USE OF FEM FOR REDUCTION OF TRANSFORMER STRAY LOSS

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ABSTRACT:*The load loss in the transformer consist of losses due to the ohmic resistance of windings and certain additional losses. These additional losses are generally known as stray losses. The stray losses take place in the winding and metal parts surrounding the windings. These also take place in the metal parts around the leads. The stray losses are largely associated with the leakage flux and magnetic field surrounding the leads. The work is associated to the practical approach and FEM based analysis at manufacturing and Design stage respectively for stray loss calculation, measurement and respective reduction. Stray loss analysis is presented herewith in form of case study for 15 MVA, 25 MVA & 31.5 MVA transformers. We have used calibrated measurement instruments in all the experiments. Moreover, a 3-D finite-element analysis of the geometry of interest has been used to verify the leakage flux and metallic part interaction.*

Keywords: Transformer Design, Stray loss,FEM, Power Transformer

I. INTRODUCTION

Power transformer is most important and most costliest component of transmission network hence from early times, their design, manufacturing, Fault diagnosis and condition based monitoring have been a major concern and has been the subject of extended research.

In this paper the stray loss phenomenon in transformer, their cause and method of reduction are discussed in detail. Apart from conventional it is discussed with latest techniques like FEM 2D and 3D modeling and respective electromagnetic analysis.

II. TRANSFORMER DESIGN

Transformer design is a complex task in which engineers have to ensure that compatibility with the imposed specifications is met, while keeping manufacturing costs low.

Early efforts were based on conveniently adapted analytical solutions enabling one to optimize their construction and to take advantage of the improvements in magnetic and electric material properties for design and trial and error methods for design verification and condition monitoring.

During recent decades the development of the philosophy of transformer design has been a logical extension of the use of computers and numerical tools enabling one to model accurately the geometrical complexities as well as the nonlinear material characteristics for problem analysis. In addition, optimization algorithms have been very successfully combined with numerical techniques to represent the electromagnetic and thermal phenomena developed in power transformers, resulting in very powerful composite computational methodologies. In particular, artificial intelligence algorithms incorporated in such techniques have dramatically enhanced the speed and capability for achieving detailed optimum designs and assessment of transformer life.

It is only customized product. It designs and manufactures according to the customer's requirement. Transformer caters huge cost of power system .So its utmost responsibility of designer to design most efficient and reliable transformer at low cost, which is prime requirement both for manufacturer and utility.

The conventional design methodology is sufficient to design and manufacture the transformer but when the matter of reliability and long-term performance of transformer to be focused by designer, it will certainly ask for innovative ideas for critical characteristic like stray analysis, Hot spot detection, Impulse distribution, Short circuit. Withstand capability and many more. Further the Designing a reliable yet cost-effective transformer is a very challenging task. Needless to say, this requires a sound design philosophy supported by advanced design and analysis techniques.

The Finite Element Method (FEM) has emerged as the most popular numerical method for product design and analysis, and many commercial 2-D and 3-D FEM packages are available for the purpose. The available literature shows that, over the last two decades, a number of intricate problems in transformers have been resolved by the FEM analysis approach.

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III. STRAY LOSS IN TRANSFORMER

Stray loss is the byproduct of copper loss, which varies from 10% to 40% of total losses. Increase in % of stray loss compare to designed value, leads towards the hot-spot temperature increase in electrical as well as magnetic circuit in the transformer, and that is considered as a catalysts for transformer lifecycle declination.

Generally stray losses appear in all metal parts penetrated by magnetic leakage field produced by the windings or current loops. This means that there are many potential locations where stray losses may appear and the most important ones are those.

In winding conductors due to eddy-current (skin-effect), In winding parallel strands, due to circulating currents, In tank due to magnetic leakage flux from the windings, In tank cover around the high current bushings, In clamping plates of core due to winding leakage flux, in core sheets at the outer packages of the core limbs due to the winding leakage flux.

The load loss in the transformer consist of losses due to the ohmic resistance of windings and certain additional losses. These additional losses are generally known as stray losses. The stray losses take place in the winding and metal parts surrounding the windings. These also take place in the metal parts around the leads. The stray losses are largely associated with the leakage flux and magnetic field surrounding the leads.

Leakage flux dominantly affect the stray loss, leakage impedance and electromagnetic force under short circuit conditions. The leakage flux can some time lead to local overheating. Hence in large power transformer, the leakage is decisive factor in design of the transformer. For a transformer with a certain impedance ,some amount of leakage flux can be controlled and stray losses resulting out of the leakage flux can be considerably reduced, and local over heating can be controlled .decrease in stray loss will improve the efficiency , and will effect large saving in cooler ,oil steel costs.

