

## FIELD BEHAVIOR OF A TRANSFORMER UNDER VARIOUS FAULT CONDITIONS AND EVALUATION OF REACTANCE

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**Abstract**-Transformer is one of the major elements of the power system network. Even though the transformers are designed with high efficiency, at very high ratings improvements are still needed in its design for economic and technical reasons. With the appearance of deregulation, Transformer predictive maintenance is becoming more important for utilities to prevent forced outages with the consequential costs. To detect and diagnose the Transformer internal fault requires a Transformer model to accurately simulate these faults. This paper presents a Finite Element Method (FEM) based analysis of internal winding faults in a transformer. The transformer with a turn-to-turn fault is modeled using FEM. The comparison of results is done with practically available data and validates the FEM results for the evaluation of leakage reactance to analyze internal faults and short circuit currents in a Transformer. This is a 31.5 MVA, 132KV/33 KV unit and a YNd11 connection, ONAF cooled, 3  $\Phi$  transformer.

**Index Terms**-Finite element method – leakage reactance -Transformer – short circuit current - Short circuit KVA

### I. Introduction

Transformer is one of the major elements of the power system network. Even though the transformers are designed with high efficiency, at very high ratings improvements are still needed in its design for economic and technical reasons. In this work a few of these aspects of transformer design are addressed. Finite Element Method of Simulation and Analysis using ANSYS16.2 is employed to make the procedure easier and the design effective.

A good deal of attention has been paid to the problems associated with conventional concentric winding transformers and some ingenious methods of reactance calculation have been published [1]. However no reliable solution of the problems presented by the sandwich winding seems to have been published. There are some formulae available for the reactance of sandwich winding [2], but these are not very reliable as they are based on the assumption that lead to approximate results. So the main attention is towards studying a more accurate method to calculate leakage reactance of sandwich windings (the also works for concentric windings) with irregular distribution of fluxes. The results obtained are checked with the FEM values for the validation.

Thus the major problems considered in this work are Leakage reactance calculation for irregular ampere-turn distribution and in evaluating the above, finite element analysis approach is used, which is briefly explained below.

### II. Finite Element Approach

In finite element method, the actual continuum or the body of matter like solid, liquid or gas is represented as an assemblage of subdivisions called finite elements. These elements are considered to be interconnected at specific joints, which are called nodal points or simply 'nodes'. The nodes usually lie on the element boundaries where adjacent elements are considered to be connected. Since the actual variation of the field variable (like current density, voltage, displacement, stress, temperature etc.) inside the continuum is not known, it is assumed that the variation of the field variable inside the finite element can be approximated by a simple function. These approximating functions are called interpolation models and are defined in terms of values of the field variable at the nodes. When field equations (like equilibrium equations) for whole continuum are written, the new unknowns will be the nodal values of the field variable. Once these are solved for, the approximating functions define the field variable throughout the assemblage of the elements of the entire domain.

Leakage reactance plays major role in finding the efficiency and regulation of the transformer. Both the primary and secondary windings contains its own value of leakage reactance, But calculation of leakage reactance is a challenging task as the normal calculations will not give the proper results. If the flux distribution is irregular then it is very difficult to find the value of leakage reactance using analytical methods. Its value also depends upon the type of winding whether it is sand witched or distributed. If it is distributed then no problem in finding the value of leakage reactance but if it is sand witched then proper care should be taken.

Thus the major problem considered in this work is Leakage reactance calculation for irregular ampere-turn distribution and to evaluating the short circuit current from the leakage reactance. Here the Finite element analysis approach is used.

**III. Fem Formulation Equations**

FEM (finite element method)-

The finite element analysis of any problem involves basically four steps:

- a) Discretizing the solution region into a finite number of sub regions or elements,
- b) Deriving governing equations for a typical element,
- c) Assembling of all elements in the solution region and
- d) Solving the system of equations obtained.

**Finite Element Descretization:**

We divide the solution region into a number of finite elements where the region is subdivided into four non overlapping elements (2 triangular and 2 quadrilaterals) and seven nodes. We seek an approximation for the potential  $V_e$  within an element  $e$  and then interrelate the potential distributions in various elements such that the potential is continuous across inter element boundaries[9]. The approximate solution for the whole region is

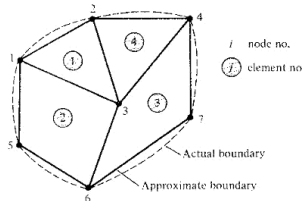


Figure 3.2.1 A typical finite element subdivision of an irregular domain.

$$V(x, y) = \sum_{e=1}^N V_e(x, y)$$

where N is the number of triangular elements into which the solution region is divided.

