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CALCULATING STRAY LOSSES IN POWER TRANSFORMERS USING SURFACE IMPEDANCE WITH FINITE ELEMENTS

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Abstract **- The paper describes the results obtained from a rarely published method of calculating eddy losses in thick conducting materials. The Surface Impedance formulation is used in a finite element software package which is applied, in turn, to the design of large power transformers. The transformer and model details are discussed as are the excellent results obtained by employing these techniques. The paper then discusses the further application of these methods and their implications for transformer design.**

I. INTRODUCTION

With the increased pressure on manufacturers to produce lower loss power plant for reasons of energy conservation and environmental considerations as well as the obvious money savings, designers are having to turn to more reliable methods of calculating the losses caused by stray field effects.

Until recently many companies have relied mainly on empirical calculations, either derived experimentally from older designs or from papers dating from as far back as the early part of the century to determine the stray losses on power transformers [1]. For the majority of standard designs these have served as good gauges of eddy induced loss but for designs of special transformers or units with very tight specification tolerances these have often proved to be inadequate. This has often led, after testing, to expensive modifications with the changes being made without the full knowledge of the effects of the alterations.

It is to this end that Brush Transformers Ltd, within the Hawker Siddeley group, have employed finite element and other modern techniques [2] in order to improve their product design and efficiency. The work has come out of a "Teaching Company Scheme" with Nottingham Polytechnic.

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II. TEACHING COMPANIES

A Teaching Company is a government sponsored partnership between industry and an academic institution in the pursuit of technology transfer. Haydock et al [3] have recently discussed these types of arrangements in more detail.

III. SKIN DEPTH OF TRANSFORMER FITTINGS AND TANK.

The method of surface impedance is particularly applicable to transformer design since a considerable loss is due to eddies induced in steel fittings, clamps and the tank wall. Equation (1) shows the generally accepted expression for the skin depth in a conductor, δ is the skin depth, ω is the angular frequency, μ is the permeability and σ is the conductivity of the material. For non-saturated mild steel at 50Hz the skin depth is of the order of 0.5mm.

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad ......(1)$$

Therefore, considering the large size of power transformers and the appreciable thickness of tank walls it can be assumed that the loss is on the surface.

IV. SURFACE IMPEDANCE AND CLASSICAL METHODS

The origins of the formulation are from the Poynting Vector and applications of this method have been used in transformer design for many years [4]. At the surface of good conductors the tangential component of the electric field ($\mathbf{E}_T$) is approximately proportional to the tangential component of magnetic field ($\mathbf{H}_T$) and thus;

$$E_T = Z^{(m)}[H_T \times \mathbf{n}] \qquad ....(2)$$

where $Z^{(m)}$ is the complex surface impedance of the metal where it is equal to

$$\sqrt{\frac{-j\omega\mu}{\delta'}} \qquad \text{........(3)}$$

where the symbols are the same as in equation (1) except σ' is σ-$j\omega\varepsilon$ which is the specific admittance, and ε is the dielectric permittivity. This leads to the use of (4) which yields the surface loss per unit area of the conductor;

$$W = \frac{1}{2} R_e Z^{(m)} |H_T|^2 \qquad \text{........(4)}$$

where

$$R_e Z^{(m)} = \sqrt{\frac{\omega\mu}{2\sigma}} \qquad \text{........(5)}$$

which is termed the surface resistance and is simplified since displacement current is neglected compared with conduction current.

The problem is now one of calculating the tangential component of magnetic field at the tank wall of a transformer. There are many ways that this is done analytically, some methods use a basic formula to calculate it at a point half way up the wall and use geometric factors for the rest of the surface [4]. For clamps and other internal fittings this is a very difficult calculation to perform because of the complicated geometries involved. Most methods are based on curved tanks as in Fig (1) and difficulties arise when straight tank walls are used because some of the symmetry is lost. The loss on the tank wall is found by integrating the specific losses over the inside surface of the tank.

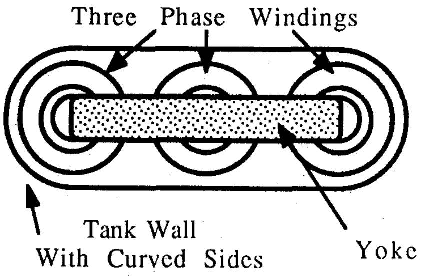

Fig. 1. Plan View of a Power Transformer with Curved Tank Walls.

