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Evaluation and improvement of the main insulation structure of 33kV distribution transformer based on FEM

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ABSTRACT

This paper introduces a 2-D FE model to analyze the electric field distribution to evaluate and improve the insulation structure of the 250kVA, 33/0.4kV wound core type distribution transformer using the ANSYS 17.2 by implementing APDL program. The dielectric lighting impulse test was simulated in order to test the presented transformer model according to the IEC67006-3 standard, the assessment process is based on determining the electric stresses and compare it with the maximum permissible value of electric field intensity. Three proposed FE model as an improvement to the insulation structure of the transformer included reducing the insulation distances, changing the materials type, and mix both of them. The results obtained from the FE solution were compared with those of the real test, and presented in form of contours, curves, and vectors. The results obtained from the presented model can be further treated as a reference data in the design process.

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1. INTRODUCTION

Due to the significant development of computer technology, many studies have been conducted about the numerical simulation of the electromagnetic and became more preferable as compared with the analytical and the experimental methods, since the cost and efforts were significantly reduced [1]. Because of the continuous increase in the level of the transmitted voltage in the past decades, which is a result of the increasing demand for the electrical energy, a need arises to increase the life span and optimum economic operation of the high voltage apparatus and became of a significant importance. Thus, by improving the design quality, these requirements get enhanced [2, 3]. Power transformers are one of the crucial elements of power distribution networks. Most of the power transformers in current use are oil-immersed power transformers [4]. Many studies tended to improve the insulation materials used in the high voltage devices in order to withstand higher voltages, yet studies and researches are progressing in order to find new insulation designs, in order to satisfy the increasing demand for the electrical energy, maximize the profit with minimum cost [5, 6]. A transformers are exposed to certain conditions during its normal operation while being in service, such as impulse overvoltages, or lighting impulse during sever weather conditions, therefor, certain tests that simulate these conditions which a transformer must be subjected to them in order to fulfill that a transformer can withstand such conditions. In the standard waveform of the test voltage, the peak value is reached within 1.2µs, then decays to 50% of the peak value within 50µs, and the test is considered to be successful if no fail in the insulation system has taken palce [7-9], Figure 1 shows the typical wave form of the impulse voltage applied to test the transformers. The electric field is simply defined as the quantitative description of the amount of force generated between any two charges that works to attract or repel them [10]. The precise calculation of the electric field intensity is of major importance in order to optimize the main insulation structure of the high voltage device, and improve its reliability [11].

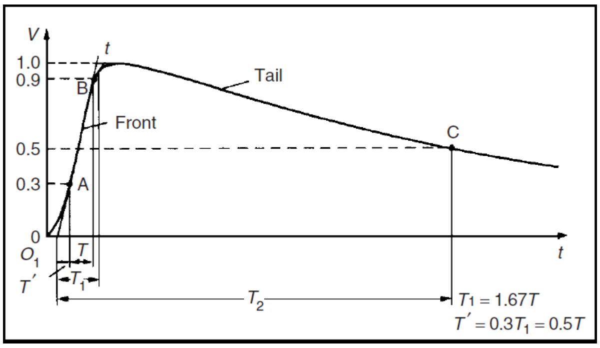


Figure 1. Standard impulse voltage waveform

In this research, the main insulation structure is classified into the three parts, the first is the H-L insulation which is the insulation between the high voltage windings and the low voltage windings, the H-C insulation represents the insulation between the high voltage windings and the iron core, and the third part is the H-H insulation which represents the insulation between the high voltage windings of the adjacent phases [6].

2. FINITE ELEMENT MODEL

Finite element method is one of the famous numerical techniques used to solve and analyze the complex geometries and showed significant importance in the physical fields such as electro-magnetic fields, fluids, and soil mechanics [12]. The finite element model of 250kVA, 33/0.416kV was implemented in ANSYS using APDL (Ansys parametric design language) which gives the reliability to analyze the dielectric response of the wound core type transformer for different ratings by simply change the input parameters that represent transformer's dimensions. The dimension of the transformer under study were taken from the design documents from the Factory of Distribution transformers/ Dyala Company for Electrical Industries. The thickness of the H-L insulation is 20mm, also thickness of insulation between the high voltage windings and the iron core is 23.5mm from the windings sides (i.e. H-C insulation), while the thickness between the high voltage windings and the iron core from the top and bottom is 51mm, and the gap distance between the high voltage windings of the adjacent phase is 22mm [13, 14]. Figure 1 & 2 shows the 2-D model and the mesh pattern respectively. Mesh pattern of the transformer under study as shown in Figure 3.

