



IMPACT OF INTER-WINDING MAGNETIC AND CAPACITIVE COUPLING ON SFRA SIGNATURE

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ABSTRACT

Sweep Frequency Response Analysis (SFRA) serves as a highly sensitive diagnostic technique for identifying mechanical deformations within power transformer windings. The inherent magnetic and capacitive inter-winding couplings in transformers mean that a fault localized to a single winding can propagate detectable anomalies across the frequency responses observed at the terminals of all windings. This study systematically explores this interdependency through detailed simulations and case studies. A comprehensive six-winding equivalent circuit model of a 40 MVA, 132/11 kV power transformer, incorporating both magnetic and capacitive coupling effects is simulated to validate the underlying hypothesis. Complementing this, faults comprising an open-circuit condition and radial buckling were deliberately induced in the low-voltage (LV) winding of a 20 MVA, 66/11 kV oil-immersed transformer for experimental validation. The resultant frequency response traces reveal pronounced deviations in both LV and high-voltage (HV) signatures attributable to faults within a single phase winding. The study concludes that, due to unavoidable coupling, analyzing a single winding signature is sufficient to ensure the presence of mechanical deformation, whereas comparison of multiple signatures retains value for fault localization and severity assessment.



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I. INTRODUCTION

Mechanical faults in transformer windings caused by short-circuit forces, transportation shocks or ageing remain a major cause of unplanned outages [1], [2]. Sweep Frequency Response Analysis (SFRA) has become the most widely accepted non-destructive technique for assessing winding integrity because of its high sensitivity to small geometrical changes [3–7]. Recent literature has significantly advanced SFRA interpretation through statistical indices, machine learning classifiers and online monitoring concepts [8–14]. However, the majority of published case studies and interpretation guidelines still treat each winding measurement independently, even though transformer windings are strongly linked by mutual inductance and inter-winding capacitance. Only a few works have systematically investigated how a local deformation propagates through coupling to remote windings [15–16]. In this paper, the influence of inter-winding couplings on the frequency response of the winding under the test is probed through case studies. Also, how this affects the diagnosis about winding deformation is commented. The paper is organized into six sections. Section-02 briefs about inter-winding couplings of transformer and its impact on frequency response. Section 3 demonstrates validation of the impact of inter-winding couplings on the frequency response through simulation. Case studies are presented to understand the winding deformation's interference on the frequency response of a winding undergoing the test, in section-04. Section-05 discuss the case studies results and impact on the diagnosis. Section-06 concludes about the study.

II. INTER-WINDING COUPLINGS AND ITS IMPACT ON FREQUENCY RESPONSE

Transformer design inherently incorporates inter-winding interactions. Windings typically share the core, creating a unified magnetic pathway and enabling inductive linkage [17]. Transformer also provides exposure for the capacitive couplings. The studies have considered the capacitance formed between the turns, between the discs, and between the winding and core / tank. In addition to this, as the outer high-voltage (HV) winding encases the inner low-voltage (LV) winding, with transformer oil providing dielectric separation, facilitating capacitive effects between HV-LV windings. Likewise, the high voltage windings are oriented besides, each other and electrically isolated by the transformer oil. A capacitive coupling can also be observed between HV-HV windings [18]. Figure 1 showcase the capacitive coupling between HV – LV and HV – HV windings. Hence the transformer windings are coupled through the common magnetic domain and the capacitance between HV windings and between HV-LV windings. The magnetic & capacitive couplings are shown in Figure 2.

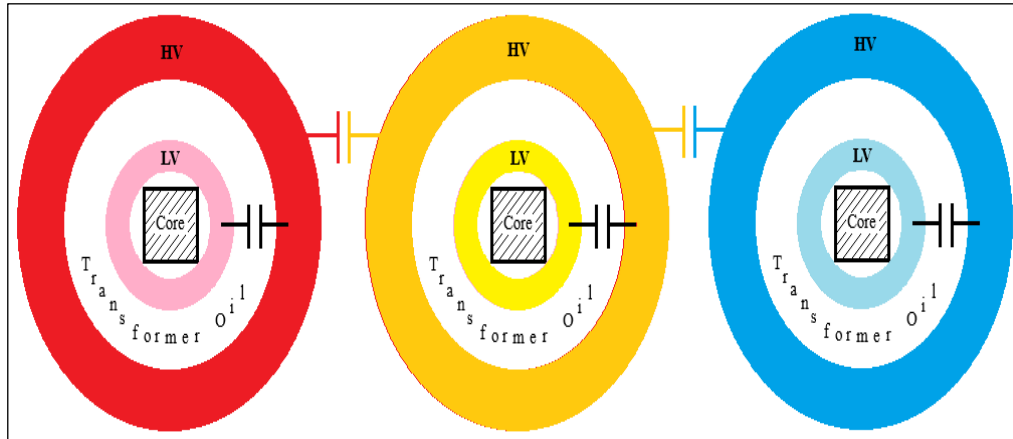


Figure 1: Capacitive coupling between HV – LV and HV - HV windings.
Source: Authors, (2026).

