Evaluation of flitch plate losses in power transformers

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Abstract - Although Eddy current losses in flitch plates of large power transformers may form a small part of total transformer losses, they are important because they can appear concentrated in a small area and cause hazardous hot-spots. An analytical method to calculate flitch plate eddy loss is a very useful practical guide to a transformer designer, but for high power transformers, a more accurate analysis by techniques such as the Finite Element Method (FEM) is desirable. A series of 2-D FEM simulations, using a statistical technique - orthogonal array design of experiments, have been carried out to find the effect of various factors on the losses in a mild steel flitch plate. The procedure for carrying out the experiments and the results obtained thereof are presented. The more involved analysis of slotted flitch plates, has been done using 3-D FEM. Loss and eddy current patterns in mild steel and stainless steel flitch plates have been studied. In both cases, the effect of the number of slots and slot length on the losses is discussed. Effect of slots on eddy current pattern is explained. Results of simulation of laminated flitch plate are presented. The eddy loss distribution obtained by 3-D FEM electromagnetic analysis is used in 3-D FEM thermal analysis to estimate temperature rise of the flitch plate. Verification of 3-D FEM analysis has been done by measurement of temperatures on a slotted mild steel flitch plate of a 33 MVA, single phase, 220/132/11 kV auto-transformer. The estimated temperatures have been found to be in good agreement with that obtained by measurements.

I. INTRODUCTION

The problem of stray field losses becomes increasingly important with growing transformer ratings. Stray flux departing radially through the inner surface of windings hits the core and fittings such as the flitch plate mounted on the core. On the surface of the flitch plate (lying on the outermost core step of the limbs for holding the core laminations together vertically), stray flux density may be much higher than that on the tank. Hence, although the losses occurring in the flitch plate may not form a significant part of the total losses of the transformer, the local temperature rise is much higher due to a higher value of incident flux density and poorer cooling conditions. The loss density may attain levels that may lead to hazardous local temperature rise if the material and type of flitch plate are not selected properly. Such high temperatures can cause deterioration of insulation, thereby jeopardizing the service reliability of the transformer [1].

Literature available on flitch plate loss analysis is quite scarce. Calculation of losses and temperature rises occurring in structural parts of a transformer is a very complex task due to magnetic and thermal non-linearity. Karsai et. al. have given an approximate but practical method of calculation of losses and temperature rise of critical structural parts of a transformer [2]. Eddy-current losses arising in metallic parts of rectangular cross section are calculated by an analytical method which makes certain approximations based on experimental factors [3]. Field strength at the inner edge of the LV winding is assumed to vary periodically with a sinusoidal distribution in the space along the height of the winding, and the non-sinusoidal nature is accounted by multiplying loss by a factor. The approximations made are: eddy current reaction is neglected and only amplitude of harmonic components of the field strength in the z direction (perpendicular to plate surface) are subject to change, their wavelengths and phase positions remaining unaltered. For a fully slotted flitch plate, the analytical formulation is modified by considering splitting of plate into distinct parts. Even though this analytical formulation helps the transformer designer in quick estimation of flitch plate losses, more accurate analysis by advanced numerical techniques, such as FEM, is desired.

Another important aspect is the study of the effect of slot length on the eddy current and loss distributions (slots may be provided only in the zone where radial flux is incident on the flitch plate). The analytical formulation cannot be modified for flitch plate of limited slot length.

The above limitations of the analytical formulation underline a need for FEM analysis to obtain a good amount of accuracy in predicting the eddy loss and temperature rise of flitch plates. The paper describes details of statistical analysis used in conjunction with 2-D FEM, for quantifying the effect of various factors affecting flitch plate loss. The 2-D FEM analysis is done for an x-y geometry of infinite extent in z direction. This approximation is reasonable because of the large coil sizes. Calculated quantities are per unit length in the z direction. The paper also presents results of 3-D FEM simulations carried on slotted and laminated flitch plates. Comparison of results of combined 3-D FEM electromagnetic and thermal simulations, with actual measurements carried out on a 33 MVA, single phase, 220/132/11 kV auto-transformer is presented.
Orthogonal array design of experiments, a statistical technique, allows the effect of several factors on a response to be determined efficiently [4]. Analysis of relative effects of different factors can be obtained by decomposition of variance, which is commonly called Analysis of Variance (ANOVA). A cross-section of a transformer depicting a core, flitch plate, flame, windings and tank is shown in Fig. 1. Symmetry is assumed about the center plane of the windings. The various geometrical dimensions that have a pronounced effect on flitch plate loss (response) are chosen as parameters (factors) for design of experiments, Each factor is assigned 3 equidistant levels, as given in Table I (all dimensions in mm), to examine non-linear relationship between factors and response. The levels correspond to range of these factors for transformers of rating from 5 MVA to 315 MVA. Five factors viz., half winding height (x1), end clearance (x2), core-LV gap (x3), LV-HV gap (x4) and HV winding to tank clearance (x5) which affect the losses considerably, only have been chosen for the analysis, reducing the number of experiments [5]. Radial depths of windings are kept fixed for all experiments. Effect of frame is indirectly taken, since the frame height varies in accordance with the level of factor x2. The regression model has a constant term and 20 variables (regressors) : 5 linear terms, 5 quadratic terms, and 10 interaction terms. The minimum number of experiments required to evaluate the 20 regression coefficients is 21, which necessitates use of L27 orthogonal array [6]. Thus, number of experiments to be carried out are reduced from 243 (3^5, 5 factors at 3 levels each) to 27 without losing out on accuracy. The LV and HV windings are defined as current driven coils with ampere-turns of 10^5 and -10^5 respectively. Core symmetry axis and tank outer boundary are constrained with Dirichlet condition, so that the field lines are parallel to these boundaries. Center line of windings is left unconstrained (Neumann condition) so that field lines are perpendicular to this boundary axis. The FEM analysis was done for 27 combinations of 5 factors as per L27 orthogonal array for a mild steel flitch plate (12 mm thick). Leakage field plot for a certain combination of factors is shown in Fig. 2.

