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Turn Fault Characteristics Of Transformer Using Transfer Function Method

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The paper presents the transfer function method used to study the turn fault characteristics behavior of a 100 MVA, 220/66/11 kV transformer. The whole transformer is modeled by subdividing into 44 sections and represented by self-inductance, mutual inductance and capacitance parameters. The current in the neutral is computed by solving the network for applied impulse voltage. The transfer function is obtained for various turn faults simulated by reducing the number of turns in the electrical data for a given section. The location of the turn faults along the height of the winding is varied to study the characteristics behavior of the transformer by computing transfer function. Details of modeling, simulation of turn faults, computation of neutral current, transfer function are presented in the paper. The effect of turn fault on the characteristic changes in the transfer function of the transformer is presented and discussed.

1. INTRODUCTION

The impulse test is used as an acceptance test on transformers to ascertain the withstand capacity of the winding insulations at Basic Impulse Level (BIL). Conventionally, neutral currents recorded both at reduced and full voltages are compared and any variation is attributed to faults internal to the transformer leading to the rejection of the transformer. However, it is occasionally difficult to differentiate the minor changes in the neutral currents. Also, sometimes there are differences between the two applied voltages and this makes it difficult to judge the test if differences in response currents are subtle. This may lead to misinterpretation of the results. The transfer function method, wherein the trans admittance computed at reduced and full voltages has been considered to eliminate this difficulty [1,2,3]. The basic principle involved is to compute the transfer characteristic between the applied voltage and response currents by dividing their frequency spectra in the frequency domain employing Fast Fourier Transform (FFT) technique. Furthermore, it has the possibility to realize a fault location process by developing the diagnosis process of the transfer function method and this aspect has been investigated in this paper by theoretically obtaining the transfer function on a transformer.

The transfer function method is used to investigate the characteristic behavior of a 100 MVA, 220/66/11 kV transformer. The paper presents the details of modeling of this transformer, the inductance and capacitance calculations as well as formulation of electrical network. The method of neutral current, transfer function calculation for impulse voltages and characteristic changes in the frequency spectra of the transformer with respect to the turn faults created along the height of the winding is discussed.

2. MODELING OF TRANSFORMER

A high voltage power transformer can be represented by an equivalent electrical circuit. In principle, transformer turns, which make up the windings,

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are separate coils with certain self-inductance. In addition, a mutual inductance is present between each pair of turns regardless of whether these turns are located in separate windings or the same winding. Capacitances exist between neighboring windings. Capacitances also exist between some turns and the core and other grounded assemblies. Ohmic resistance is present in each turn and it is in series with the self-inductance of that turn. In addition to direct current losses caused by ohmic resistance, alternating current losses caused by eddy currents, which increases with frequency also appear. The complete model can be mathematically described with a number of matrices. The transformer model need not be as detailed as it would be unacceptably time consuming to compute this model because there are many equations with many unknowns [4]. Instead, each winding is sectioned into a number of blocks. Each block represents a number of turns. The electrical network is formed by dividing the winding into a suitable number of sections taking in to account the type of winding. The different sections are electrically connected to one another [5]. The windings of 100 MVA, 220/66/11 kV transformer are divided into a total of 44 sections. The two grouped partially interleaved HV winding is divided into 30 sections. The tapping and LV winding are divided in 8 and 6 sections respectively. A schematic diagram of the winding arrangement used and its equivalent electrical network are shown in Fig. 1. Mutual inductances and core are not shown for clarity.

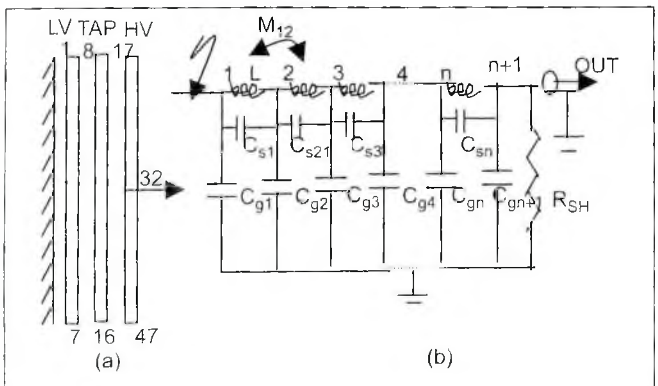

FIG 1 a) SCHEMATIC DIAGRAM b) EQUIVALENT NETWORK OF THE HV WINDING OF 100MVA, 220/66/11 kV TRASNFORMER

The winding parameter comprise of self-inductance (L) and mutual inductances (M), the capacitances inside the section called series capacitances (C_s) capacitance between section called mutual capacitance and capacitance to ground (C_g) called shunt capacitances. These parameters are calculated using geometrical transformer data such as core dimensions, winding dimensions, distance to tank / core, inter winding separation together with the electrical data such as number of turns, type of winding, duct dimensions and insulation details. In the present work, as shown in Fig. 1, the single winding model of a transformer in the form of ladder network is used as the other windings during the impulse test are short circuited and earthed. The transient voltage at every node can be computed at every instant of time. The neutral current is calculated by Eigen Value method [5,6] as described below.

