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Computation of Power Transformer Reactance using Finite Element Method

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Abstract: ***The reactance of the transformer windings is an important component for the design which has a direct effect on its operation. Reactance is used for computation of not only the transformer equivalent circuit parameters and also for designing its protection. The Roth's method, Rabin method, method of images, and classical methods are the traditional methods used for its calculation. The finite element method can be used for the calculation of transformer reactance. In the industrial revolution 4.0 all manufactured transformers would be evaluated through their 3D design and performance analyzed by computational methods. In this work the reactance calculated by the finite element method has been compared to that calculated by the classical method. The calculated values of energy stored in the windings and other parts and the reactance can be found.***

Keywords: ***Finite Element Method, Leakage Reactance, Transformer, Windings***

I. INTRODUCTION

The leakage impedance of a transformer comprises of resistive and reactive components is one of the most significant details that have a substantial impact on the overall design. The reactance of a transformer is an important specification. While designing a transformer different method namely; Roth's method, Rabin's method, method of images, and classical methods are used. These methods are assumption based and have considered simple configuration. The finite element method (FEM), a computational method can be used to calculate the of transformer winding reactance. The FEM is also known as the coupled field method, is the most ideal mathematical technique because of its geometric complexity, for handling nonlinearity. This method can easily solve the problems that involve the coupling of electromagnetic fields. The method can be used to calculate the self-inductance and mutual-inductance between turns and winding sections, dielectric stresses in insulation. 3D finite element analysis simulation is used to geometry model [1], stray losses [2] and electromagnetic forces [3]. To calculate the parasitic capacitance of secondary winding [4], the forces in the winding during inter turn short circuit faults [5], FEM is used.

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II. LEAKAGE REACTANCE

The leakage reactance in a transformer is because all the flux does not confine inside the core. In the transformer, both the primary winding and the secondary winding overlap the structure of the core and net magnetic flux is produced by these windings. An ideal transformer all the flux in the core links both the primary winding and the secondary winding. In a practical transformer, not all the flux produced by the one winding links the other winding. The difference between the total flux linking with the primary and the useful mutual flux linking both the windings is called the primary leakage flux. Similarly, there exists a secondary leakage flux. With each cycle of the power supply, energy is alternately stored and discharged in the magnetic field. The leakage flux is represented by reactance of the primary and secondary. The primary winding reactance can be transferred to the secondary side and vice-versa, using the turn-ratio. Practically, the reactance of a transformer is found by performing the short-circuit test on the low voltage side. The leakage reactance in theory is calculated by classical methods. Work has been carried out for computation reactance using classical methods to improve the design [6].

III. APPROACHS FOR LEAKAGE REACTANCE CALCULATION

The method used for the calculation of the leakage flux that is represented as of the windings of a transformer are; Roth's method, Rabin's method, method of images, and classical methods.

A. Rabin's Method

In this method, we assumed that current density (J)depends on the axial position. This method uses single Fourier series. The magnetic vector potential A, is given by the expression:

$$\nabla^2 A = -\mu J \qquad (1)$$

Rabin's method is more suitable to solve the Poisson's equation using cylindrical coordinates. The equation in cylindrical coordinates is:

$$\frac{\partial^2 A_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial A_\theta}{\partial r} - \frac{A\theta}{r^2} + \frac{\partial^2 A\theta}{\partial z^2} = -\mu J_\theta \qquad (2)$$

B. Roth's Method

This method is used for calculating the leakage reactance of windings that have asymmetrical arrangement. The method is based on a doubled Fourier series, and is relevant to both uniform and non-uniform distributions of mmf of windings.
The dimension of the core region over which the windings are placed is taken as π radians, along both the width and length. The ampere-turn density and flux distribution are considered to be involving components that differ harmonically along the radial axis (x-axis) and axial axis (y-axis). A dimension for the depth (in z-direction) is taken as unity. To get the total volt-ampere the corresponding mean perimeter is multiplied to it. The reactive volt-amperes are used to calculate the current harmonics. For the double Fourier series, the number of space harmonics should be equal to 20 for the low voltage winding, while in case of high voltage windings the ampere-turns are symmetrically distributed. As the number of the space harmonics is increased, the variation of flux density decreases, thus demonstrating better accuracy.

