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Analysis of Stray Losses Calculation in Auto-Transformer Using Coupled IEM and FEM Technique

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Abstract— Transformers are classified among the most important building blocks of any electric power system network. Transmission and Distribution losses are among the main thing that is emphasized and is taken into consideration by demands of the customer. The T & D loss varies in a range of 10 to 40% which is considered to be significant high. In a process of reducing total T & D losses, Loss capitalization for the modern age transformers has increased in a great extent. This indicates necessity of reducing losses (i.e. no load loss and load loss).

Stray losses in the transformer contribute around 15 to 40% in the load losses which is considered to be a significant amount. Hence to match the loss capitalization stray losses shall be reduced. This is achieved by controlling the leakage field. Large rating transformers are with strong electromagnetic field; If the field is not controlled it links with the various structural parts of the transformer and will result in to excessive loss concentration, local heating (i.e. hot spots) and further gasification during service conditions. Various measures e.g. magnetic and nonmagnetic shields are known to control the stray field in the transformers. Effective solution needs to be selected to make shielding measure more optimum. This paper presents a case study involving estimation of stray losses in a 200 MVA, 220/132/11kV Auto transformer using an Integral Equation Method (IEM) and Finite Element Method (FEM) based EDMAG-3D software program.

Keywords— Finite Element Method, Power transformer, Electromagnetic field, Stray losses

I. INTRODUCTION

Transformer losses comprise a small percentage of the power throughput in a transformer. Yet these losses can produce localized heating which can compromise its operation. It is important to be able to calculate these losses at the design stage so that adequate cooling can be provided. There are two main categories of losses, no-load and load losses. No load losses are basically core losses associated with energizing the transformer and driving flux through the core. Load losses are further subdivided into I^2R losses and stray losses. The I^2R losses are resistive losses in the windings and leads caused by the main current flow. The stray losses are the result of the stray flux from the windings or leads impinging on metal parts such as the tank walls, the clamps, and even the windings themselves, resulting in induced eddy currents [1].

II. CASE STUDY

It always becomes a design necessity to reduce stray losses for efficient operation of transformers. A precise prediction of these losses is necessary before attempting any reduction. Towards this, a case study was carried out on a 200 MVA, 220/132/11 kV Auto transformer with load losses of 281.489 kW (at 75 Deg C tap) involving 3-D magnetic field mapping. Fig. 1 shows the FEM modelled H.V side 3-D geometry using software program. Similarly, the L.V side geometry is modelled and analysed.

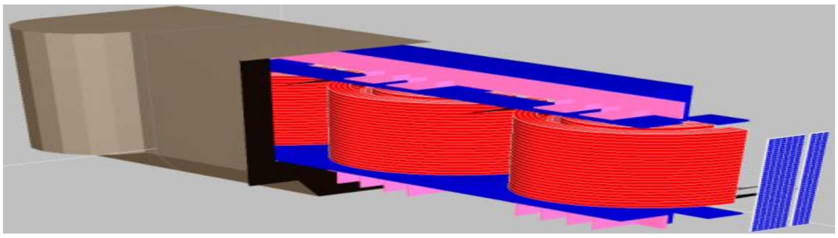

Figure 1. FEM Modelled H.V side geometry of transformer

III. METHODOLOGY

The main tool used for stray loss analysis is Finite Element Method (FEM) and Integral Equation Method (IEM). This program is used for calculation of the magnetic field intensity (H, A/m) and magnetic field density (B, Tesla) of the three dimensional magnetic field together with the eddy current losses in the structural elements and the resultant temperature rises. It calculates values of the magnetic field quantities at pre-defined locations in space, as a sum of field created by the current sources with specified distribution of current using Biot-Savart law and the field created by the fictitious magnetic charges on the interface of magnetic and nonmagnetic media using algebraization of integral equations.

The complete transformer model comprising of Core, Windings, Frames, Flitch plates, Tank, Edge stack and the epures (pre-defined line on which magnetic field values are computed in all 3-directions) is modelled for stray losses computation. The field quantities obtained at these observational points are used for computation of various stray load loss components.

