

Frequency Response Analysis Techniques and Their Applications in Electrical Power System: A Review

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ABSTRACT: Over the years, a number of methods have been developed to diagnose and monitor electrical and mechanical integrity of the power system equipment. Frequency response analysis (FRA) is one of the popular methods used for evaluating electrical as well as mechanical condition of power system components, especially for Power Transformers. This review presents a comprehensive and chronological overview of FRA applications in power systems. The evolution of methodologies from early offline methods to advance online approaches discussed in this article. This review aims to clarify current state of the FRA applications in power system.

KEYWORDS: Frequency Response Analysis (FRA); Transformers; Rotating Machines; impulse Frequency Response Analysis (IFRA); Sweep Frequency Response Analysis (SFRA)

I. INTRODUCTION

Power system equipment like, transformers, rotating machines, power cables are essential for the stable and reliable operation of entire power system. Sometimes these power system equipment face several discontinuity or instability which can affect the overall functioning of the system [1], [2], due to which continuous monitoring and the identification of discontinuity or instability as early as possible is essential so that maximum damage and maintenance cost can be reduced [3].

Some standard electrical diagnostic techniques for electrical as well mechanical tests in power systems such as Partial Discharge (for insulation degradation) [4], tan delta test[5] and transformers related diagnostic techniques and analysis such as turns ratio test, winding resistance test, recovery voltage method (RVM), Dielectric Response Analysis, and frequency response analysis. Out of these techniques the frequency response analysis (FRA) is quite popular and used frequently for the diagnostics purpose [6], [7]. FRA is a diagnostic method which is highly applicable to power transformer to evaluate it's electrical as well as mechanical integrity windings and core structure [8].

While several studies had been done on specific applications of FRA, a comprehensive review that combines its principles, applicability across targeted power system equipment becomes necessary. therefore, this paper provides a detailed examination consolidating FRA's working principles,

measurement methodologies, and applications to Electrical power system components.

II. FRA TECHNIQUES

Based on injecting signal, this technique is classified into two methods, impulse Frequency Response Analysis (IFRA) and Sweep Frequency Response Analysis (SFRA). In impulse frequency response analysis the injecting signal is an impulse signal while in sweep frequency response analysis, the injecting signal is a swept frequency (sinusoidal low voltage signal with varying frequency) signal [9].

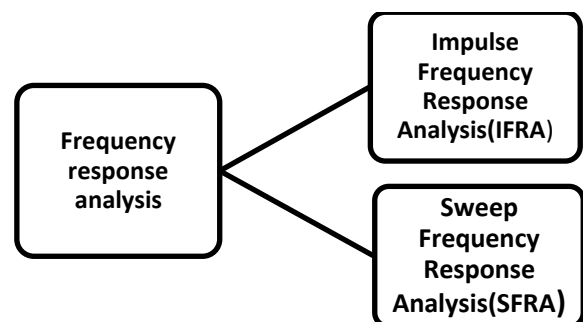


Fig.1 Classification OF FRA techniques

These two techniques usually used in offline mode but some recent studies hinted that these can be used in online mode as well.

A. Impulse frequency response analysis (IFRA)

Impulse frequency response analysis (IFRA) assumes transformer windings as linear passive networks of distributed resistance, inductance, and capacitance under high-frequency excitation. Injecting a fast-rising impulse voltage into a winding produces a transient response that propagates through the network, embedding details of its electrical and mechanical integrity [9].

This impulse signal intrinsically spans a wide frequency spectrum. Time-domain responses of voltage or current are recorded at specific terminals and using Fast Fourier Transformation (FFT), frequency domain responses of both input and output signals can be collected. The magnitude of the transfer function for the IFRA signature is a function of frequency, commonly calculated in dB, and is determined by the transfer function equal to the ratio of the response signal (output) voltage magnitude to the source (input) voltage magnitude [10].

$$H(j\omega) = 20 \log_{10} \left(\frac{V_{out}}{V_{in}} \right) \quad (1)$$

However FFT is prone to noise interference and spectral leakage with transients [11]. To overcome its limitations, wavelet-based processing methods are used. One of the wavelet-based methods like The Morlet wavelet transform provides better time-frequency resolution and noise immunity by identifying shifts in resonance as well as anti-resonance frequencies rather than full waveform correlation [12]. Advanced techniques, such as multi-scale complex continuous wavelet transforms also used for better resonance characteristics amid online noise, providing sharp IFRA signatures than FFT [13].

