World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:12, No:5, 2018

Comparison of Electrical Parameters of Oil-Immersed and Dry-Type Transformer Using Finite Element Method

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***Abstract*—**The choice evaluation between oil-immersed and dry-type transformers is often controlled by cost, location, and application. This paper compares the electrical performance of liquid-filled and dry-type transformers, which will assist the customer to choose the right and efficient ones for particular applications. An accurate assessment of the time-average flux density, electric field intensity and voltage distribution in an oil-insulated and a dry-type transformer have been computed and investigated. The detailed transformer modeling and analysis has been carried out to determine electrical parameter distributions. The models of oil-immersed and dry-type transformers are developed and solved by using the finite element method (FEM) to compare the electrical parameters. The effects of non-uniform and non-coherent voltage gradient, flux density and electric field distribution on the power losses and insulation properties of transformers are studied in detail. The results show that, for the same voltage and kilo-volt-ampere (kVA) rating, oil-immersed transformers have better insulation properties and less hysteresis losses than the dry-type.

***Keywords*—**Finite element method, flux density, transformer, voltage gradient.

I. INTRODUCTION

NOWADAYS, for small and medium power applications, different types of transformers are available in the market [1], [2]. The main categories are gas-insulated transformers, oil-filled transformers and dry-type transformers. In gas-insulated and oil-filled transformers, the gas is used as an insulation and oil as a cooling medium. However, the dry-type transformer lacks any fluid for cooling [3].

For customers, the choice between liquid-filled or dry-type transformers is more difficult today than a decade ago, with improved insulation systems and computer design of dry-type transformers. In the literature, a few researchers compare the oil-filled and dry-type transformers technologies. The authors in [4], [5] assemble data from various sources in order to evaluate the choice between liquid and dry-type transformers from the customer's perspective, and the choice is controlled by application, cost, and location.

In [6]-[10], several researchers carried out thermal, mechanical, and transient analyses of oil-filled and dry-type industrial transformers. The works in [6], [7] focused on a magneto-thermal analysis of oil-filled transformers, while in [8], [9] a numerical investigation of the thermal and mechanical properties of dry-type transformers is presented. In [10], the author presents a high-frequency model to investigate the transient behavior of dry-type transformers using FEM. In the literature, several papers relate the transformer winding and core design with its performance. The work in [11] investigates the distribution of stress along the winding as a function of winding position and surge rise time. In [12], the author proposes a new hexagonal T-joint design of core and compares the results with the widely used Butt-lap core design to analyze the magnetic flux density and core losses. The influence of mixed core design on transformer core losses is presented in [13].

To the best of authors' knowledge, an analytical and experimental investigation based on the electrical performance of oil-immersed and dry-type transformers has not been clearly reported in the literature. This paper presents comprehensive results and thorough analysis of flux density, electric field intensity and voltage distribution in a 300-kVA oil-immersed and dry-type transformer's cores and windings. Through critical analyses of results, the electrical performance of these two types of transformers, for example hysteresis losses and insulation properties, can be compared. The aim is to facilitate the customer choice between oil-immersed and dry-type transformers based on the electrical performance of the transformers. FEM is used to perform the numerical analysis to calculate the electrical parameter distribution in both types of transformer core and winding.

II. TRANSFORMER MODELING

A. Finite Element Analysis

FEM is used to develop models of dry-type and oil-immersed transformers in order to investigate the electrical performance of transformers. FEM is chosen as it is an efficient numerical method to solve complex higher-order-integral and differential equations. It offers great freedom in the selection of elements and basic functions. In FEM, the subject domain is broken down into small areas or elements where we can increase our focus on the area of interest, and hence the level of precision obtained increases over this focused area. This ensures that cumulative approximation

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errors of the simulation do not lead to erroneous results [14]. By using this method, finite element domain (magnetic field equations) and electric-circuit domain (electric circuit equations) can be solved simultaneously. To define the finite element domain, the transformer winding and core structure were geometrically described in order to outline the experimental set-up region. The geometric representation of winding and core is based on their surface in a 2-D cut section. Further, the magnetic properties of the winding and core structure were assigned. In order to describe the electric-circuit domain, the potential differences across windings and their interconnections with the current-carrying regions, such as coils were described by means of electrical components. Moreover, electrical components were associated with the corresponding regions in the finite element domain. Lastly, the limit of the problem was defined and appropriate boundary conditions were assigned to solve the problem in the finite element domain.

