Analysis of Power Transformer Insulation Design using FEM

Tathagat Chakraborty, Akik Biswas, Sudha R.

Abstract: ***A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling.***

If a load is connected to the secondary, current will flow in the secondary winding, and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding (Vs) is in proportion to the primary voltage (Vp) and is given by the ratio of the number of turns in the secondary (Ns) to the number of turns in the primary (Np) as follows:

By appropriate selection of the ratio of turns, a transformer thus enables an alternating current (AC) voltage to be "stepped up" by making Ns greater than Np, or "stepped down" by making Ns less than Np.

In the vast majority of transformers, the windings are coils wound around a ferromagnetic core, air-core transformers being a notable exception.

Transformers range in size from a thumbnail-sized coupling transformer hidden inside a stage microphone to huge units weighing hundreds of tons used to interconnect portions of power grids. All operate on the same basic principles, although the range of designs is wide. While new technologies have eliminated the need for transformers in some electronic circuits, transformers are still found in nearly all electronic devices designed for household ("mains") voltage. Transformers are essential for high-voltage electric power transmission, which makes long-distance transmission economically practical.

Finite element modeling (FEM) is a useful and commonly used tool in the solution of electromagnetic problems that arise in the design of power transformers. With approximately 30% of all transformer failures being due to insulation breakdown (due to excessive electrostatic stress), electrostatic FEM techniques are providing engineers with a valuable means of more accurately quantifying the electric stress in their designs.

The validity of FEM, in general, always depends on having sound modeling assumptions and techniques. In addition, this problem introduced further complications that required carefully considered assumptions and treatments.

Keywords: EMF, FEM.

Manuscript received on July, 2012.

Tathagat Chakraborty, School of Electrical Sciences and Technology, VIT University, Vellore - 632014, Tamil Nadu, India

Akik Biswas, School of Electrical Sciences and Technology, VIT University, Vellore - 632014, Tamil Nadu, India

Sudha R., School of Electrical Sciences and Technology, VIT University, Vellore - 632014, Tamil Nadu, India

I. INTRODUCTION

With the ever-increasing competition in global market, there are continuous efforts to reduce insulation content in transformers. This requires greater efforts from researchers and designers for accurate calculation of stress levels at various critical electrode configurations inside a transformer under different voltage test levels. Advanced computational tools such as finite element method are being used for accurate estimation of stress levels, which can be compared with standard withstand levels.

Fundamentals of stress and strength

- The force experienced by a material due to unit positive is called Stress.
- The ability to withstand the stress is called Strength.
- Strength depends upon the property of the material.

Factors affecting the Insulation strength

- Moisture and impurities
- Time and frequency
- Temperature
- Thickness - $E \alpha (\text{thickness})^{n}$
- Stressed volume effects
- Creepage Phenomenon
- Cumulative stress calculation

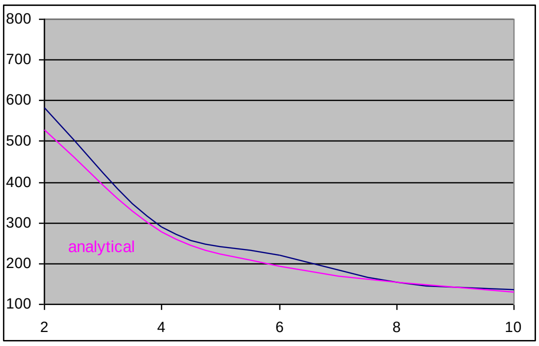
Problem definition of FEM Analysis

- Problem definition - To calculate stress value at different field configurations
- Problem domain - Domain is enclosed in a boundary
- Dimension - 2D in RZ plane
- Medium - Homogenous medium
- Type of Problem - Electrostatic Problem
- Governing Equation - Laplace equation ($\nabla 2V=0$)
- Boundary condition - Dirichlet boundary condition