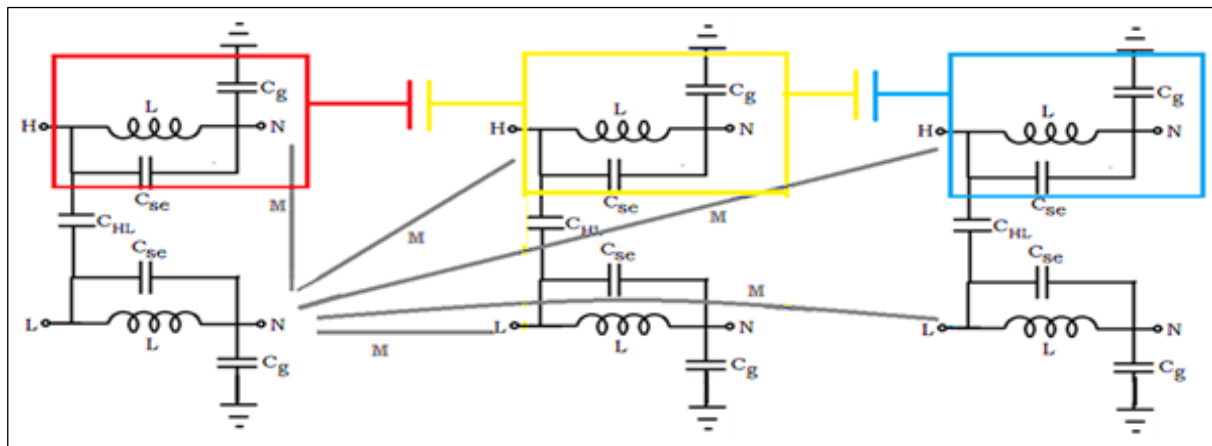


Figure 2: Schematic of capacitive and inductive couplings between transformer windings.
Source: Authors, (2026).

To diagnose the winding deformation, a sweep frequency signal of wide frequency band (20 Hz to 2 MHz, generally) is injected at a terminal of a winding. The test signal comprises of low, medium and high frequency segments. The inter-winding magnetic coupling is dominant in low frequency domain, whereas the capacitive couplings are in high frequency domain. All the inter-winding couplings are active in the window of medium frequency. Hence, the test signal can find the passage through inter-winding couplings to interact with all the windings of the transformer. The frequency response derived from such test signal can carry the information all from the windings. The deformation present in a winding may reflect in the frequency response derived irrespective of pair of winding terminals. It seems the frequency response obtained irrespective to the pair of winding terminals, is the overall response of windings. In the presence of inter-winding couplings, it is almost impossible to obtain individual winding response. Therefore, the study of a frequency response obtained using any pair of the terminals may be sufficient to get an idea about overall condition of windings.

III. SIMULATION

The hypothesis regarding the influence of magnetic and capacitive inter-winding couplings is verified via simulations. For this purpose, a six-winding equivalent circuit model of a 40 MVA, 132/11 kV power transformer—incorporating the magnetic and capacitive couplings as detailed in [19]—is employed. The corresponding inductance matrix and winding parameter values are presented in Tables 1 and 2, respectively, while the simulated winding configuration is illustrated in Figure 3. The fault scenario is emulated by imposing a 30% reduction in the shunt capacitance of the high-voltage (HV) phase-B winding relative to its initial value.

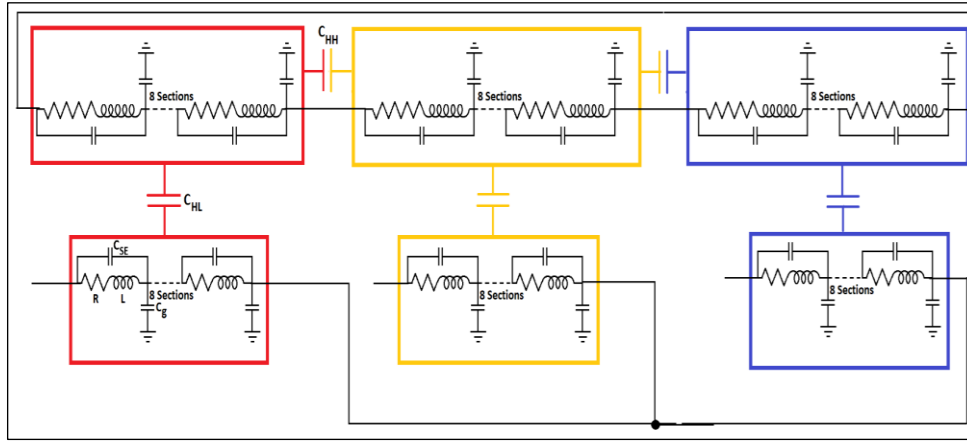


Figure 3: Six winding simulation model with inter-winding couplings.
Source: Authors, (2026).

Table 1: Inductance Matrix – Healthy (in milli henry).

		LV			HV		
		R	Y	B	R	Y	B
LV	R	0.47	0.41	0.05	0.47	0.41	0.05
	Y	0.41	0.82	0.41	0.41	0.82	0.41
	B	0.05	0.41	0.47	0.05	0.41	0.47
HV	R	0.47	0.41	0.05	0.47	0.41	0.05
	Y	0.41	0.82	0.41	0.41	0.82	0.41
	B	0.05	0.41	0.47	0.05	0.41	0.47

Source: Authors, (2026).