V. SURFACE IMPEDANCE WITH FINITE ELEMENTS

The calculation of eddy currents in 3-D finite elements is computationally expensive as well as being difficult to build models where thin skin depths occur. A power transformer has dimensions in metres and the skin depths are in millimetres and using solid elements would cause errors due to the poor aspect ratio of these elements. Consider a large transformer of tank dimensions 8m long, 6m high and 5m depth. To accurately calculate the fields required up to 60,000 solid elements may have to be used. Then consider putting on the tank wall with solid elements and modelling a number of skin depths. The size of the model would increase rapidly as well as solution time.

It is in these types of cases that surface impedance modelling has been developed [5]. Using the simple formulation of reduced scalar potential as an energy function from [6] as in (6) can be used with the simple addition of the surface impedance terms as in (7). The letters t_1 and t_2 are the tangential directions to the surface elements.

$$\chi = \frac{1}{2}\int_v \left\{ \mu_x \left(\frac{\partial\Omega}{\partial x}\right)^2 + \mu_y \left(\frac{\partial\Omega}{\partial y}\right)^2 + \mu_z \left(\frac{\partial\Omega}{\partial z}\right)^2 \right\} dV \qquad \text{.......(6)}$$

and

$$\chi' = \chi + \frac{Z}{j2\omega}\int_s \left\{ \left(\frac{\partial\Omega}{\partial t_1}\right)^2 + \left(\frac{\partial\Omega}{\partial t_2}\right)^2 \right\} dS \qquad \text{.......(7)}$$

VI. EXAMPLE TRANSFORMER

Work has been continuing at Brush Transformers Ltd for some time now, analysing a whole range of transformer problems with the application of finite element computations . The first example presented demonstrates the advantages of using surface impedance with finite elements.

The following example is a 90MVA, 3-phase, 132/33kV transformer mounted in a straight sided mild steel tank. In this unit tank wall mounted magnetic shunts were employed in order to reduce the stray losses. These shunts made of plates of transformer core steel, stacked to around 10mm thick, and mounted close to the transformer wall. They are arranged so that they shield the wall from the leakage field produced by the unit when on load. The shunts have a much lower loss characteristic than the mild steel of the tank as well as a higher permeability and so reduce the stray loss. Table I shows results from tests performed on the transformer.

TABLE I
TEST DETAILS (@NORMAL TAP) FOR 90MVA TRANSFORMER

	Stray Loss in (kW)		
	In Tank	Out of Tank	Difference
No Shunts	51.68	14.38	37.30
With Shunts	29.78	-	15.40

The load loss test, a reduced voltage short circuit test, is performed by short circuiting the secondary winding and applying impedance volts, ie; the voltage necessary to cause full load current to flow. The impedance voltage establishes the leakage flux which in turn causes these stray losses. In this transformer the impedance voltage was 25.46%

VII. MODEL DETAILS

The transformer was modelled using 28,962 surface and tetrahedral brick elements, the surface elements being used for the tank wall. The 3-D solver [7] uses only the reduced scalar potential formulation since the excitation of the coils is performed using magnetic shells. The solver may also model the non-linear characteristics of the core steel, but since there was no mutual flux then the permeability of the steel was very high and so a linear study was used where the relative permeability was chosen to be 28,000 which is typical of non-saturated transformer core steel, which was in this case 23M3 grade. One important facility that the solver does have is that the permeability of the steel across the laminations is taken into account by a stacking factor. Equation (8) shows the calculation of the permeability of the core steel in the direction across the laminations. In this case the stacking factor was chosen to be 0.95.

$$\mu_{effective} = \frac{\mu}{S.F. + \mu(1-S.F.)} \qquad ....(8)$$

Non-linearity in the tank wall and fittings is accounted for by the application of Aggarwal's approximation, which is detailed in [5]. The B-H curve of the mild steel is not used in any way, although the application of this type of modelling would probably improve the accuracy of the analysis.

VII. RESULTS FROM ANALYSIS

The following details the results of the tank wall loss and impedance calculations.

TABLE II
RESULTS OF FINITE ELEMENT ANALYSIS FOR 90MVA TRANSFORMER

Tank Wall Loss (no shunts)	35.5kW
Tank Wall Loss (with shunts)	14.8kW
Impedance	25.5%

The loss is calculated for each element and so the total loss is simply the integral of the elemental losses. A designer may examine contour plots of the loss on the surface of the tank wall to check for hot spots which may cause oil failure due to overheating.

These results correlate very well with those obtained from actual tests performed in the factory. The impedance calculation is the application of;

$$L = N\Phi/I \qquad ....(9)$$

where N is the number of turns in a winding, I is the exciting current and Φ is the average flux in the winding.

