Impact of Axial Displacement on Power Transformer FRA Signature

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***Abstract*— Frequency response analysis (FRA) is gaining global popularity in detecting power transformer winding movement and core deformation due to the development of FRA test equipment. However, because FRA relies on graphical analysis, interpretation of its signatures is still a very specialized area that calls for skillful personnel to detect the sort and likely place of the fault as so far, there is no reliable standard code for FRA signature classification and quantification. This paper investigates the impact of transformer winding axial displacement on its FRA signature as a step toward the establishment of reliable codes for FRA interpretation. In this context a detailed model for a single-phase transformer is simulated using 3D finite element analysis to emulate a close to real transformer. The impact of axial displacement on the electrical distributed parameters model that are calculated based on the transformer physical dimension is examined to investigate how model's parameters including inductance and capacitance matrices change when axial displacement takes place within a power transformer.**

***Index Terms*--Power transformer, FRA, condition monitoring, finite element.**

I. Introduction

THE majority of transformers currently in service worldwide were installed prior to 1980 and as a result the bulk of the population is approaching or has already exceeded its design life. This poses a significant risk for utilities and other power network stakeholders as the impact of in service transformer failure can be catastrophic. The mechanical forces that a transformer is exposed to during faults, switching transients and other system events result in magnetic forces being imposed on the windings. If these forces exceed the withstand capability of the transformer, winding deformation may occur. One of the causes of transformer mechanical damages and windings deformation is the loss of clamping pressure because of insulation degradation resulted by ageing[1, 2]. While with only minor winding deformation transformer can still working normally, its capability to withstand any further through faults will gradually decrease. Therefore, it is very essential to identify any minor winding deformation as soon as possible and take a proper asset management decision to avoid disastrous failures including environmental hazards due to oil spillage. Winding deformation has various configuration moods such as spiral tightening, conductor tilting, radial buckling and collapse of the winding end supports and it is hard to identify these types of internal faults using conventional testing methods [3].One of the powerful diagnostic techniques in identifying internal faults of power transformers is the frequency response analysis (FRA) test. Since power transformer components including windings, core and insulation can be represented by equivalent electrical parameters comprising resistors, capacitors, and self / mutual inductances, the value of these electrical parameters will be altered for any mechanical fault within the power transformer and hence the frequency response of the winding will change accordingly [4]. FRA is an offline test to detect the mechanical damages to transformer windings. This test is conducted by injecting a sweep frequency, low voltage to one terminal of transformer winding and measuring the response across the other terminal of the winding with reference to the tank. The FRA response is the ratio between the magnitude of the response signal Vo and the source voltage Vi as a function of the frequency in decibel (dB). The FRA signature is considered as a fingerprint of the transformer that can be compared with its previous signatures to identify any changes to the fingerprint and hence identification and quantification of any mechanical deformation can be achieved. Transformers fingerprints however are rarely available, particularly for old transformers. In this case other comparison methods such as phase to phase comparison or comparing the signatures of sister transformers can be adopted. The frequency signature of a transformer winding is characterized by its resonances and anti-resonances frequencies and any type of mechanical faults will vary these characteristic in a particular way. While the testing technique is quite simple because of the development of FRA test equipment, FRA signature interpretation is still a very specialized area that calls for skillful personnel to detect the sort and likely place of the fault [5, 6].

In this paper, a detailed model based on physical dimension of a power transformer is simulated using finite element analysis to examine the influence of axial displacement on the transformer equivalent distributed parameters model. The extracted information of the finite element model are then used to build a transformer distributed parameters model to investigate the effect of axial displacement on the model's FRA signature.

II. Finite Element Analysis

Finite element method (FEM) is considered as a close to real emulation of power transformer as it considers all dimensions and material properties details of the physical transformer [9]. Axial displacement can be emulated by modifying the geometrical configuration of the windings [10, 11].