Table 2: Equivalent circuit parameter values.

	LV	HV
R (Ω)	0.25	1
C _{se} (pF)	3212	3114.4
C _{HL} (pF)	3000	
C _g (pF)	5514	2000
C _{HH} (pF)	315.66	

Source: Authors, (2026).

Frequency response signatures are captured for all phase windings across both the HV and low-voltage (LV) sides under healthy conditions and post-fault simulation. Comparative analyses of these signatures for the respective phase windings are depicted in Figures 4–9.

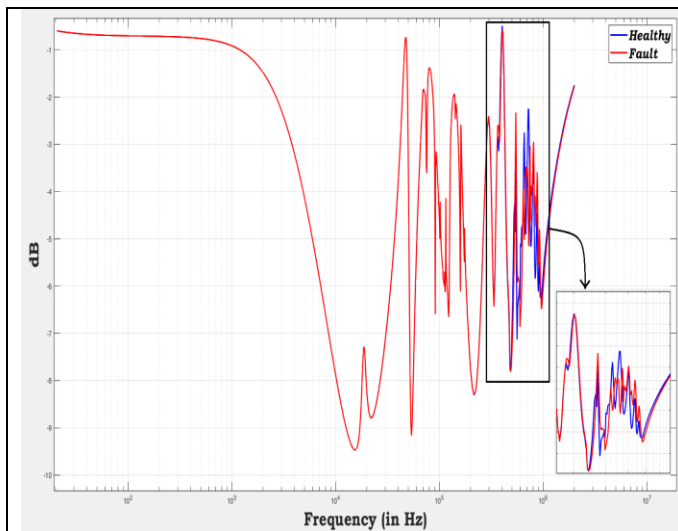


Figure 4: Frequency response comparison of low voltage winding phase R.
Source: Authors, (2026).

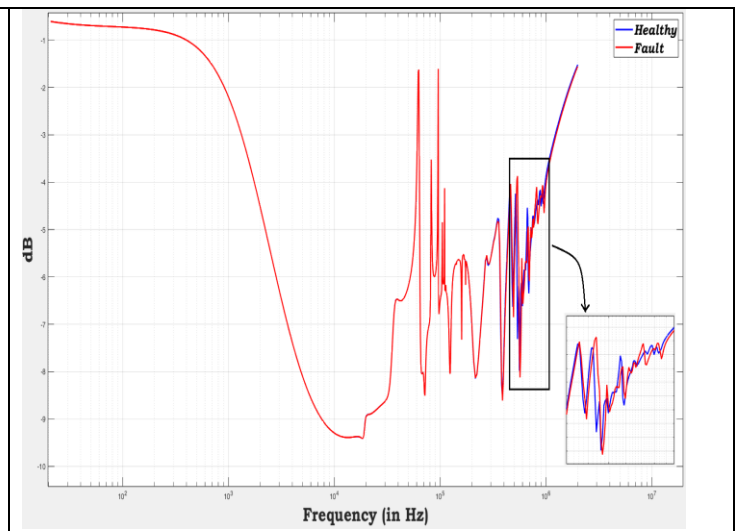


Figure 5: Frequency response comparison of low voltage winding phase Y.
Source: Authors, (2026).

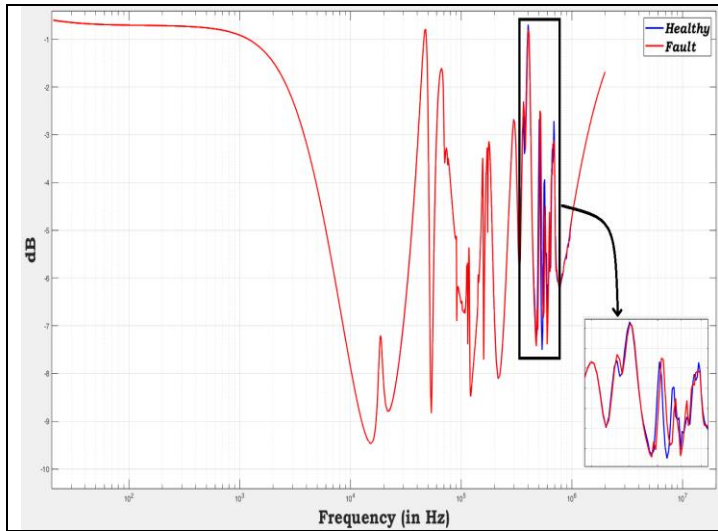


Figure 6: Frequency response comparison of low voltage winding phase B.
Source: Authors, (2026).