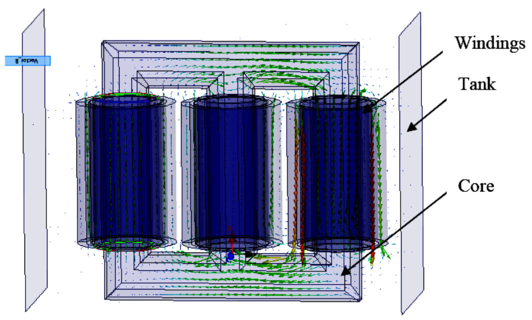


Figure: 1A 3-D Flux distribution during operation

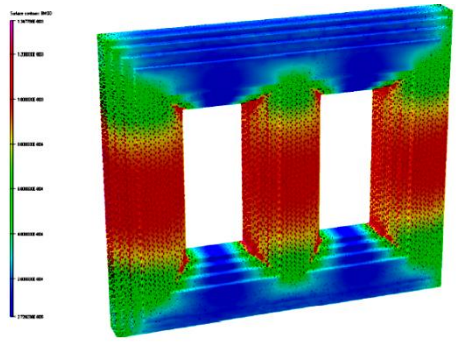
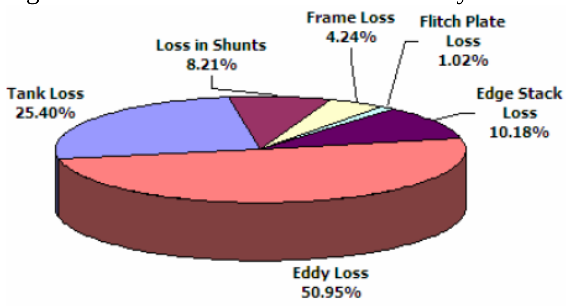


Figure: 2 Flux distribution in the core of a three phase three limb power transformer

Distribution of component stray losses, calculated as percentage of the total stray load losses

IV. LOSSES IN WINDING

The major portion of stray losses take place in the winding and is called eddy current losses. In large transformers, the turns in the winding consists of large numbers of conductors and if theyare not



Component stray losses as percentage of the total stray losses

Figure: 3 Component stray losses as percentage

suitably transposed can give rise to circulating currents within the parallel conductors. In such arrangement, unequal voltage are induced in different conductor due to varying leakage field .Unequal voltages in parallel strands gives rise to circulating current. The losses due to circulating current within few strands of conductor may not reflect much in overall losses but still can cause overheating of strands.

V. CASE STUDY

Transformer of 15 MVA 66/11 was designed for 65 Kw load loss. The I2R & stray losses were calculated 55 kW and 10 kW respectively. After manufacturing, the transformer was tested. The measured losses were 110 kW instead of 65 kW, which comprises 54.7 kWI2R loss and 55.3 stray loss. The load loss test value unexpected in which the stray losses value was most volatile. After investigation it was concluded that the transposition in LV winding was improper and that was initiating the circulating current for boosting the winding eddy current losses. The same was rectified and all winding were remanufactured and completed the entire transformer manufacturing process. Now the tested Load loss value was almost near to the design value i.e. 63.75 KW.

The above presented real case study indicates the vulnerability of wrong transposition in the winding.

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VI. LOSSES IN METALLIC PARTS DUE TO LEAKAGE FIELD

The leakage field cuts the various metallic parts namely tank wall, core clamping plates, flitch plates on limb etc. Whereas magnetic field cuts the metallic face eddy current are set up in the plate and give rise to additional losses and the losses in the region of high intensity of field can lead local overheating.