The Simplorer and Maxwell software are used to simulate the transformer model geometry shown in Fig.1. Maxwell software uses the Maxwell's equations to solve the magnetic and electric fields in order to extract the self/mutual inductance and capacitor matrices. 3-D model of the transformer is solved in magnetostatic and electrostatic solvers. Resistance of the windings is calculated using eddy current solver because of its dependency on the frequency. The high voltage (HV) and low voltage (LV) windings consist of 5 disks each that comprise 100 and 50 turns respectively.

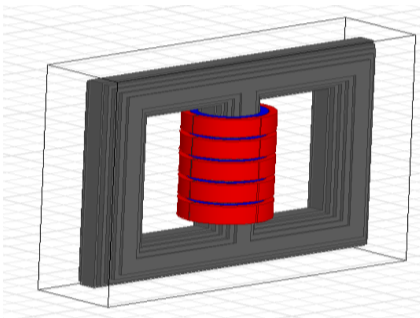


Fig. 1 3D model of one phase Transformer

The equivalent distributed parameters model consists of series resistance (R_s) and inductance (L_s) shunted by a capacitor (C_{sh}) and a conductance (G_{sh}). The capacitance between HV winding and LV winding (CHL) is shunted by dielectric conductance (GHL), and the mutual inductances (Mij) between relevant coils are represented. The dielectric insulation between the LV winding and the earthed core and that is between the HV winding and the earthed tank are simulated by a capacitance (Cg) and dielectric conductance (G) as shown in Fig. 2. The extracted parameters from physical geometry of the power transformer shown in Fig. 1 using 3D finite element analysis are given in the Appendix. The physical meaning of the model parameters allows the detection of the internal problem of the transformer.

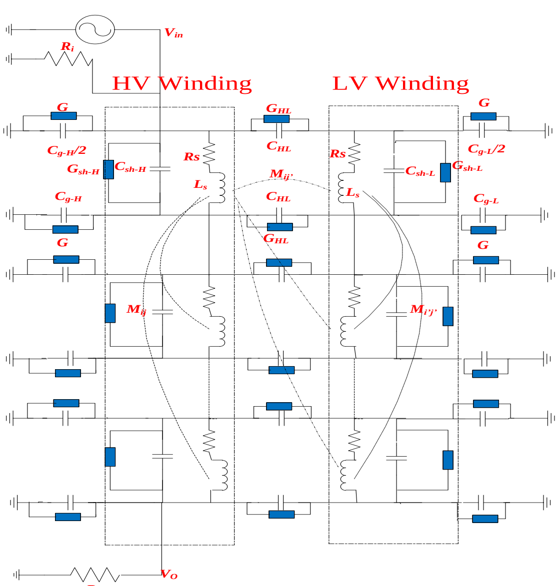


Fig. 2 Transformer distributed parameters model

A. Transformer parameters using FEM

Using vector potential formulation is preferable in solving magnetic problems in FEM, since the vector potential formulation can easily be related to both flux and magnetic energy. Maxwell's fourth equation states the fact that the flux density is divergence-free [11]. The vector potential is chosen so that

$B = \nabla \times A$ which fulfiles $\nabla.(\nabla \times A)$ (1)

The average complex flux can be obtained by integrating the vector potential across the conductor's cross-section as shown in (2). The reflected inductances and losses attributed to the windings can be used and represented in the model as linear lumped elements. These elements will be frequency dependent due to skin- and proximity effect. The average complex flux flowing through an element *j* can be found as below.

$$\phi_j = \frac{1}{S_J}\iint_{S_J} \vec{A}.\,ds \quad (2)$$

$$\phi_j = n_j \phi_j = \left(-L_{ij} + j\frac{R_{ij}}{\omega}\right).I_i \quad (3)$$

The mutual inductance and dielectric resistance due to the core can be calculated according to [12] as below.