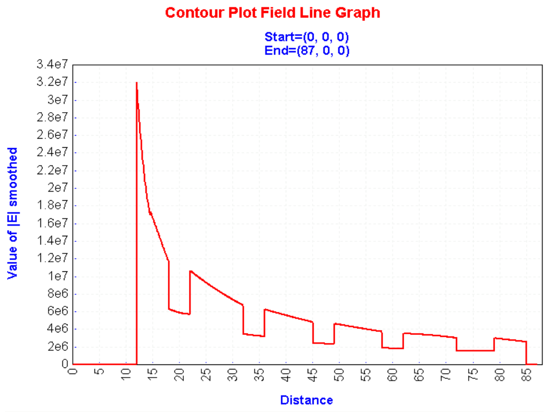
II. UNDERSTANDING THE STRESSES FOR SIMPLE CONFIGURATIONS

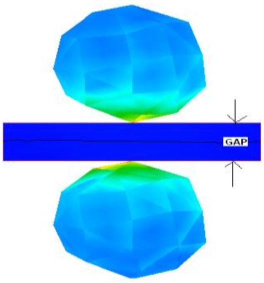
A. Field Plot For Spheres For Various Gap Thicknesses

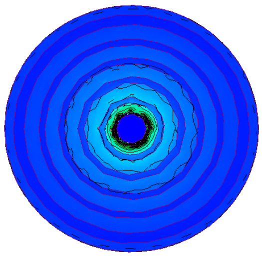
Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication



In the above plot: Pink line: analytical solution Purple line: elecnet solution



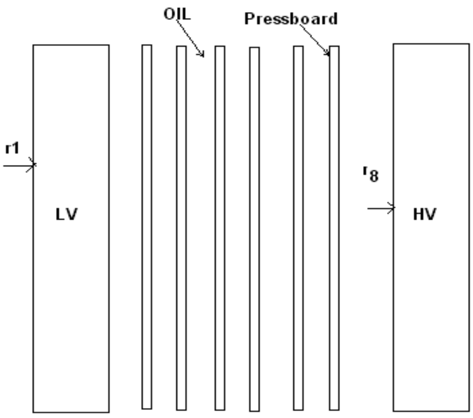




B. Design of insulation

- Major Insulation - between two windings
- Minor Insulation - between two discs
- End Insulation - Effect of contouring

III. DESIGN OF MAJOR INSULATIONS BETWEEN TWO WINDINGS



$$E_i = \frac{V}{r\,\varepsilon_i \left(\frac{1}{\varepsilon_1} \ln \frac{r2}{r1} + \frac{1}{\varepsilon_2} \ln \frac{r3}{r2} + \frac{1}{\varepsilon_3} \ln \frac{r4}{r3} + \cdots \right)}$$

