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# Impact of Transformer Model Parameters Variation on FRA Signature

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*Abstract*-- Power transformers are critical components within the electrical power network. In the event that a failure occurs in service, the impact can be far reaching. Not only causing extended outages, but costly repairs and potentially serious injury or fatality can result. 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. However, because FRA has been relying on graphical analysis, it calls for an expert person to analyse the results. So far, there are no standard codes for FRA interpretation. This paper investigates the impact of parameters variation of a high frequency transformer model based on distributed parameters approach on the FRA signature. The physical meaning of the model parameters allows the identification of the problem inside the transformer and helps in establishing a standard code for FRA signature interpretation.

**Index Terms** -- Condition monitoring, power transformer, frequency response analysis.

## I. INTRODUCTION

THE majority of transformers currently in service were installed prior to 1980 and as a result the bulk of the population is approaching or has already exceeded its design life [1, 2]. This poses a significant risk for utilities and other power network stakeholders as the impact of an in service transformer failure can be catastrophic. Transformer age is determined by the condition of its insulation and an ageing transformer population greatly increases the likelihood of failure [3]. 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 can occur [4]. One of the reasons a transformer experiences mechanical damage to the windings is as a result of loss of clamping pressure due to insulation degradation caused by ageing. With only minor winding damage the transformer is still capable of normal operation however its ability to withstand faults is greatly reduced. As a result of the ageing asset population, it is becoming more critical to detect even slight winding deformations as early as possible. Transformers are expected to survive a number of short circuit faults without failure but once any significant winding deformation is produced, the likelihood of surviving further short circuits is greatly reduced because of the locally increased electromagnetic stresses.

Furthermore, any reduction in winding clamping due to insulation shrinkage caused by ageing will also increase the probability of failure by reducing the mechanical strength of the winding assemblies [5]. Winding deformation can take many forms including radial buckling, conductor tilting, spiral tightening and collapse of the winding end supports. It is difficult to detect these types of internal faults with traditional testing techniques [6]. Frequency response analysis (FRA) is a powerful diagnostic method in detecting transformer winding deformations. Since transformer windings can be modelled as a network of capacitance, resistance, self-inductance and mutual inductance; the values of these parameters are altered when a fault occurs on the winding, and hence the frequency response of the winding will change accordingly [7]. FRA is an offline test and is used to measure the input/output relationship as a function of frequency (typically in the range of 2 MHz). This provides a fingerprint of a transformer and is compared with its previous signatures to detect winding displacement. However, the fingerprints are rarely available, especially for transformers in service. Thus other information such as comparison between identically constructed transformers has to be taken for diagnosis. To conduct an FRA test, a sweep frequency voltage of low amplitude is applied to a transformer terminal and the response voltage is measured across another transformer terminal with reference to the tank. The FRA response is the ratio between the amplitudes of the response signal  $V_o$  and the source voltage  $V_i$  as a function of the frequency expressed in dB. The input, response and reference coaxial cables are tapped together near the top of the bushing. A ground extension is run along the body of the bushing down to the flange to connect it to the tank. While the testing method is relatively simple since the development of specific FRA test equipment, conventional FRA has been relying on a graphical analysis for transformer diagnosis, which requires trained experts to interpret test results and to identify failures as so far, there is no reliable code for FRA signature interpretation [8]. This paper introduces sensitivity study for various high frequency transformer model parameters variation on the FRA signature. The physical meaning of the model parameters allows the identification of the problem inside the transformer and helps in establishing a standard code for FRA signature interoperation.

## II. TRANSFORMER MODEL

The term "Frequency Response" refers to the steady state response of a system to a sweep frequency sinusoidal voltage of low amplitude [9]. In this paper, the impact of various parameters variation of the distributed transformer model shown in Fig. 1 on the frequency response of the model is examined [10-15].

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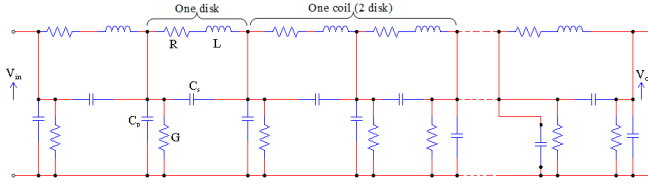


Fig. 1. Transformer distributed parameters model.