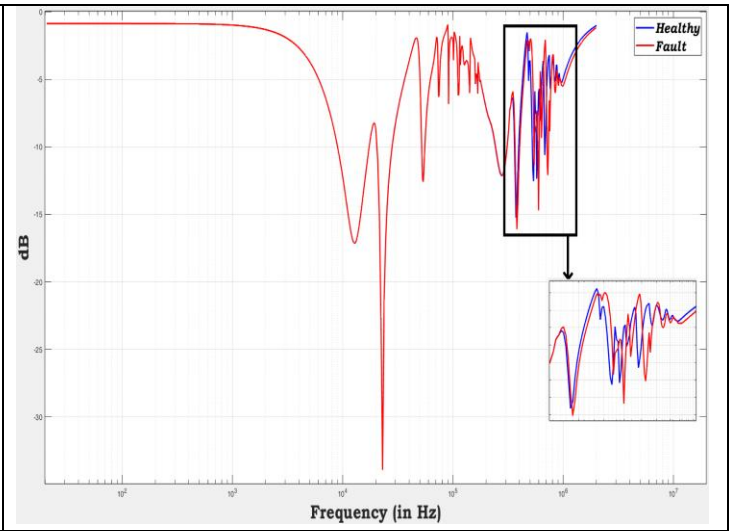


Figure 7: Frequency response comparison of high voltage winding between phase R.
Source: Authors, (2026).

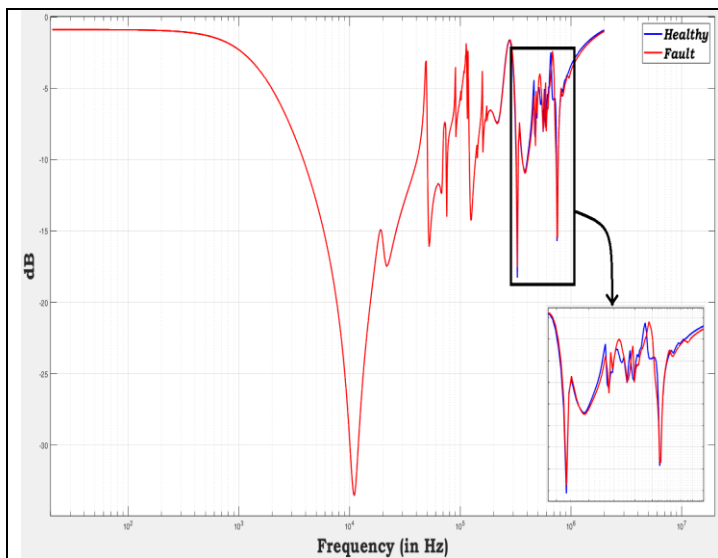


Figure 8: Frequency response comparison of high voltage winding between phase Y.
Source: Authors, (2026).

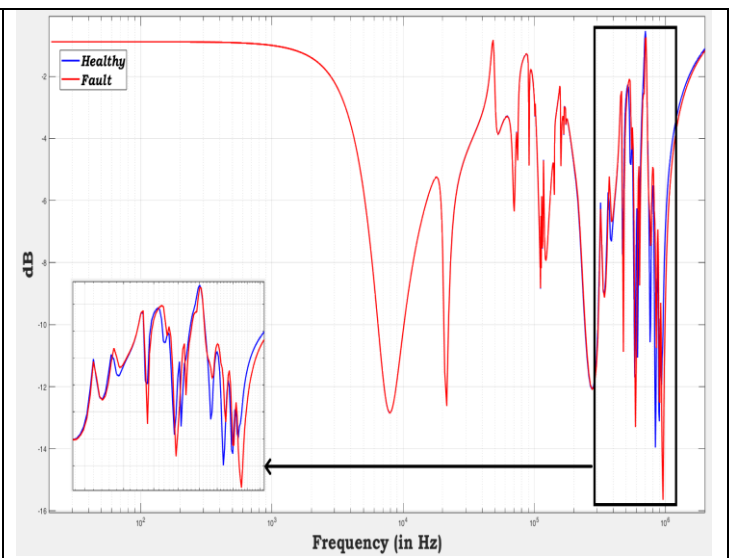


Figure 9: Frequency response comparison of high voltage winding between phase B.
Source: Authors, (2026).

Despite the fault being localized to the HV phase-B winding, discernible deviations manifested in the frequency responses of the LV windings as well as the HV phases R and Y, thereby evidencing the propagated impact. Capacitive elements within the winding model predominantly govern the high-frequency region of the frequency response. Consequently, the observed disparities in Figures 4–9 are confined to high frequencies. The delta-connected configuration of the HV windings implies that the equivalent circuit, when referenced to any HV terminal pair, encompasses contributions from all three HV windings. This inherent interconnectedness accounts for the susceptibility of the HV phase-R and phase-Y responses to perturbations in the HV phase-B winding. Furthermore, inter-winding capacitances between the HV and LV windings (CHL) and among the HV windings themselves (CHH) engender coupling effects. As such, the equivalent circuit referenced to any LV terminal pair integrates the dynamics of all HV and LV windings. These coupling mechanisms collectively ensure that alterations in the shunt capacitance (C_{se}) of the HV phase-B winding are reflected across the frequency responses of every phase windings.

IV. CASE STUDY

In order to verify the influence of deformation present in the winding – Not Under the test, on the frequency response, a 20 MVA, 66 / 11 kV transformer is introduced with open circuit and radial buckling, in-turn, into phase B of the low voltage side. The frequency response of windings is recorded using a commercial SFRA instrument (Omicron FRAnalyzer) for the stated winding deformation and for the healthy condition. The measurements were performed with End-to-End Open Circuit test configuration, used 50 Ω coaxial cables, frequency sweep 20 Hz – 2 MHz, 1200 logarithmic points and source impedance of 50 Ω .

