Stray Loss Evaluation in Power Transformers – A Review

S. V. Kulkarni, Member, IEEE
Transformer Division
Crompton Greaves Ltd., Mumbai, India
svk@tone cgl co.in

S. A. Khaparde, Senior Member, IEEE
Indian Institute of Technology
Mumbai, India
eesakia@ee.iitb.ernet in

Abstract Survey of current research papers reveals the continued interest in application of advanced techniques for accurate estimation and control of stray loss in transformers. This paper gives an overview of research, development and application of various computational tools for stray loss analysis, based on over 50 published papers. All landmark papers are systematically classified. Practicality of application of methods by transformer designers is discussed The report concludes with critical comments on efficacy of all approaches and directions for pursuing further research.

I. INTRODUCTION

Last couple of decades have seen advent of research orientation towards application of advanced computational methods to estimate and control stray losses. Stray load loss in large ratings of generator transformers and auto-transformers can be appreciably high. Challenge for designer today is higher loss capitalization, optimum performance, and low cost, space and weight requirements; for which he needs advanced analysis tools that provide synergistic effect leading to optimum designs and product performance improvements. The paper contains a review of about 50 papers, which have dealt with one or more components of stray loss from the point of view of estimation and reduction. Stray losses include eddy and circulating current loss in windings, losses in flitch plate, core edge loss, loss due to high current field, and frame and tank losses. The paper has compared, for each stray loss component, pros and cons of various methods of estimation, and these methods are reviewed in today's context, where state-of-the-art analysis softwares are available. Control measures for each stray loss component are discussed.

II. STRAY LOSS COMPONENTS

References on basic eddy current theory [1-3], since 1950s have tried to make eddy current analysis understandable and practically applicable for solving complex engineering problems, and even in 1990s such papers give basic foundation to eddy current researcher for analysis of various stray losses components mentioned below.

A. Winding Eddy Loss

Two-dimensional Finite Element Method (2-D FEM) is most commonly used to compute eddy loss due to axial and radial leakage fields [4]. The knowledge of flux density distribution in the winding helps in choosing proper axial and radial dimensions of conductors. This is particularly very important for winding having tapings within the main body where high radial component of flux density can cause excessive loss and temperature rise. In large generator transformers, low voltage winding may be designed with Continuously Transposed Cable (CTC) with lower axial and radial dimensions of individual strip, to minimize the eddy loss. Eddy loss in individual turn/disc needs to be exactly estimated to calculate hottest spot in the transformer, which is generally at the top of the windings. In case of small distribution transformers with crossmatic LV winding (copper flat conductor), each turn has to be modeled in FEM, as the thickness of flat is comparable to or sometimes more than depth of penetration, in which case modification of leakage field due to eddy currents cannot be neglected. In case of foil windings, radial leakage field will cause higher eddy losses at the ends of the winding. Mullineux et al. [5] obtain current density as the solution of integral equation (Fredholm type) for a two winding transformer. For specific transformer dimensions given in paper, the coefficient of additional loss is 1.046. Turowski's method [6] assumes the foil winding as a vertical section of an infinitely wide and deep conducting plate, which is assumed symmetrically penetrated on both sides by plane electromagnetic waves. Today, 2-D FEM can easily analyze the foil winding eddy losses without any simplifications. The analysis of winding eddy loss by 3-D FEM analysis will be more accurate than 2-D methods, but the complexity in calculations increases manifold.

B. Circulating Current Loss in Windings

In transformers, loss due to circulating currents in parallel strands, due to unequal linkage of leakage field, can be reduced to a negligibly small value by continuous transposition (like in CTC) or by employing number of transpositions at pre-determined intervals along the winding height. Kaul [7] has given analytical method for calculation of circulating current loss in stranded winding with standard transposition schemes. The radial field at winding ends is not considered in the calculation, which can be easily taken into account by 2-D FEM as given in [8]. This paper has compared currents and loss calculated by analytical formulation (based on multi-winding network formulation) and 2-D FEM. The analytical formulation can be used for any transposition scheme; reactance and resistance of parallel strands are calculated separately depending on the positions they take along the winding height, and these are then placed in a network scheme. Recently a detailed 2-D FEM analysis has been reported [9], in which analysis of layer and disc winding has been done for various transpositions cases for strip as well as bunch conductors. The circulating current loss is also being calculated even more accurately by 3-D FEM [10], but the efforts involved for simulations may not be justified for the inappreciable increase in accuracy.