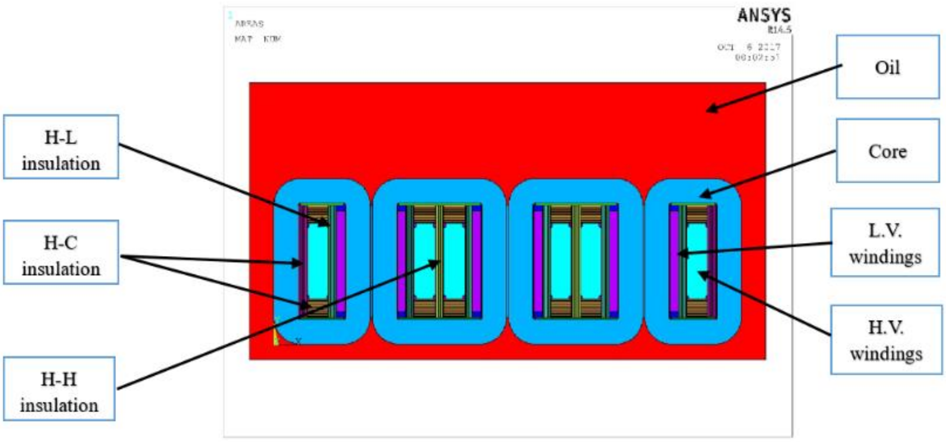


Figure 2. 2-D model of the transformer under study

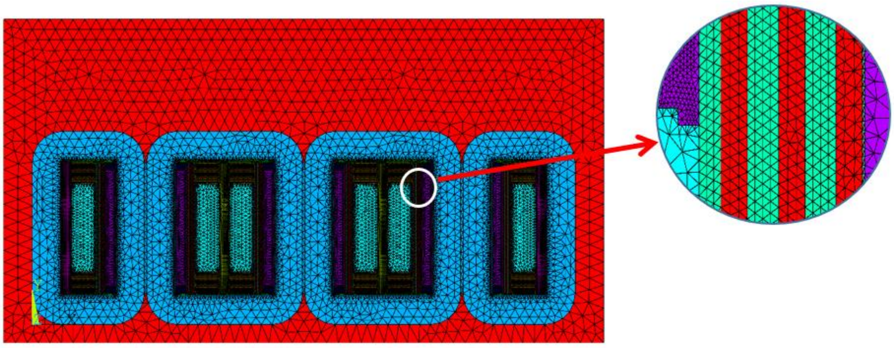


Figure 3. Mesh pattern of the transformer under study

The loading process in ANSYS done according to the instructions mentioned in the IEC67006-3 standard, such that each phase of the high voltage windings is excited seperatly and the other phases are connected to the ground, also the low voltage windings are shorted together and connected to the ground as well as the iron core, as shown in Figure 4.

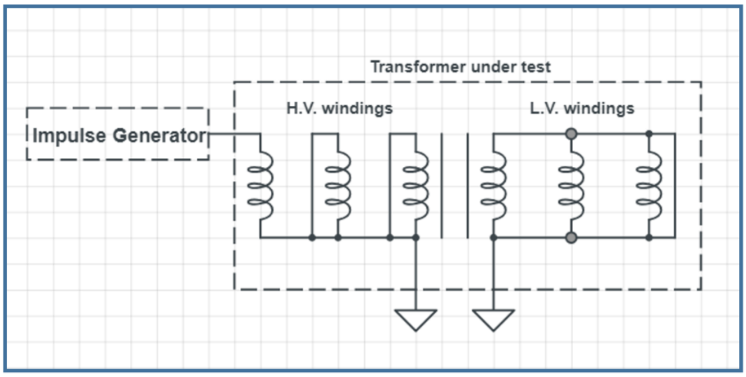


Figure 4. Schematic connection for the distribution transformer under test

2.1. Aplying Loads and Boundary Conditions

In order to obtain significantly accurate results, the program must be fed by the appropriate electrical properties of the insulating material, also if the dimensions of the electrical device modelled in the program is the same as the real case, the results obtained are more accurate and can be considered for further work or as a reference data [15]. In order to compare the obtained electric stress values with the registered standard breakdown values, the test voltage is converted in equivalent AC values by use of certain factors developed over years of high voltage labrtory tests, Table 1 shows the factors used for this purpose [16].