IV.1 WINDING DEFORMATION TYPE – LV PHASE B OPEN CIRCUITED

Post-deformation FRA traces, captured via a commercial analyzer, are compared in Figures 10-15.

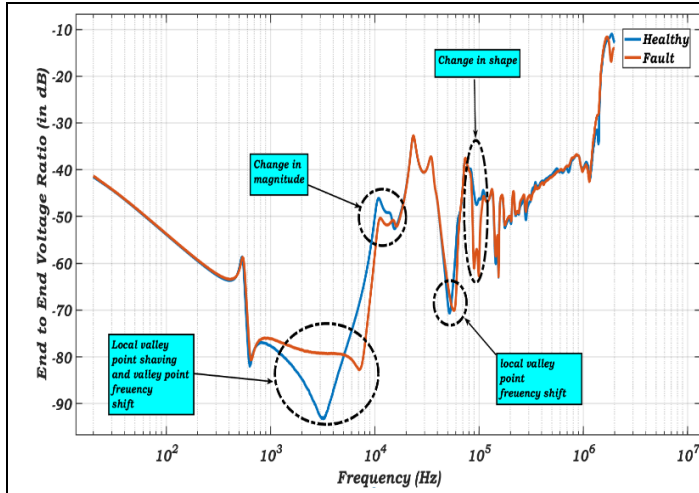


Figure 10: Frequency response comparison of high voltage winding between phase R.
Source: Authors, (2026).

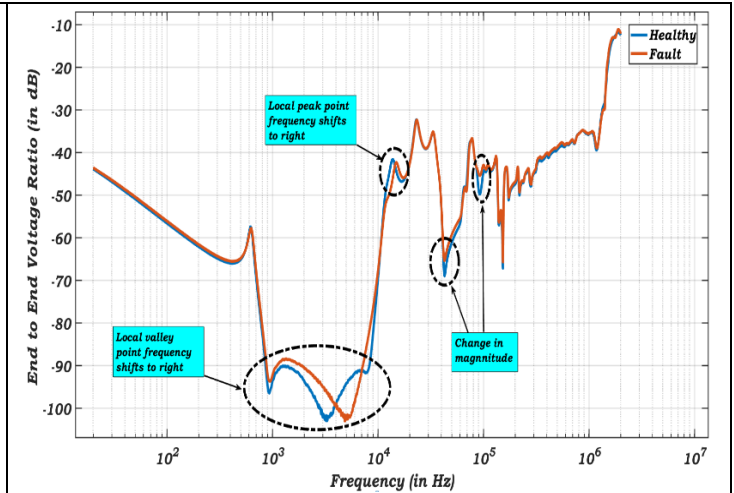


Figure 11: Frequency response comparison of high voltage winding between phase Y.
Source: Authors, (2026).

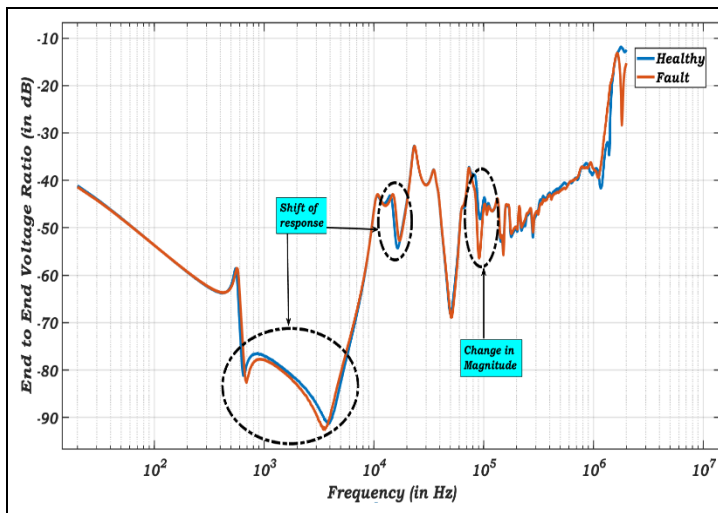


Figure 12: Frequency response comparison of high voltage winding between phase B.
Source: Authors, (2026).

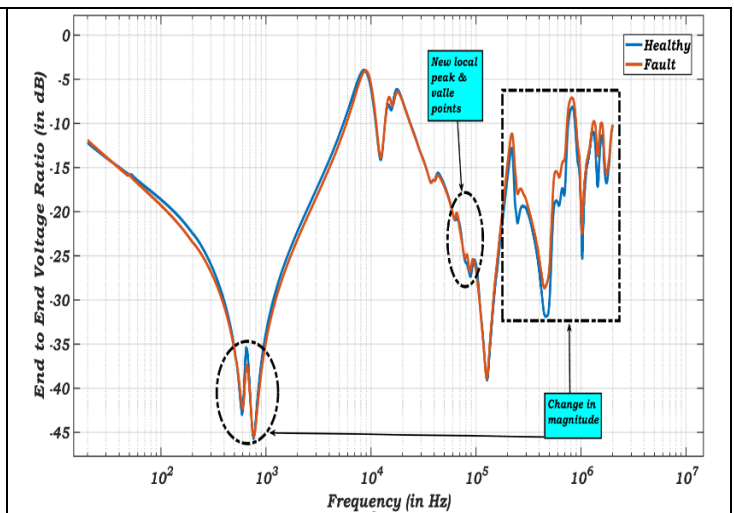


Figure 13: Frequency response comparison of low voltage winding phase R.
Source: Authors, (2026).