C. Flitch Plate and Core Edge Loss

Stray flux departing radially through the inner surface of winding hits the core and fittings such as the flitch plate mounted on the core. Although the losses occurring in flitch plate may not form a significant part of total losses of a 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. Literature available on flitch plate loss analysis is quite scarce. Eddy-current losses arising in metallic parts of rectangular cross-section are calculated by an analytical method, which is based on certain approximations [11]. 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 analytical formulation cannot analyze flitch plate with slots of limited length provided in radial flux zone. These limitations of the analytical formulation can be overcome in FEM analysis [12]. 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 paper also presents results of 3-D FEM simulations carried on slotted and laminated flitch plates. Performances of mild steel and stainless steel flitch plates are compared by a detailed examination of eddy current patterns. 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. Simulation of laminated flitch plate proved that the loss in laminated case is much lower as compared to stainless steel plate. Hence for higher 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. Analysis has been verified by measurement of temperature of flitch plate on a transformer.

In large transformers, penetration of leakage flux into the cores, in a direction at right angles to plane of lamination, causes eddy currents and local hot spots. Methods of slitting the first step or shielding (laminated flitch plate) are adopted to reduce this core edge loss. Leakage flux penetration into laminated core poses an anisotropic and three-dimensional non-linear field problem. Carpenter [13] has solved the problem by formulating differential equations in terms of an electric vector potential T and magnetic scalar potential Ω. Solution is expressed in the form of three different characteristic modes in a network model, two associated with the core surfaces and the third describing the flux penetration into the interior. However, the method is not so general, since the network is rigid and has to be modified for any change in geometry. Formulation in the paper was verified on two experimental models of core [14,15]. Advance of 3-D FEM with features of anisotropic modeling (of permeability and conductivity) may help to overcome the difficulties for accurate calculations.

D. Stray Loss due to High Currents

Poritsky et al. [16] discuss a method to evaluate eddy losses in a semi-infinite solid nearby a filament current. Practical cases, however, involve plates of finite thickness and hence a modification of the solution is required. Deuring [17] has presented an empirical formula for eddy loss calculation in steel plates based on an experiment. Jain et al. [18] evaluated field pattern and eddy current losses in aluminium sheet due to current carrying strip bus bars. Current distribution is expressed as made of an infinite number of sinusoidal distributions with the help of Fourier integral, and then the field due to any current distribution is obtained by superimposition of fields due to sinusoidal components. Various curves for loss are given, which are of practical use. Experimental analysis of eddy current phenomenon in structure that surrounds the high current bushings of large capacity transformers is presented in [19,20]. Means to prevent overheating are also presented. Eddy current pattern has been explained for various configurations of terminations in [19]. The 2-D formulation, used to estimate the eddy current patterns, is based on some approximations and experimental data. Krakowski et al. [21] have presented a method for analyzing the electromagnetic field in a system that comprises of parallel current carrying bars placed above a steel wall. The current density within the cross-section of bars is computed using the integral equation technique. Thus it can be seen that most of the papers published from 1970s have concentrated on analytical methods, which due to some assumptions and approximations, are useful to only simplified 2-D geometries and cannot be applied to complex 3-D structures. With improvements in 3-D FEM software capabilities, now such complicated structures can be easily simulated and analyzed. Analysis of eddy current pattern, in a complex three-dimensional model of furnace transformer LV lead termination, is reported in [22]. Total eddy loss estimated is found to be in close agreement with that observed during testing of the transformer.

E Frame Loss

Frames (yoke beams), serving to clamp the yoke and support the windings, are in a vicinity of stray magnetic field of windings. Due to large surface area and efficient cooling, hot-spots seldom develop. Losses in frames have been calculated by Finite Difference Method (FDM) and analytically, and loss in frames made up of mild steel, aluminium and non-magnetic steel are compared in [23]. Loss in frames can also be calculated efficiently by 3-D Reluctance Network Method (RNM) [24], but may not be as accurately as that by FEM [25]. The loss in frames can be reduced by either aluminium shielding or by use of non-metallic platforms for supporting the windings.

F. Tank Loss

Valkovic has [26] presented an analytical method in which current sheet, a sum of trigonometric functions in between core and tank (two half spaces), represents mmf of winding. The method can only be applied for a particular tank shape and effect of shields on tank wall may not be easily estimated. Szabados et al. [27] have formulated analytical approach, which requires the knowledge of incident flux density on tank wall obtained by any other method. The incident flux density is expressed in terms of double Fourier series. Since 1960s, the research reported for calculation of tank loss has been mainly concentrating on various analytical methods involving complex mathematics, which are mostly based on approximation of 3-phase transformer geometry. Turowski's 3-D Reluctance Network Method [28] fulfills designers' requirements of quick estimation of tank loss. Reluctances for conductive tank parts are calculated analytically by taking into account the skin effect, eddy current reactions with phase shift, non-linear permeability inside solid metals and effect of eddy current shield. The designer can define locations of magnetic and / or eddy-current shield on the tank wall. The RNM-3D approach for tank loss estimation has been verified [29] on various ratings of power transformers.