In Fig. 1, a single transformer winding is divided into cascaded pi-network comprising self/mutual inductances, resistance, series/shunt capacitances and shunt dielectric conductance. For simplicity, it is assumed that the mutual inductances are lumped into series inductances. The overall transfer function of such a 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 R-L-C network with a shift in resonant pole to another frequency. Based on this model, the transfer function of a transformer can be analyzed and any changes in inductance and capacitance are shown as either a shifting of an existing, or creation of a new resonant pole frequency. This method relies on the principle that every transformer has a distinctive transfer function, commonly known as a “fingerprint”. This is due to the complex capacitive and inductive impedance relationships between the winding, core and tank of a transformer which results in a non-linear response that is unique to each individual unit. Changes in resistances are shown as either an increase or decrease in transfer function magnitude at critical frequencies [16]. Winding inductances and capacitances are a function of material properties and geometry, and any winding movement will result in substantial changes to these values at a local level. There is direct relationship between geometric configuration of the winding and core within a transformer and the distributed network of resistances, inductances and capacitances that make it up [17].

TABLE I  
TRANSFORMER ELECTRICAL PARAMETER AND FAULT TYPE  
RELATIONSHIP

Physical Parameter	Type of Fault
Inductance	Disk deformation, local breakdown, winding short circuits.
Shunt Capacitance	Disc movements, buckling due to large mechanical forces, moisture ingress, loss of clamping pressure.
Series Capacitance	Ageing of insulation.
Resistance	Shorted or broken disk, partial discharge.

Table I outlines a number of physical parameters of the transformer impedance network and the type of fault these are associated with [18, 19]. When a transformer experiences an event that results in deformation of the windings the impedance relationships vary and this alters the transfer function. These changes to the transfer function can be detected through the use of the FRA technique, even if they are only minor variations. Diagnosis of the problem is achieved by comparing the healthy transformer fingerprint to the faulty one and identifying discrepancies in the two transfer functions.

### III. SIMULATION RESULTS

In this paper, 102 disk of the power transformer model

shown in Fig. 1 was simulated. A sweep frequency AC source of low amplitude ( $V_i$ ) is connected to the input terminals while the response ( $V_o$ ) is measured across the output terminals. The magnitude of the transfer function ( $V_o/V_i$ ) in dB as a function of the frequency is plotted. In order to analyze the sensitivity of the proposed approach, variations were made to individual electrical components in a number of disk locations in the transformer model and the results were compared to the transformer signature with base parameters as will be elaborated in the following sub-sections.

#### A. Effect of Self/Mutual Inductance

The value of inductance ( $L$ ) in disks 41 to 50 is changed by  $\pm 10\%$ . The FRA signature in each case is compared to the FRA signature that obtained using the base values as shown in Fig. 2 (a) and 2 (b), respectively.