Voltage values, such as the magnitude and the electric phase are assigned to the coil. The induced voltage and the current driven by the voltage source in the transformer core at each time step prescribe the average flux density and electric field intensity distribution of the magnetic core in a finite element domain. A schematic view of dry-type transformer-developed model is shown in Fig. 1. Using FEM, the three-dimensional problem is reduced into two-dimensional space variables (r=124 and z=85) to decrease the size and time of calculation. MATLAB has been used to integrate with the finite element method magnetics (FEMM) simulation toolbox. A graphical output is generated to aid visual understanding of the analyzed data.

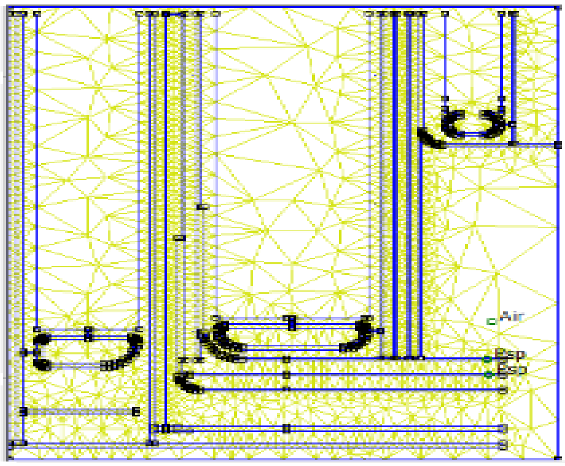

Fig. 1 Schematic of transformer with elements in the FEMM

B. Mathematical Modeling

1. Induced Voltage

The induced voltage $V(t)$ in a loop of wire caused by a change in the total flux Φ(t) passing through the interior of the loop, according to Faraday's law, is given by:

$$V(t) = N_2 \frac{d\Phi(t)}{dt} \qquad (1)$$

where N_2 is the number of secondary turns of winding, $\frac{d}{dt}\Phi(t)$ is the rate of change of flux in Weber and $V(t)$ is the induced voltage in Volts (V).

2. Flux Density

Flux density is a measure of amount of magnetic flux passing through a unit area. According to Faraday's law of induction, the total magnetic flux Φ(t) passing through a surface of area A_c with uniform flux distribution $B(t)$ is defined as

$$\Phi(t) = B(t)A_c \qquad (2)$$

Hence, with uniform flux distribution (1) can be re-written as

$$V(t) = N_2 A_c \frac{dB(t)}{dt} \qquad (3)$$

Using (3) the expression of the flux density $B(t)$ can be derived from the induced voltage $V(t)$ as:

$$B(t) = \frac{1}{N_2 A_c} \int V.dt \qquad (4)$$

where the surface area A_c is in square meters (m^2) and the flux density B is measured in Tesla (T).

3. Magnetic Field Strength

Ampere's law relates the magnetic field strength $H(t)$ around a closed path to the winding current $i(t)$ passing through the loop. From Ampere's law, the expression of the magneto- motive-force (MMF) around the path for a uniform magnetic field strength $H(t)$ can be written as:

$$H(t)l_m = N_1 i(t) \qquad (5)$$

where N_1 is the number of primary turns of winding, i(t) is the magnetizing current, l_m is the mean flux path length in meters (m) and *H(t)* is the magnetic field measured in Amperes per meter (A/m).

Using (5), the expression for the total magnetic field strength H can be derived from the magnetizing current $i(t)$ as:

$$H(t) = \frac{N_1 i(t)}{l_m} \qquad (6)$$

4. Electric Field Intensity

The induce voltage $V(t)$ between two points of a conductor with length l in meters (m) is related to the electric field of strength E as:

$$V(t) = E(t)l \qquad (7)$$

where the electric field intensity $E(t)$ is measured in volts/meter (V/m).

III. COMPARISON RESULTS OF ELECTRICAL PARAMETERS

By using the transformer modeling developed in Section II, the voltage, flux density and electric field intensity distribution in oil-immersed and dry-type transformers are evaluated.