IX. FURTHER WORK WITH STRAY LOSSES AND STEEL FITTINGS

An appreciable amount of loss is experienced by the clamps and other fittings in the transformer. The clamps generally take two forms. The yoke/core clamps hold the core together and are often made of mild steel plates that are placed along the length of the yoke of the transformer core. Bolts and tie rods hold these clamps together and so can significantly contribute to stray loss production since they form a circuit with many parallel paths. Insulators are often used to break up these paths. The other type of clamps are the winding clamps which are often used in smaller units. These often take the form of semi-circular plates of steel at the top and bottom of the windings, the top clamps having jacks to create the compression required. Below are listed two more units, having these types of devices, analysed using surface impedance with finite elements.

TABLE III
COMPARISON OF TESTED AND CALCULATED RESULTS FOR TWO FURTHER UNITS

Transformer Details	(Loss) Tested	Calculated
T1. (16MVA,33/11kV)	40.33kW	38.29kW
T2. (20MVA,66/11kV)	39.91kW	40.88kW

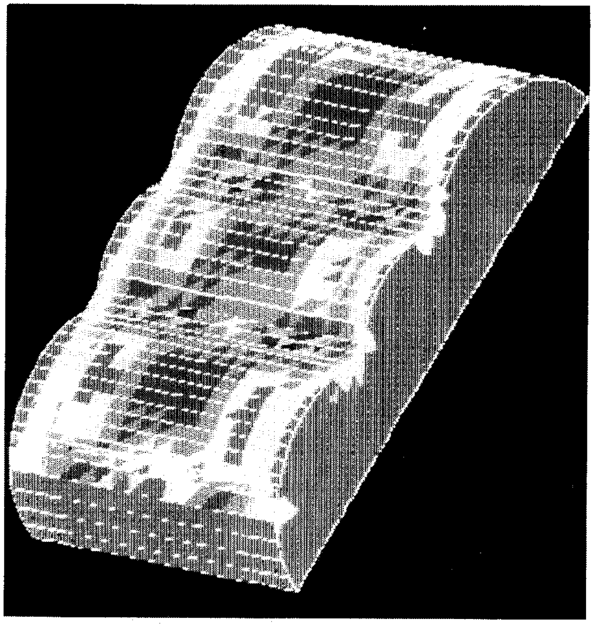

Fig. 2. Contour Plot of Stray Loss on a Curved Tank Wall of a 500MVA Unit

Accurate results, such as these, require nearly all steel components to be modelled hence the models become very complex and large but the surface impedance method helps to keep the model size to a manageable one.

Other transformers that have been analysed are large transformers, as in Fig. 2, up to 750MVA. Fig. 2 shows the contour plot of stray loss for a 500MVA unit. These units are more difficult to model since they often employ shaped core steel packets at the end of the windings to redirect the leakage flux straight back into the transformer core thus reducing the tank wall loss.

The procedure used to model the whole of a transformer is to model it as a solid model and then to cover the steel components with surface elements and delete the solid elements inside. This decreases the size of the model and hence reduces computation time. There are limitations to the method. Aluminium components cannot be modelled using surfaces since the skin depth is too thick.

X. CONCLUSION

The results obtained suggest that the surface element/impedance method is an excellent one for the applications described. These results were also appreciably closer to the test results than other more traditional calculations. The transformer tank wall and fittings can be modelled accurately with surface elements removing the need for complex layers of brick elements to account for skin effects and this, in turn, reduces the complexity and size of models. This method thus yields advantages of reduced complexity especially important in the analysis of very large devices such as 3-Phase transformers.

REFERENCES

[1] S. Mamota, "Stray Load Losses in Transformers", Journ. Japanese Inst. Elect. Engnrs., May, 1926, No.454, pp. 505-580

[2] L. Haydock, S. Holland, W. Hudson, "A Hybrid Finite Element and Distributed Magnetic Equivalent Circuit Modelling Methodology for Electromagnetic Devices.", Advances in Electrical Engineering Software Electrosoft Conference 1990, pp 43-53.

[3] L. Haydock, S. Holland, G. P. O'Connell, "Teaching Companies - A Case Study", proc. The 12th E.C.O.O. and 8th I.C.T.E. Conference, Toronto, 1990.

[4] A. A. Berezovski et al., "Calculation of Stray Losses in Transformer Tanks", Elektrichestvo, No.9, pp. 1-7,1966.

[5] T. W. Preston: "3-Dimensional Eddy Currents in Turbine-Generators.", Phd Thesis, University of London, 1984.

[6] A. Coulson, M.A., Preston, T.W., and Reece A.B.J., "3-Dimensional Finite Element Solvers For The Design Of Electrical Equipment", IEEE Trans. Mag. Vol.2, No.6, 2476-2479. 1985.

[7] G.E.C. - Alsthom - S.L.I.M. Software - G.E.C. - Alsthom Engineering Research Centre, Litchfield Road, Stafford, U.K.