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Characterization of Transformer FRA Signature under Various Winding Faults

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Abstract- Frequency response analysis (FRA) is gaining global popularity in detecting power transformer winding and core deformations 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 aims to initiate the establishment of standard codes for FRA signature interpretation through comprehensive simulation analysis on a detailed transformer distributed parameters-based model. Various mechanical faults such as axial displacement, buckling stress, disk space variation and bushing fault are simulated on the model to study its impact on the FRA signature. The main contribution of this paper is the comprehensive table it presents for FRA signature sensitivity to winding and core deformations that can be used for classification and quantification of the transformer FRA signature.

Index Terms: Power transformer, FRA, condition monitoring, core and winding deformation.

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 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 [3, 4]. One of the causes of transformer mechanical damages and windings deformation is the loss of clamping pressure because of insulation degradation resulted by ageing. While with only minor winding deformation transformer can still working normally, its capability to withstand any further through faults will gradually decrease [5]. 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. Winding deformation has various configuration moods such as spiral tightening, conductor tilting, radial buckling and collapse of the winding end supports. It is hard to identify these types of internal faults with conventional testing methods [6]. One of the powerful diagnostic techniques in identifying internal faults of power transformers is the frequency response analysis (FRA) test [7]. 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. FRA is an offline test that 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 V_o and the source voltage V_i as a function of the frequency in decibel (dB) [8]. 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 identifying any mechanical deformation. 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. 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. This is not always an easy task especially for young and inexperienced power engineers. This paper introduces an attempt to quantify and classify transformer FRA signatures using sensitivity analysis. Detailed simulation analysis is performed on a transformer distributed parameters model to investigate and to classify the impacts of internal faults on the FRA signature. Mechanical faults such as axial displacement, radial buckling, disk space variation, loss of clamping, bushing and leakage faults are emulated by appropriately modifying the transformer distributed parameters. Finally, a general interpretation code that can be readily used to classify FRA signatures is developed.

II. TRANSFORMER MODEL

Simplorer software is used to simulate the transformer model shown in Fig.1 [9]. In the model under study, the high voltage (HV) and low voltage (LV) windings are assumed to consist of 10 disks. Each disk comprises 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 (C_{HL}) is shunted by dielectric conductance (G_{HL}), also mutual inductances (M_{ij}) 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 (C_g) and dielectric conductance (G) as shown in Fig. 1. 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.

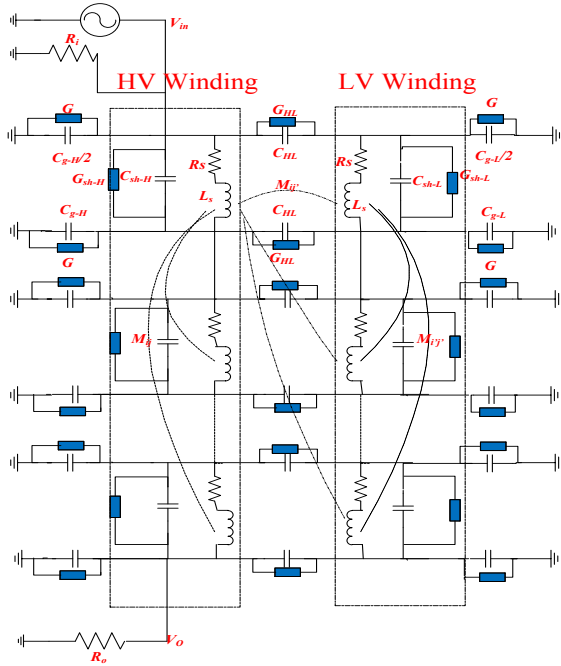


Fig. 1 Transformer distributed parameters model

III. FAULT ANALYSIS

In this section various mechanical faults are simulated within the transformer model by changing particular parameters. The faulty signature is compared with the healthy one in order to investigate the impact of each fault on the FRA signature.

A. Loss of Clamping Pressure

Losing clamping-pressure is a common problem particularly for aged transformers. This is caused by the mechanical hysteresis in pressboard and paper [10]. Loss of clamping causes an increase in oil conductivity because of the reduction in dielectric thickness between winding layers. This type of fault can be simulated by increasing the value of the shunt conductance G_{sh} [11]. Figs. 2 and 3 show the effect of 20% loss of clamping pressure on the FRA signature for HV and LV windings. According to these two figures, this type of fault will not affect the location of resonance and anti-resonance frequencies. However, it significantly reduces the magnitude of maximum and minimum peaks in the mid and high frequency ranges.

