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Frequency Response Analysis using High Frequency Transformer Model

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Abstract–**The concept of Frequency Response Analysis (FRA) has been successfully used as a diagnostic technique to detect winding deformation, core and clamping structure for power transformers. The main problem about FRA techniques is to interpret the observed evolution of the frequency response in order to identify failures. Transformer high frequency computer modeling is proposed in this work to be used with the practical FRA measurements. The physical meaning of the model parameters allows the identification of the problem inside the transformer. Two high frequency transformer models based on lumped and distributed parameters approaches are investigated. A comparison of both models is conducted using their transfer function plots, and hence based on the amount of information revealed from the plots, a distributed model is chosen for further analysis. The model validation is carried out through the comparison of the simulation and field results. Mechanical and short circuit faults are simulated into the model to compare the differences in the frequency response of healthy and deformed transformer signatures. The advantage of this technique is that the FRA measurements can be obtained from meaningful parameters that can aid interpretation and classification of FRA signatures.**

I. INTRODUCTION

Power transformers are critical links within a power network and hence any failure can potentially cause long interruptions and costly repairs. They are subjected to heavy loading often in a very hostile environment which can lead to considerable damage to property, environment and potential risk to human life. Traditionally, routine preventative maintenance programs combined with regular testing were used [1, 2]. The increased need to reduce maintenance costs and equipment inventories has led to a reduction in routine maintenance. Hence instead of doing maintenance at a regular interval, it is now carried out only if conditions of the equipment require it [3, 4]. One mode of transformer failure is winding deformation. Winding deformation may be caused by the mechanical forces exceeding the winding withstand capability during short circuit faults [5]. This can occur either when the force is beyond the design limits such as tap-changer failure or the capability is reduced due to a loss of clamping pressure caused by ageing of the winding insulation [6]. The latter is of a great concern since most of the transformers in the power system network have been operational for about 30 to 40 years with the exclusion to the new installations arising due to the ever increasing power demand. Small winding deformations need to be identified because although the transformer may still be capable of normal service the short circuit withstand capability is probably reduced. Every transformer has a unique transfer function which is considered as a "finger print" or "signature" that can be used to analyse the internal structure without dissembling the equipment [7]. The concept of Frequency Response Analysis (FRA) has been used for detecting winding deformation that can be caused by several fault conditions in a transformer [6-15]. A transformer represents a nonlinear system and its electrical equivalent circuit is very complex network of distributed resistive, capacitive, inductive elements and conductors between high voltage and low voltage windings. Hence, the frequency response of a transformer is dependent on the formulation of complex series and parallel resonant circuits. Deformation results in relative change to the inductance and capacitance of the winding structure, which can be detected externally by FRA method. The tests are conducted off-line by measuring the input/output relationships as a function of frequency in a typical range of 2 MHz to provide a current state wave form of the transformer [16], which is then compared with the signature wave form. Any change in the parameters of the transformer will show the effect of these changes in the transfer function plot. Resonant frequency shifts in the FRA measurement are the key parameters to indicate winding deformation. This method is capable of diagnosing several other faults such as partial discharge, ground leakage, displacement, local breakdown and many more [17]. In this paper a comparison of two transformer models for FRA studies is investigated. The model validation is carried out through the comparison of the simulation and experimental results. Simulation of winding deformation and interpretation of the differences in the healthy and deformed winding FRA signatures is also presented.

II. TRANSFORMER MODEL

The practical application of any diagnostic technique to detect mechanical damage in a transformer depends on its sensitivity to any change in the distributed inductance and capacitance. Transformer can be modelled by a string of inductances to earth and shunted by their stray capacitances between windings. The equivalent circuit is useful in modelling the sensitivity of FRA to winding changes. It also can be used for the localization of partial discharges [18]. A change in response could be related to a calculated amount of winding deformation. FRA results can be used to construct models of transformer winding. These models can be used to relate frequency response data to the transformer mechanical structure and to quantify significant winding changes. High frequency transformer models are based on lumped or distributed circuit approaches where elements of transformer including windings, core, etc are represented by electrical parameters that can be measured or calculated. The selection of these parameters determines the accuracy of the model. The two transformer models are investigated in the following subsections.

A. Lumped Parameter approach

Constant power frequency models provide a good basis for the development of variable frequency models. However, there are three major shortcomings:

(i) They fail to recognize the insulation systems of the transformer as electrical entities.
(ii) They fail to consider the changing effects of the core with respect to frequency.
(iii) They fail to account the effects of varying frequency on transformer parameters.