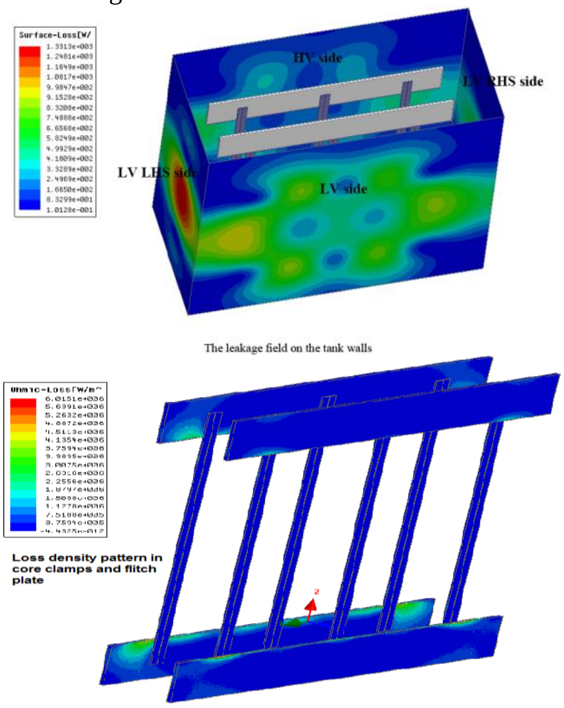

Figure: 4 Leakage field on tank walls

VII. CASE STUDY

Transformer of 25MVA 66/11 was designed for 120 kW load loss. The I^2R & stray losses were calculated 100 kW and 20 kW respectively. After manufacturing, the transformer was tested for 75% load current in open condition without tank. The measured Load losses were 117 kW (99 kW I2R + 18 kW Stray) .The same CCA was placed in its tank and again measures the Load losses and that t was 132 kW(99kW I2R+ 33 kW Stray).That means the excess 15 Kw stray losses due to tank wall and leakage flux interaction. In similar transformer the top and bottom yoke clamp were replaced from Mild steel material to laminated insulated perm wood. That again resulted in reduction of stray loss up to 4 kW. Further in similar transformer the flitch plate of core was change from Mild steel to stainless steel material. That also respond to further reduction of stray loss of 1 KW.

The above presented real case study with consecutive experiment indicates the phenomenon of stray loss in Metallic parts due to leakage field in the transformer.

VIII. LOSSES DUE TO CURRENT CARRYING LEADS

Leads carrying current, in duce magnetic field around the leads. The field if strong and in close vicinity of metallic parts produces eddy current losses. The interconnection used for making star delta connection in 3 phase transformer carries heavy current produces high flux intensities in the nearby tank surface and clamping structure. The effect of the current in the lead depends upon the magnitude of current, distance of lead from metallic parts and resistivity of material.

IX. METHODS OF STRAY LOSS REDUCTION

Stray losses in the transformer are reduced by taking several appropriate measures depending on the type and geometry of the transformer. Few among them are as following.

Use of small dimensioned conductors for windings, Use of CTC conductors in case of Higher current windings, Optimum transposition of the parallel strands, Magnetic shielding of the inner tank walls, Use of Non-Magnetic shield in the area of strong magnetic fields, Optimum selection of winding type, which can reduce the stray up to 50 to 60 % compare to conventional design.

A minimum losses design can be achieved by analyzing symmetrically the source of leakage flux, path of leakage flux and it's relation to the stray losses. Main leakage in the transformer will always exist and losses arising out of this can be reduced by various means. Stray loss due to leads can either be eliminated or reduced to great extent by properly running the leads or shielding the leads.

X. EDDY-STRAYLOSSES REDUCTION IN WINDING

Subdivision of conductors radially reduces the eddy current due to axial leakage field and subdivision of conductor axially reduces the eddy current loss due to the radial component of leakage field. Complete transposition of the conductors equalizes induced voltage in each strip and eliminates the circulating current. For high current windings, use of pre-transposed conductors would be ideal to minimize total eddy current losses. The reduction by CTC is about 75 % on large transformer.

In High voltage winding with moderate current requirement 2-3 conductors in parallel, bunched conductor can be used to improve winding spacefactor, and to improve radial subdivision of conductors.

XI. STRAY LOSS REDUCTION BY MAGNETIC SHIELDING ON TANK WALL

Transformer with large rated power and high stray fluxes have the side wall of the tank and some cases the covers provided with a screen to reduce eddy current losses in the tank wall and covers and pre vent Local overheating .For this purpose either magnetic shunt or electromagnetic screen are used.

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In the large power transformers the stray-field loss and the local loss density caused in the conducting parts are considerably increased with the capacity, which probably result in the hazardous local overheating and/or because the insulation material destroyed, consequently endanger the transformer running.

In the electromagnetic design of larger powertransformer, the stray-field loss must be controlled in an acceptable level for saving energy, as well as avoiding the un-allowed overheating. So the possible engineering strategies to cope with it have been adopted, such as the optimum material configuration and structures, and any possible shielding, etc. An example of the magnetic shields installed inside the oil-tank of a large power transformer is shown in Fig. The electromagnetic shielding is used to prevent the leakage magnetic flux into the conducting parts by the reaction of the eddy current field induced in the shields of high conductivity, which is also called electromagnetic screen; however the magnetic shielding makes the leakage magnetic flux changing the path into the shields of high permeability, named magnetic shunt.