Table 1. DIL Factors Referenced to 1 Min. Ac Power Frequenct Test

Test type	DIL factor
Lighting impulse	2.3-2.7
Switching impulse	1.8-1.9
AC 1-min test level	1
AC 1-hour test	0.8
AC normal operation	0.55-0.59

According to the table above the equivalent AC voltage would be 170kV/2.7 = 73.913kV.
The calculation of the electric field is done by satisfying Laplace equation which states that [6][15]:

$$\nabla^2 V = 0 \tag{1}$$

While the electric field intensity is calculated from:

$$E = -\nabla V \tag{2}$$

And the relation between the current density and the electric field intensity, the electric flux density and the electric field intensity are respectively as follows:

$$J = \sigma E \tag{3}$$

$$D = \varepsilon E \tag{4}$$

By applying the divergence theorem to the both sides of the continuity and substituting (3) & (4) the result is:

$$-\nabla.([\sigma]\nabla V) - \nabla.\left([\varepsilon]\nabla \frac{\partial V}{\partial t}\right) = 0 \tag{5}$$

For time varying electric field, equation () is written as follows:

$$-\nabla.([\varepsilon].V) + \frac{j}{\omega}\nabla.([\sigma]\nabla.V) = 0 \tag{6}$$

And ω is the angular frequency.

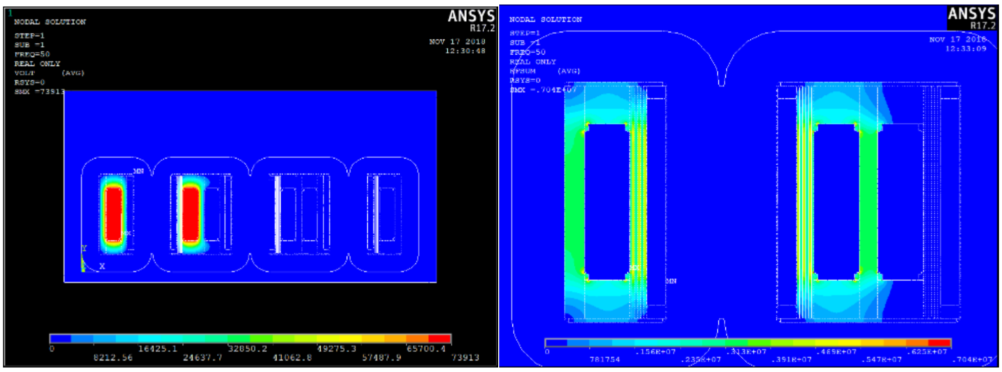
3. FEM RESULTS AND ANALYSIS

In order to obtain considerably accurate results, the appropriate material properties must be fed to the program, these properties are the bulk resistivity, relative permittivity, and loss tangent, and the values of these properties are given in Table 2, which are oil immersed values [17]. The assessment is based on determining the maximum value of electric stress over a specified region and compare with practical measures of minimum breakdown electric stress.

Table 2. Of Electric Properties of Common Insulating Materials used in Power Transformers

	Relative Permittivity	Resistivity	Loss Tangent
insulating paper	3.5	2.4×10e15	39×10e-4
Press-board	4.4	10e6	50×10e-4
Transformer oil	2.2	7.6×10e15	10e-4

After the FE solution is done, it is found that the results obtained due to exciting each phase of the high voltage windings while keeping the other phases grounded are the same, there for, only the results obtained from exciting phase A will be illustrated. Figures 5 show the potential and electric field distributions due phase A loading.



(a) (b)

Figure 5. (a) Contour plot of potential distribution due to lighting impulse test. (b) Electric field distribution of transformer insulation due to impulse test

In order to study the dielectric response, each of the H-L, H-H, and H-C insulation is divided into two regions, along the hight of the insulation region. Figure 6 shows the regions at the H-L insulation.

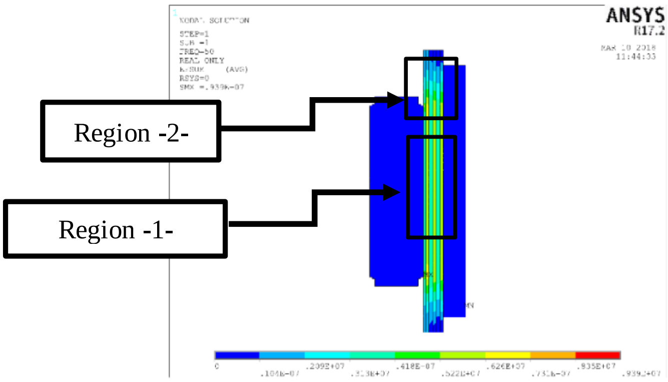
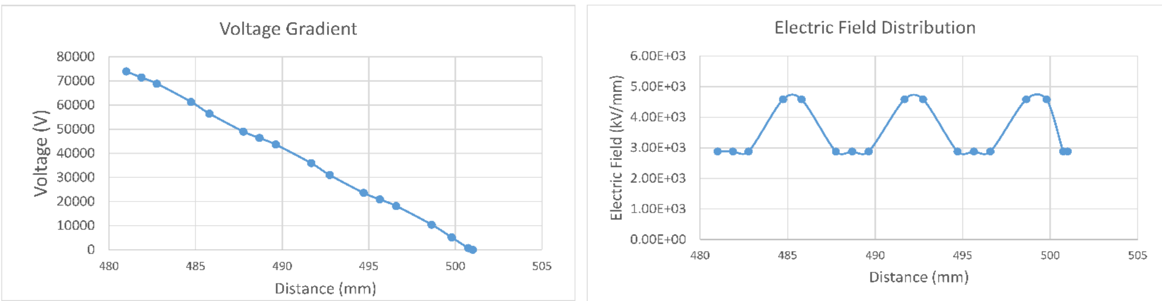