$$L_{ij} = -n_i n_j \mathrm{Re}(\phi_j)/I_i \quad (4)$$

$$R_{ij} = \omega n_i n_j \ \mathrm{Im}\ \phi_j / I_i \quad (5)$$

Self-inductance and resistance can be calculated as:

$$L_{ii} = 2.\frac{n_i^2.\mathrm{Re}\{W_{mag,ii}\}}{I_{ii}^2} \quad (6)$$

$$R_{ii} = 2.\frac{n_i^2.\omega.\mathrm{Im}\{W_{mag,ii}\}}{I_{ii}^2} \quad (7)$$

Mutual inductance and resistance are calculated employing the parameters established in (6) and (7),

$$M_{IJ} = \frac{n_i.n_j.\mathrm{Re}\{W_{mag,ij}\} - \frac{1}{2}L_{II}.I^2 - \frac{1}{2}L_{jj}.I_j^2}{I_j.I_i} \quad (8)$$

$$R_{IJ} = \frac{n_i.n_j.\omega.\mathrm{Im}\{W_{mag,ij}\} - \frac{1}{2}R_{II}.I^2 - \frac{1}{2}R_{jj}.I_j^2}{I_j.I_i} \quad (9)$$

Where W(mag,ij) is the total magnetic energy when current is applied to both coil i and j. L_{jj} and L_{jj} are calculated using (7). Resistance and inductance can be derived in the same way as for the flux. The capacitance between two disks can be found by calculating the surface charges on the electrodes disk divided by the voltage between them.

$$C = \frac{Q}{V} \quad (10)$$

When calculating a capacitance matrix between a set of electrodes, (10) can be used to calculate the coefficients of the matrix as shown below.

$$C_{ij} = \frac{Q_j}{V_I} \quad (11)$$

Since the calculation of the total surface charge is based on a boundary integral, the accuracy depends on the subdivision/mesh on these boundaries. The calculation of the capacitance is similar to inductance-calculation and can be more accurate by using the electrostatic energy W_{el}.

$$W_{el} = \frac{1}{2}CV^2 \quad (12)$$

The self and mutual capacitances are calculated from the real part of the energy as shown below:

$$C_{ij} = \frac{\mathrm{Re}\{W_{el,ij}\} - \frac{1}{2}V_i^2 C_{ii} - \frac{1}{2}V_j^2 C_{jj}}{V_i.V_j} \quad (13)$$

$$C_{ii} = 2\frac{\mathrm{Re}\{W_{el,ii}\}}{V_i^2} \quad (14)$$

More details of calculating the capacitors between phases of transformer and between disks of windings can be found in [11]. These parameters are calculated for different axial displacement fault levels of the HV winding of the studied model using FEM and are compared with the parameters of the normal winding configuration as shown in tables I and II.

TABLE I
CAPACITANCE VARIATION DUE TO AXIAL DISPLACEMENT

Fault Percentage	$C_{gH\text{-}T}$ *pf*	C_{HL} *nf*	C_{sh} *nf*
Healthy	37.56	3.53	2.20
Axial Fault (5%)	38.917	3.20	3.9
Axial Fault (10%)	39.59	2.88	1.61
Axial Fault (20%)	41.37	2.45	1.15
Axial Fault (30%)	42.42	2.23	1.01
Axial Fault (50%)	44.62	1.89	0.518
Axial Fault (60%)	46.56	1.01	0.351

TABLE II
MUTUAL INDUCTANCE VARIATION DUE TO AXIAL DISPLACEMEN

Fault Percentage	Mutual Inductance (μH)
Healthy	142.25
Axial Fault (5%)	135.69
Axial Fault (10%)	110.56
Axial Fault (20%)	89.71
Axial Fault (30%)	50.42
Axial Fault (50%)	10.92
Axial Fault (60%)	0.45

When short-circuit forces result in deformed windings in a transformer, it is expected that the basic parameters of the winding model are altered as the geometry is changed. In order to build an accurate model involving such changes, it is essential also to identify precisely the impacted elements by each fault. When axial displacement takes place within a transformer, the leakage field at the ends of the windings spread out and a radial component of the leakage field is formed. This radial field causes axial force to increase along the winding. As long as the ampere-turns are balanced, the net force would be zero and the only force happening is a compressed force. Once the ampere turns become imbalanced axially, the total force will rise this imbalance [14]. This causes the impacted winding to move axially as shown in Fig. 3.