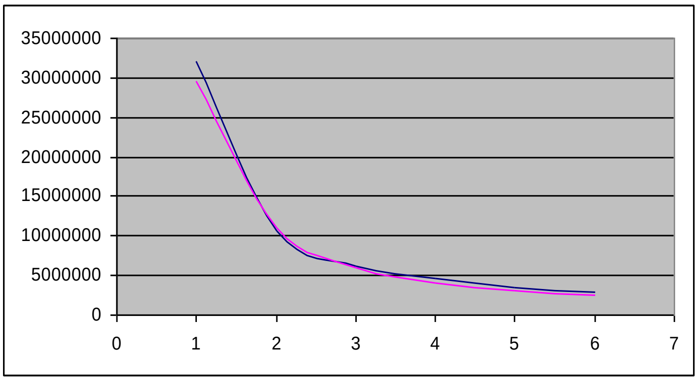
Where, V= 395kV

r1=10mm,	r2=12mm,
r3=22mm,	r4=36mm,
r5=49mm,	r6=62mm
r7=79mm,	r8=85mm

A. Field plot for two windings Field plot for two windings

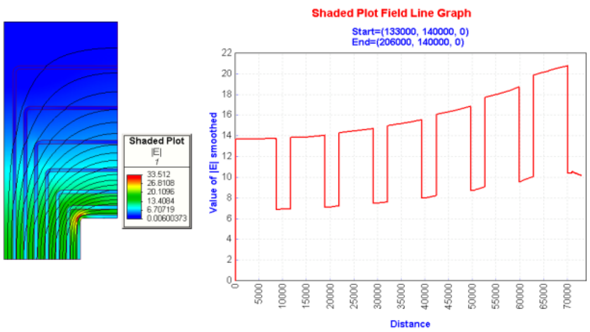
IV. COMPARISON OF FIELD USING FEM & VSTRESS PROGRAM DESIGN OF

Pink: Vstress; Blue: Elecnet

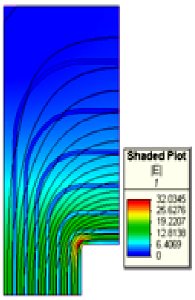


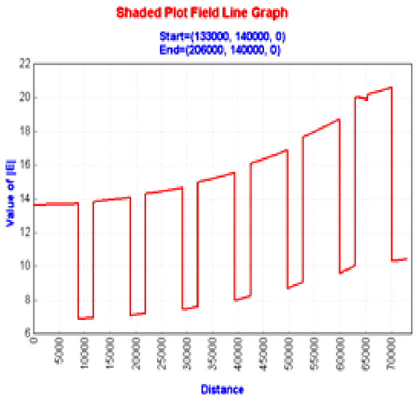
V.DESIGN OF END INSULATION

A. Field distribution along X-X' Axis



Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

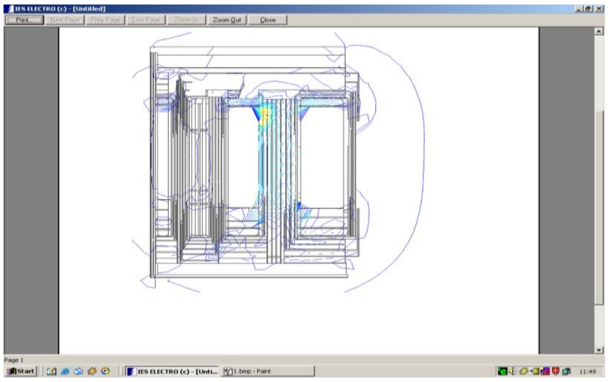


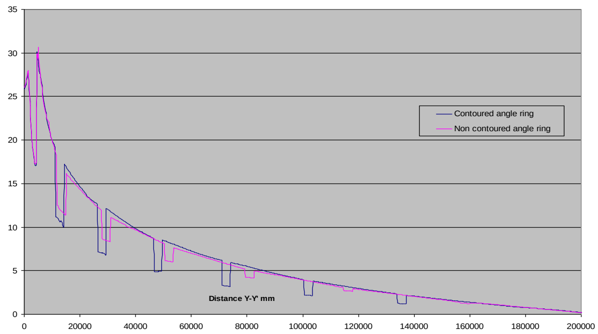


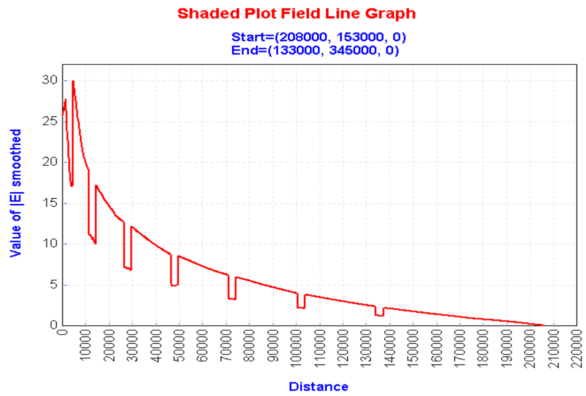
Non Contoured angle rings Contoured angle rings

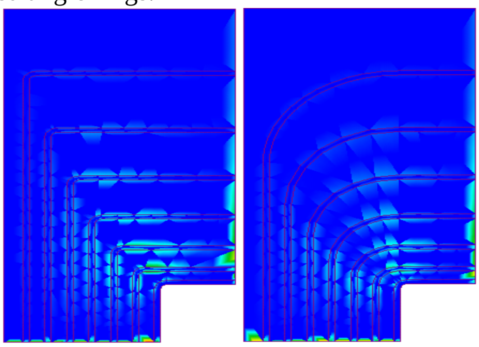
B. Effect of Angle ring contouring

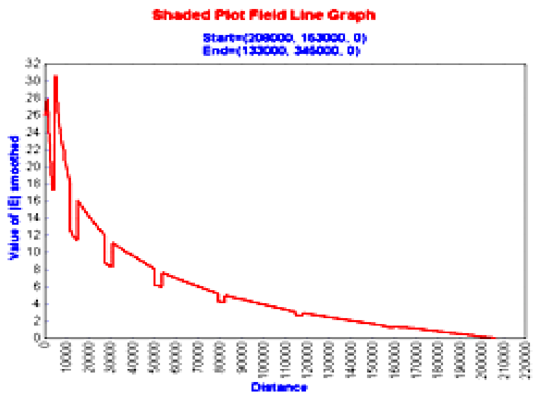
Angle ring should be placed along the equipotential lines so as to reduce the creepage stress along their surface. The effect of tangential stress in contoured is less compare to non contoured angle rings.