3. COMPUTATION OF NEUTRAL CURRENT AND TRANSFER FUNCTION

The neutral current for the electrical network of the transformer is the current flowing between the n^{th} and $(n+1)^{th}$ node. This is the sum of transient currents in the inductance and capacitance connected to nth and $(n+1)^{th}$ nodes. The inductive current between nth and $(n+1)^{th}$ nodes is dependent on the currents in all other inductive branches because of mutual coupling among themselves. Since all the node voltages at any instant of time are known [5], the matrix equation relating branch currents and node voltages can be given as

$$[di_L/dt] = [L]^{-1}[V] \tag{1}$$

where, $[L]$ is n x n matrix representing self and mutual inductances of all the branches, $[V]$ is a $n \times 1$ matrix representing different node voltages and $[di_L/dt]$ is a $n \times 1$ matrix representing the rate of change of current with time. Solving equation (1), we have

$$\int_{i_{Ln}(t_0)}^{i_{Ln}(t_1)} di_{\mathrm{Ln}} = \int_{t_0}^{t_1} P_0\, dt = P_0\, \Delta t$$

$$i_L(t_m) = P_{m-1}\Delta t + i_{Ln}(t_{m-1}) \tag{2}$$

where i_{Ln} is the inductive current from the n^{th} node to the ground; t_m is the m^{th} interval of time; P_{m-1} is assumed to be constant during small $(m-1)^{th}$

interval of time and is different in different intervals. Hence the current in the C_{gn+1} becomes the total capacitive current. The relation between node voltage and capacitive current can be given by

$$C_{sn}[dV_{n,n+1}/dt] = i_{c(n,n+1)} \tag{3}$$

$$I_{cn}(t_m) = \left[\{V_{n,n+1}(t_m) - V_{n,n+1}(t_{m-1})\} C_{sn}\right]/\Delta t \tag{4}$$

I_{cn} is the capacitive current from the n^{th} node to ground and Δt is a small interval of time. The capacitive current can be calculated using equation (4). The neutral current is the sum of inductive and capacitive current. Hence the neutral current can be given as:

$$I(t) = i_L(t) + i_{Cn}(t) \tag{5}$$

The impulse voltage that is applied to the winding model transformer is of the form

$$V(t) = V_0(e^{-\alpha t} - e^{-\beta t}) \tag{6}$$

where α and β are selected to obtain 1.2/50 μs waveform.

The transfer function is defined as the ratio of the output response signal to the input signal in frequency domain. The applied voltage and neutral current, given by equation (6) & (5) respectively, are de-convoluted into frequency domain using Fast Fourier Transform (FFT). Then Transfer Function (TF) is given by

$$Y(n\omega) = FFT[I(nt)]/FFT[V(nt)] \tag{7}$$

4. TURN FAULT CHARACTERISTICS EVALUATION

The neutral current is computed for the applied impulse voltage after modeling the transformer as discussed in the above sections. The transfer function is then obtained to characterize the transformer behavior. Reducing one or more turns in the electrical data for a given section simulates the turn fault. The circuit parameters are then recomputed to yield new set of inductances and capacitances. Thus for every such turn faults, the parameters are calculated and then the network is solved to obtain the neutral current for the applied impulse voltage. Fig. 2 shows the neutral currents obtained after solving the network for a) no turn fault b) one turn fault c) two turn fault d) four turn fault and e) eight turn fault created in the first section of the high voltage winding i.e, section 17-18.

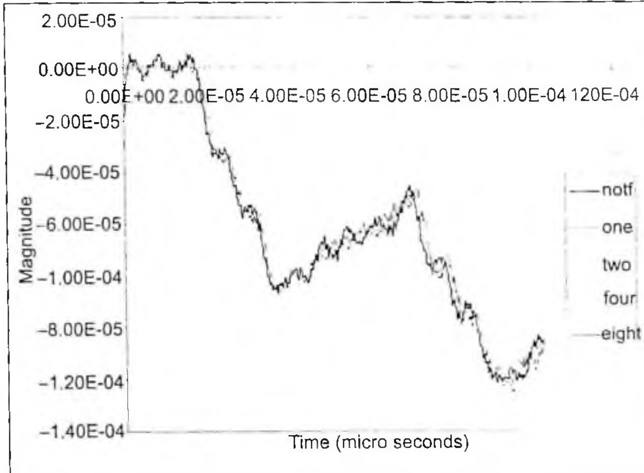

FIG. 2. NEUTRAL CURRENTS FOR VARIOUS TURN FAULT CONDITIONS IN SECTION BETWEEN NODE 17-18

It can be observed that the neutral current obtained for various turn fault levels do show minor changes at various times from no fault condition. However, it is difficult to characterize any behavioral changes with regard to turn faults. Similarly, the neutral currents were obtained for number of turn fault levels across different height of the HV winding.