The most common form of approximation for  $V_e$  within an element is a polynomial approximation, namely

$$V_e(x, y) = a + bx + cy \tag{2.1}$$

for a triangular element and

$$V_e(x, y) = a + bx + cy + dxy \tag{2.2}$$

for a quadrilateral element. The potential  $V_e$  is nonzero within element  $e$  but zero outside  $e$ . It is difficult to approximate the boundary of the solution region with quadrilateral elements; such elements are useful for problems whose boundaries are sufficiently regular. In view of this, we prefer to use triangular elements

throughout our analysis. Our assumption of linear variation of potential within the triangular element as in eq.(2.2) is the same as assuming that the electric field is uniform within the element; that is

$$E_e = -\nabla V_e = -(ba_x + ca_y) \tag{2.3}$$

**Element Governing Equations:**

Consider a typical triangular element shown in the figure 3.2.2. The potential  $V_{e1}$ ,  $V_{e2}$  and  $V_{e3}$  at nodes 1, 2 and 3, respectively, are obtained using eq.(3.2.2); that is,

$$\begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2.4}$$

The coefficients a, b and c are determined as

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} V_{e1} \\ V_{e2} \\ V_{e3} \end{bmatrix} \tag{2.5}$$

**Assembling of All Elements:**

Having considered a typical element, the next step is to assemble all such elements in the solution region. The energy associated with the assemblage of all elements in the mesh is

$$W = \sum_{e=1}^N W_e = \frac{1}{2} \epsilon [V]^T [C][V] \tag{2.6}$$

where

$$V = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix}$$

n is the number of nodes, N is the number of elements, and [C] is called the overall global coefficient matrix, which is the assemblage of individual element coefficient matrices.

The major problem now is to obtain [C] from  $[C^{(e)}]$

The process by which individual element coefficient matrices are assembled to obtain the global coefficient matrix is best illustrated with an example. Consider the finite element mesh consisting of three finite elements as shown in figure 2.4. Observe the numberings of the nodes. The numbering of nodes as 1, 2, 3, 4 and 5 is called global numbering. The numbering i-j-k is called local numbering

and it corresponds with 1-2-3 of the element in figure 2.4.

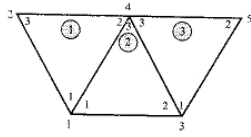


Figure 3.2.4 Assembly of three elements corresponds to local numbering 1-2-3 of the element in Figure 3.2.2

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} \end{bmatrix}$$

which is a 5\*5 matrix since five nodes(n=5) are involved. Again, C<sub>ij</sub> is the coupling between nodes i and j.

**IV. Fault Analysis And Reactance**

The continuous increase in demand of power has resulted in the addition of more generating capacity and interconnections in power systems. Both these factors have contributed to an increase in short circuit capacity of networks, making the short circuit duty of transformers more severe. Failure of transformers due to short circuits is a major concern of transformer users.

**Short circuit currents**

There are different types of faults, which result into high over currents, viz. single-line-to-ground fault, and line-to-line fault with or without simultaneous ground fault and three-phase fault with or without simultaneous ground fault. When the ratio of zero-sequence impedance to positive-sequence impedance is less than one, a single-line-to-ground faults in higher fault current than a three-phase fault.

The symmetrical short circuit current for a three-phase two-winding transformers is given by,

$$I_f = V / (Z_t + Z_s) \text{ KA}$$

Where V is rated line-to-line voltage in KV, Z<sub>t</sub> is short circuit impedance of the transformer, and Z<sub>s</sub> is short circuit impedance of the system given by

$$Z_s = (V * V) / S_f \text{ ohms or}$$

$$Z_s = S / S_f \text{ per-unit} \tag{3.1.2}$$

Where S<sub>f</sub> is short circuit apparent power of the system in MVA and S is the three phase rating of the transformer in MVA. Usually, the system impedance is quite small as compared to transformer impedance and can be neglected, given safety margin.

For a line-to-line fault (between phases b and c)

$$I_a = 0, I_b = -I_c = -j (Z_1 + Z_2) \tag{3.1.3}$$

$$I_a1 = -I_a2 = 1 / (Z_1 + Z_2) < 0 \tag{3.1.4}$$

$$I_a0 = 0$$

**Short circuit test**

The short circuit test can be performed by one of the two techniques, viz. pre-set short circuit and post-set short circuit.

In the pre-set short circuit test, a previously short circuited transformer is energized from primary side. If the secondary winding is the inner winding, the limb flux is quite low resulting in an insignificant transient inrush current.