Figure 6. Electric field distribution at the H-L insulation illustrating the selected regions

At region -1- , the electric stress at the insulating paper has regular distribution along the insulation thickness due to regular gradient in voltage as shown in Figure 7-a, and equals to 2.88kV/mm which is lower than the minimum breakdown stress which equals to 8.5kV/mm [15], also it can be noticed in Figure 7-b, the distribution of electric stress along region -1- is fluctuating due to the presence of the gaps filled by the transformer oil, which has different value of relative permittivity than that of the insulating paper, as a results an overall distribution would be in this manner. Figure 8 shows the distribution of electric for the corresponding region.



(a) (b)

Figure 7. (a) Potential distribution at region -1- of H-L insulation, (b) Electric field distribution at region -1- of H-L insulation

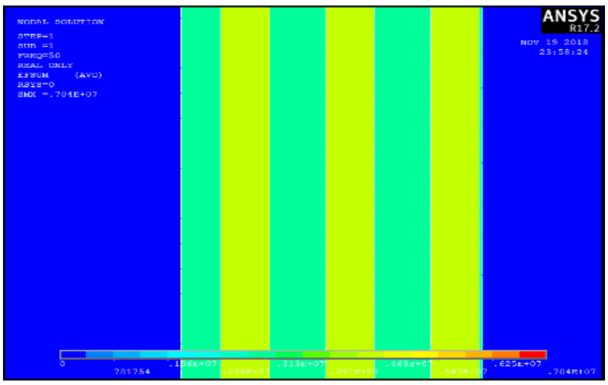
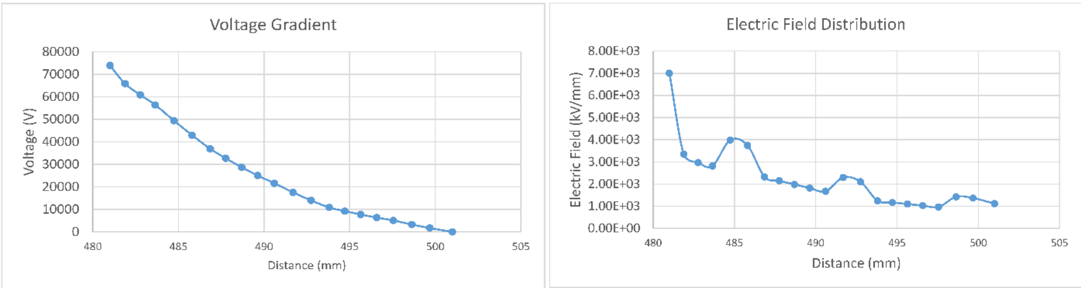


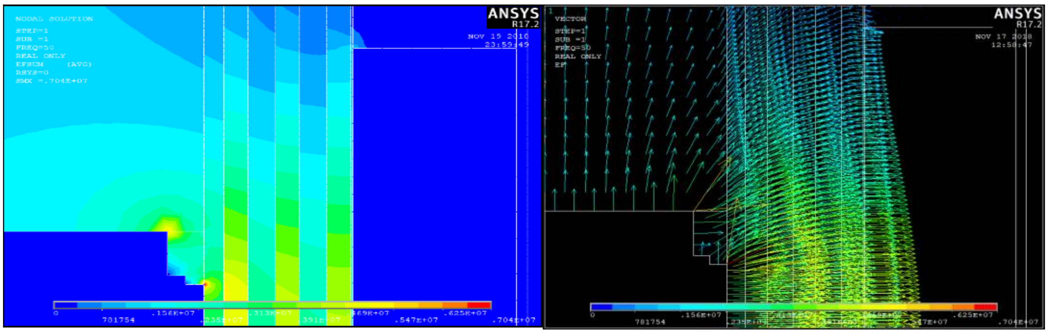
Figure 8. Contour plot of electric field distribution at region -1-

For region -2- of the H-L insulation, the maximum value of electric stress in the entire model is appeared at the corner of high voltage windings which equals 7.03kV/mm, which is less than the minimum breakdown values (i.e. 8.5kV/mm). it can be seen from Figures 9 & 10 that the distribution of electric field is not regular and the electric stress has different values across the insulation distance between the high voltage windings and the low voltage windings; this is because of the unequal distances between the equal-potential lines at this region which make the gradient in voltage is non-linear, and as a result the distribution of the electric field is non-linear.