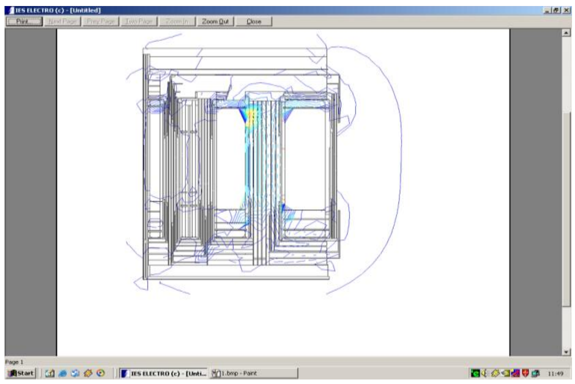




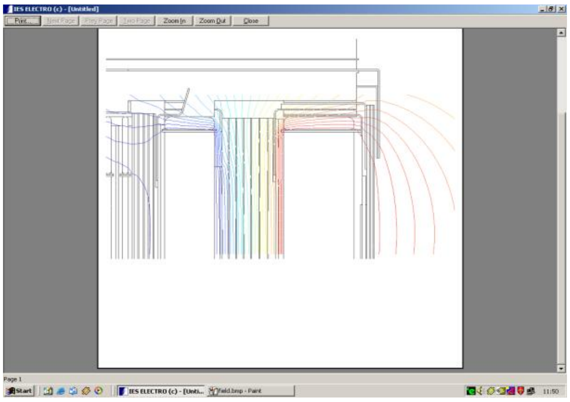
VI. STEPS INVOLVED IN CALCULATING THE STRESS AND STRENGTH FOR POWER TRANSFORMER

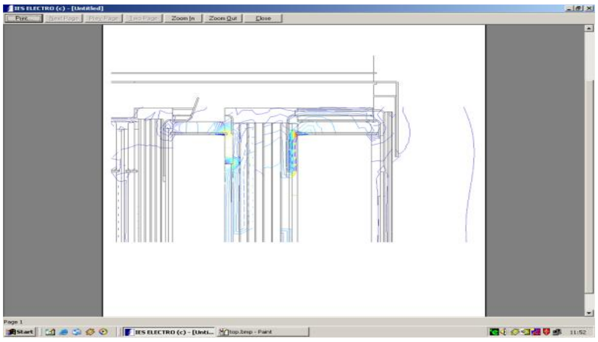
- Understanding the insulation arrangement in transformer
- Calculating the impulse voltage distribution at various points using Volna
- Converting the voltages under all test conditions to equivalent voltage level called, Design Insulation Level
- Computing the fields at various major and minor gaps.
- Identifying the critical paths
- Bulk oil
- Creepage
- Bulk oil + Creepage

Estimation stress with strength curve.



Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication





VII. CONCLUSION

Electrostatic stress analysis for various configurations has been done and compared with Empirical formulae. Stress analysis between two discs shows that the total stress in oil is 9.6kV/mm. This value has to be compared with the strength of the oil used in Power Transformer to arrive at Design Margin etc. Use of angle rings reduces the electrostatic stress. By properly contouring the end insulation, stress can be controlled.

From this paper we have acquired

- knowledge on transformers
- geometry of transformers
- learned Impulse Voltage Distribution
- learned Stresses for simple configurations
- understanding Elecspec, Insulation arrangements, Rating & Diagram.
- modeled the various insulation systems of power transformers
- learned the Package ElecNet, Volna

REFERENCES

1. Elecnet Package Manual
2. Volna package Manual.
3. Karsai K, Kerenyi D. and Kiss L, “Large power transformer”, Elsevier, Amsterdam, 1987.
4. Kulkarni S.V, Khaparde S,A, “Transformer Engineering Desing and Practices” 2004
5. Moser, H.P Transformerboard, Scientia Electrica, 1979
6. Wirgau.K.A, “Inductance calculation of an air-core disk winding”, IEEE, Trans., 1976.
7. Alfred I. Jones, Bynum E.Smith, Daniel J.Ward, “Considerations for higher voltage distribution”, IEEE Transactions of Power Delivery, Vol.7, No.2, April 1992.
8. Frederick W.Grover, “Inductance Calculations”, Nostrand Company, 1947.
9. Yoshikazu Shibuya, and Shigeto Fujita, “High Frequency Model and Transient Response of Transformer Windings”, IEEE, 2002.
10. O.Honorati, E.Santini, “New approach to the analysis of impulse voltage distribution in transformer windings”, IEE Proceedings,Vol.137,No.4, July 1990.