A transformer equivalent circuit lumped approach based was proposed by Douglass [19] as shown in Fig. 1.

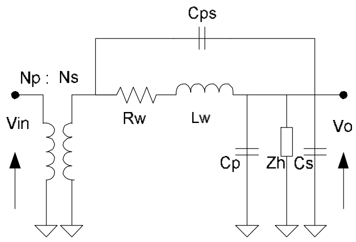

Figure 1, Transformer lumped parameters equivalent circuit

In the model the following parameters are in their lumped form and all referred to the secondary side:

(i) an ideal transformer for ratio purposes only.
(ii) C_p and C_s represent the primary and secondary winding capacitances to ground respectively.
(iii) L_w is the equivalent leakage inductance of the primary and secondary windings.
(iv) Z_h is the core exciting impedance (resistance and inductance in parallel).

The transfer function of the circuit shown in Fig. 1 can be written as:

$$\frac{V_o}{V_i} \quad \frac{\frac{C_{ps}}{C_{eq}} s^2 (s \quad \frac{R_w}{L_w})}{s^3 \quad s^2 (\frac{R_w}{L_w} \quad \frac{1}{R_h C_{eq}}) \quad s \frac{1}{C_{eq}} (\frac{-1}{L_h} \quad \frac{R_w}{L_w R_h} \quad \frac{1}{L_w}) \quad \frac{R_w}{L_h L_w C_{eq}}} \qquad (1)$$

Where

$$C_{eq} \quad C_s \quad C_p \quad C_{ps}$$

The design data of the transformer is used to compute the inductances and capacitances shown in the above equation[20].

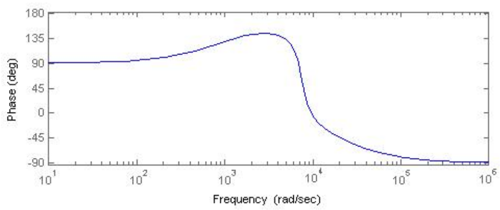

Figure 2. Phase plot of the model TF

It can be observed from the transfer function and its phase plot shown in Fig. 2 that at low frequencies, the influence of capacitance is negligible and the winding behaves as an inductor. This is due to the fact that at low frequency range, flux penetration of the core is significant and hence Z_h, the core excitation impedance, is included. As the frequency increases, the circuit capacitances dominate and tend to shunt the winding inductance. The core will likely have some effect at the lower frequencies and skin effect will become a factor at higher frequencies.

To validate model accuracy, experimental FRA was carried out on a 15 MVA 22/0.415 kV power transformer (vector group dY11). The test conditions were oil winding temperature 25°C, ambient temperature 22°C and relative humidity 46%. Figure 3 shows a comparison of the frequency response of the model and the actual FRA signature measured using sweep frequency response analyzer.

The experimental FRA signature reveals that the frequency range less than 10 kHz, the response is characterized by resonance at 7 kHz corresponding to the half-wave space harmonics in the winding due to the low impedance terminations of the measuring circuit. In the low frequency range the transformer winding response is dominated by inductance. As the frequency increases more space harmonics are built up in the winding. In the medium frequency range multiple resonances can be observed over the entire frequency range. In the low frequency range the oscillation is most likely to be affected by coil configuration, in the middle range by layer and section effects and at higher frequencies by individual turns.

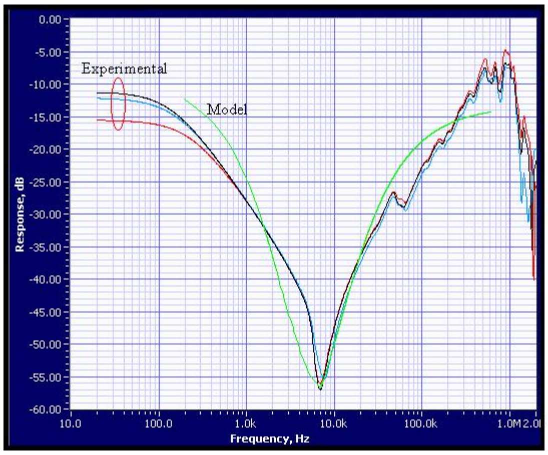

Figure 3. Transformer actual and lumped parameters model frequency responses

As can be shown in Fig. 3, in the high frequency range, the model and experimental responses are correlated to far extent. However, model signature can not reflect all resonance and anti-resonance frequencies seen in the practical measurements. Also it can be observed that at low frequency range, the experimental response tends to shift towards left. This may be attributed to the presence of residual magnetism in the core. The model can not simulate the distortion appears in the very high frequency range which is most probably caused by the end leads associated with tap-changer leads and bushing tails.