C. Method of Images

The method of images used the coordinate system. In this method, the winding is supposed to be of finite dimensions and represented by straight coils. All coils that represent the winding, must give a similar value of the leakage flux along the line that aligns with the geometry of the windings. The windings are surrounded by the iron edge. The value of the leakage flux is found by using the magnetic field due to it at any point. The Biot-savart's law is applied for the current distribution.

D. Classical Method

The classical method is used to analysis the problems that are usually time and task limited. In this method, the transformer windings are represented by straight coils to calculate the leakage field, which has an axial and a radial component many attempts were made to devise accurate methods. [7].

IV. REACTANCE CALCULATION BY CLASSICAL METHOD

For the three-dimensional analysis, there is difference in the transformer structure in the core-window cross-section and the cross-section perpendicular to the window, as a result of which the leakage fields in these sections differ. The accuracy in the 3-D calculations may not be required as tolerance for the values of reactance of a transformer are in the range of ± 7.5 % to ±10%. The winding height (H_w) is divided by Rogowski factor (K_R) to get the equivalent height (H_{eq}).
The leakage magnetomotive force (mmf) at any point depends on the ampere-turns bounded by the flux there. The value of mmf is constant since the contour of flux at any point encloses the ampere-turns of that winding. It is assumed that the magnetic properties of the core are ideal, hence mmf is not consumed in the path from where of the flux returns. For a closed contour of the flux, at a distance x from the inner diameter of the low voltage (LV) winding can be written as

$$\left(\frac{Bx}{u_0}\right) H_{eq} = (NI)x \qquad (3)$$

The flux at distance x is

$$B_x = \frac{u_0(NI)x}{H_{eq}} \qquad (4)$$

In the general expression, of the flux leakage the radial depth and equivalent height are considered of a tube of flux. The inner diameter (ID), and outer diameter (OD) of the ampere-turns enclosed by a flux contour. For the rated ampere-turns (NI) the flux density is:

$$B_x = \frac{u_0}{Heq}\left[\left(a + \frac{b-a}{R}x\right)NI\right] \qquad (5)$$

where a is inside diameter of flux tube and b is outside diameter of flux tube.
The flux linkages (ψ) of an incremental flux tube of the width dx placed at x are:

$$d\psi = N_x\phi x = N_x B_x A \qquad (6)$$

area of flux tube (A) is given by:

$$A = \Pi(ID + 2x)\,dx \qquad (7)$$

Using the value of B_x and A in equation 4, we get

$$d\psi = \left\{\left(a + \frac{b-a}{R}x\right)N\right\}\left\{\frac{u_0}{Heq}\left[\left(a + \frac{b-a}{R}x\right)NI\right]\right\}[\Pi(ID + 2x)\,dx] \qquad (8)$$

the total flux linkage is given by:

$$\psi = \int_0^R d\psi = \frac{u_0\Pi N^2 I}{Heq}\int_0^R \left(a + \frac{b-a}{R}x\right)^2 (ID + 2x)\,dx \quad (9)$$

Solving by integration and arithmetic operation, the expression is

$$\psi = \frac{u_0\Pi N^2 I}{Heq}\frac{R}{3}\left[(a^2 + ab + b^2)ID + \frac{(a^2+ab+b^2)3R}{2} - \frac{2a^2+ab}{2}R\right] \qquad (10)$$

For regular design, the square bracket term can be neglected

$$\psi = \frac{u_0\Pi N^2 I}{H_eq}\frac{R}{3}(a^2 + ab + b^2)\left[ID + \frac{3R}{2}\right] \quad (11)$$

The mean diameter of the flux tube is in the last term of the square bracket.

$$\psi = \frac{u_0\Pi N^2 I}{Heq}\frac{R}{3}(a^2 + ab + b^2)D_m \quad (12)$$

Now, the ampere turns distribution (ATD) is

$$ATD = \frac{R}{3}(a^2 + ab + b^2)v \quad (13)$$

For a transformer having n flux tubes, the leakage/equivalent reactance X is:

$$X = 2\Pi f \frac{u_0\Pi N^2}{H_eq}\sum_{k=1}^{n} ATD \qquad (14)$$

The percentage of leakage reactance is:

$$\%x = 2\Pi f \frac{u_0\Pi(NI)}{H_{eq}(v|N)}\sum_{k=1}^{n} ATD \times 100 \quad (15)$$