(a) (b)

Figure 9. (a) Potential distribution at region -2- of H-L insulation. (b) Electric field distribution at region -2- of H-L insulation



(a) (b)

Figure 10. (a) Contour plot of electric field distribution at region -2- (b) Vector representation of electric flux lines at region -2-

The H-C insulation which is consisted from pressboard layers of 3.2mm thickness, also divided into two regions, region -1-, and region -2- as shown in Figure 11.

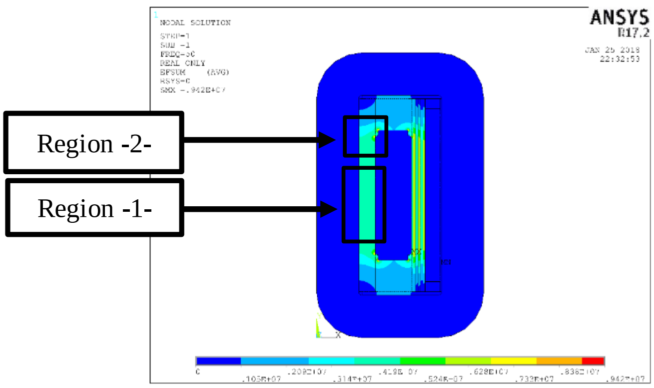
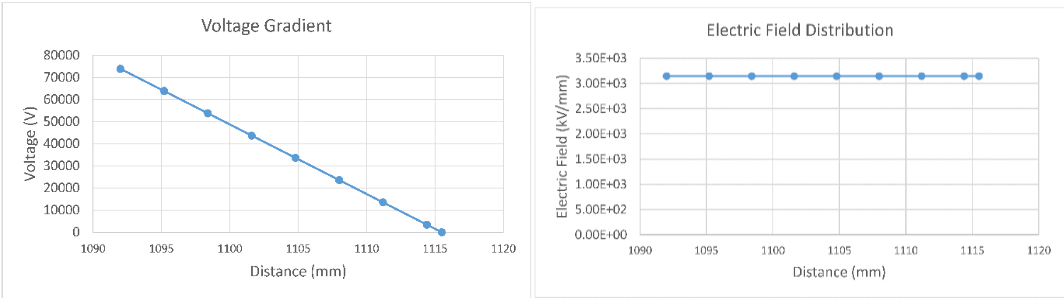


Figure 11. Contour plot pf electric field distribution at H-C insulation illustrating the regions

For region -1-, the electric stress is constant along the insulation distance from the high voltage till the iron core, due to regular gradient in voltage along the insulation distance, and equals 3.15kV/mm which is less than the minimum breakdown value which obtained practically and equals to 9.6kV/mm, due to regular gradient in voltage as shown Figures 12 & 13. It can be noticed that there is no fluctuation in the electric field distribution, due to the fact that H-C insulation contained only of pressboard layers.



(a) (b)

Figure 12. (a) Potential distribution at region -1- (b) Electric field distribution at region -1-

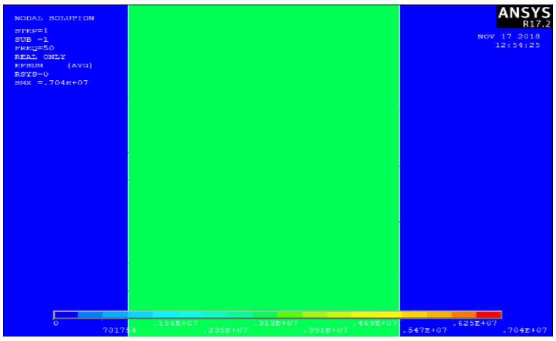
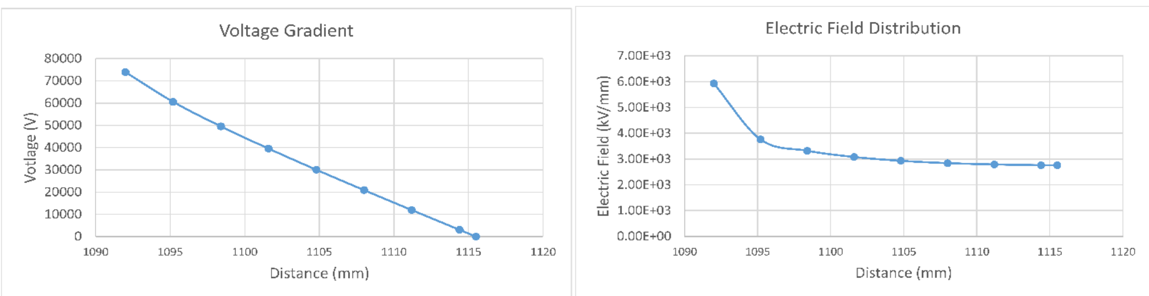