B. Inter Disk Fault

The inter-disk fault is considered as one of the most common mechanical faults within power transformers. Studies show that around 80% of transformer breakdowns are due inter-disk fault [12]. This fault is due to axial disk space variation which is caused by the excess mechanical stress and through faults and can be simulated by increasing the series capacitance (C_{sh}) and the mutual inductance between the two impacted disks [12]. Fig. 4 shows the impact of 10% of such fault on the HV FRA signature when occurs at different locations in the transformer model shown in Fig. 1.

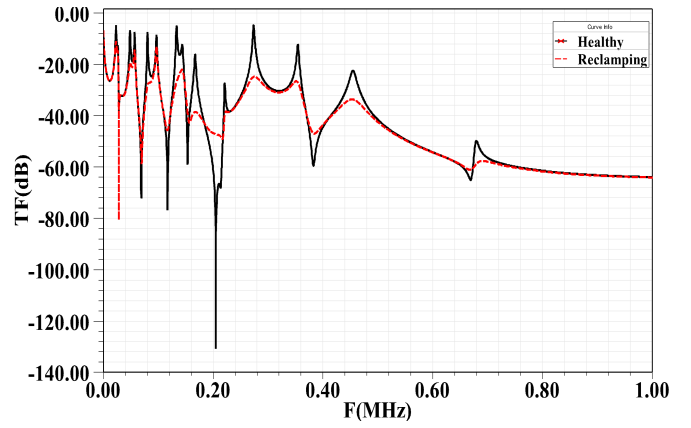


Fig. 2 Impact of clamping fault on the HV FRA signature

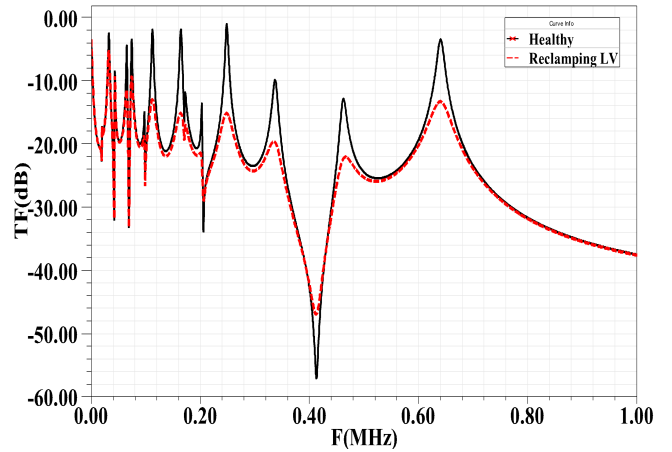


Fig. 3 Impact of clamping fault on the LV FRA signature

Fig. 4 shows that this fault has no significant impact on the signature in the low frequency range. A shift to the right in the resonance and anti-resonance frequencies can be observed after 100 kHz with significant change in the peak magnitudes. The shifts in resonance and anti-resonance frequencies are more observable when the fault occurs at the top or bottom disks of the winding while the impact of this fault is less when occurs at the middle disks of the windings.

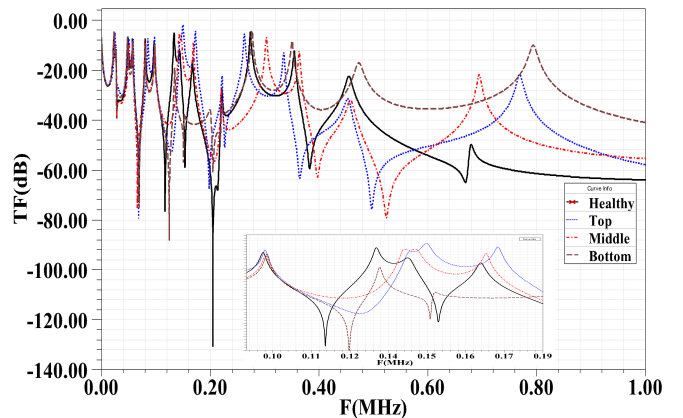


Fig. 4 Impact of inter-disk fault on the HV FRA signature

C. High Voltage Bushing Fault

Bushing can be simulated by adding a "T" circuit model to the transformer model as shown in Fig. 5 [13]. The impact of

10% change in bushing capacitance on the FRA signature is shown in Fig. 6. The results reveal that there is no impact of this fault on the signature in the low and medium frequency range. However, a slight change in magnitude can be observed after 250 kHz and the magnitude increases in the high frequency range but there is no change in the position of resonant peaks.