B. Distributed parameter approach

The transformer can be modelled with sufficient accuracy as a distributed analogue R-L-C circuit over a wide frequency range. Miki et al [21] shows that the effect of iron core had minimal role to play in an impulse stressed winding. This agrees well with the fact that in a rapid transient condition the flux lines tend to centre around the conductors rather than penetrating the iron core and for high frequency components of surges the iron core acts effectively as an earthed boundary [4]. Recent studies [12, 22] have neglected the effect of distributed shunt conductance. This will be a valid assumption for impulse voltage distribution analysis in the case of a faultless transformer, but may not be adequate in the case of fault diagnosis. Neglecting shunt conductance in the equivalent circuit will eliminate the study of leakage fault inside a transformer which could have been caused by several reasons such as insulation damage, ground shield or hot spots. The equivalent model (neglecting shunt conductance) could be ideal for verifying measured transfer function for inter-disc, coil short circuit and winding displacements. Hence the model needs a variation to incorporate the study of leakage faults and partial discharges in the winding. These shortcomings of the computational model can be overcome if parameters which would allow for simulation of ground leakage and void in the insulation are taken into consideration. The distributed transformer model equivalent circuit shown in Fig. 4 has been proposed in this paper. A single transformer winding is divided into cascaded pi-network comprising self/mutual inductances, resistance, series/shunt capacitances and shunt dielectric conductance. The overall transfer function of such network shows poles as the resonant frequencies of the winding model. Breakdown between turns or coils of winding under test corresponds to short circuit of one of the local LC network with a shift in resonant pole to another frequency.

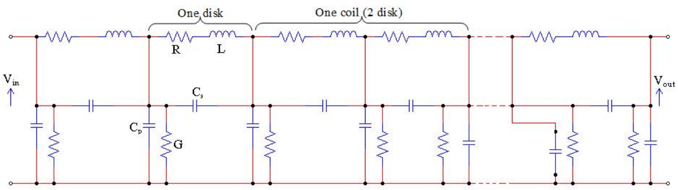

Figure4. Transformer distributed parameter model

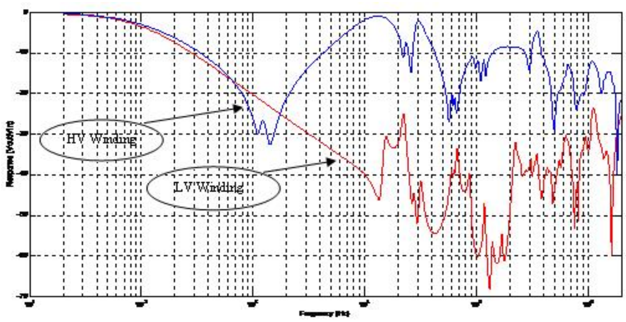

Figure5. Frequency response of the distributed parameter model

Figure 5 shows the high and low voltage windings frequency responses of 21 coils of the circuit shown in Figure 4. The number of resonant points is directly related to the intrinsic characteristics of each transformer and hence the concept of "finger print" or "signature". Unlike the lumped parameter model, more information of the windings can be deduced from the frequency response of a distributed parameters model. The parameters of the model can be calculated/measured using the design data of the transformer [20, 23-26].

To show the effect of the number of disks taken into account in the model on the frequency response, simulation using 4 and 20 disks has been performed. Figure 6 shows the impedance plot with a varying sweep frequency up to 100 kHz for each model. As shown in Fig. 6, the starting resonant frequency shifts to the left with increasing number of disks. Also, the number resonance and anti-resonance frequencies increase with increasing the number of disks.