A. Voltage Gradient

Figs. 2 and 3 show contour plots of the voltage distribution in oil-immersed and dry-type transformers. The graphical outputs provide a reference glimpse of the voltage gradient in oil-immersed and dry-type transformers winding.

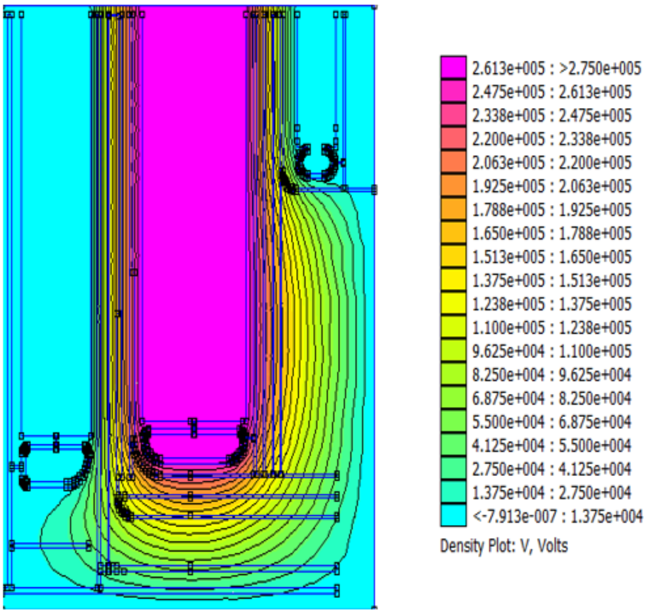

Fig. 2 Oil-immersed transformer voltage gradient

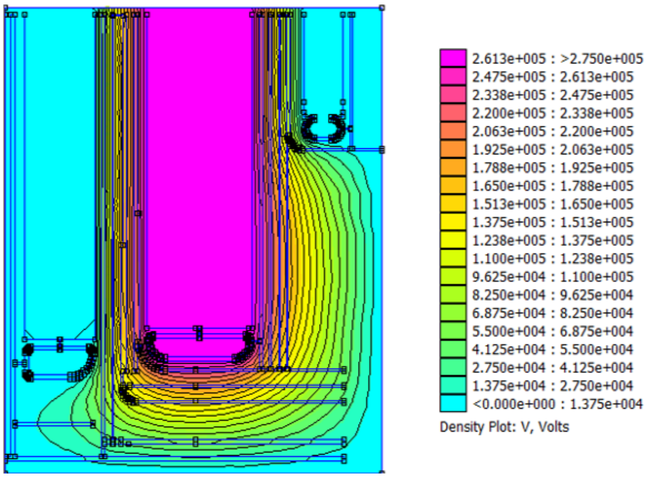

Fig. 3 Dry-type transformer voltage gradient

The results clarify that the potential difference is much more evenly distributed in an oil-immersed transformer than in air (dry-type transformer). The non-uniform voltage distribution affects the insulation properties of the dielectric medium by lowering the breakdown voltage of the insulating material as compared to a uniform voltage distribution. The uneven distribution of voltage also creates concentrated stress in certain parts of the winding that causes electric and magnetic field stresses to accumulate on the lesser cross-sectional areas, of insulation [15]. Therefore, there is a need to use much thicker insulation in dry-type transformers than in oil-immersed transformers.

B. Flux Density

Figs. 4 and 5 show contour plots for oil-immersed and dry-type transformers of the flux density distribution. The graphical outputs compare the flux density distribution in both types of transformers, where the oil dielectric medium provides much more coherent flux lines than air as indicated by the color spectrum spread. It is clear from Fig. 4 that the flux density is not uniform along the cross-section of the core.

The uneven flux density distribution inside the transformer core would cause the no-load loss of the core to be higher than if the core was uniformly magnetized at the nominal flux density. The no-load losses include core/hysteresis loss, dielectric loss and copper loss in the winding due to the excitation current.