Substituting and adjusting the constant to change the dimensions in cm in the formula, the equation is

$$\%x = 2\cdot 48 \times 10^{-5} f \frac{(Ampere\ Turns)}{H_{eq}(Volts/Turn)}\sum_{k=1}^{n} ATD \qquad (16)$$

If D_1, D_2 and D_g are the mean diameter of LV winding, HV winding and gap between them. $T_1$and T_2 are the radial depth of LV and HV winding respectively, T_g is gap between them, then

$$\sum ATD = \frac{1}{3}(T_1 \times D_1) + (T_g \times D_g) + \frac{1}{3}(T_2 \times D_2) \quad (17)$$

The value of Rogowski factor K_R is

$$K_R = 1 - \frac{1-e^{-\Pi Hw/(T_1+Tg+T_2)}}{\Pi Hw/(T_1+Tg+T_2)} \quad (18)$$

V. NUMERICAL FIELD SOLUTION METHOD

Thermal electrical fields can be solved by finite difference method, boundary element method and finite element method.

A.Finite Difference Method

Finite difference methods are used to solve the differential equations and convert linear ordinary differential equations into a system by approximating them. FDM is complicated to handle the problems. It makes a difference between the exact analytical solution and approximation. It makes pointwise to leading the equation. FDM makes continuity at node points and not ensure continuity along the sides of grid lines. It makes step type approximation to sloping and curved the boundaries. FDM cannot handle complicated problems and takes a large number of nodes to get good result (8).

B.Boundary Element Method

The Boundary element method (BEM) is used to solve the partial differential equation. BEM is more efficient and reliable for modelling thin shells and numerical solutions. This method helps to give boundary conditions to fit the boundary values. BEM is of two types, direct and indirect boundary element method. The direct boundary element method requires a closed boundary and indirect boundary element method considers both sides of the surface.

C.Finite Element Method

The finite element method is a numerical method used to calculate the problems in engineering, linear, non-linear and mathematical models. FEM has an accurate and easy representation of complex geometry and total solution. The FEM is used to solve the partial differential equation or integral equation by subdividing the system into smaller sections. The partial differential equation can categorize as hyperbolic and parabolic. Boundary and initial conditions need to be provided to solve the differential equation. It uses the mesh generation technique to divide the element into smaller sections to solve a complex problem. The sub-division or sub-domain simply called the nodes or grid points and these are assigned to each element. The subdivision of the domain makes exact representation to solve the complex geometry. FEM simulation provide valuable resources to remove the multiple occurrence and reliability situation. This method allows the detailed visualization of twist or bend structure and provide the simulation to control the complexity of modelling. FEM used or analyse the problems, smooth solution and changes in domain. The finite element method formulates the boundary value to find the algebraic equations by estimated the unknown function over the domain. It breaks a complex problem into simpler and use mathematical terms to solve the problem. In analysis the problems 2D and 3D modelling generally used. 2D modelling preserves simplicity while 3D modelling produces an accurate result. 2D element has a variety of flat or curved shapes. Three-dimensional elements used for modelling 3-D designs such as machine components and solid masses. FEM helps to develop the equations for an element and assume the shape of the element to represent the physical behaviour. It is used to analyse the effect of mechanical stress, mechanical vibrations, fluid flow and heat transfer, electric fields.

There are three different approaches used to formulate a FEM problem, namely: Direct Approach, Variational Approach, and Weighted Residual Method. The direct approach method used to solve simple problems and basic techniques to analyse the structure. The direct approach method solves field and non-field problems. The variational approach method works on the principle of minimum potential energy to solve any physical problem. The weighted residual method used to obtain the approximate solution for linear and non-linear differential equations. The main disadvantage of this method is that it is difficult to find good trail function

The FEM used to solve the structural, heat transfer, beam analysis and complex elasticity problems in civil Engineering and Aeronautical Engineering. The Finite element method is of various types like, the applied element method, the generalized finite element method, the mixed finite element method, and the extended finite element method. The extended finite element method is constructed on the generalized finite element method and partition of the unity method. It is a numerical technique that has been implemented in codes like ASTER.