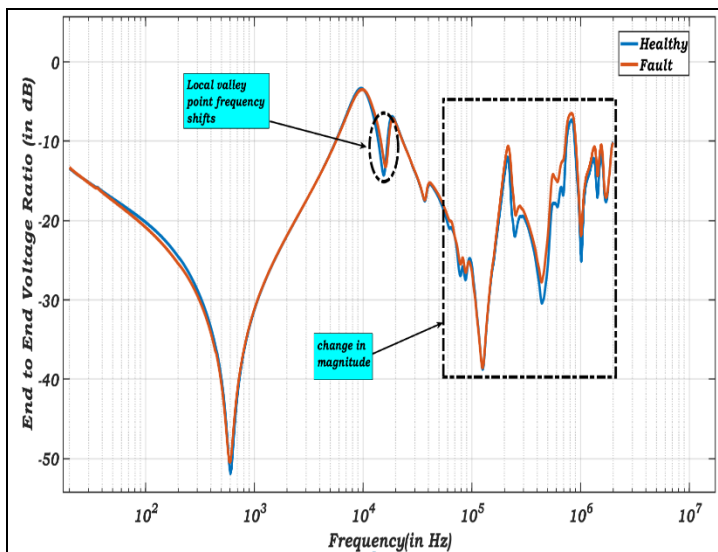


Figure 14: Frequency response comparison of low voltage winding phase Y
Source: Authors, (2026).

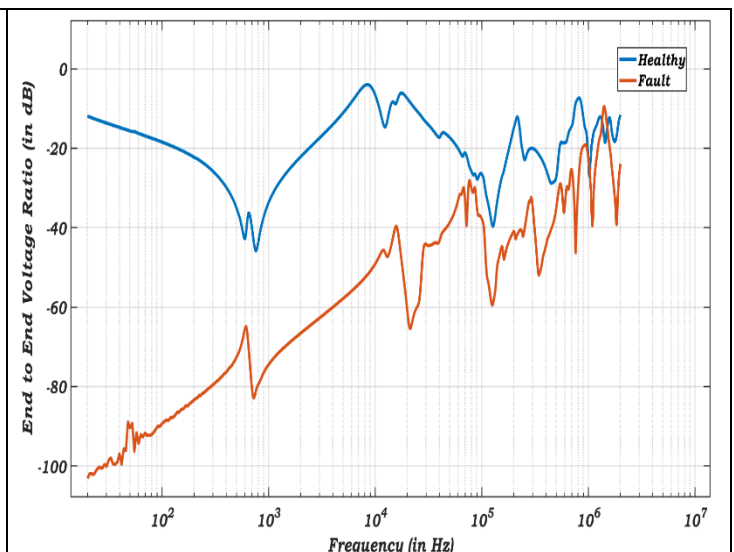


Figure 15: Frequency response comparison of low voltage winding phase B.
Source: Authors, (2026).

The observations are:

- High Voltage Windings - it seems the low and middle frequency regions are disturbed, mostly. It is obvious, as the open circuited LV phase - B has altered overall inductance of the windings and the low and middle frequency regions of signature reflect inductive property of winding. The signatures in low and middle frequency regions show local valley point shaving, shifts in valley and peak frequencies, and change in the shape of the response.
- Low Voltage Windings - the signature of phase B shows complete disagreement with the reference signature, as it is the host of deformation. The signatures of phases R & Y report their partial disagreement in term of change in magnitude of local peak & valley point, introducing a new pair of local peak & valley point and by shift of response.

IV.2 WINDING DEFORMATION – LV PHASE B RADIAL DEFORMATION

Figures 16–21 highlight the comparison between signatures captured after introducing radial deformation to the LV phase B winding and their respective baseline signatures.

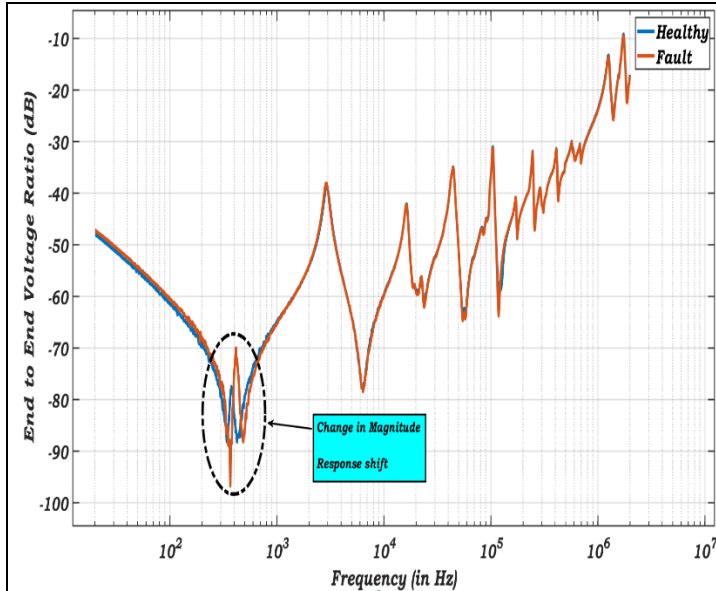


Figure 16: Frequency response comparison of high voltage winding phase R.
Source: Authors, (2026).