B. Sweep Frequency Response Analysis (SFRA)

Sweep frequency response analysis (SFRA) is a diagnostic technique which is used for analysis of electrical as well as mechanical integrity of power transformer in Frequency domain. In this technique, frequency dependent transfer function calculated by injecting low voltage swept frequency signal within predetermined frequency range. Any electrical and physical deformation or discontinuity leads to alteration in the frequency response profile of that particular equipment [14].

$$H(j\omega) = \frac{V_{out}}{V_{in}} \quad (2)$$

$$Magnitude(dB) = 20 \log_{10} \left(\frac{V_{out}}{V_{in}} \right) \quad (3)$$

$$Phase(\theta) = \tan^{-1} \left(\frac{V_{out}}{V_{in}} \right) \quad (4)$$

In this technique magnitude and phase data can be collected in the frequency domain. Magnitude is the ratio between output and input voltage calculated in dB, while phase is angular displacement between output and input

voltage waveforms across the swept frequency range calculated in degree [15].

III. APPLICATIONS OF FRA IN POWER SYSTEM

Power system equipment such as transformers, reactors, generators and cables are subject to electrical, mechanical, thermal and environmental stresses, transportation or installation as well as aging. For stable and reliable operation of power system, diagnosis of these disturbances is necessary. FRA is One of the widely used method for electrical as well as mechanical condition monitoring of these equipment. This diagnostic technique is mainly used for transformers and rotating machines. Here are the applications of Traditional as well as advanced FRA techniques for diagnosis of Transformers and Rotating machines.

A. Applications of IFRA for Transformers

Some studies exist where impulse frequency response analysis used with algorithm like support vector machine (SVM) for identification of winding deformation in power transformer [16]. investigation regarding effects of impulse repetition frequency on the accuracy of IFRA test for performing to detect winding deformation carried out [17]. Detection of transformer winding deformation using continuous wavelet transform (CWT) also proved satisfactory [11], [18].

Detection of inter-turn short-circuit faults can be done using offline as well as online IFRA-based method in transformer windings in which reduction in inductance occurred due to inter-turn short-circuit fault mainly in low frequency range[19], [20], [21]. Extending the research from winding deformation and inter-turn short-circuit, effect of capacitive coupling circuit due to coupling capacitance variance and dielectric breakdown of bushing on Online IFRA explored[10]. Injecting partial discharge pulse, Online IFRA also used for identifying how PD produces distinct resonance shifts different from mechanical faults [22]. However PD is only detectable when IFRA is applied at moderately high voltage (50 percent of basic insulation level) which enables non-destructive preliminary PD diagnosis and from that it’s safe to say that low voltage IFRA is sufficient only for inter-turn shorts while high voltage IFRA is useful for diagnostics of PD sources [23].

B. Applications of IFRA for Rotating Machine

Latest studies have progressed towards application of Frequency Response Analysis techniques to rotating electrical machines mainly for the detection of short-circuit faults in stator winding. due to safety and non-uniform voltage distribution issues of traditional IFRA testing, low-voltage Sweep Frequency Response Analysis (SFRA) is preferred which is sensitive to single inter-turn faults in stator of low voltage motors and results also showed that both fingerprint-based and phase-to-phase comparisons can reliably identify faults[24]. however, a nanosecond pulse-

based IFRA method introduced for synchronous machines in which systematically analysis of pulse parameters, influence of rotor position, and sensitivity of frequency band, and experiment showed that IFRA can accurately detect inter-turn and ground short-circuit faults with high sensitivity. This advancement in IFRA application for rotating machines offers the utility of FRA techniques beyond transformers for non-destructive fault detection in complex machines system [25].