The circuit theory models are not accurate to determine the design of transformer and parameters like windings, leakage reactance in Electrical Engineering. FEM used to design power transformers and distribution transformers.

VI. METHOD FOR FIELD PROBLEM SOLUTION

The field problems can be solved by three methods namely: Galerkin's method/Classic Residual Method, Rayleigh-Ritz's method/Classic Variational Method, and Finite Element Method. For a field problem with boundary condition, the differential equation of the vector field defined in the domain D is given by

$$L\Phi\,(P,t) = f(P,t) \quad (19)$$

along with the boundary Γ (Greek function gamma in capitals) of the domain under analysis. Where, L is a differential operator, Φ is the unknown function to be determined it may be a vector or a scalar field, f is the forcing function of the position P in space (x, y, z), and of the time t. In case the electric permittivity is non constant then the differential operator L is expressed by

$$L = -\text{div}\,(\varepsilon\,\text{grad}\,)$$

The behavior of the function Φ on Γ depends on the boundary conditions. The boundary conditions are of two type, namely Neumann's condition, and Dirichlets's condition. The Neumann's condition is given when a value of the derivative of Φ is assigned normal to the boundary Γ. The Dirichlet's condition is when a given value of Φ is assigned on the boundary Γ. All the methods for field problem solution approximate the function Φ as closely as possible. And define a function Φ^*, that is commonly expressed as a linear combination of the basic functions and is given by:

$$\Phi^*(P,t) = \sum_{j=1}^{N} \Phi_j v_j (P,t) \quad (20)$$

where v_j are interpolation/expansion functions. The unknown coefficients Φ_j are determined during computation. The classical methods (Galerkin's Method and Rayleigh-Ritz's method) take into account the entire analysis domain and the functions v_j are defined on the entire domain while in the FEM the entire domain is subdivided into subdomains, in this case Φ^* is a combination of functions v_j that are defined in the subdomains. For volume τ the inner product between two functions Φ and φ is defined as:

$$\langle \Phi, \varphi \rangle = \int_t \Phi\tilde{\varphi}\, d\tau \quad (21)$$

where ˜ indicates complex conjugate. The inner product is a linear operation because the properties of additively and the product by a constant are satisfied

$$\langle \Phi_1 + \Phi_2, \varphi \rangle = \langle \Phi_1, \varphi \rangle + \langle \Phi_2, \varphi \rangle \quad (22)$$

$$\langle \alpha\Phi, \varphi \rangle = \alpha\langle \Phi, \varphi \rangle \quad (23)$$

It needs to be verified if the differential operator L is positive, which is defined as

$$\langle L\Phi, \varphi \rangle = \begin{cases} > 0, & \Phi \neq 0 \\ = 0, & \Phi = 0 \end{cases} \quad (24)$$

and if it is possible to change the argument of the operator L within the operation of the inner product

$$\langle L\Phi, \varphi \rangle = \langle \Phi, L\varphi \rangle \quad (25)$$

A. Galerkin's Method or Classic Residual Method

The Galerkin's method deals directly with the differential equation (19). The residual of this differential equation is reduced so as to solve the problem. It is assumed that the function Φ^* that better approaches the exact solution Φ corresponds to a residual given by

$$r = L\Phi^* - f \quad (26)$$

and it equal to zero in the entire domain of analysis. In the residual method the weights function w_i is introduced. This weight function forces the integral of the residual to be zero over the domain volume τ_D. This forced condition is expressed by

$$R_i = \int_{\tau_n} w_i (L\Phi^* - f)\, d\tau = 0 \quad (27)$$

The weigh functions w_i is taken such that its is equal to the interpolating function v_i i.e.

$$w_i = v_i \qquad i = 1, 2, 3, \ldots, N \quad (28)$$

On using the approximation of equation (20) equation (27) becomes

$$R_i = \int_{\tau_n} v_i L\left(\sum_{j=1}^{N} \Phi_j v_j\right) - v_j f d\tau \qquad i = 1, 2, 3, \ldots, N$$

(29)