The TF for six cases across the height of the winding is considered for computation to study any characteristic behavior of the transformer. Fig. 3 shows the transfer functions of the various turn faults created in the first section between node 17$^{\text{th}}$ and 18$^{\text{th}}$

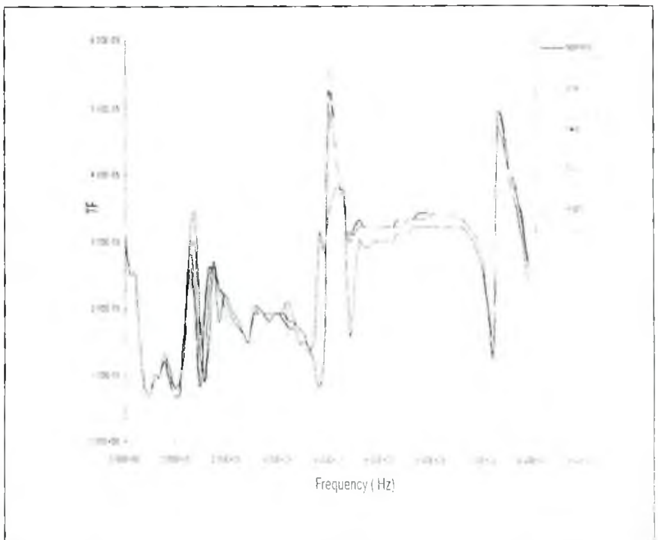

FIG. 3. TRANSFER FUNCTION FOR TURN FAULTS IN SECTION BETWEEN 17$^{\text{th}}$-18$^{\text{th}}$ NODE

of the HV winding for which neutral currents are indicated in Fig. 2.

The transfer function of the transformer obtained for various turn fault levels at the HV end (node 31-32) in the interleaving portion of the winding is as shown in Fig. 4. Fig .5 gives the same for the 13th section between node 29th and 30th (at the junction of plain disc and interleaved disc winding).

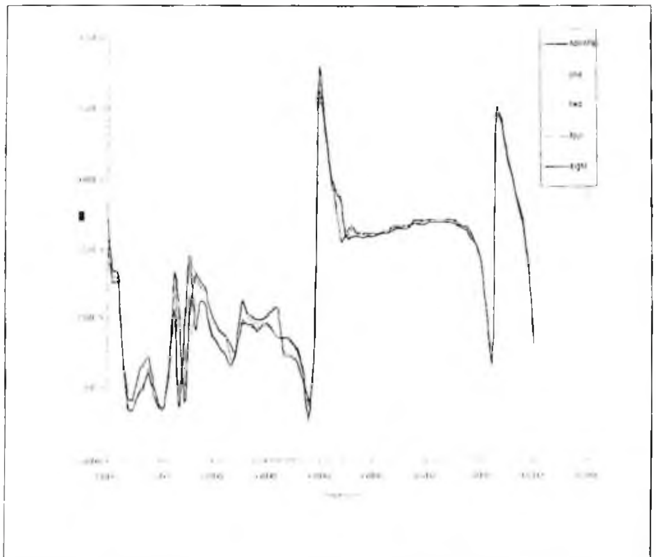

FIG. 4. TRANSFER FUNCTION FOR TURN FAULTS IN SECTION ADJACENT TO HV TERMINAL (NODE 31-32)

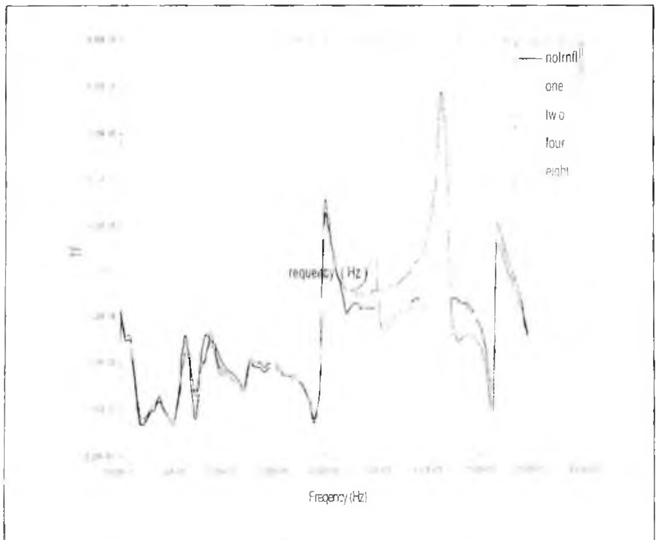

FIG. 5. TRANSFER FUNCTION FOR TURN FAULTS IN THE SECTION BETWEEN NODE 29-30

It can be observed from Fig. 3, 4 and 5 that there is considerable change for the eight-turn fault in the resonant frequencies as compared to the lower order turn fault. Also, the deviation in the frequency shifts are very negligible for one & two turn faults suggesting the poor sensitivity of the method for identification of lower order turn faults in the transformer. It can also be seen that characteristic changes in the frequencies are occurring only up to 800 kHz and no changes are visible beyond this frequency for the faults under investigation.