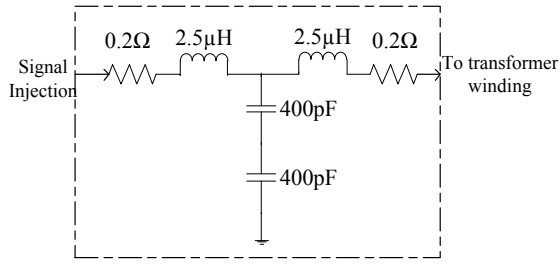


Fig. 5 Bushing model [13]

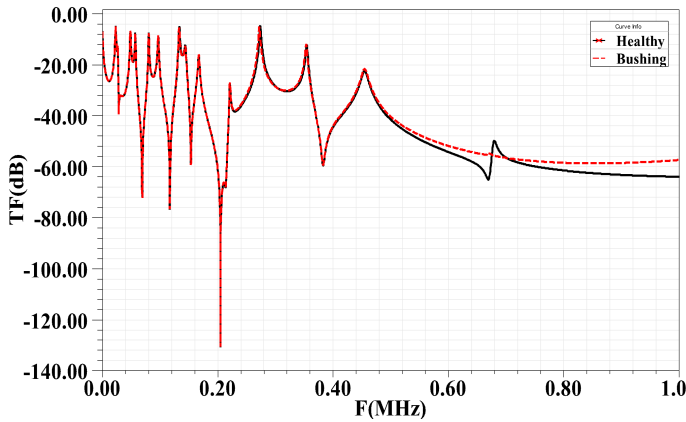


Fig. 6 Impact of high voltage bushing fault on the FRA signature

D. Axial Displacement

This fault occurs due to the imbalanced magnetic forces generated in one winding as a result of a short-circuit fault [11] which leads to the movement of the impacted winding axially. This fault can be simulated by changing the values of the series capacitance (C_{sh}) and mutual inductance [14]. Fig. 7 shows the impact of 10% of such fault on the FRA signature of the HV winding when it is moved axially up or down. As shown in Fig. 7, this fault has no impact on the FRA signature in the low frequency range. However, after 200 kHz a slight shift of anti-resonance frequencies to the right with observable increase in the magnitude can be detected. The trend is similar for both fault directions.

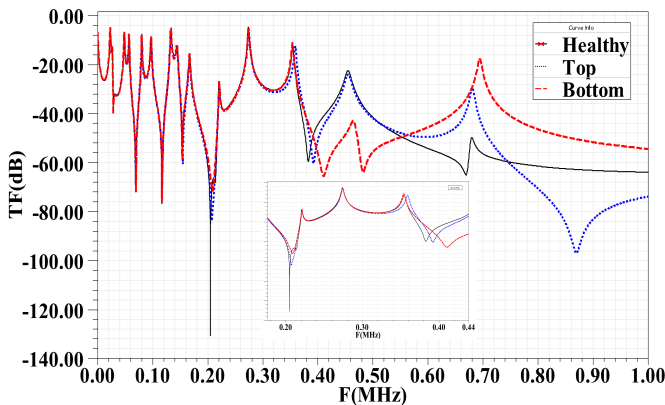


Fig. 7 Impact of HV axial displacement on the FRA signature

E. Leakage Fault

Ground shield damage, insulation damage, high moisture content in the winding, abrasion, hotspot and aging insulation, are the main causes for leakage fault within a power transformer [15]. This type of fault can be simulated by increasing the conductance to ground (G) [16]. As can be observed from Fig. 8, there is no significant variation on the FRA signature. Although, a slight change in magnitude in the mid and high frequency range can be noticed.

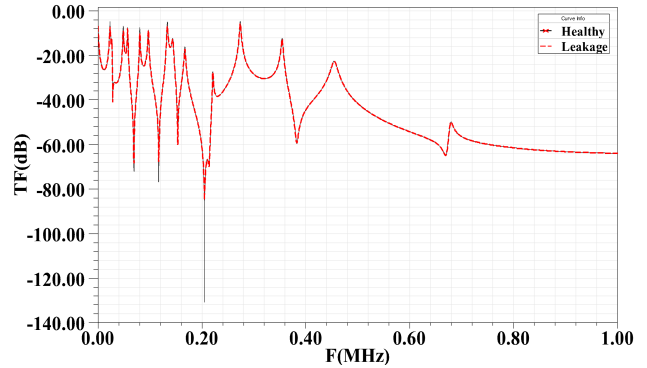


Fig. 8 Impact of leakage fault on the FRA signature

F. Short Circuit Fault

This fault is caused due to erosion of the winding and conductor insulation because of vibrations caused by the electromechanical forces that can lead to over current in the winding and severe damages such as winding deformation, oil heating and even core damages may occur [17]. This fault can be simulated by short circuiting the series resistance and inductance [18]. Fig. 9 shows the impact of this fault on the FRA signature. It can be seen that the magnitude is significantly reduced at low frequency range. Different fault locations have a similar impact on the FRA signature.