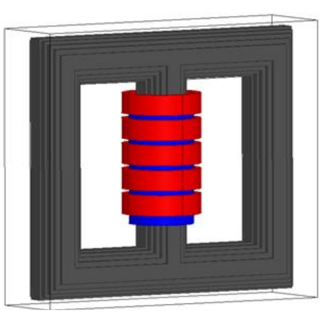
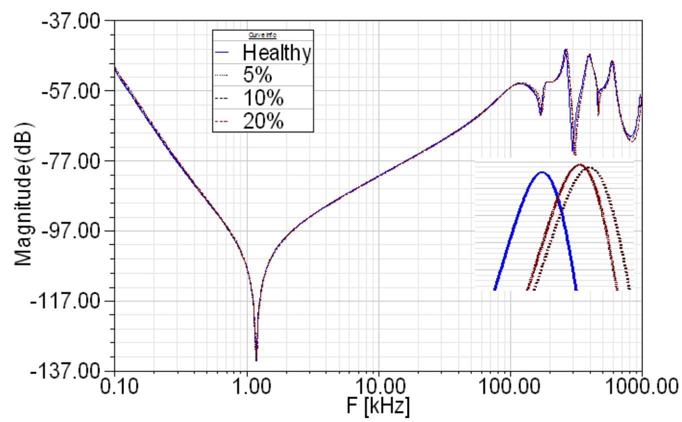


Fig. 3 3DAxial displacement

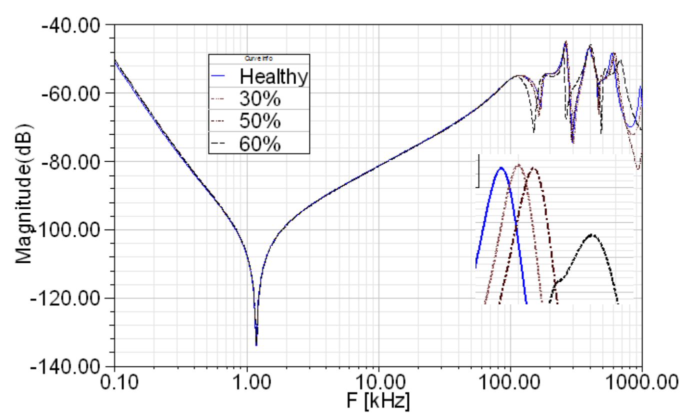
According to [4], in the case of an axial displacement , a change in the magnetic and electric fields can be observed. The axial displacement changes the elements of the inductance matrix that describe the mutual inductance between disks of HV winding and disks of LV winding. In addition, the changes of capacitance can be neglected in the distributed parameters model for axial displacement studies. This however is not reliable way to emulate axial displacement on a distributed parameters model as Table I shows that even though the change in distributed capacitances due to axial displacement is not significant, it has to be taken into account in simulating axial displacement fault on power transformer distributed parameters model as it will influence the FRA signature of the model as will be elaborated below.

III. SIMULATION RESULTS

In order to further understanding the effects of model parameters in FRA testing, sensitivity of the model's FRA signature to different severity levels of axial displacement is performed. Parameters in tables I and II for healthy and faulty transformer model calculated using FEM are used for the distributed parameters model shown in Fig. 2 to plot the FRA signature for healthy and faulty cases. The FRA signature for the transformer model shown in Fig. 2 is performed by energizing the HV winding by a 10 V, variable frequency sinusoidal source and the response is measured at the other terminal of the winding. The input / output coaxial leads used in practical measurements are represented by 50 Ω resistors (Ri and Ro in Fig. 1) and the transfer function (TFdB=$|V_0/V_i|$) is plotted against frequency