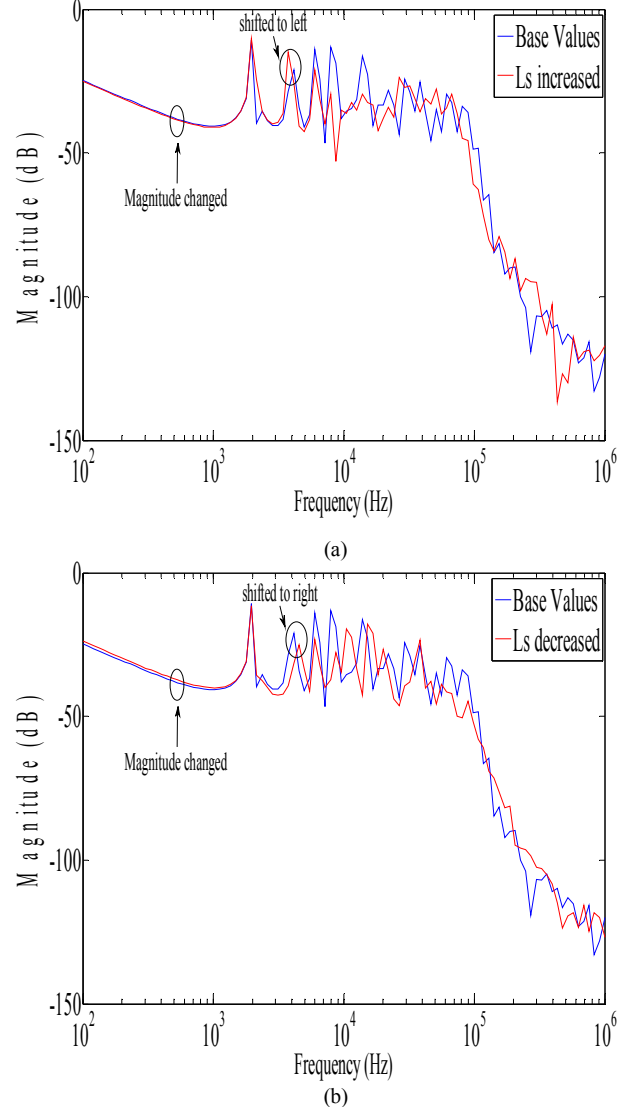


Fig. 2. Effect of inductance variation on the FRA signature.

As can be seen in Fig. 2 (a), increasing the inductance will shift the resonance and ant-resonance frequencies to the left over the entire range of frequency. It will also have a minor impact on the amplitude. On the other hand, decreasing the inductance value will shift the resonance and anti-resonance frequencies to the right when compared with the base values-

signature as shown in Fig. 2 (b). It is worth to mention that, the effect of varying  $L$  is more dominant in the low and medium frequency range.

### B. Effect of Series Capacitance

The value of  $C_S$  in disks 41 to 50 is changed by  $\pm 10\%$ . The FRA signature in each case is compared to the FRA signature that obtained using the base values as shown in Fig. 3 (a) and 3 (b) respectively.

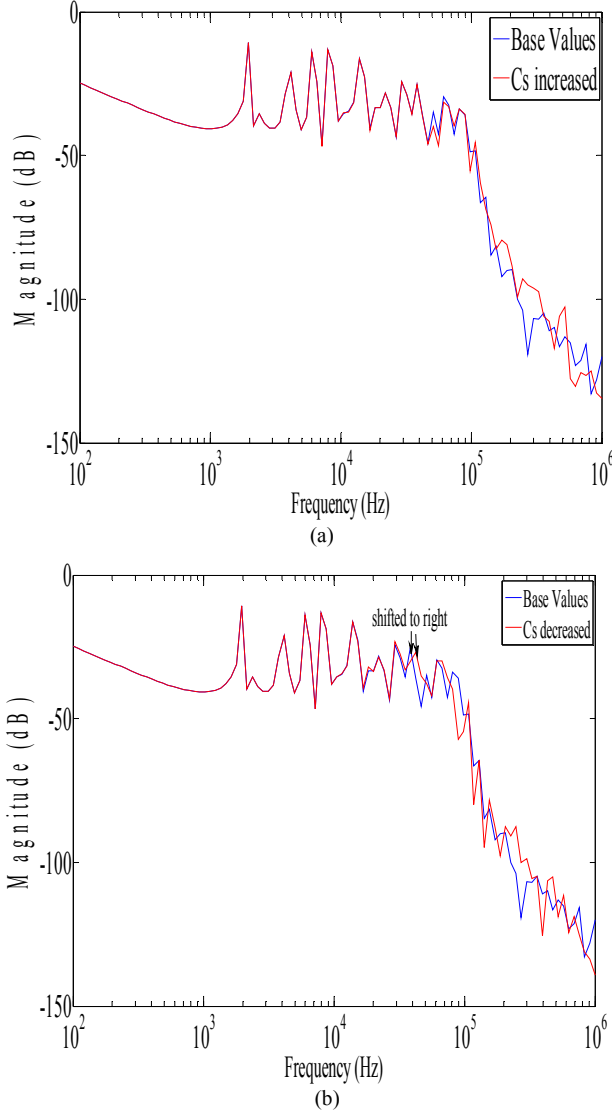


Fig. 3. Effect of series capacitance on the FRA signature.