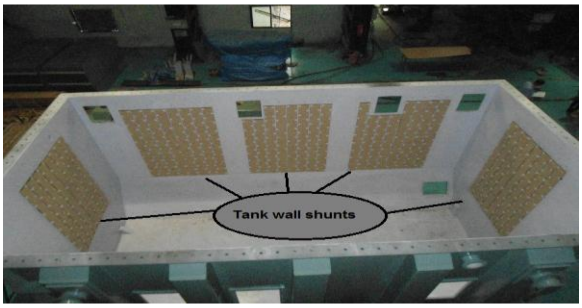

Figure: 5 Shunting on tank walls as per design change

XII. STRAY LOSS REDUCTION BY MAGNETIC YOKE SHEILD APPLICATION

Magnetic shield, made up of laminated core plates are used under the yoke providing a low reluctance return path. A large proportion of axial leakage flux is fed back in to the transformer yokes. The yoke clamp assembly is shielded and reduction of radial flux to tank side is also achieved depending on the pacing between shield & winding.

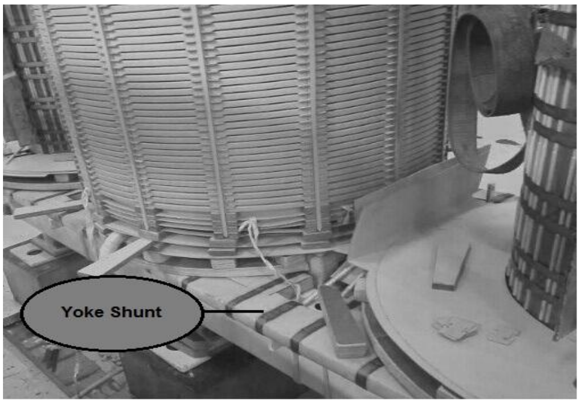

Figure: 6 Yoke shunting for stray reduction

XIII. STRAY LOSS REDUCTION BY FITCH PLATE MODIFICATION CONCEPT

The core limb plates are very near to the leakage field are and are subjectedto increase radial field and of winding. The losses in the Fitchplates are significant but the temp rise should be controlled. Severe heating of Fitch plates can take places in large transformer due to high intensity of radial flux. The reduction of losses in Fitch plates can be achieved by using Fitch plates of high resistivity material like SS or other material. Substantial reduction of losses & temperature rise can be achieved by provision of slots on the Fitchplates. This slots helps in subdividing the Fitch plate's width.

XIV. STRAY LOSS REDUCTION AT BUSHING MOUNTING PLATE ON TOP COVER OR SIDE WALL

Line lead from the winding are connected to the bushings mounted on the tank plates or tank cover. This area is prone to high eddy current and excessive heating. To reduce the losses and heating nonmagnetic steel inserts are welded in to the mounting plates at bushing locations. Sometimes mounting plates of Non-magnetic material like aluminum are used for high current bushings.

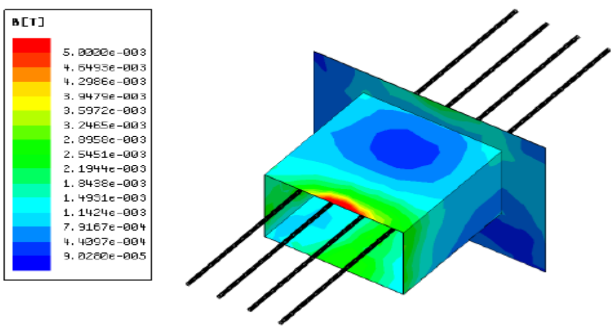

Figure — Magnetic flux density distribution in the LV throat (T).

Figure: 7 Magnetic flux density distribution in LV.

In Table-I it can be observed that there is a significant difference in total losses of a 4000 kVA transformer with and without throat, as total losses increase from 630 W to 1650 W, the comparison is made when both transformers have the SS plate in the tank wall where the LV bushings are mounted. Authors recommend the use of plastic throats to

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avoid the 1020 watts of losses in the low voltage throats of 4000 kVA transformers.