The method will work quite well. If the primary is the inner winding, there is substantial flux density in the limb and hence the inrush current gets superimposed on the short circuit current. Since the inrush current flows through the primary winding only, it creates a significant ampere-turn unbalance between the primary and secondary windings resulting in high short circuit forces.

In the post-set short circuit test method, in which the transformers are in the energized condition, the secondary winding is short circuited. Naturally, this method is preferred as there are no inrush currents and the related problems, and also due to the fact that it represents the actual fault conditions at site. However, the disadvantage of this method is that the short circuit capacity of the test stations has to be much higher than the first method to maintain the rated voltage across the transformer terminals and establish the required value of short circuit current.

Short circuit tests on large transformers are usually carried out by the pre-set method.

**Symmetrical fault calculations**

Most of the faults on the power system lead to a short circuit condition. In such a condition a heavy current flows through the equipment. The choice of apparatus and the design and arrangement of all equipment in the power system depends upon short circuit current considerations. That fault on the power system which gives rise to symmetrical currents is called a symmetrical fault. When short circuit occurs at any point in a system the short circuit current is limited by the impedance of the system up to the point of fault. In many situations the impedances limiting the fault currents are largely reactive such as transformers, reactors and generators. Cables and lines are mostly resistive but where the total reactance in calculations exceeds the three times the resistance. Therefore the resistance is usually neglected. The error introduced by this assumption will not exceed 5%.

**Percentage reactance**

It is the percentage of the total phase voltage dropped in the circuit when full load current is flowing that is

$$\%X = (IX/V) * 100 \quad (3.1.1)$$

Where I is full load current V is phase voltage

X is reactance in ohms per phase

$$\%X = (KVA * X) / (10 * KV * KV) \quad (3.1.2)$$

$$ISC = V/X \quad (3.1.3)$$

$$= I * (100/\%X) \quad (3.1.4)$$

Unlike ohmic reactance which become multiplied by the square of transformer ratio.

(a) Percentage reactance and base KVA

$$\% \text{ age reactance at base KVA} = (\text{Base KVA} / \text{rated KVA}) * \%$$

$$\% \text{ age reactance at rated KVA}$$

(b) Short circuit KVA

The product of normal system and short circuit at point of fault expressed in KVA is known as short circuit KVA.

$$ISC = I * (100/\%X) \quad (3.1.5)$$

For 3-phase

$$ISC = 3VISC/1000 \quad (3.1.6)$$

$$\text{Short circuit KVA} = \text{base KVA} * (100/\%X)$$

$$= (3VI/1000) * (100/\%X) \quad (3.1.7)$$

### 3.1.5 REACTANCE

The Estimation of reactance is primarily the estimation of the distribution of the leakage flux and the resulting line linkages with the primary or secondary coils. An accurate solution to this problem is well-nigh impossible--as is, in fact, almost every problem of magnetic field distribution in the neighborhood of iron masses.

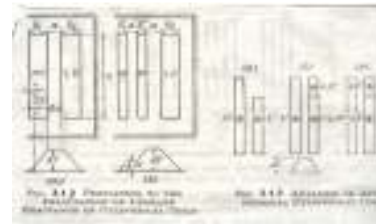
The distribution of the leakage flux depends on the conformation of the coils and of the neighboring iron masses, and also on the permeability of the latter. The diagrams in fig. show typical calculated distributions based on simplifying assumptions (such as constant permeability  $\mu_r=10$ , two dimensional symmetry etc.) in case (a), that of cylindrical is noteworthy how the leakage field is packed into the space between the windings, and how it runs parallel with the core of nearly the full length of the coils. Where is an inequality in the coil-lengths, however, the field is very considerably altered, as shown in fig. for the shell-type transformer with sandwich coils, fig shows a typical leakage-field distribution.



Fig 3.1 Leakage Flux

### Cylindrical Concentric Coils, Equal Length

For this case the actual leakage field, e.g. fig. is assumed to consist of a longitudinal flux of uniform and constant value in the interspaces between primary and secondary; and a field crossing the conductors, reducing linearly to zero at the outer and inner surfaces. Further, the permeance of the leakage path external to the coil length  $L_c$  is assumed to be so large as to require the expenditure of a negligible M.M.F.; is experienced on the length  $L_c$ . the effect of the magnetizing current in unbalancing the primary and secondary ampere-turn equality is neglected.