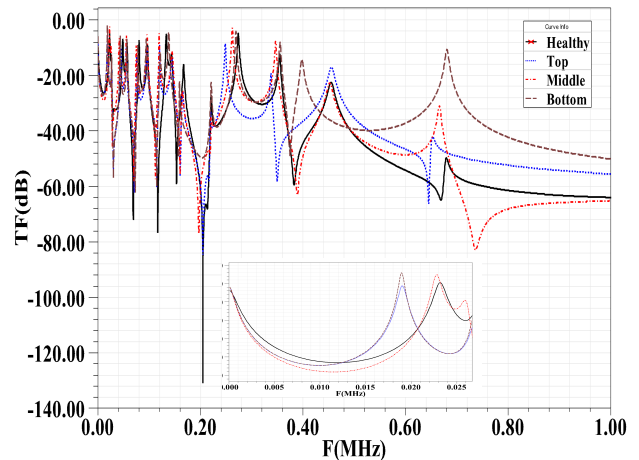


Fig. 9 Impact of HV short circuit fault on the FRA signature

G. Radial Fault

The windings of power transformers might be subjected to radial forces due to interactions of the winding current and magnetic flux. Significant amount of radial forces may lead to winding buckling [19]. This fault can be simulated by changing the capacitor to ground (C_g) and the capacitor between the HV and LV windings (C_{HL}) along with the mutual

inductance of the impacted disks (M_{ij}) [20]. 10% of this fault is simulated at three different locations on the HV windings (top, middle and bottom) and the FRA response is shown in Figs. 10, which reveals that resonance frequencies are shifted to the right in the entire frequency range due to this type of fault. Also, the magnitude is increasing in the high frequency range. The trend for the three studied fault locations is quite the same.

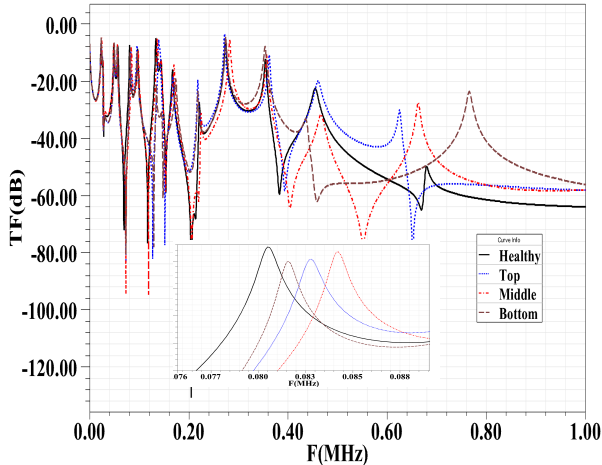


Fig. 10 Impact of radial fault on the HV winding FRA signature

TABLE I
SUMMARY OF VARIOUS FAULTS ON TRANSFORMER FRA SIGNATURE

Fault Type	Frequency Range		
	Low	Medium	High
Axial	Magnitude decreased slightly	Anti resonates shifted to right	Magnitude increased and resonate peaks shifted to right
Radial HV & LV	Resonant peaks shifted to right slightly	Resonant peaks shifted to right	Magnitude increased and resonant peaks shifted to right
Bushing	Magnitude increased slightly	Magnitude increased slightly	Magnitude increased significantly
Leakage	Magnitude decreased	Magnitude decreased	Magnitude decreased
Inter Disk	Magnitude decreased	Anti resonates shifted to right and magnitude increased	Magnitude increased and resonant peaks shifted to right
Short Circuit	Magnitude decreased sharply and resonant peaks shifted to left	Resonant peaks shifted to left magnitude increased	Magnitude increased and resonate peaks shifted to left
Clamping HV& LV	Magnitude decreased	Magnitude decreased	Magnitude decreased

Table I summarise the the impact of individual faults on the transformer FRA signature and be used as a step toward the establishment of standard codes for power transformer FRA signature interpretation.

CONCLUSION

This paper presents a comprehensive simulation analysis to explore the impact of various transformer mechanical faults on its frequency response analysis (FRA) signature. Results show that the effects of axial and radial faults are more observable at the medium to high frequency ranges and they are affecting

the location of anti-resonances and resonance peaks. Short circuit fault can be detected at low frequency range as it will change the magnitude of the FRA signature. Inter-disk fault is clearly detectable at medium frequency range. Leakage fault and high voltage bushing fault affect the magnitude at the high frequency range and they have insignificant impact on the position of resonance and anti-resonance peaks. A comprehensive table highlighting transformer FRA sensitivities to mechanical faults is generated and can be used to establish standard codes for power transformer FRA signature interpretation.

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