Figure 13. Contour plot of electric field distribution at region -1-

For region -2-, the electric stress appears to have nonlinear distribution due to unregularly gradient in voltage because at this region, the distances between the equipotential lines are not equal along the insulation distance between the high voltage windings and the iron core, and the maximum value for the electric stress at the H-C insulation is located at the corner of the high voltage windings which equals 5.93kV/mm, which is less when compared with the minimum breakdown value of the pressboard paper. Figures 14 & 15 show the distribution of potential and electric field distribution at region -2- of the H-C insulation.



(a) (b)

Figure 14. (a) Potential distribution at region -2- of H-C insulation. (b) Electric field distribution

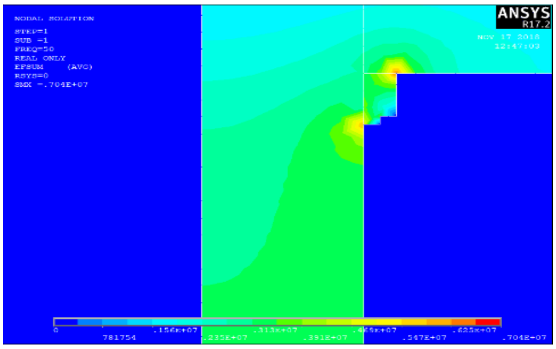


Figure 15. Contour plot of electric field distribution at region -2- of H-C insulation

For the H-H insulation which consists also of pressboard layers each of thickness 3.2mm, also divided into regions 1 & 2 as shown in Figure 16.

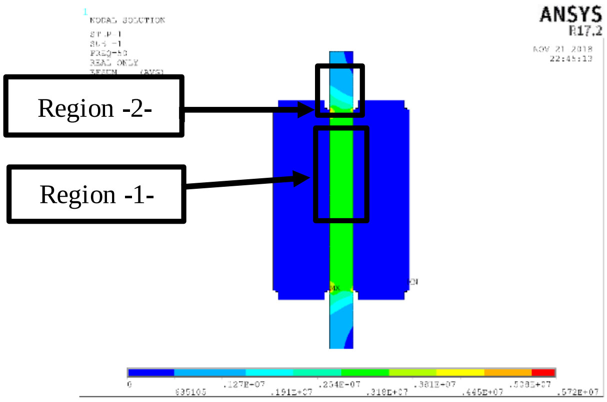
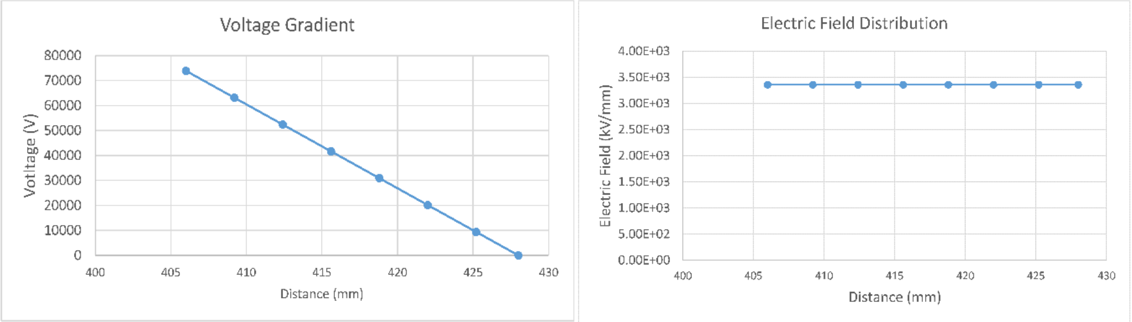


Figure 16. Contour plot of electric field distribution at H-H insulation illustrating the regions

For region -1- of the H-H insulation, the distribution of the electric field shows regular as shown in Figure 17-b along the insulation distance due to regular gradient in voltage as shown in Figure 17-a, also there is no fluctuation in the electric stress because there are no air gaps which filled by transformer among the pressboard layer as that existed among the insulation layers of the H-L insulation. Figures 17 & 18 show the potential distribution and the field distribution for the corresponding region.