As can be shown in Fig. 3 (a) and (b), the effect of series capacitor is prominent in the high frequency range. In both cases resonance and anti-resonance frequencies will shift to the right. The frequency shift is more observable in case of increasing the value of  $C_S$ .

### C. Effect of Series Resistance

The value of  $R$  in disks 41 to 50 is changed by  $\pm 10\%$ . The FRA signature in each case is compared to the FRA signature that obtained using the base values as shown in Fig. 4 (a) and 4 (b) respectively.

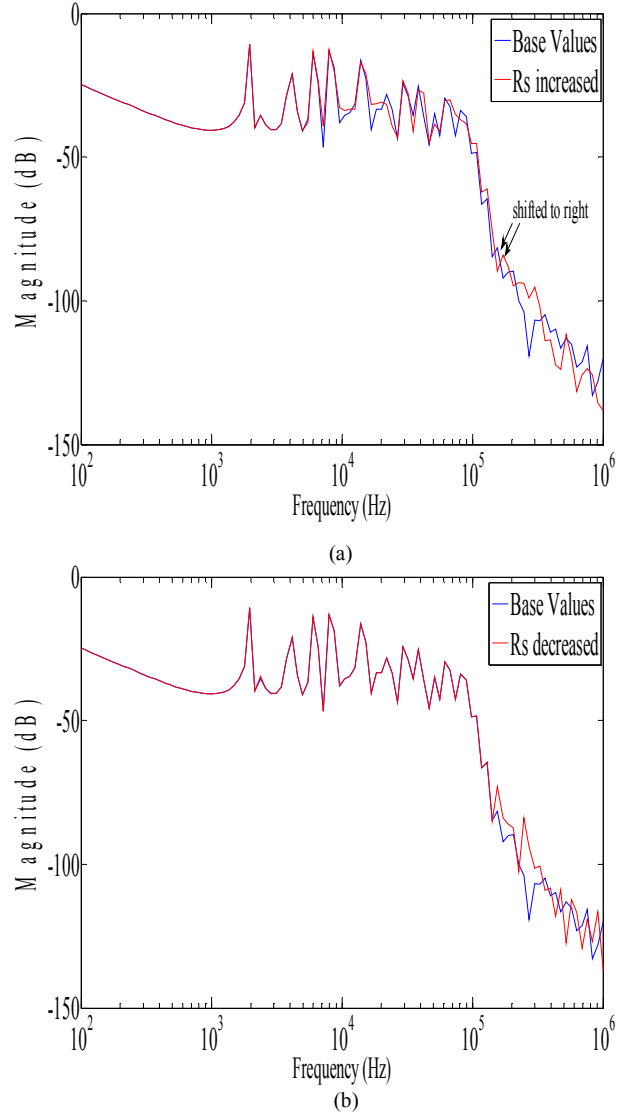


Fig. 4. Effect of series resistor on the FRA signature.

As can be seen in Fig. 4 (a), increasing the value of the series resistance will introduce minor impact on the amplitude in the medium and high frequency range. Also, some high frequency resonance frequencies will shift to the right. Decreasing the value of the series resistance will not have any impact on the FRA signature except in the very high frequency range where the amplitude will be slightly affected.

### D. Effect of Shunt Capacitance

The value of  $C_P$  in disks 41 to 50 is changed by  $\pm 10\%$ . The FRA signature in each case is compared to the FRA signature that was obtained using the base values as shown in Fig. 5 (a) and (b), respectively. The effect of increasing  $C_P$  is more visible in the high frequency range, where resonance frequencies will shift right with little impact on the amplitude (Fig. 5 (a)). On the other hand, decreasing  $C_P$  (Fig 5 (b)) will affect the amplitude of the FRA signature in the entire frequency range and resonance frequencies in the medium and high frequency range will be shifted to the right.