Let (AT) be the ampere-turns of either the l.v. or h.v. coils on one limb. Then the flux density in the duct of radial width a is  $B_a = \mu_0 (AT)/L_c$ . [9,10] Taking one-half of the total duct leakage as linking either winding (it makes little difference to the result whether this is strictly true or not), then the duct flux linkage as linking either winding (it makes little difference to the result whether this is strictly true or not), then the duct flux linking each of the T1 primary turns is approximately  $\mu_0 (AT) a L_{mt} / 2L_c$ , and the linkages are consequently  $\mu_0 (AT) T1 a L_{mt} / 2L_c$ . here  $L_{mt}$  is the mean length of a primary turn.

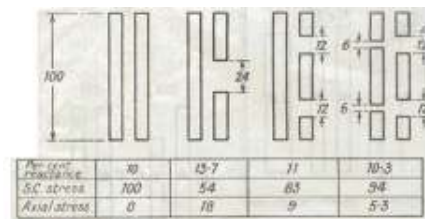


Fig 3.1 arrangement of asymmetrical cylindrical coils

The flux density at the radial distance x from the surface of the primary winding is  $xBa/b1$ . The flux in an elemental annular ring of width dx and approximate circumference  $L_{mt}$  is  $L_{mt} (xBa/b1) dx$ . This flux does not link T1 turns, but only the outer portion  $xT1/b1$ : the linkages are therefore  $L_{mt} Ba T1 (x/b1) 2dx$ . Summing the total linkages over the radial distance b1.

**Cylindrical Concentric Coils, Unequal Lengths**

As compared with the case of equal length, considerable difficulty will be found in making suitable simplifying assumptions. Obviously the assumption illustrated is quite inadmissible. The leakage field depends on the proportional difference in length, and on where difference occurs (e.g. at one or both ends, or in the middle, etc.). The case is common one, as it may be produced by end-turn reinforcement, tappings, or by the normal small difference of coil length usual in the absence of tappings, etc.

**Sandwich Coils**

It is usual to arrange the winding, where the end coils have one-half the turns of the remainder. There will be n h.v. coils, (n-1) l.v. coils of equal ampere turns, and two l.v. half-coils. Taking two adjacent half-coils as a unit, the reactance of such an arrangement is, by analogy with eq.

$$X_{1n} = 2\pi f \mu_0 (T_{1n}/2)^2 L_{mt} (a + (b_1 + b_2)/6) / w \text{ ohms} \quad (3.1.8)$$

Where,  $T_{1n}$  is the number of turns per whole section. For the n sections and 2n units, the total reactance is

$$X_1 = 2\pi f \mu_0 2n (T_{1n}/2)^2 L_{mt} (a + (b_1 + b_2)/6) / w \text{ ohms} \quad (3.1.9)$$

$$\approx \pi f \mu_0 (T_1)^2 L_{mt} (a + (b_1 + b_2)/6) / n w \text{ ohm} \quad (3.1.10)$$

Since  $nT_{1n} = T_1$ . The effect of subdivision is apparent. The per-unit reactance is

$$\epsilon_x = \pi f \mu_0 (AT)^2 L_{mt} (a + (b_1 + b_2)/6) / (E_t n w) \text{ per unit} \quad (3.1.11)$$

(AT) is the full phase ampere-turns of either primary or secondary.

**V. Reactance And Short Circuit Current Calculations Using Fem**

Case(1): To obtain the values of inductance and reactance from FEM results, the required hand calculations are done as follows using some empirical formulae, which are mentioned below:

- Capacity : 31.5MVA
- Voltage : 132KV/33KV
- Frequency : 50 Hz
- Amp-turns LV winding: 126882.4;
- HV winding: -126882.4