(a) (b)

Figure 17. (a) Potential distribution at region -1- (b) Electric field distribution at region -1-

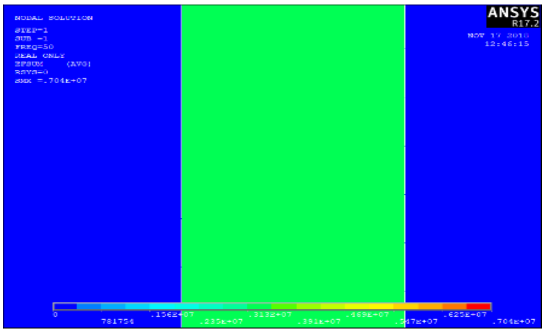
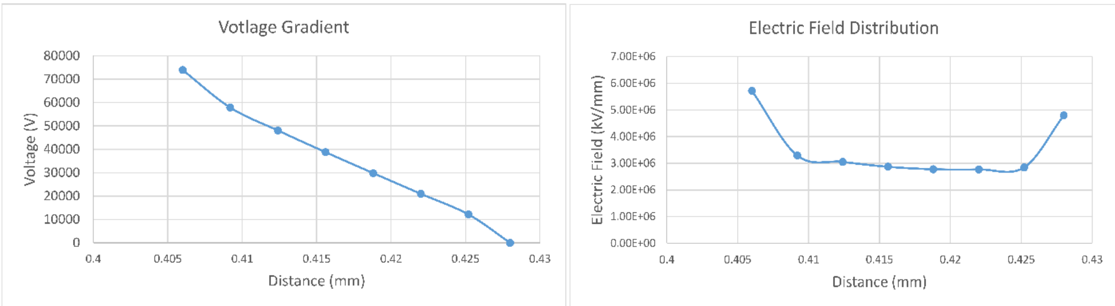


Figure 18. Contour plot of electric field distribution at region -1-

At region -2-, the distribution of electric stress is non uniform as shown in Figure 19-b, due to unequal distances between the equipotential lines at this region, which makes the gradient in voltage non-uniform as shown in Figure 19-a. Also the maximum value of electric stress at the H-H insulation is located at the corner of the high voltage windings of phase A, which equals 5.72kV/mm, which is less as compared with the minimum breakdown value of the pressboard (i.e. 9.6kV/mm). Figure 20 shows the 2-D contour plot of the electric field distribution at region -2- of the H-H insulation.



(a) (b)

Figure 19. (a) Potential distribution at region -2- (b) Electric field distribution at region -2-

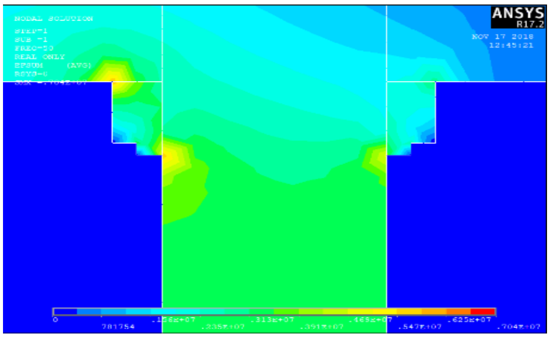
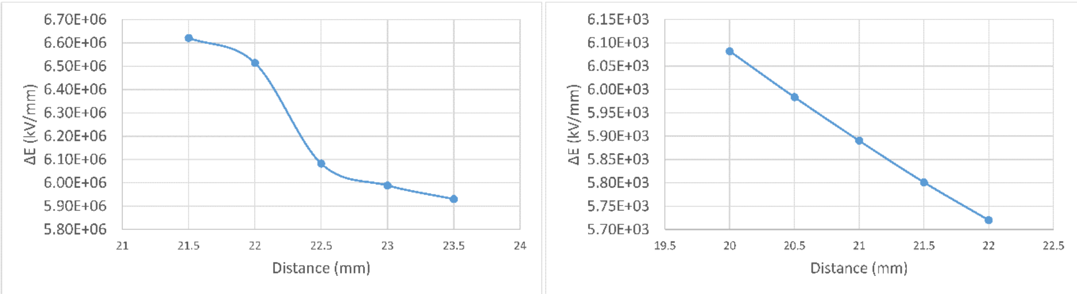


Figure 20. 2-D contour plot of electric field distribution at region -2-

4. PROPOSED TRANSFORMER INULSATION MODEL

The simulation results obtained illustrate that all the values of the electric stress are less than the addressed minimum breakdown values of electric stress for the insulation materials used in forming the insulation structure of the transformer under study, there for, an improvement can be applied to the insulation structure.