(a).5%-20% axial displacement



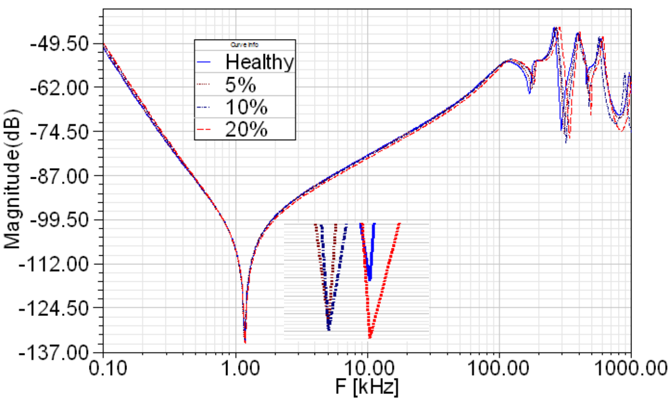
(b).30%-60% axial displacement

Fig. 4. FRA signature for axial displacement (considering only Inductance variation)

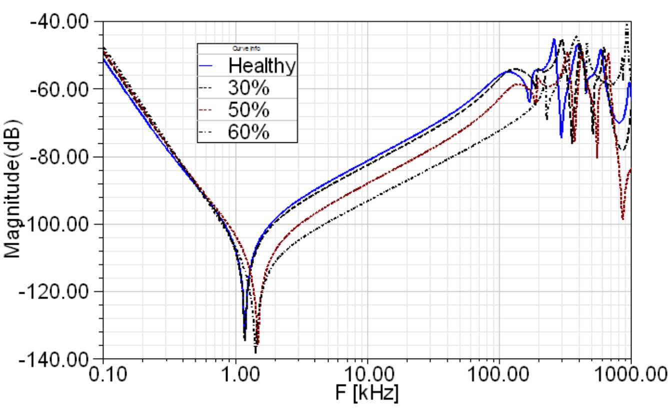
Fig. 4.a shows the influence of 5%, 10% and 20% of axial displacement on the FRA signature of the HV winding when it is moved axially upward when variation in mutual inductance

is only considered. This fault has no effect on the FRA signature in the low frequency range. However, after 100 kHz a minor shift of resonances and anti- resonances frequencies to the right with visible changes in the magnitude can be observed. This confirms the previous work done in [4] that in Axial displacement variations starts after 100kHz. Fig.4.b shows that an increased percentage level of axial displacement, more variations on FRA signature can be observed.

According to the FEM results, accurate axial displacement can be emulated on the distributed parameters model by considering the change in distributed capacitances as well as mutual inductances. Fig.5 shows the impact of different axial displacement levels on the FRA signature of the model shown in Fig. 2. Fig. 5 reveals that variations in FRA signature starts slightly at low frequency range and is observable at the high frequency range. As the percentage level of the fault increases to 60% this variation is more visible at low frequency range and rises at high frequency range. The trend of resonances and anti-resonances frequencies shifting still in the right direction as in the pervious studied case.



(a).5%-20% displacement



(b).30%-60% displacement

Fig.5. FRA signature for Axial displacement (considering both Inductance and Capacitance variation)

The result of Fig .5 shows that variations of capacitance matrix should be taken into account to precisely emulate axial displacement on transformer distributed parameters model as it influences its FRA signature.

IV. CONCLUSION

This paper presents a comprehensive simulation analysis to explore the impact of transformer winding axial displacement on the individual parameters of high frequency transformer distributed parameters model using finite element method which shows that axial displacement impact both inductance and capacitance matrix of the transformer model. In contrary to the published papers in the literatures that only considered the variation in the mutual inductance matrix, which impact the FRA signature in the middle frequency range, an observable change in the entire frequency range of the FRA signature can be observed by considering the variation of capacitance matrix as well.

APPENDIX

EXTRACTED PARAMETERS OF THE TRANSFORMER LINEAR MODEL BY USING FEA

	R_s	L_s	C_{sh}	C_g	C_{hl}	$1/G$
HV	1.2Ω	145μH	2.20nF	37pF	3.53nF	7 MΩ
LV	0.75Ω	110μH	0.2nF	6pF	3nf	7 MΩ

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