IV. COMPUTATION OF STRAY LOSSES

This section explains the modelling of transformer and computation of stray losses in the following structural parts.

A. Edge Stack
B. Tank
C. Flitch Plates
D. Frames

A. Computation of stray loss in Edge Stack

Core edge loss is the stray loss occurring due to flux impinging normally (radially) on core laminations. The amount and path of leakage field in the core depends on the relative reluctances of the alternative magnetic circuits. In large transformers, the radially incident flux may cause considerable eddy currents to flow in the core laminations resulting in local hot spots.

The first step of the core is usually split into two or three parts to reduce the core edge loss in large transformers. If the stack height of the first step of the core is less than about 12 mm, slitting may have to be done for the next step also.

For estimation of stay loss in edge stack it is essential to compute the 3-D magnetic field values along & across the height of the edge stack. Fig. 2 & 3 below show the plots of the modulus of flux density components (Bx, By, Bz) along and across the height of edge stack respectively, at normal tap position on the HV side of the transformer. The curves A, B and C indicate the component of flux densities normal to the edge stack, along the width of edge stack and along the height of edge stack respectively.

As the magnitude of normal magnetic flux density is higher at the top and bottom winding edges, Fig. 2 represents first and second triangle with peak value flux densities 0.04892T & 0.04817T respectively (at winding edges) along the height of edge stack. The length covered by first and second triangle is represented by notations L1 & L2 in Fig. 2 is 852.5 & 1030.8 mm respectively and distance between the peaks of two triangles represented by notation L12 in Fig. 2 is 1905.6 mm.

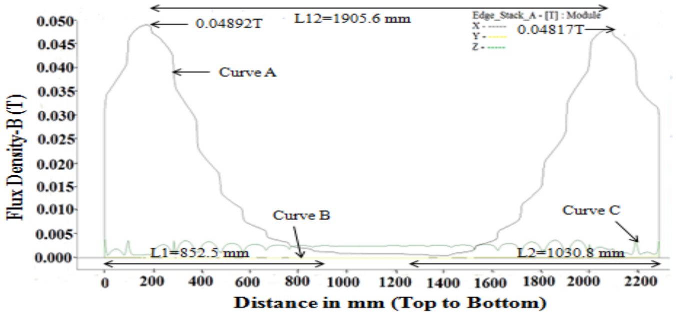

Figure 2. Flux density variation along the height of the edge stack

The average value of magnetic field across the length of edge stack is computed from Fig. 3. The maximum and minimum value of magnetic field at top winding edge position across the edge stack, represented by notations Bm1 & Bm2 in Fig. 3 is 0.09249T & 0.05209T respectively.

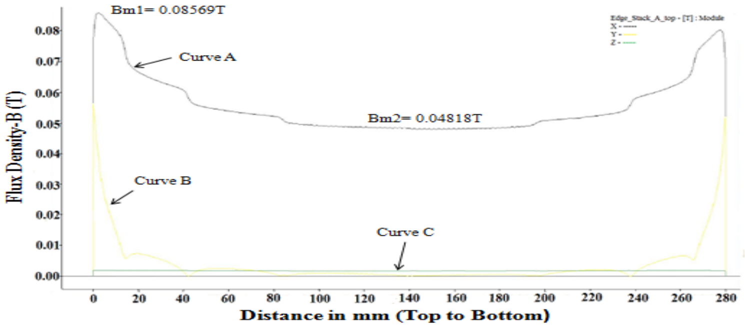

Figure 3. Flux density variation across the height of the edge stack at top winding edge position

Similarly, the maximum and minimum value of magnetic field at bottom winding edge is also obtained. These magnetic field values are estimated for all phases at principal & extreme tap positions on both HV & LV sides of transformer. The stray loss based on above magnetic field values obtained in edge stack for minimum, normal and maximum tap positions as shown in Table I below.

Table I. Stray loss in the edge stack

Mode	Stray loss, kw
Max. Tap	4.376
Nor. Tap	4.136
Min. Tap	3.226

B. Computation of stray loss in Tank

The tank is made of mild steel which is a having a nonlinear permeability, it is always possible to calculate the magnetic field value at the tank surface by decoupling the effect of nonlinearity. After estimation of the magnetic field, losses are calculated considering nonlinearity by an iterative estimation of coefficient of the tank influence factor.