Table –I Total Losses with and Without CS throat for a 4000 KVA transformer

Simulation	Tank Wall Losses (W)	CS throat Losses (W)	SSP Losses (W)	Total Loss(W)
Without LV Throat	580	---	50	630
With LV Throat	415	1175	70	1650

XV. STRAY LOSSES DUE TO THE CORE CLAMPS OF A TRANSFORMER AND METHOD FOR REDUCTION

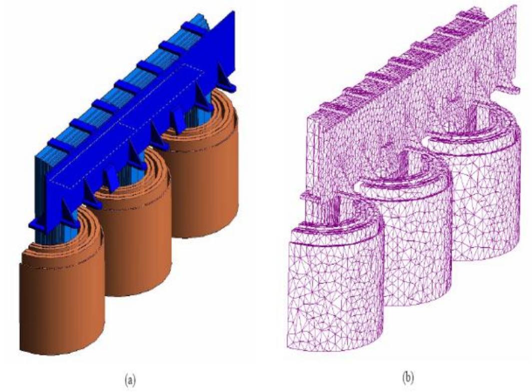

Figure: 83-D finite-element model of the transformer (a) solid model. (b) Meshed model

XVI. LOSS CALCULATION

The losses have been calculated for the case of reduced voltage short circuit test with rated current flowing in 31.5 MVA 110/33 kV transformer. There are 698 turns at high-voltage (HV) side which corresponds to the tap position for rated voltage and 146 turns at low voltage (LV) side. The current at HV side is 165 A and at LV side is 551 A. For all parts of the clamps the material of constant relative permeability μr and constant electric conductivity σ is used. The permeability and conductivity are slightly varied and the results areshown in Table I. The distribution of losses on the front (away from the core) and the back (closer to the core) sides of the core clamps is shown in Fig. (a) From Table I it is present that slight variations of relative permeability and conductivity do not seriously affect the calculated losses.

Table: 1 Clamp Losses as a function of iron permeability and conductivity

Material properties	P_{loss} (W)
$\mu_r = 300, \sigma = 5 \cdot 10^6$ S/m	3233.2
$\mu_r = 500, \sigma = 5 \cdot 10^6$ S/m	3232.8
$\mu_r = 700, \sigma = 5 \cdot 10^6$ S/m	3198.8
$\mu_r = 300, \sigma = 6 \cdot 10^6$ S/m	3218.8
$\mu_r = 500, \sigma = 6 \cdot 10^6$ S/m	3239.6
$\mu_r = 700, \sigma = 6 \cdot 10^6$ S/m	3220.4
$\mu_r = 700, \sigma = 8 \cdot 10^6$ S/m	3238.8

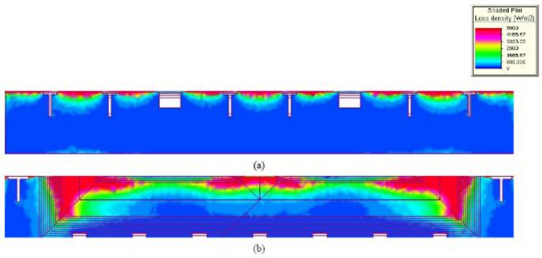

Figure: 9 Distribution of losses on the surface of the core clamps (a) front side (b) back side

The losses in the clamps can be reduced by usingdifferent materials and by changing the clamp dimensions. Fig. shows an example of using a narrower clamp whose width has been reduced so that its edge coincides with the narrowest core lamination step.

		Material properties	P_{loss} (W)
Core clamps with reduced width of the plate by 38 %		μ_r=500, σ=5·10^6 S/m	2101.6
Twice shorter winding clamps		μ_r=500, σ=5·10^6 S/m	2492.8
Iron core clamps with regular size winding clamps made of chrome alloy	Core clamp	μ_r=500, σ=5·10^6 S/m	1762.8
	Winding clamp	μ_r=1, σ=1.4·10^6 S/m	86.8
		Σ	1849.6

Figure: 10 Cross-section of the transformer core and core clamp with reduced width

Table: 2 Losses in the clamps with modified dimensions and material properties

XVII. CONCLUSION

Use of small dimensioned conductors for windings, Use of CTC conductors in case of Higher current windings, Optimum transposition of the parallel strands, Magnetic shielding of the inner tank walls, Use of Non-Magnetic shield in the area of strong magnetic fields, Optimum selection of winding type, which can reduce the stray up to 50 to 60 % compare to conventional design.

These all are the practical constraint to be considered while designing the transformer. But the analytical tools like ANSYS, FEM and COMSOL

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has made revolution in the transformer engineering as they are producing most efficient analysis of electromagnetic ,thermal and insulation characteristics. Especially the FEM based analysis of electromagnet characteristic helps a lot to predict and resolve the stray loss phenomenon in large power transformer at design stage instead of manufacturing stage. Plenty of work done in this stray loss reduction field but still there is wide scope for reduction of stray losses as even today they are in the range of 15 to 30 % of Load loss.

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