Table 1, 2 and 3 give the dominant frequencies for the turn faults created in the first, thirteenth and last section for the high voltage winding listed out from the Fig. 3, 5 and 4 respectively. The shift in these frequencies from the base frequency representing no turn fault condition is calculated for the trend analysis. The numbers in bracket indicate the percent change in the frequency with respect to the no turn fault as base.

TABLE 1

DOMINANT FREQUENCY COMPONENTS FOR FIRST SECTION BETWEEN NODES 17th AND 18th

Base frequency (kHz)	126	146	166	244	[illegible]	400
One turn	126 (0)	146 (0)	166 (0)	244 (0)	380 (0)	400 (0)
Two turn	126 (0)	146 (0)	176 (5.8)	244 (0)	380 (0)	400 (0)
Four turn	126 (0)	156 (5.8)	176 (5.8)	244 (0)	380 (0)	400 (0)
Eight turn	126 (0)	156 (5.8)	176 (5.8)	244 (0)	380 (0)	400 (0)

TABLE 2

DOMINANT FREQUENCY COMPONENTS FOR SECTION BETWEEN NODES 29th AND 30th

Base frequency (kHz)	126	146	166	244	380	400
One turn	126 (0)	146 (0)	176 (5.8)	234 (−4)	380 (0)	400 (0)
Two turn	126 (0)	146 (0)	176 (5.8)	234 (−4)	380 (0)	400 (0)
Four turn	126 (0)	146 (0)	176 (5.8)	234 (−4)	380 (0)	400 (0)
Eight turn	126 (0)	156 (0)	176 (5.8)	234 (−4)	380 (0)	400 (0)

It can be observed from the above tables that there is no appreciable change in frequencies for 126 kHz and for frequencies beyond 380 kHz except that additional poles or zeroes are appearing for eight turn fault level as seen from the corresponding figures. Absolutely no significant change in frequencies was seen beyond 700 kHz. However,

TABLE 3

DOMINANT FREQUENCY COMPONENTS FOR LAS SECTION BETWEEN NODES 31st AND 32nd

Base frequency (kHz)	126	146	166	244	380	400
One turn	126 (0)	146 (0)	156 (−5.8)	244 (0)	380 (0)	400 (0)
Two turn	126 (0)	146 (0)	156 (−5.8)	234 (−4)	380 (0)	400 (0)
Four turn	126 (0)	136 (−6.7)	156 (−5.8)	234 (−4)	380 (0)	400 (0)
Eight turn	126 (0)	136 (−6.7)	156 (−5.8)	244 (−4)	380 (0)	400 (0)

no change in frequency shift between 500kHz to 700kHz except in the middle section where additional poles and zeroes are observed. Significant shifts in frequencies are found to appear only at 146. 166 and 244 kHz. It was observed from the table and from figures that the frequency shift occur, from −6.8% to +5.8% at 146 kHz, from −5.8% to +5.8% at 166 kHz and −4% to 0%, as the fault condition moves from last section towards the first section for all levels of fault. Also, for turn fault levels beyond four turns, additional poles and zeroes are present. Hence, there seems a possibility to locate the position and identify the severity of the turn faults by studying the trends and correlating the percent change in frequency shifts with reference to no turn fault frequencies. Additional studies are needed to be carried out on a few more transformers to correlate with the analysis presented to concretely suggest the location and severity of the turn faults. It was also observed that the frequency interval for computing the FFT must be reduced in order to study the sensitivity of the frequency shifts for relating the changes with regard to identification of turn faults.

5. CONCLUSIONS

Transfer function method to study the turn fault characteristics behavior of a 100 MVA, 220/66/11 kV transformer is presented. The location of the turn faults along the height of the winding is varied to study the characteristics behavior of the transformer by computing transfer function. Details of modeling, simulation of turn faults, computations of neutral current and transfer function are presented in the paper. The effect of turn fault on the characteristic changes in the transfer function of the transformer is presented. It may be observed from the results that there seems a possibility to locate the position and identify the severity of the turn faults by studying the trends and correlating the percent change in frequency shifts with reference to no turn fault frequencies.

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