Loss is calculated as the integral of ρJ^2 (ρ=resistivity, J=current density) over the volume of conducting flitch plate material in which eddy currents are produced. The ANOVA was subsequently carried out to quantify the effect of each factor on the flitch plate loss. Results of ANOVA are shown in Fig. 3. It can be seen that only factor x4 (LV-HV gap) has a more or less linear relation to the loss. Variation of factor x5 (HV winding to tank clearance) has a relatively less effect on the loss as compared to other factors. For fixed ampere turns, as axial length of winding reduces, leakage field increases correspondingly. Also, as the axial height of windings is reduced (with other factors unchanged) the radial leakage field incident on the flitch plate will increase. Hence there is an increase in flitch plate loss with reduction of winding height. Similar explanation can be given for the effect of variation of other factors on the loss. Regression analysis was subsequently carried out to compute regression coefficients of the quadratic surface.

The quadratic surface generated can be used by designer for a quick estimate of loss in the flitch plate after correcting for...
Fig. 4. View of 3-D model

by a factor [3] for finite dimension of plate in z direction. Inputs required for the loss estimation are: values of factors, ampere-turns and width of flitch plate. More accurate estimation of losses is possible by 3-D FEM analysis. Also the effect of the number of slots and slot length on the eddy loss and eddy current distribution cannot be studied in 2-D FEM. Detailed 3-D FEM analysis of a slotted and laminated flitch plate of a particular transformer is described in the following section.

III. 3-D FEM ELECTROMAGNETIC ANALYSIS

A. Model

A single phase, 33 MVA, 220/132/11 kV autotransformer was modeled with various types of flitch plates, viz., no slots, slots throughout the length of the plate, slots of 400 mm length in the radial leakage field zones. Only one-eighth of the transformer was modeled in MagNet 5.2 FEM software, as shown in Fig. 4 (tank not shown), by taking symmetry about y-z (x=0), x-z (z=0) and x-y (z=0) planes. Meshing in the base plane was carried out in such a way that the area of interest (flitch plate) was meshed densely. The problem was solved using second order elements in the flitch plate. All other materials had first order elements. The loss values reported are the stabilized values after using adaptive solving facility of MagNet software, in which improvement parameter was set at 25% (order of 25% of elements having highest error is increased). Provision of modeling up to seven slots was made in the 3-D model. The length, width and thickness of the flitch plate were 1335 mm, 200 mm and 12 mm respectively. Each slot was of 5 mm width. Boundary conditions are so defined that the flux lines are parallel to x-z and y-z symmetry planes and tank outer boundary, and are perpendicular to the x-y plane.

B. Analysis of Mild Steel Flitch Plate

A mild steel flitch plate (relative permeability $\mu_r = 1000$, conductivity $\sigma = 4 \times 10^6$ S/m) with 1, 3 and 7 slots was studied. Results obtained are summarized in Table II. The loss values shown are for one-fourth of a complete plate. The LV and HV windings are defined as current driven coils with ampere-turns of 71449 and -71449 respectively.