Base reactance of the transformer,

$$X \text{ base} = KV^2 / MVA = 553.14\Omega$$

And Normal rated current,  $I = 137.78 \text{ A}$

Now the collected result from FEM is used as follows,

Stored Energy (Calculated as 'sene' from FEM by using ANSYS16.2) = 1947.51J

By using the general formula for stored energy, we can write as follows,

$$L = (1947.51 * 2) / 137.78^2 = 0.2052 \text{ H}$$

we get Leakage reactance  $X_L = 64.46\Omega$

Percentage reactance,  $X = 11.65\%$

$$\text{Short circuit current} = I * (100/\%X) = 1182.66 \text{ A}$$

| Sl.No | Name of the job | Capacity (MVA) | Voltage Rating (KV) | Value of Reactance from data sheets (%X) | Reactance value calculated by FEM (%X) |
|-------|-----------------|----------------|---------------------|--|--|
| 1.    | Case I          | 31.5           | 132                 | 11.89                                    | 11.65                                  |
| 2.    | Case II         | 100            | 66                  | 13.6                                     | 13.45                                  |
| 3.    | Case III        | 315            | 400                 | 12.86                                    | 12.36                                  |
| 4.    | Case IV         | 100            | 38.1                | 14.61                                    | 14.76                                  |
| 5.    | Case V          | 6.35           | 3.3                 | 13.68                                    | 13.71                                  |
| 6.    | Case VI         | 0.5            | 7.61                | 15.3                                     | 15.33                                  |
| 7.    | Case VII        | 16.65          | 34.5                | 171.5                                    | 168.5                                  |
| 8.    | Case VIII       | 9.064          | 11                  | 178.56                                   | 173.18                                 |
| 9.    | Case IX         | 0.184          | 0.433               | 4.2                                      | 4.4                                    |

Table 4.1: Comparison of leakage reactance from FEM and practical values

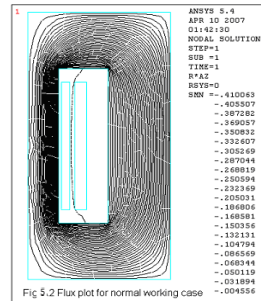


Fig 4.1 magnetic flux pattern under normal working case

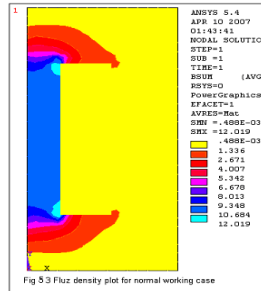


Fig 4.2 flux density plot under normal case

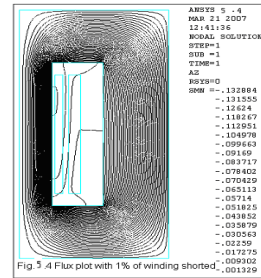


Fig 4.3 magnetic flux pattern with 1% of winding shorted

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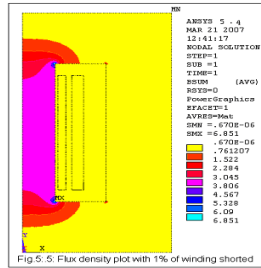


Fig 4.4 flux density plot with 1% of winding shorted

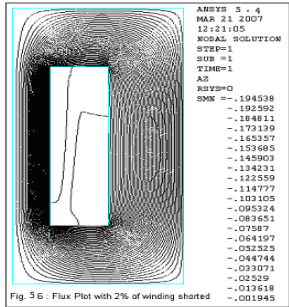


Fig 4.5 magnetic flux pattern with 2% winding shorted

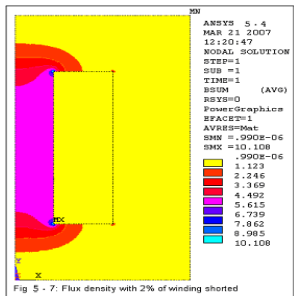


Fig 4.4 flux density plot with 2% of winding shorted

| Sl.No | Name of the job                      | Capacity (MVA) | Voltage Rating (KV) | Reactance value calculated by FEM (%X) | Value of Short circuit Current (A) |
|-------|--------------------------------------|----------------|---------------------|--|------------------------------------|
| 1.    | Normal case of (I) in Table 5.       | 31.5           | 132                 | 11.65                                  | 1182.66                            |
| 2.    | The above case with 1% Shorted turns | 31.5           | 132                 | 35.98                                  | 3653.18                            |
| 3.    | The above case with 6% Shorted turns | 31.5           | 132                 | 208.63                                 | 21179.2                            |

Table 4.2: Comparison of short circuit currents from FEM for case(I)

By using FEM simulations we can evaluate the short circuit currents from the design data itself before manufacturing. From the above table 4.2, we can conclude

that for case (I), the short circuit current is getting doubled, which is twenty six times greater than the normal rated current. From this we can conclude the severity of incipient fault, i.e. very much higher than the normal conditions beyond which a transformer is tend to fail due the internal short circuits.

**Results**

We calculated the value of percentage leakage reactance of transformer for different situations. Mainly the analysis is based on the value of inductance, which is obtained by using finite element analysis. As the short circuit percentage increases in the windings, the short circuit current is going to be increased. From this we can estimate the maximum possible value of short circuit current for least short circuited turns, which will mostly affects the Transformer.

Thus the evaluation of design of any transformer can be carried out to conclude that for what level of incipient fault the short circuit current reaches to worst level. This provides better information for a design engineer to go for online monitoring of Transformer.

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