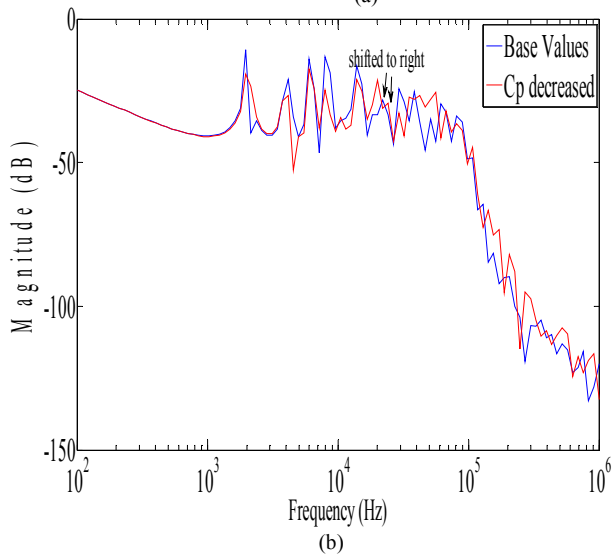
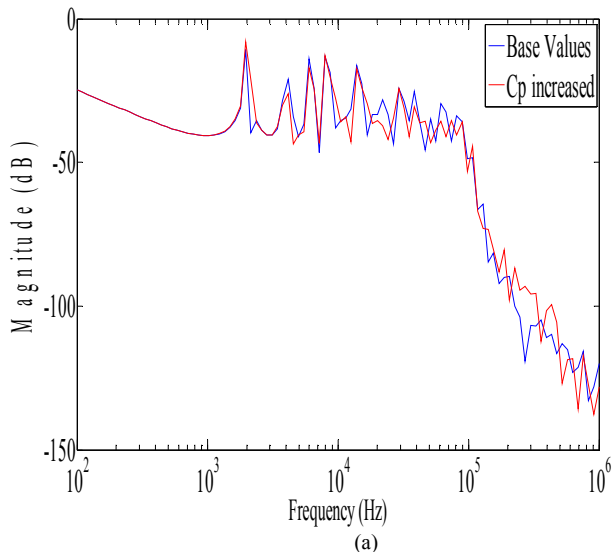


Fig. 5. Effect of shunt capacitance on the FRA signature.

#### E. Effect of Shunt Conductance

Neglecting the 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. Leakage fault can be simulated by increasing the shunt conductance.

The value of  $G$  in disks 41 to 50 of the model shown in Fig. 1 is increased by 10% and 50% and the FRA response for each case is plotted and compared to the FRA response that was obtained using the base values as can be seen in Fig. 6 (a). The impact of increasing  $G$  is only visible in the very high frequency range for 50% change while increasing  $G$  by 10% will not have any impact on the FRA signature over the entire frequency range as can be shown in Fig. 6 (a). In fact, increasing  $G$  by any value less than 50% will not have any impact on the FRA signature. The impact of decreasing  $G$  by any value will not have any impact on the FRA signature as can be shown in Fig. 6 (b). This is attributed to the fact that the lower conductance value is corresponding to a higher dielectric strength and consequently the probability for leakage fault to occur is reduced.