The loss for '7 slots throughout' case is approximately 4 times less than that of 'no slots' case. Theoretically, loss is proportional to square of width, hence for n slots, the loss should reduce approximately by a factor of $(n+1)$ i.e. 8. (If a plate width of $3w$ is divided by 2 slots into 3 plates of width $w$, then loss will theoretically reduce by a factor of $(3w)^2$ divided by $3w^2$, i.e. 3). The pattern of eddy currents is complex in mild steel material. Eddy loss in mild steel has two components: loss due to radial incident field, and the other due to axial field (the incident radial flux changes its direction immediately once it penetrates inside the plate due

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description</th>
<th>Losses (in Watts)</th>
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<tbody>
<tr>
<td>1</td>
<td>No slots</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>1 slot throughout</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>3 slots throughout</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>7 slots throughout</td>
<td>32</td>
</tr>
<tr>
<td>5</td>
<td>1 slot of 400mm length</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>3 slots of 400mm length</td>
<td>52</td>
</tr>
<tr>
<td>7</td>
<td>7 slots of 400mm length</td>
<td>45</td>
</tr>
</tbody>
</table>
to small depth of penetration of MS, viz. 1.1 mm). This phenomenon is evident from the eddy current pattern at the plate cross section taken at 0.5 mm from the surface facing windings in y-z plane (Fig. 5a and Fig. 5b). There is hardly any change in eddy current pattern in this cross section, after the introduction of slots. The direction of eddy currents suggests the predominance of axial field at 0.5 mm from the surface. There are also eddy current loops in thickness of the plate (x-y plane, at the position of slots in z direction, between slot and edge of plate) as shown in Fig. 5c. These may be the reasons for the ineffectiveness of slots in MS plate which in turn explain as to why the reduction of losses is not by a factor of 8. The Table also demonstrates that slots of limited length in the radial leakage field zone may be sufficient for transformers where incident flux density on the flitch plate is smaller.

If higher tensile strength mild steel is used, having lower conductivity ($\sigma = 2.2 \times 10^6$ S/m) and lower permeability ($\mu_r = 50$), losses are lower as compared to normal mild steel material (for 3 slots of 400 mm long, the loss is 40 watts).

**C. Analysis of Stainless Steel Flitch Plate**

Four simulations were carried out on stainless steel ($\mu_r = 1$, $\sigma = 1.13 \times 10^6$ S/m) flitch plate. Results are summarized in Table III. Due to a large penetration depth of stainless steel (67 mm), the incident field penetrates and hits the core laminations. This phenomenon is evident from the eddy current pattern at the plate cross section taken at 0.5 mm from the surface in y-z plane (Fig. 6a and Fig. 6b). There is appreciable distortion in eddy current pattern after the introduction of slots. The direction of eddy currents indicates the predominance of radial field at the cross section, 0.5 mm from the surface. There are no eddy current loops in thickness of the plate (x-y plane at the position of the slots) as shown in Fig. 6c. These may be the reasons for the effectiveness of slots in SS plate. Thus, almost all the eddy current loops are parallel to face that sees the flux indicating that eddy loss in SS plate is predominantly due to radial field. Hence slots in SS plate are more effective as compared to MS plate. This means that losses should actually vary inversely as the number of slots. From the first two results we see that the reduction in losses is more (12 times) than is expected (8 times). This may be due to fact that each slot is 5 mm wide causing an appreciable reduction in losses due to reduced area of conduction. Due to higher resistivity of SS, the losses are correspondingly lower than MS.

**TABLE III**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description</th>
<th>Losses (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No slots</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>3 slots throughout</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>3 slots 400 mm long</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>3 slots 400 mm long</td>
<td>17</td>
</tr>
</tbody>
</table>

**D. Analysis of Laminated Flitch Plate**

Laminated flitch plate (consisting of M4 grade CRGO laminations) was modeled using anisotropic modeling facility available in MagNet 5.2 software. Direction z is defined as soft direction and other two directions are defined as hard directions. As expected, loss value obtained for the laminated flitch plate is 2.5 watts which is quite lower than SS plate. Hence laminated flitch plates are generally used for large power transformers, particularly generator transformers, where incident flux density is quite high.

The eddy loss distribution obtained by 3-D FEM electromagnetic analysis, as explained in this section, can be used in estimation of the temperature rise of the flitch plate by 3-D FEM thermal analysis (NISA software), which is explained in the following section.
IV. 3-D FEM THERMAL ANALYSIS

The auto-transformer analyzed in the earlier section has a MS flitch plate with 400 mm slots in the top and bottom radial leakage field zones. Heat generation rates were defined for various zones of the flitch plate surface (y-z plane) and also along the plate thickness (x direction). These heat generation rates (watts/m³) were obtained for various zones from the 3-D FEM electromagnetic analysis.