From above equation the system equation that is developed is given by

$$[SS][\Phi] = [T] \quad 30)$$

where $[\Phi]$ is a column vector, and $[SS]$ is a matrix vector which depends upon the interpolating functions. The elements of matrix are given by

$$s_{ij} = \frac{1}{2}\int_{\tau_n} (v_i L v_j + v_j L v_i)\, d\tau \quad (31)$$

$[T]$ is a column vector whose elements depend upon the forcing function which is given by

$$t_i = \int_{\tau_n} v_i\, f d\tau \quad (32)$$

B. Rayleigh-Ritz's Method or Classic Variational Method

The Rayleigh-Ritz method to solve field problem uses an integral approach. A function is built from the differential equation (19), such that minimum of the function corresponds to the solution of the field problem. The function that is built is called variational function. The minimum of the variational function that corresponds to the solution is expressed by

$$F(\Phi) = \frac{1}{2}\langle L\Phi, \Phi \rangle - \frac{1}{2}\langle \Phi, f \rangle - \frac{1}{2}\langle f, \Phi \rangle \quad (33)$$

If function Φ is substituted by Φ^* of equation (19) and $v_j$are defined in the entire domain D. On substituting (19) in (22) and equating to zero the derivatives of the variational F with respect to unknown coefficients Φ_i, a system of linear equations is obtained. The variational function property (24) needs to be satisfied. The matrix vector [SS] is symmetrical and the system that is obtained is identical to that of the Residual Method.

C. FEM for Magnetic-Field Problem

The finite element analysis is organized in the following steps:

Step 1: The domain is subdivided into subdomains that are characterized by reduced dimensions. The domain *D* is subdivided into N_m elements of D_m $(m = 1,2,3, \ldots . N_m)$.

Step 2: The function v_j are chosen generally with small dimensions of the subdomains, these functions can be very simple. A linear interpolation is achieved, if the first-order polynomial is chosen. A quadratic interpolation is achieved, if the second order polynomial is chosen. The accuracy of interpolation is higher for higher order polynomials, however, the formulation is complex. The solution of the m^{th} element is written as:

$$\Phi_m^* = (x, y, z, t) = \sum_{j=1}^{n} \Phi_{mj}\, v_{mj}\, (x, y, z, t) \quad (34)$$

where n is number of nodes of element and Φ_{mj} is value of Φ in the j^{th} node of the m^{th} element.

Step 3: The system of equations, representing the field solution, is developed by means of Galerkin's Method or Rayleigh-Ritz's method.

For Galerkin's method, the equation (27) is applied to each element and the residual integral is put to zero. The m^{th} element, the n integrals by

$$R_{im} = \int_\Gamma v_i\, (L\Phi_m^* - f_m) d\tau$$

$$= \int_\Gamma v_i L \sum_{j=1}^{n} (\Phi_{mj}\, v_{mj}) d\tau - \int_\Gamma v_i\, f_m d\tau \qquad i = 1,2,3, \ldots, n$$

(35)

are equated to zero. A system of n equations with n unknown Φ_{mj} is obtained. If the above equation (35) is applied to all N_m elements, the system obtained is

$$[SS][\Phi] - [\Gamma] = 0 \quad (36)$$

which is formed by N_m equations, having N_n unknown Φ_j.

In Rayleigh-Ritz method, the function is given by

$$F(\Phi^*) = \sum_{m=1}^{M} F(\Phi_m^*)$$

$$= \sum_{m=1}^{M}\left[\frac{1}{2}\int_{\Gamma} \Phi_m^* L \Phi_m^* d\tau - \frac{1}{2} f_m \Phi_m^* d\tau\right]$$

and in matrix form it results in

$$F(\Phi^*) = \frac{1}{2}[\Phi]^t[SS][\Phi] - [\Phi]^t[T] \qquad (37)$$

The system is achieved by imposing the stationery condition; i.e. all partial derivatives of equation (37) with respect to Φ_j are equated to zero, i.e.

$$\frac{\partial F}{\partial \Phi_j} = 0 \qquad j = 1,2,3,\ldots,N \qquad (38)$$

system of N_n equations of the form (t) is obtained

Step4: Once the system is developed it is possible to compute the values of Φ_j in the N_n nodes of the domain. The solution is obtained by solving system of equation by means of common numerical algorithms.