In EDMAG-3D, the geometry of the tank is simulated by slicing various horizontal levels at different heights followed by connecting these levels using vertically defined epures. Fig. 4 shows the local coordinate system of the tank depicting the horizontal and vertical epures.

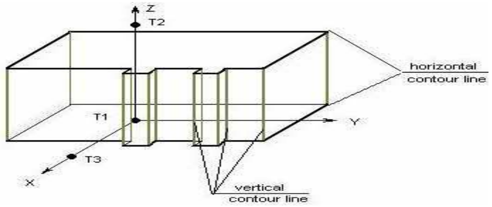

Figure 4. Local co-ordinate system for construction of levels in a tank

The variation of the modulus of flux density components (Bx, By, Bz) along the height of the tank surface (on HV side) opposite to the winding axis, when the tank is completely shielded by the shunts & shields is shown in the figure 5.

For estimate losses in the tank it is necessary to obtain the values of Heff, Heff_w, Hmax and Seff. Where, Heff: effective tangential magnetic field strength on the tank surface (A/m); Heff_w: effective tangential magnetic field strength (opposite to the winding axis) on the tank surface (A/m); Hmax: maximum tangential magnetic field strength on the tank surface (A/m) & Seff: loss emission area (mm2).

Tables II and III shows these values for minimum, normal and maximum tap positions in the HV and LV side respectively.

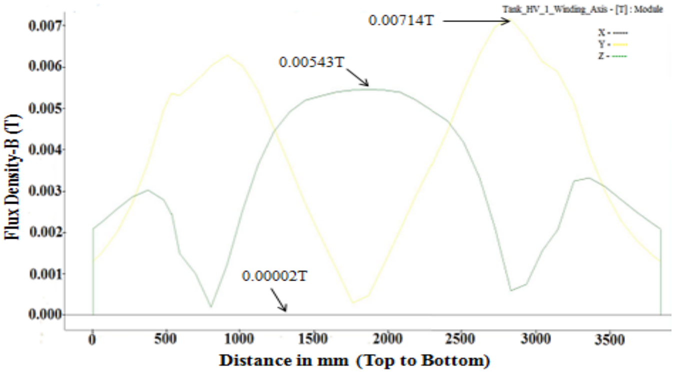

Figure 5. Flux density variation on the HV side tank surface at central phase (opposite to winding axis)

Table II. Magnetic field strength on H.V side tank surface

Mode	**Magnetic field Intensity (HV Side), A/m**			**Seff (mm^2)**
	Heff	**Heff_w**	**Hmax**	
Max. Tap	481	519	1542	54.71
Nor. Tap	1674	1802	5257	54.71
Min. Tap	1573	1693	4903	54.71

Table III. Magnetic field strength on H.V side tank surface

Mode	**Magnetic field Intensity (LV Side), A/m**			**Seff (mm^2)**
	Heff	**Heff_w**	**Hmax**	
Max. Tap	291	375	1356	68.10
Nor. Tap	973	1264	4325	68.10

Min. Tap	903	1176	3950	68.10

Based on the above magnetic field intensity, the losses are calculated for minimum, normal and maximum tap positions in H.V Side and L.V Side tank as shown in Table IV below.

Table IV. Stray losses in the tank

Mode	**Stray loss, kw**		
	HV Side	**LV Side**	**Total**
Max. Tap	9.43	7.11	16.54
Nor. Tap	16.24	10.67	26.91
Min. Tap	14.70	9.80	24.5

C. Computation of stray loss in Flitch Plates

Flitch plates made of MS and with slots of full length are used in the present case. The flitch plates are 200 mm wide and 16 mm thick modelled to the scale, taking care of the slots and analysis carried out using FEM technique. It is important to note that the stray losses in such structural elements are quite low but the incident magnetic field on them can be quite high for the exposed area leading to unacceptable local hot spots.