The heat transfer coefficient (h) was calculated by the basic thermal theory of a vertical plate in an oil medium [7]. The oil film temperature (average of measured values of plate and oil temperature) was 46.5°C. Properties of oil at 46.5°C are [2]:
Density, \( \rho = 886 \text{ kg/m}^3 \)
Thermal Conductivity, \( K = 0.1294 \text{ W/m } ^\circ \text{C} \)
Kinematic Viscosity, \( \nu = 10.96 \times 10^{-6} \text{ m}^2/\text{s} \)
Prandtl number, \( Pr = 143 \)
Coefficient of thermal cubic expansion, \( \beta = 7.68 \times 10^{-4} \text{ oC}^{-1} \)
Average temperature difference between plate and oil = \( \Delta T = 11^\circ \text{C} \)

\[ g = 9.8 \text{ m/ s}^2 \]
Length of Plate = \( l = 1.535 \text{ m} \)
Rayleigh number (Ra) = \( (g \beta \Delta T)^1 \times Pr = 3.56 \times 10^{11} \)

Nusselt Number (Nu) can be found out by,
\[
\text{Nu}^{1/2} = 0.825 + 0.387 \text{ (Ra)}^{1/6} \left[ 1 + (0.492/Pr)^{7/8} \right]^{2/7} = 33
\]
Hence, Nu = 1089

\[
h = \text{Nu.K} = 91.8 \text{ W/m}^2 \circ \text{C}
\]

The above calculated value of h was given as an input to the 3-D FEM thermal analysis. Results of 3-D FEM thermal analysis are displayed in Fig. 7(case with 100% load). It can be observed that, as expected, the temperature of the plate is maximum (about 51°C) in the region just above the slot. The temperature is well within limits for this transformer (due to low incident flux density on the flitch plate and low top oil temperature) and hence the design of the flitch plate (of mild steel with slots of only 400 mm length in the fringing zone) is quite safe. In higher rating transformers, particularly generator transformers, where the incident flux density on the flitch plate is quite high, flitch plate design may have to be modified completely to either fully slotted SS flitch plate or laminated flitch plate.

Temperature measurements were done on the auto-transformer at various points near the slots of the flitch plate by thermocouples at 80%, 100% and 120% load along with top oil temperature. Comparison of calculated and measured values of temperatures at point-A (Fig. 7) on the flitch plate is given in Table IV.

Results of 3-D FEM and measurement are quite close which gives confidence to the method of calculation of flitch plate loss and temperature by using combined 3-D FEM electromagnetic and thermal analysis.

V. CONCLUSION

The paper has presented a statistical analysis for quantifying the effects of various geometrical factors influencing the flitch plate loss in a power transformer. Dependence of flitch plate loss on axial length of winding, core-LV gap, end clearance and LV-HV gap is quite high as shown by Analysis of Variance (ANOVA). Flitch plate loss varies almost linearly with LV-HV gap. A quadratic surface subsequently derived by multiple regression analysis can be used by designers for quick estimation of flitch plate loss. The loss value obtained can be used to decide type (with slots/without slots) and material (mild steel/ stainless steel) of flitch plate to control loss and avoid hot spots.

For more accurate evaluation of the flitch plate loss, three dimensional FEM studies were carried out on slotted mild steel and stainless steel flitch plates. The effect of number of slots and slot length on losses was studied in both cases. The eddy current patterns clearly indicate that loss in mild steel is due to both radial incident field (on the surface) and axial field (inside the surface). The slots are more effective in the stainless steel flitch plate than the mild steel flitch plate, as the field in case of stainless steel is predominantly radial due to large penetration depth. Slots of limited length in the radial leakage field zone for mild steel or stainless steel flitch plate may be adequate for transformers, if the incident field on the flitch plate is low. Simulation of laminated flitch plate proved that the loss in laminated case is much lower as compared to stainless steel plate. Hence for higher

**TABLE IV**

<table>
<thead>
<tr>
<th>Load current</th>
<th>3-D FEM analysis</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>47.6°C</td>
<td>48°C</td>
</tr>
<tr>
<td>100%</td>
<td>50.3°C</td>
<td>52°C</td>
</tr>
<tr>
<td>120%</td>
<td>55.8°C</td>
<td>58°C</td>
</tr>
</tbody>
</table>

**Fig. 7. Temperature distribution**
rating transformers, particularly generator transformers, a laminated flitch plate may be necessary. The eddy loss distribution in the flitch plate obtained by 3-D FEM electromagnetic analysis was used in a 3-D FEM thermal analysis to compute the temperature distribution. In order to verify the 3-D FEM analysis, temperature measurements were done on a flitch plate of a 33 MVA, single phase, 220/132/11 kV auto-transformer at various load currents. The computed temperatures by 3-D FEM analysis have been found to be in good agreement with that obtained by measurements. Thus the method of combined 3-D electromagnetic and thermal FEM analysis for estimation of the temperature rise of the flitch plate has been justified and can be used for any other transformer for proper design of the flitch plate to eliminate the possibility of hot spots.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES


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