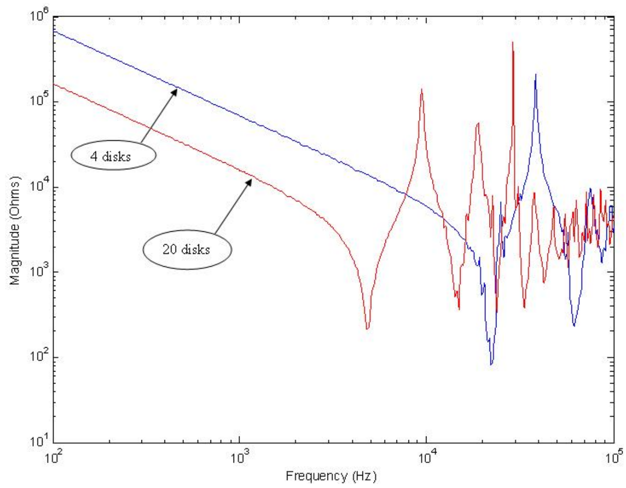

Figure 6. Impedance plot with varying disk numbers

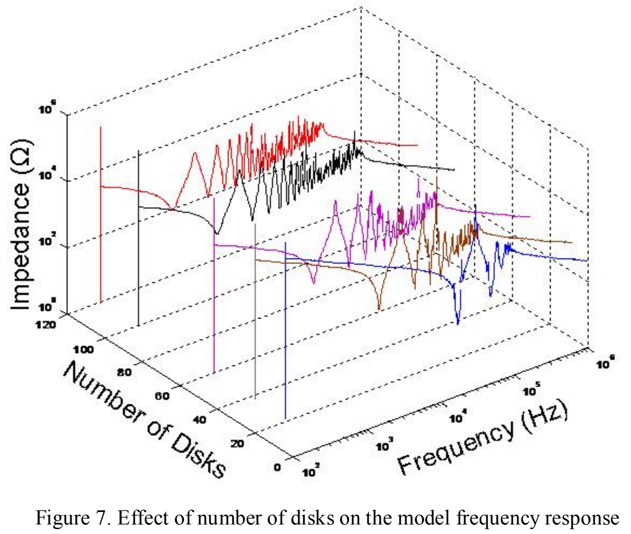

Figure 7. Effect of number of disks on the model frequency response

Figure 7 shows the frequency response of five models with different number of disks (20, 40, 60, 100 and 120). As have been observed in Fig. 6, the starting resonant frequency shifts to the left as the number of disks increases and the number of resonance and anti-resonance frequencies increases with increasing the disk numbers.

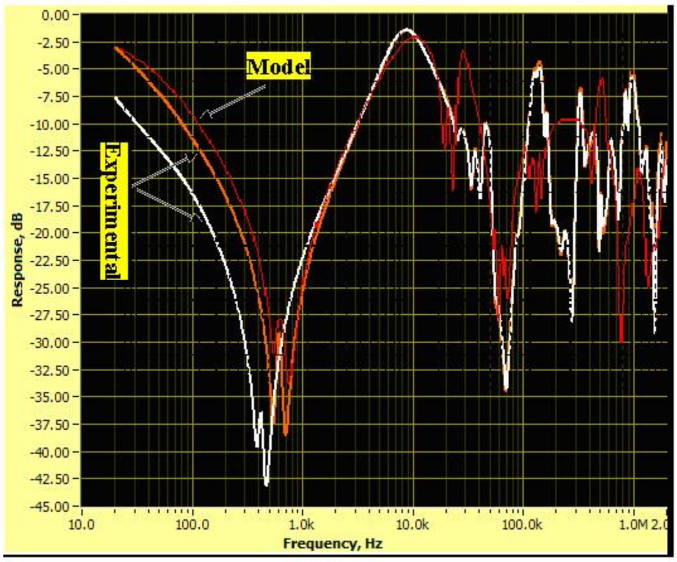

Figure 8. Transformer actual and distributed parameters model frequency responses

The simulation results are compared with the experimental FRA measurements carried out on 250 MVA, 345/16 kV transformer. Figure 8 shows a good correlation between the model and experimental results. Unlike lumped parameters frequency response, the distributed parameters frequency response reveals most of the resonance and anti-resonance frequencies appearing in the actual response. The shift between the experimental response and the model response in the low frequency range is attributed to the presence of residual magnetism in the actual core. The shift in resonant frequencies and the difference in the peak amplitudes of the model and experimental frequency responses at higher frequency range are attributed to the accuracy of the parameters values used in the simulation. Moreover, the following model constrains affect its results:

i. The incremental mutual inductance of the distributed model was lumped into the single series inductance.
ii. In a practical case, a transformer will have a component of energy loss through partial discharges, but the model assumes that this loss is negligible and hence had no effect on the overall results.
iii. The period of analysis (transient study period) was assumed to be very small compared to the time constant of the polarization process in the insulation

III. FAULT ANALYSIS

To identify the features of winding deformation and effect of model parameters on FRA signature, some faults such as buckling stress of inner winding, axial displacement and turns short circuits have been simulated. A comparison between the healthy and deformed signatures will help interpreting the actual FRA responses. The advantage of this methodology is that the meaningful physical parameters change can aid interpretation and classification of actual FRA signatures [27].