Karsai et al. [11] have almost analyzed all the above mentioned stray loss components. In addition to describing 2-D and 3-D analytical methods for loss calculation, practical guidelines are given for reducing losses due to leakage and high-current fields. Performances of various shielding arrangements are compared. Turowski [24] has also covered number of topics useful to practicing transformer engineers, and useful formulae, thumb-rules, curves are given to take quick and reasonably accurate decisions in the area of stray loss estimation and control.

III. GENERAL OVERVIEW OF METHODS

Krawczyk et al. [30] have presented an overview of methods for eddy current analysis. The paper compares methods based on differential formulation (analytical, FDM, RNM), integral formulation (volume integral, boundary element method) and variational methods (weighted residual, FEM) on attributes such as accuracy, ease of use, practicality and flexibility. For estimation of stray losses in transformers, the methods can be broadly classified into three categories, as they progressed from 2-D analytical methods to 3-D FEM, as given below.

A. Two-dimensional Methods

Boyajian [31] has given a method for estimating leakage field, in which any kind of current density distribution can be resolved into space harmonics by a double Fourier series. The method is very useful, mathematically less complex and can be used for calculation of eddy loss and circulating current loss in windings. Sato et al. [32] have presented analogy between magnetic field equations for two-dimensional cartesian and axi-symmetric problems, and usefulness of this analogy for numerical calculation has been mentioned. Komulainen and Nordman [33] have used 2-D FEM to get static magnetic field solution, and losses in tank are calculated by analytical formulae. The paper contains test results of tank loss with magnetic and eddy-current shielding. Geometric parameters affecting tank loss are explained through graphs. Pavlik et al. [25] have emphasized the need of analyzing the eddy and stray losses as a complete system and not on an individual component basis. The authors have done a number of 2-D FEM simulations to understand the effect of magnetic/eddy-current shields, placed to cover tank wall, on the other stray loss components (winding, flitch plate, frame and core edge losses). Effect of change in permeability of magnetic shunts on the tank loss has been analyzed. It can be concluded that even in this era of 3-D calculations, two-dimensional methods are preferred for routine calculations of stray losses.

B. Three-dimensional Formulations

Sironi, et al. [34] have formulated quasi 3-D method in which axi-symmetric leakage flux of the transformer in the absence of tank wall is superposed with that of the images reflected in the magnetic surface. El Nahas et al. [35] developed a method to calculate 3-D magnetic flux density on tank wall using a 2-D solution for one phase of a 3-phase transformer. These analytical methods may not be easily applied to complicated tank shapes and for finding the effect of magnetic/eddy-current shielding on tank, which now can be comfortably done by 3-D FEM.

C. Three-dimensional FEM Analysis

Haack and Girgis [36] have verified 3-D FEM calculations of flux densities along the height and breadth of the windings on experimental shell type transformer. Subsequently, Girgis et al. [37] have assessed the need and estimated the benefits of using 3-D magnetic field calculations, particularly for eddy and circulating current losses in windings. Dexin et al. [38] have presented three-dimensional FEM analysis of eddy current problems using the complex magnetic vector potential. Eddy current losses in steel materials are computed by combining numerical method with analytical formulation because of problem of discretisation due to very thin skin depth of about 1 mm. A power transformer has dimensions in few meters, whereas skin depths are in millimeters resulting into errors due to poor aspect ratio of elements. Holland et al. [39] have outlined the method of modeling tank wall and other fittings with surface elements removing the need of complex layers of brick elements to account for skin effects and this, in turn, reduces the complexity and size of models. Many commercial 3-D FEM softwares now have the feature of this surface impedance element modeling, and thus permit designers to calculate tank losses efficiently and accurately. The 3-D FEM analysis, which started gaining importance in 1980s, is being constantly upgraded to improve its modeling capabilities and accuracy for eddy current analysis.

IV. STRAY LOSS CONTROL

Measures for stray loss control are discussed with reference to large power transformers in [40-42]. Methods of reducing the loss in various structural components due to high current and leakage field are described in brief in [40]. Curves are given for calculation of tank loss with and without shielding in [41]. Kozlowski and Turowski [43] have given formula for calculating the limiting value of conductor width to avoid hot spots in windings. Now by tools such as FEM, it is easily possible to optimize the total winding losses (I^2R and eddy losses) by, for example, using different conductor width and thickness at the winding ends. The paper has also given permissible values of tangential components of magnetic field strength on various constructional elements to eliminate local overheating. Principles for selection of the type and thickness of tank shields are presented, and the shielding efficiency is discussed. Kazmierski et al. [44] have given guidelines and useful curves for preventing overheating hazard due to stray field in various components such as windings, first step of core, flitch plate, frames and tank. Bose et al. [45] have given experimental results of a 37 MVA transformer with various proportions of tank shielding by magnetic shunts. The effect of positioning inter-phase connections of high current carrying leads of generator transformer on the tank loss has been explained with experimental verification.