Advance techniques where transforming IFRA curves into images and applying deep learning-based image classification with Smooth Grad-CAM++ also exists. This research achieved high classification accuracy, enhancing the physical interpretation into the frequency bands and resonance regions for fault discrimination [26]. Improved study introduced an automated IFRA interpretation framework using lifelong learning through the incremental classifier and representation learning (iCaRL) strategy. Experimental evaluation confirmed the robust classification efficiency on 5 kW synchronous machine [27]. latest study presents a time-frequency technique based on the stationary wavelet transform (SWT) during the startup of salient-pole for detecting high-impedance earth faults, even near the neutral point and identifying faulty phase under varying position and speed of rotor [28].

C. Application of SFRA for Power Transformers

Existing studies have shown the feasibility of SFRA for the diagnostics of power transformer core and winding deformation, inter-turn fault location and assessment of clamping structure as well. Experimental and modelling studies consistently show that mechanical deformations such as axial and radial displacement, inter-disc and inter-turn short circuits, core movement, and loosening of clamping structures produce characteristic deviations in SFRA magnitude and resonance patterns, enabling fault detection even when conventional electrical tests remain inconclusive [29], [30], [31], [32].

SFRA interpretation is strongly frequency dependent: low-frequency regions reflect bulk winding and core behaviour, mid-frequency regions are dominated by inter-disc and inter-layer capacitances and high-frequency regions are sensitive to localized effects such as insulation irregularities, winding leads, and grounding configuration [29], [33].

Study using traveling-wave theory, the mathematical explanation for mid-frequency oscillations in transformer exists which shows how that mid frequency resonances depend on winding inductance, series and shunt capacitance and winding structure. Calculation of transferred lightning over-voltages between the windings of power transformer [34]. While early applications relied on expert visual comparison of response traces, multiple studies highlight the subjectivity of this approach and propose quantitative interpretation techniques, including correlation-based similarity metrics, statistical indicators, fault factors, and

frequency-band-based analysis, to improve repeatability and diagnostic confidence [31], [32], [35]. Contributions extend SFRA beyond fault detection by demonstrating its suitability for wideband transformer modelling and admittance extraction using commercial test equipment, thereby linking condition assessment with electromagnetic transient analysis [30].

D. Application of SFRA for Rotating Machine

The SFRA technique is also used for electrical rotating machines. using low measuring voltage for the fault diagnostics such as inter-turn, inter-winding, and phase-to-phase faults for the synchronous machine[36], [37] and induction machine[38], [39], [40]. Since there are structural similarity between machine windings and transformer windings, The application of SFRA to rotating electrical machines has emerged more recently. However its use remains largely experimental. Experimental studies demonstrate that SFRA is sensitive to a range of faults in induction and synchronous machines, including stator inter-turn short circuits, stator ground faults, insulation degradation, winding deformation, and rotor-related defects, some of which are difficult to detect using conventional current- or vibration-based diagnostic methods [41], [42], [43], [44]. Unlike transformer applications, SFRA measurements in rotating machines are strongly influenced by rotor position, electromagnetic coupling between phases and air-gap effects which leads to periodic variations in frequency response and increases the measurement variability[42], [44]. Several studies presented that even low-severity or single-turn inter-turn faults produce measurable SFRA deviations, highlighting the technique’s potential for early fault detection [41], [45]. In addition, online and continuous SFRA concepts have been experimentally explored using low-amplitude signal injection and inverter-based excitation, demonstrating feasibility under controlled operating conditions [41]. To address the increased complexity of interpretation, advanced analysis approaches such as equivalent-circuit fitting, fault-diagram representations, and multidimensional statistical analysis have been proposed to reduce dependence on subjective visual comparison [42].

IV. CONCLUSION

This paper describes focusing on recent developments in applications of FRA diagnostic techniques in power system and to shed light on the opportunities provided for the diagnosis of faults in power system. A systematic review attempt determined that there are a variety of Frequency response analysis techniques available for monitoring power transformers, rotating machines. First, frequency response analysis methods and their working principles have been discussed. Then their applications to different power system equipment like Transformers and Rotating machines presented. Both of the techniques used for diagnostics of

transformers and rotating machines with different approaches including online and offline. However, in context of applicability, these FRA techniques are mainly utilized for transformers and rotating machines. Application to the other power system components like cables has less documented process. Some authors have made several attempts to use these techniques for other power system components and in this area research is still ongoing.

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