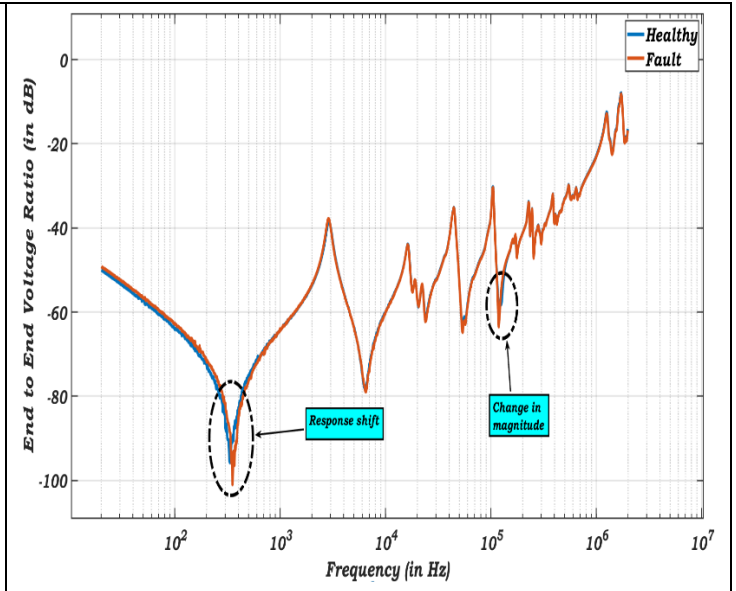


Figure 17: Frequency response comparison of high voltage winding phase Y.
Source: Authors, (2026).

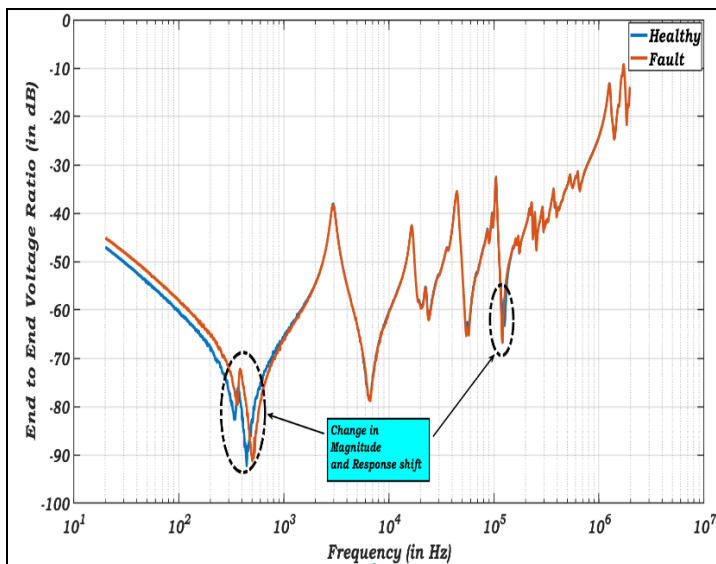


Figure 18: Frequency response comparison of high voltage winding phase B.
Source: Authors, (2026).

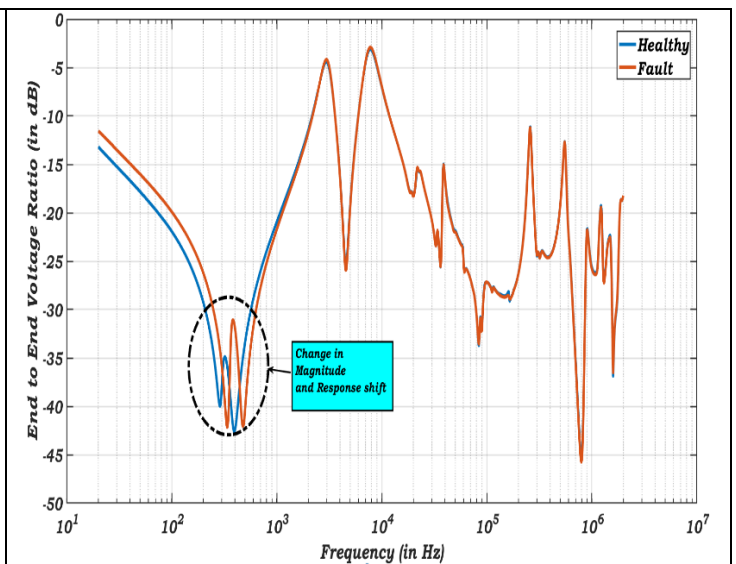


Figure 19: Frequency response comparison of low voltage winding phase R.
Source: Authors, (2026).