A. Magnetic Shielding

Inui et al. [46] have evaluated effect of tank and tank shields on stray loss in the windings by detailed measurements on a 150 MVA transformer. D'jurovic and Carpenter [47] have studied the effects of a horizontal shunt assuming that the shunt is connected directly to the yoke. The work is extended in [48-49] to study the effect of a small gap between shunt and yoke on leakage field distribution. It has been emphasized that the gap between shunt and yoke must be kept reasonably small for effective control of leakage flux. Laminated iron is treated as solid anisotropic block. The parameters of such a block include the directional effects of both the material anisotropy and lamination stacking factor [50]. The papers [47-49] give useful practical guidelines for designing of horizontal magnetic shunts. Bereza [51] has compared effectiveness of flat and edge-wise magnetic shunts by finding their effective anisotropic permeability. Merits and de-merits of magnetic and eddy-current shielding are explained in [52]. Loss measured under various combinations of shielding (yoke shunts, flux collectors and flux diverters) are reported, which is of practical significance.

B. Eddy Current Shielding

Mullineux, et al. [53] have given analytical formulation wherein the windings are replaced by infinite array of line currents by using the theory of images. The flux carried by tank, which is shielded by aluminium shield, is calculated by assuming infinite permeability. Eddy current loss in non-magnetic shields of air core reactors is evaluated by image method using Fourier - Bessel integral in [54]; 2-D approximations and end effects make the formulation less accurate. With developments in FEM, it is now easy to assess the effect of such eddy current shields on tank loss performance even for 3-D complex structures. Eddy current shields are generally used in case of odd tank shapes, where magnetic shunts can not be used. This is because, there is extra loss in the eddy current shield itself, and the diverted flux from the shield may cause overheating in the nearby structural part, if not studied properly.

V. CONCLUSIONS

In today's competitive environment, accurate estimation and subsequent optimization of stray loss by advanced techniques such as FEM will give a competitive advantage. The paper has analyzed all the components that constitute the stray loss in a transformer from the point of view of methods of estimation, control and elimination of hot-spots. For computing and controlling stray loss components in windings, viz. eddy and circulating current loss, 2-D methods, analytical or FEM, have been successfully applied; efforts required for 3-D analysis may be justified only for large power transformers where improvement in accuracy will be appreciable.

Accurate analysis of loss in various types of flitch plates (mild steel, stainless steel and laminated) can be done by 3-D FEM; analytical formulation is less accurate due to many approximations. Although core edge loss can be easily controlled, problem of evaluation of exact stray loss in core due to leakage field is quite complicated. The advance of 3-D FEM with features of anisotropic modeling may help to overcome the difficulties in calculations.

Estimation of loss due to field of high currents has progressed from analytical methods to 2-D FEM for simple geometries, and then finally to 3-D FEM for complex geometry like that of LV terminations of large furnace or generator transformers.

Frame losses can be calculated with reasonable accuracy by 2-D FEM. Tank loss estimation, which again poses a real 3-D asymmetric problem, has graduated from 2-D/3-D analytical, RNM to FEM formulations. Use of user-friendly 3-D FEM software, on high speed and memory computers, with features such as surface impedance elements, will help overcome computational difficulties, although tank loss reduction by magnetic/eddy current shielding has been successfully practiced by transformer manufacturers.

Survey of papers reveals that judicious choice of method of estimation of various stray loss components has to be made by a transformer designer, for which sufficient indications are given in this paper.

VI. ACKNOWLEDGEMENT

The authors are thankful to the management of Crompton Greaves Ltd., India, for permitting publication of the paper.

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VIII. BIOGRAPHIES

S.V. Kulkarni (M' 1999) was born at Dombivli of Maharashtra state in India in 1967. He received his B.E. in 1988 and M.Tech in 1990 from Indian Institute of Technology (IIT), Mumbai in Electrical Engineering. He is working as Deputy Chief Design Engineer at Transformer Division, Crompton Graves Ltd. He has several publications to his credit and his research interests include optimization and reliability improvement of EHV Transformers and Reactors. He is currently pursuing his Ph.D. degree in Electrical Engineering at IIT Mumbai.

S.A. Khaparde (M' 1987, SM' 1991) was born at Amravati of Maharashtra state in India, received his B.E. in 1971, M.Tech. in 1973 and Ph.D. in 1980 from Indian Institute of Technology, Kharagpur. He is currently professor of electrical engineering at IIT Mumbai. He has several publications to his credit and his research interests include pattern recognition, power system security, Artificial Intelligence and applications, parallel processing and neural networks. He is senior member of IEEE and International Neural Network society.