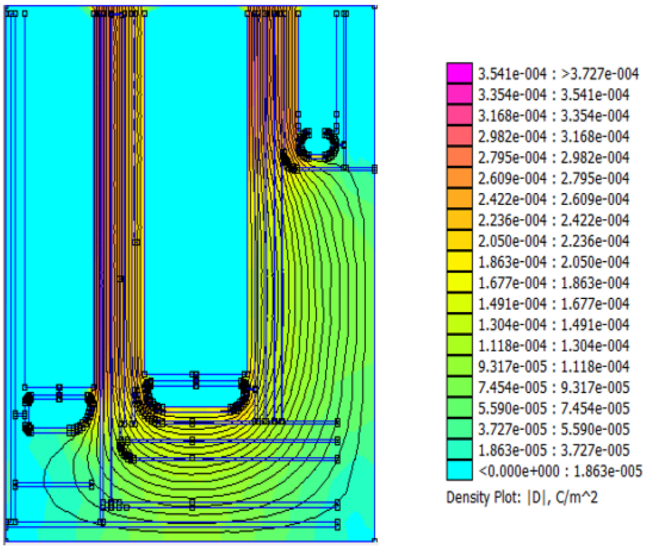

Fig. 4 Oil-immersed transformer flux density

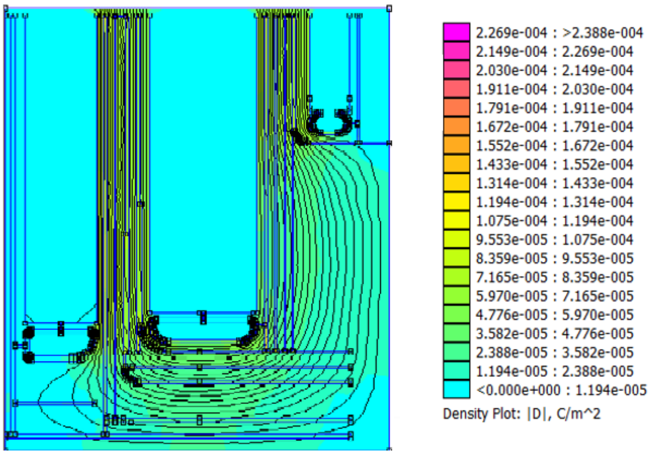

Fig. 5 Dry-type transformer flux density

The energy loss per cycle, or the hysteresis loss in the transformer, can be calculated by:

Energy loss per cycle = (Core volume) (Area of B-H loop)

By relating the winding voltage $V(t)$ and the core current $i(t)$ to the flux density $B(t)$ and the magnetic field strength $H(t)$ using (3) & (5), we obtain

$$W_l = (f)(A_c l_m)_{one\ cycle} \int H\, dB \tag{8}$$

where W_l is the energy loss per cycle and f is the magnetizing frequency. The term $A_c l_m$ is the volume of the core, while the integral is the area of the *B-H* loop. It is clear from (8) that the power loss is directly proportional to the area of the *B-H* loop and the core volume. The higher excitation current in dry-type transformer cores leads to an increased use of material, causing a larger core volume and *B-H* loop area than for oil-immersed transformers. Therefore, dry-type transformers have higher hysteresis losses.

C. Electric Field Intensity

Figs. 6 and 7 show contour plots of oil-immersed and dry-type transformers electric field intensity distribution. The graphical output compares the inconsistency of the electric field distribution of dry-type transformers and oil-immersed transformers. The results are the same as for the flux density; the electrical field lines in oil are more coherent [8].