The magnitude of normal flux density being the highest at top and bottom winding edges, it results in higher losses and hotspots in those regions of the flitch plates. In order to avoid such situations, the slots are provided in the flitch plates at both top and bottom locations. Based on the magnetic field density, the losses are calculated for minimum, normal and maximum tap positions in the flitch plates as shown in Table V below.

Table V. Stray losses in the flitch plates

Mode	**Nel**	**Stray loss, kw**	
		MS Plate with slots at top & bottom	**MS Plate with slots throughout winding height**
Max. Tap	6	0.705	0.142
Nor. Tap	6	5.118	1.028
Min. Tap	6	3.824	0.773

The temperature profile of MS plate with slot at top & bottom and MS plate with slots throughout winding height is estimated by specifying heat transfer co-efficient and using 3-D FEM shows Fig. 6 and Fig 7 respectively.

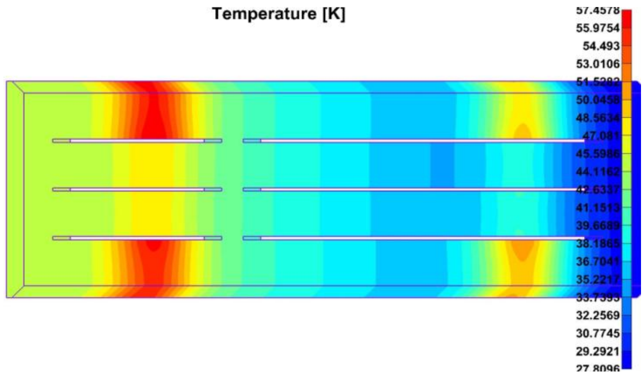

Fig. 6. Temperature profile of MS plates with slots
Slot at top & bottom.

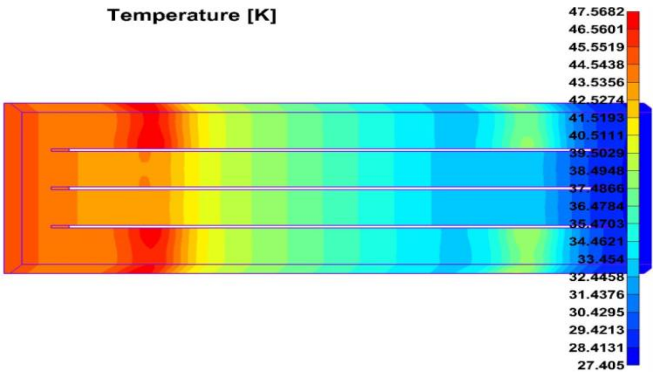

Fig. 7. Temperature profile of MS plates with throughout winding height.

D. Computation of stray loss in Frames

Frames, also called yoke beams, are made of mild steel material and are used for clamping of yokes and supporting the windings. The frames are modelled as epures coinciding with their physical locations for estimation of losses.

The temperature profile in the frames is estimated by specifying heat transfer co-efficient and using 3-D FEM shows Fig. 8 below.

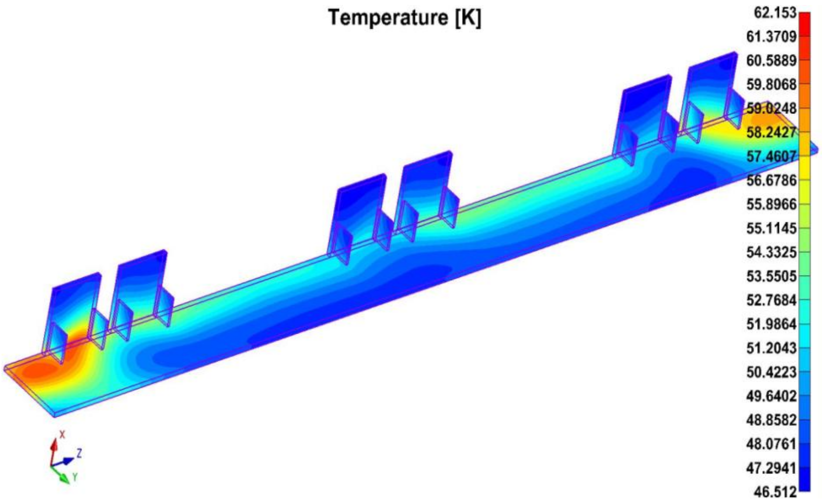

Fig. 8. Temperature profile in H.V Side Bottom Frame at Min. Tap Position

Based on the magnetic field density, the losses are calculated for minimum, normal and maximum tap positions in H.V Side top & bottom and L.V Side top & bottom frames as shown in Table VI below. Where, Nel is quantity of calculation elements.

