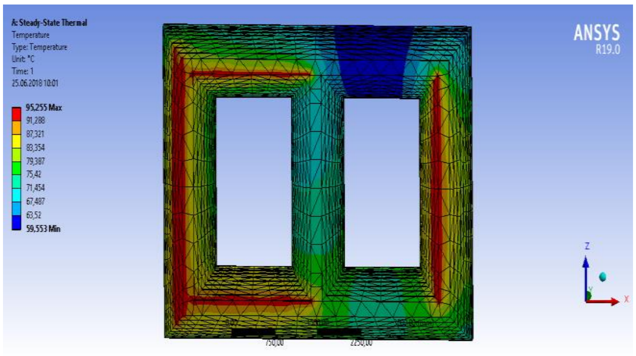

Figure 10: Heat distribution on the core.

All simulations using Ansys Electronics 19.0 were performed on a personal computer with the following features.

- İntel Pentium
- 16 GB RAM
- 256 GB SSD
- 2 TB HDD
- 3.8 Ghz processor speed
- 4 GB dedicated video card

6. Conclusion

The duration of the simulation is quite long, but this can be shortened if an HPC license and an advanced computer are used. The highest temperature of the nucleus was found in places where the maximum of area B was. After magnetic and thermal work with Ansys Maxwell-3D and Ansys Mechanical, integration of ANSYS into other modules for structural and fluid dynamic analysis is very easy.

This study and the results obtained confirm the designed product. The designed model and the obtained results show that the model is ready for production.

- The first result is to record the highest B field for 345 kV and record the selection of core losses for the same voltage level.
- After the mesh is formed, the number of tetrahedral is 10000 elements.
- Simulation time resolution is about 13 hours.
- The maximum magnetic flux density is 1.75T.
- The minimum magnetic flux density is 1.2T.
- The core loss was 42.12 kW for 13.8 kV, and 90.3 kW for 345 kV.
- The highest temperature of the ferromagnetic core is 95.255 ° C.

This paper and the results obtained confirm the designed product. By reducing or increasing the distance between the core and the windings, designers can obtain optimum designs using laminar electrical steel such as M125-027S as the core magnetic material. Different solutions can be developed using methods such as FEM to reduce losses.

Acknowledgments

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