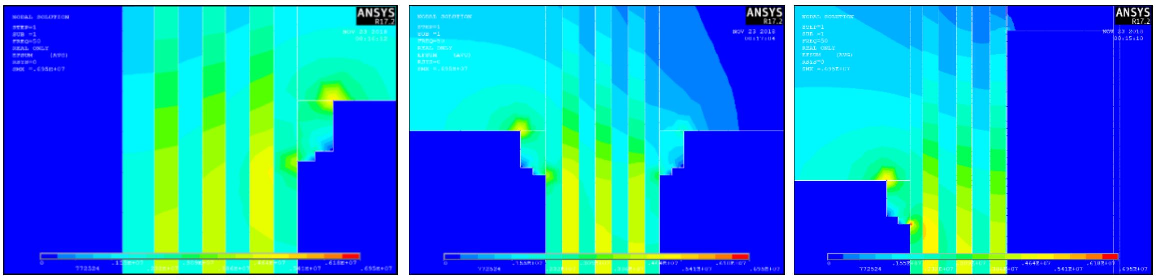
The improvement process involves three stages, the first stage is reducing the insulation thickness, which will lead to reduce the overall width of the transformer, by reducing both of the H-H and the H-C insulation 2mm, in 0.5mm steps, then the dielectric response is determined and the maximum were values registered. The results show an increment in the electric stress, because the electric stress and the insulation distances are inversely proportional, but the resulting values of the electric stress were maintained below the practical breakdown values as shown in Figure 21 which illustrates the variation of the maximum electric stress located across the H-C and H-H insulation respectively with respect to changing the insulation thickness.



(a) (b)

Figure 21. (a) Variation of maximum value of electric stress w.r.t changing the insulation thickness at H-C insulation. (b) Variation of maximum value of electric stress w.r.t changing the insulation thickness at H-H insulation

The second improvement stage involved creating gaps among the pressboard layers by adding wood ducts, while maintaining the insulation thicknesses unchanged at the H-C and H-H insulation to permit the circulation of transformer in order to benefit from its insulating properties, also using the aramid insulating paper instead of the insulating paper used in the H-L insulation, this paper has a relative permittivity equal to 4 which higher than that of insulating paper which originally used. The simulation results show that the maximum value of electric stress located at the H-C insulation had reduced from 5.93kV/mm to 4.36kV/mm, also the maximum value of electric stress located at the H-H insulation is reduced from 5.72kV/mm to 4.25kV/mm, and for the H-L insulation, the maximum values of the electric stress is reduced from 7.04kV/mm to 6.95kV/mm. Figure 22 shows the distribution of the electric stress at region -2- for the H-C, H-H, and H-L insulation respectively.



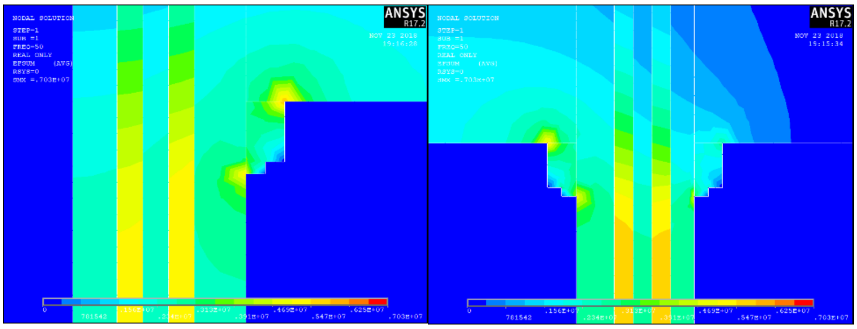
(a) (b) (c)

Figure. 22 (a) Electric field distribution at H-C insulation. (b) Electric field distribution at H-H insulation. (c) Electric field distribution at H-L insulation

The reason behind the reduction of the electric stress at the H-C, and the H-H insulation is that, by adding the multi-dielectric insulation medium between the high voltage windings, and the iron core, had led to reducing the equivalent capacitance in between.

The last improvement stage involved both of reducing the insulation distances, and creating the oil gaps. The results obtained from the FE solution show that the results show that the electric stress at the H-C insulation from 5.93kV/mm to 5.37kV/mm, while at the H-H insulation, the electric stress was reduced from

5.72kV/mm to 4.94kV/mm. and Figure 23 shows the redistribution of the electric field at both of the H-C, and the H-H insulation.



(a) (b)

Figure 23. (a) Electric field distribution at H-C insulation. (b) Electric field distribution at H-H insulation

5. CONCLUSION

The distribution of the electric field of the transformer under study has been successfully determined and the maximum values of the electric stress of the entire FE model had been determined and localized. Based on the obtained values of electric stress show that the transformer is able to withstand the full values of the impulse voltage with no failuar that can take place. The Suggested FE models can help the desiner to improve the insulation structure of the transformer and saving time and efforts spended in the design process. The reduction in the insulation thickness may lead to reduce the overall width of the transformer which will lead to change the transformer impedence, there for, the impedence value must be taken into consideration.

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