A. Buckling stress

Buckling stress will push windings inwards and enlarges the inter-winding distance. As an effect, the inter-winding shunt capacitance will be reduced. This fault type is simulated by reducing the shunt capacitance of disks 19-20 by 20%. A comparison of the impedance plot before and after capacitance change is shown in Fig. 9.

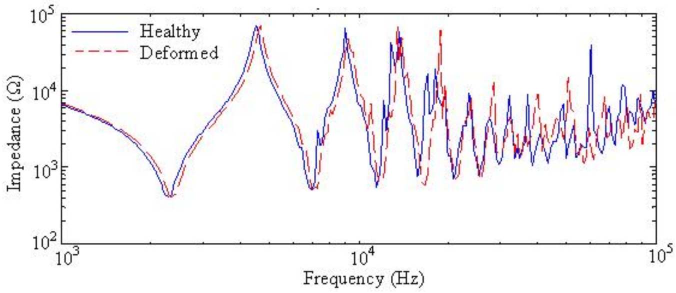

Figure 9. Shunt capacitance effect on FRA signature

As shown in Fig. 9, the effect of reducing the shunt capacitance is pronounced in the regions of frequencies higher than 10 kHz where the amplitude will be slightly changed and resonant frequencies which are the key parameter to indicate winding deformation will shift to the right side.

B. Axial displacement

Winding axial displacement changes the relative position of the winding and can be simulated by changing the mutual inductance between windings. Figure 10 shows the effect of inductance change on the frequency response. As seen from the figure, this change has no effect on the amplitude. However, resonant frequency locations will be altered and some anti-resonant frequencies will be created. The effect is more pronounced in the low frequency range.

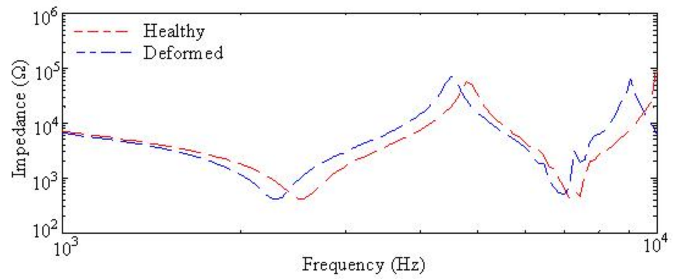

Figure 10. Inductance effect on FRA signature

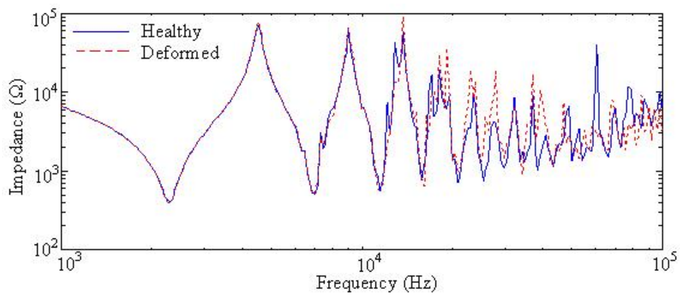

Figure 11. Effect of short circuit fault on FRA

C. turn to turn short circuit

This fault can be simulated by short circuit series resistors. Figure 11 shows the effect of short circuit the resistances of disks 9-10. This will affect the amplitude in the high frequency range. Also, some of the high frequency resonant points will be shifted due to the fact that the shunt capacitor will be also shorted as can be seen from the circuit model shown in Fig. 4.

IV. CONCLUSIONS

The main problem about FRA techniques is to interpret the observed evolution of the frequency response in order to identify failures. This paper investigates the transformer high frequency models to be used along with FRA classification and interpretation. Two high frequency transformer models based on lumped and distributed parameters approaches have been investigated. Comparison of the frequency response of the two models with the actual FRA signature has been elaborated. Results show that distributed parameters model can reveal most of resonance and anti-resonance frequencies that exist in the experimental FRA measurement. However, model based on lumped parameters approach fails to correlate with the actual measurements. Various winding deformation are simulated as the change in the electric parameters of the distributed model and a general interpretation of results is done. The physical meaning of the model parameters allows the identification of the problem inside the transformer. The simulation model is very accurate to emulate experimental FRA signature and hence it can be used in conjunction with field FRA measurement to help interpretation for its results. The proposed model is easy to implement and can be used as a successful tool for FRA and condition monitoring of power transformer.

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