Table VI. Stray losses in the frames

Mode	Nel	Stray loss, kw	
		Bottom	Top

Max. Tap	2	5.795	5.837
Nor. Tap	2	8.584	8.783
Min. Tap	2	7.259	7.369

V. TOTAL STRAY LOAD LOSSES

The stray losses in winding i.e. eddy losses are also measured as part of total stray losses during testing and are practically inseparable; hence same are calculated through SAPRTON software and added to the structural losses to get the total stray losses. The total stray losses in all structural parts and windings are computed at minimum normal and maximum tap positions and the details are as summarized in Table VII.

Table VII. Total stray load losses in overall transformer

Sr. No	**Component**	**Max. Tap (kW)**	**Nor. Tap (kW)**	**Min. Tap (kW)**
1	Edge Stack	4.376	4.136	3.226
2	Tank	16.54	26.91	24.5
3	Flitch Plates	0.142	1.028	0.773
4	Frames	11.632	17.367	14.628
5	Winding eddy	26.81	27.95	32.53
	Total Stray + Eddy losses	59.5	77.391	75.657

Distribution of component stray losses, calculated as percentage of the total stray load losses at maximum tap position is represented in Fig. 9.

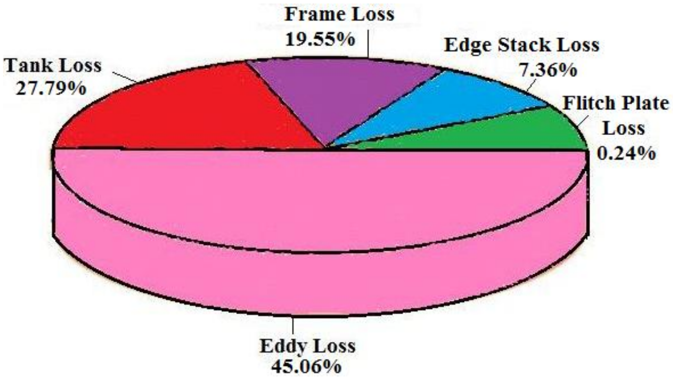

Fig. 9. Component stray losses as percentage of the total stray losses

The estimated values of stray losses are compared with the tested values to validate the above results.

VI. COMPARISON OF STRAY LOSS RESULTS

Comparison of the stray losses estimated by software program and the measured test results is shown in Table VIII below.

Table VIII. Comparison of total stray losses

Sr. No	Component	Max. Tap (kW)	Nor. Tap (kW)	Min. Tap (kW)
1.	Total Stray + Eddy losses (Tested)	59.98	75.36	73.76
2.	Total Stray + Eddy losses (by EDMAG)	59.5	77.391	75.657
	% deviation	0.80%	-2.63%	-2.51%

The reference tested values vis-à-vis the estimated values show a deviation of 0.80%, -2.63% & -2.51% at maximum normal and minimum tap positions respectively.

VII. CONCLUSIONS

A non-magnetic (stainless steel) flitch plate increases the core edge loss since it allows (due to its higher skin depth) the flux to penetrate through it to impinge on the laminations. Hence, although the use of non-magnetic flitch plate may reduce the loss in it, but the core edge loss is generally increased. and the stray loss can be reducing in flitch plate, if slot dimension provide in flitch plate. Also, the stray loss can be reducing in tank, if ferromagnetic materials used as shield in tank walls.

The predicted stray load losses compare to the tested results with 0.80 % at maximum tap, -2.63 % at normal tap, and -2.51 % at maximum tap position.

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