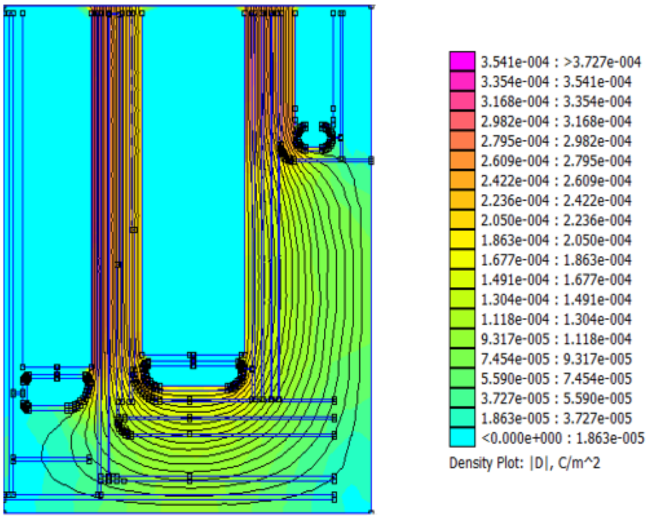

Fig. 6 Oil-immersed transformer electric field intensity

The electric field intensity, which is defined as the strength of electric field at any point, or the force per unit charge, depends on the material characteristics. Under the influence of uneven electric field regions, the particles move towards either high or low field regions because the forces acting on the two ends do not balance. In this situation, the insulator may potentially act as a conducting path between two different potentials within the transformer structure, leading to partial discharge or insulation failure. Since the electric field intensity lines for oil-immersed transformers are more coherent, they have better insulation properties than dry-type transformers [16].

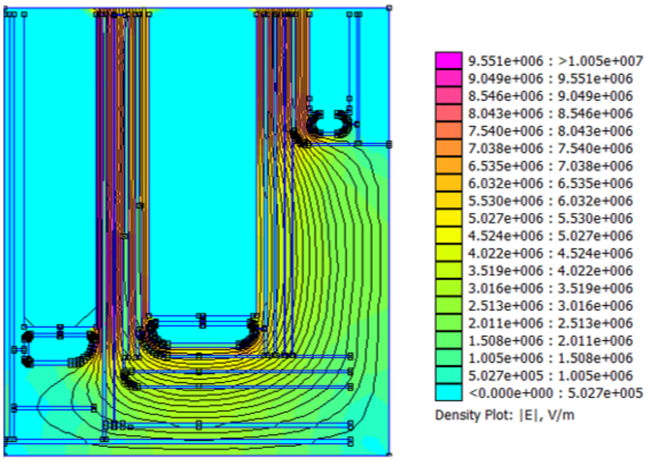

Fig. 7 Dry-type transformer electric field intensity

D. Voltage Gradient Close-Up

Close-up views of the voltage gradient are shown in Figs. 8 and 9. The graphical output shows that the voltage gradient for dry-type transformers shows stress points (path deviation) along the conductor cross-section and touch points, whereas in oil-immersed transformers the gradient lines are smooth and coherent.

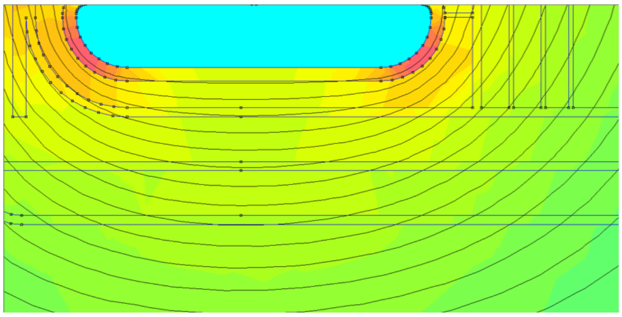

Fig. 8 Oil-immersed transformer close-up

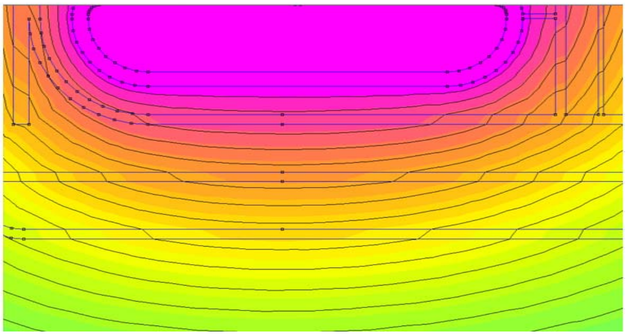

Fig. 9 Dry-type transformer close-up

IV. CONCLUSION

Numerical calculations of dry-type and oil-immersed transformer cores and windings using FEM were carried out in order to provide an explanation of the electrical performance of the transformers for comparison. The results of the voltage, flux density and electrical-field intensity distribution in air and oil dielectric media have been evaluated. The study suggests that, based on electrical performance, oil-immersed transformers are superior to dry-type transformers. Oil-filled transformers are more efficient, with an efficiency range higher than 99%, because they have less loss and a higher breakdown voltage than dry-type transformers.

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