VII. TRANSFORMER: DESIGN AND MODEL

For analysis of leakage reactance, 10MVA, 33/11kV core type power transformer has been considered. The continuous disc type windings arrangement has1352 turns in HV winding and 124 turns in LV winding turns. Both the HV winding and LV winding are divided into 15 sections of equal height. The material used for winding is copper and core material used is M4. The 3-phase power transformer has a star-delta interphase connection. [9]. The 3D model of the transformer developed is shown in figure 1. Table 1 gives the design specification of the transformer.

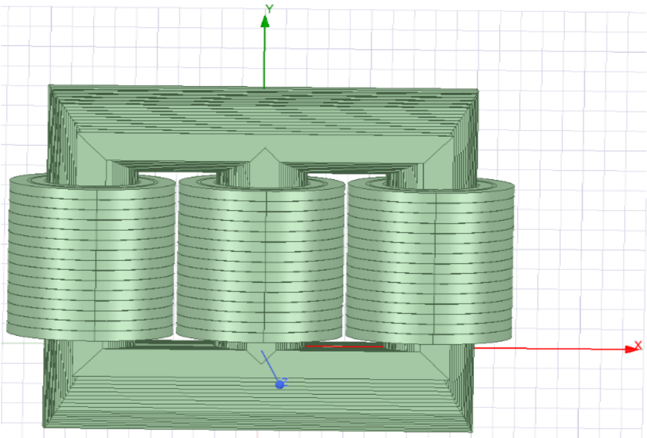

Figure 1: Transformer design in 3D

Table 1. Specification of 10MVA, 33/11KVA, 3-phase transformer

Parameter	HV Winding	LV winding
Type of coil	Continuous Disc type	
Inter Phase connection	Star	Delta
Phase	3-phase	3-phase
No. of turns per phase	1352	124
Voltage	33000V	11000V
Frequency	50Hz	50Hz
Yoke Clearance	58.5	58.5
No. of discs per limb	64	44
Number of sections	15	15
Core material	M4	M4
Window height	880	792.5

Coil outside diameter	776	577.5

VIII. RESULT AND DISCUSSION

The results for the reactance of transformer obtained be classical method and by FEM are discussed below:

A. Classical Method

To calculate the leakage reactance of the core type 10MVA, 33/11KV, power transformer having continuous disk type winding arrangement, the 1352 turns in HV windings and 124 turns of the LV windings are considered as 15 discs of equal height. The window height of 880mm. The HV current is 174.95 A. To calculate the reactance of winding, first the equivalent height is calculated from equation 3, Heq is 93.4877cm. The radial depth of the LV winding (T_1) is 6.3 cm, radial depth of the gap (T_g)1.75 cm and radial depth of HV winding (T_2) is 1.75cm. The Rogowski factor K_r is found to be 0.9413. The submission of ampere-turns distribution is calculated as per equation (17), and its value is 401.353cm^2, the voltage per turns and ampere per turns 88.7 V and 236532.4 A respectively. The leakage reactance is calculated as 14.64%.

B. Finite Element Method

Using the finite element method, the storage magnetic energy in the LV winding is 0.749J, in the HV winding is 1.448J, while that in the remaining portion 2.023J. The stored energy in core is negligible. The total energy obtained is 4.220J. The leakage inductance is calculated as 0.0482H. The results of the energy stored are given in table 2. The value of leakage impedance by the FEM analysis is 13.92%.

Table 2. Details of energy stored

Part of transformer	**Energy (J)**
LV winding	0.749
HV Winding	1.448
Other parts	2.023
Total energy stored	**4.220**

The variation in value of leakage impedance found by the classical method and the FEM analysis is 4.91%. The results obtained by FEM are comparable with that obtained by classical method.

IX. CONCLUSION

In this paper, the classical method and finite element method has been used to calculate the leakage reactance in a transformer. The results obtained by FEM are comparable with that obtained by classical method. Since FEM can handle the asymmetrical/ nonuniform distributions of ampere-turns so further work can be done for asymmetrical conditions as well. Using FEM there is scope of calculating the transformer reactance while designing it and any change in symmetry or inherent asymmetry are taken care of. The 3D design of a transformer can be conveniently analyzed for values of reactance and there is scope to even find the electromagnetic forces during inrush phenomenon, faults, and heat flow as well.

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