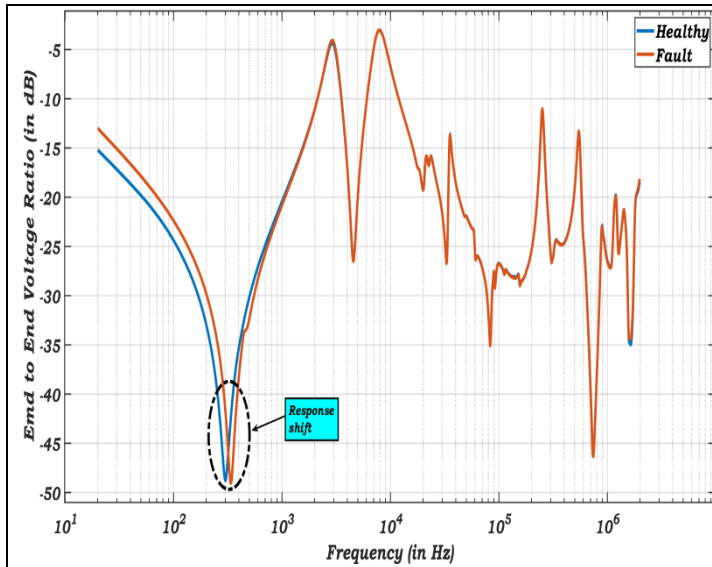


Figure 20: Frequency response comparison of low voltage winding phase Y.
Source: Authors, (2026).

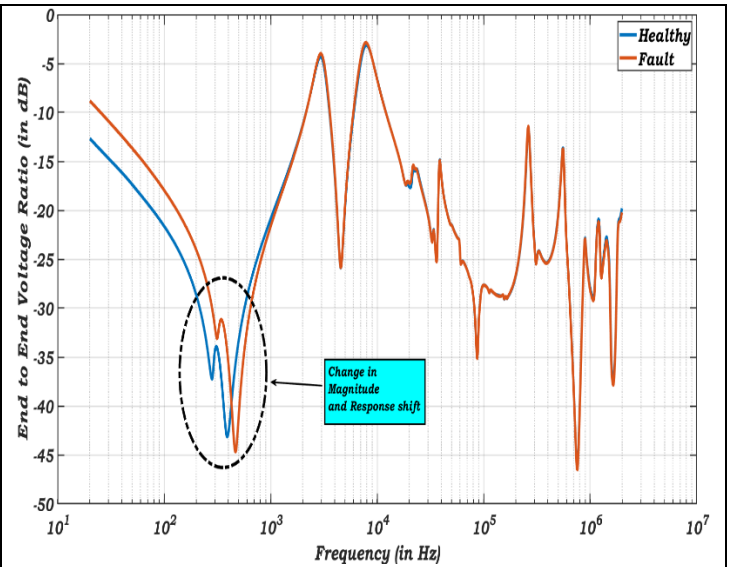


Figure 21: Frequency response comparison of low voltage winding phase B.
Source: Authors, (2026).

The observation is:

- The middle and high frequency regions of signatures have shown good degree of agreement with their respective references. The influence of radial deformation can be seen in the low frequency region of all the windings' (HVs & LVs) signatures, in term of change in magnitude and shift of the response.

V. DISCUSSION

V.1 CASE STUDY RESULTS

Due to delta connections and inter-winding linkages (inductive and capacitive couplings), test signal (sweep frequency signal) propagates system-wide, embedding condition data from multiple windings in a single trace. The experiment results clearly observe the deformation located in one of the windings, infect the signature of all the windings more or less. The degree of influence is dependent on how closely it is attached with the victim winding. The degree of disagreement offered by the deformed winding is significant large as compared to others but the scale of disagreement noticed in the signature of rest windings are not of negligible level.

V.2 PRACTICAL CONSEQUENCES FOR FIELD DIAGNOSTICS

Because of unavoidable coupling, every SFRA trace contains information about the mechanical condition of all windings. Consequently:

- Recording and analyzing a single accessible winding is sufficient to detect the presence of mechanical deformation with very high confidence.
- Comparing signatures from multiple terminals remains valuable (and recommended by standards) when the transformer is ready to get removed from service and maintenance, the phase and winding that shows the largest deviation usually indicates the fault location.

Thus, the common field practice of measuring only single accessible winding for quick screening is technically justified, whereas full measurement of all six terminals is still beneficial for detailed post-fault investigation.

VI. CONCLUSION

The results clearly show that inter-winding couplings make every SFRA trace a “global” indicator of the transformer’s mechanical integrity. A local deformation confined to one LV phase produced unmistakable changes in all HV and LV traces, especially below 200 kHz. These findings provide justification for the field practice of measuring only the most accessible terminals (typically the HV side) for rapid go/no-go screening. At the same time, recording and comparing signatures from multiple terminals continues to offer superior fault-type discrimination, location capability, and severity grading when the transformer is ready for detailed investigation. The results therefore support simplified measurement procedures without sacrificing diagnostic reliability, while preserving the full value of complete SFRA datasets for post-fault analysis and repair planning.

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Methodology: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Investigation: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Discussion of results: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Writing – Original Draft: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Writing – Review and Editing: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Resources: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Supervision: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

Approval of the final text: Mayur V Gojiya, Mehul Dansinh Solanki, Ashokkumar Parmar, Maqbul U Ghanchi.

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