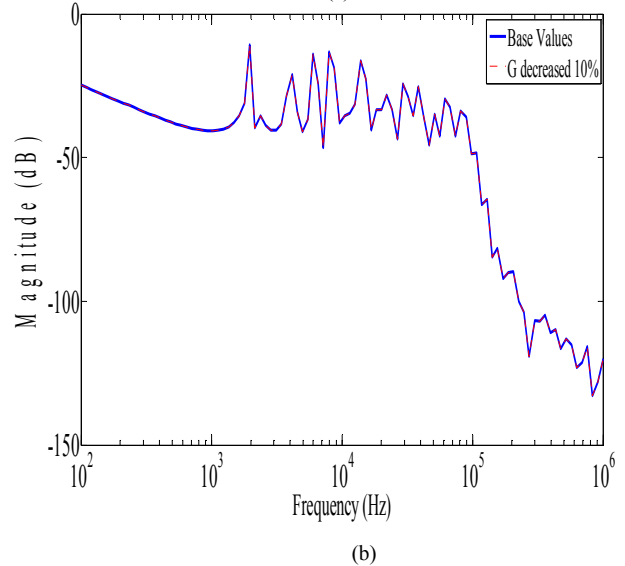
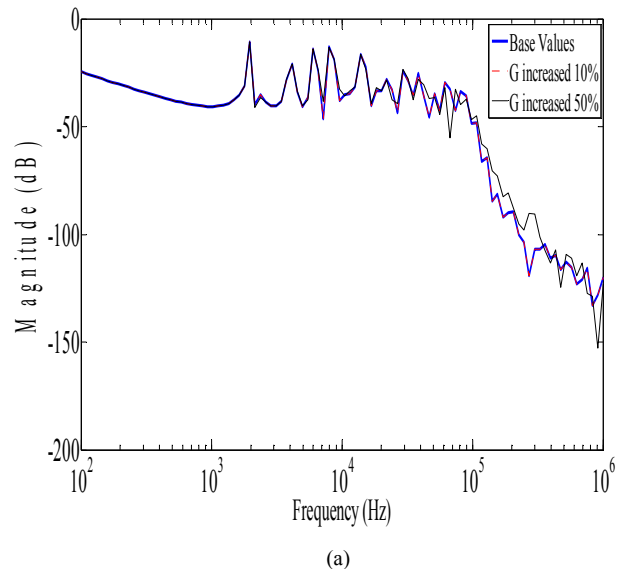


Fig. 6. Effect of shunt conductance on the FRA signature.

Table II summarizes the impact of the high frequency transformer model parameter variation on the FRA signature. It can be observed from the table that in the low frequency range, the transformer winding frequency response is dominated by the series inductance and the influence of capacitance is negligible. This is due to the fact that at low frequency range, flux penetration of the core is significant. As the frequency increases, the circuit capacitances dominate and tend to shunt the winding inductance. The core will have an effect at the lower frequencies and skin effect will become a factor at higher frequencies.

#### IV. CONCLUSION

The main problem with FRA technique is to interpret the observed evolution of the frequency response in order to identify failures. This paper investigates the impact of electrical parameters variation of a high frequency transformer model on its FRA signature to help in FRA classification and interpretation. Comparison of the frequency response of the base values model parameters and the response with a change in a particular parameter has been elaborated. Results show

that distributed parameters model is very sensitive to parameter variation and each parameter will have a unique impact on the FRA signature. While the impact of series inductance dominates the response in the low frequency range, the series capacitance dominates the response in the high frequency range. The shunt capacitance will have an impact on the signature on the entire frequency range. The series resistor will affect the amplitude mainly in the high frequency range. The effect of shunt conductance is not observable for any change less than 50%. For a 50% change in the shunt conductance, the amplitude will slightly change in the medium and high frequency range and it will introduce a slight shifting in the resonant peaks in the high frequency range. The distributed parameters model is very accurate to emulate FRA signature and hence it can be used in conjunction with field FRA measurement to establish a standard code for FRA signature.

TABLE II  
SUMMARY OF TRANSFORMER ELECTRICAL PARAMETER EFFECT ON FRA SIGNATURE

Parameters	Variations	Frequency range		
		Low	Medium	High
L	Decreased (10%)	Amplitude change	Resonant peaks shift right, Amplitude change	Amplitude change
	Increased (10%)	Amplitude change	Resonant peaks shift left, Amplitude change	Amplitude change
C <sub>s</sub>	Decreased (10%)	No impact	No impact	Resonant peaks shift right, Amplitude change
	Increased (10%)	No impact	No impact	Resonant peaks shift right, Amplitude change
C <sub>p</sub>	Decreased (10%)	Amplitude change	Resonant peaks shift right, Amplitude change	Resonant peaks shift right, Amplitude change
	Increased (10%)	Amplitude change	Resonant peaks shift left, Amplitude change	Resonant peaks shift left, Amplitude change
R <sub>s</sub>	Decreased (10%)	No impact	No impact	Amplitude change
	Increased (10%)	No impact	Amplitude change	Resonant peaks shift right, Amplitude change
G	Decreased (10%)	No impact	No impact	No impact
	Increased (50%)	Amplitude change	Amplitude change	Resonant peaks shift right, Amplitude change

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