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Modelling and Analysis of Power Transformer Using SFRA for Condition Monitoring

Humam Madara and Mr. Sachin Patel
Department of Electrical Engineering
Institute of Technology & Research Centre, Kalol, Gandhinagar

Abstract: *The (SFRA) is has become one of the most reliable non-invasive diagnostic techniques for assessing the mechanical integrity of power transformer winding's. SFRA is used to detect mechanical and some electrical faults in power transformer, like winding displacement, core movement, loosening of clamping structures, shorted turns or broken winding's, deformation due to transportation, short circuits, or seismic events. The model of power transformers is based on lumped parameter values with minimal cost and time. By interpreting the changes in frequency response, operators can gain valuable insights into the mechanical and electrical integrity of the transformer, leading to better maintenance strategies and enhanced reliability. MATLAB is an excellent choice for SFRA simulations and analysis due to its powerful signal processing and data visualization.*

Keywords: Lumped parameter equivalent circuit, sweep frequency response analysis, power transformer, transformer winding.

I. INTRODUCTION

1.1 Overview

Due to deregulation in the electricity market, power utilities face pressure to cut costs and remain competitive. Life extension of power transformers through advanced condition monitoring techniques offers a solution to reduce operational expenses. As transformers are some of the most expensive equipment within the power grid, prioritizing their monitoring is crucial. This chapter introduces the power system network and the significance of electricity. It explores the various maintenance philosophies employed by utilities and delves into the history of research on analyzing sweep frequency response for transformer health assessment. Additionally, the chapter provides an overview of the current state of the field.

Power transformers are critical components of the power grid. Moreover, replacing a failed power transformer takes significantly longer compared to other equipment. Furthermore, in the event of a transformer failure, the time required for its replacement is typically much longer compared to other equipment. This extend downtime leads to several significant consequences:

- High cost of outage time
- Increased loading on remaining transformers and associated transmission lines.
- Potential load shedding.

To guarantee a reliable power grid, close attention must be paid to the condition of transformers. This can be achieved through a well-coordinated condition monitoring program that focuses on both operation and maintenance aspects of these critical power components.

II. BASIC OF SFRA

2.1 Introduction

The efficient operation of our entire power grid relies on healthy power transformers. These transformers connect power generation to transmission lines and then down to distribution systems, ultimately delivering electricity to consumers. If a transformer malfunctions, it can cause power outages, disrupt businesses and homes, and damage the reputation of utility companies. To prevent these issues, use condition monitoring – a toolbox of various tests – to

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assess the overall health of transformers.By understanding which factors influence a transformer's condition and how they affect its performance, and identify the most relevant parameters to measure during these tests. \

2.2 Stresses on Power Transformer

Over time, various stresses can degrade a transformer's condition, reducing its expected lifespan. These stresses occur both during operation and transportation. While normal operation minimizes physical stress on the transformer, electrical stresses are always present when energized. However, these electrical stresses are carefully designed to stay within safe limits.However, transformers encounter various stresses during their journey from transportation to in-service operation. now explore the specific stress they face,

- Thermal
- Electric
- Chemical
- Mechanical

2.3 What Causes a Power Transformer Fail

Fig. 2.1 Transformer Failure

Power transformers experience a continuous battle against various stresses throughout their lifespan. These stresses include thermal, mechanical, chemical, electrical, and electromagnetic forces, all acting during regular operation and unexpected surges. This constant wear and tear gradually weakens the transformer, ultimately leading to,

- Decrease in dielectric strength (i.e., the ability to resist against lightening and impulses)
- Decrease in mechanical strength (i.e., the ability to resist any faults)
- Decrease in thermal integrity of the current carrying circuit (i.e., the ability to resist against overloads)
- Decrease in electromagnetic integrity (i.e., the ability to shift electromagnetic energy at specified conditions including over-excitation and over loading)

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2.3.1 Winding Deformation Failure Modes

The major deformation modes caused by fault currents are:
Radial buckling of inner winding.
Condutor Tilting
Spiralling in the LV winding
Collapse of the end supports of winding

Fig. 2.2 Radial buckling of inner winding [4].

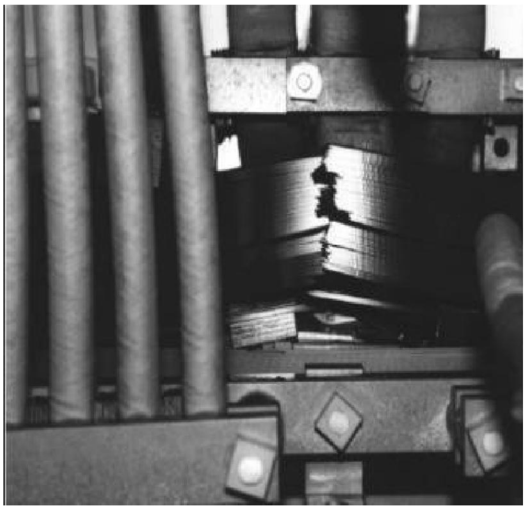

Fig. 2.3 Collapse of winding end support [4]

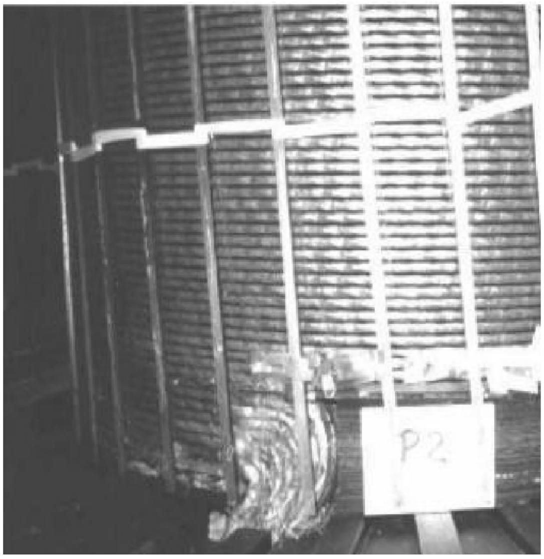

Fig. 2.4 Spiraling in the LV winding [4]

2.3.2 Condition Monitoring of Transformers

Transformer users face stricter limitations due to two key trends: deregulation of the energy market and scientific advancements. Deregulation compels them to: [8]

• Costs reduction
• Handling Power flow of a system.

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2.3.3 Advantages of Condition Monitoring

• Timely and continuous measurement
• Immediate confirmation of faults
• Proactive decision making
• Minimizing unplanned outagest
• Decreased maintenance costs

SFRA basics

Power transformers endure various stresses during operation. When a terminal fault occurs, the mechanical forces inside the transformer far exceed those under normal load current. SFRA provides valuable information about the internal condition of the transformer, including both mechanical and electrical aspects. [4] This chapter will explain SFRA in detail and its ability to detect transformer faults.

The SFRA test method is known for providing accurate and repeatable measurements. Compared to other methods for assessing transformer mechanical condition, SFRA is recognized as one of best tools for detecting mechanical faults and understanding the overall condition of power transformers, encompassing both electrical and mechanical aspects..

Power transformers must be strong enough to handle the mechanical stresses ofshipping and operation, including faults and lightning strikes. Improper clamping and restraints during transport can cause damage, such as movement of the core and windings. The most severe in-service stresses come from system faults, which exert both axial and radial forces. If these forces are too strong, the transformer can buckle radially or deform axially. Core-form designs experience mainly radial forces, while shell-form units handle primarily axial forces. This difference in force direction is likely-to affect thetypes of damage that occur. The transformer isconsidered to be a complex network of RLC components as shown in Fig. 2.6

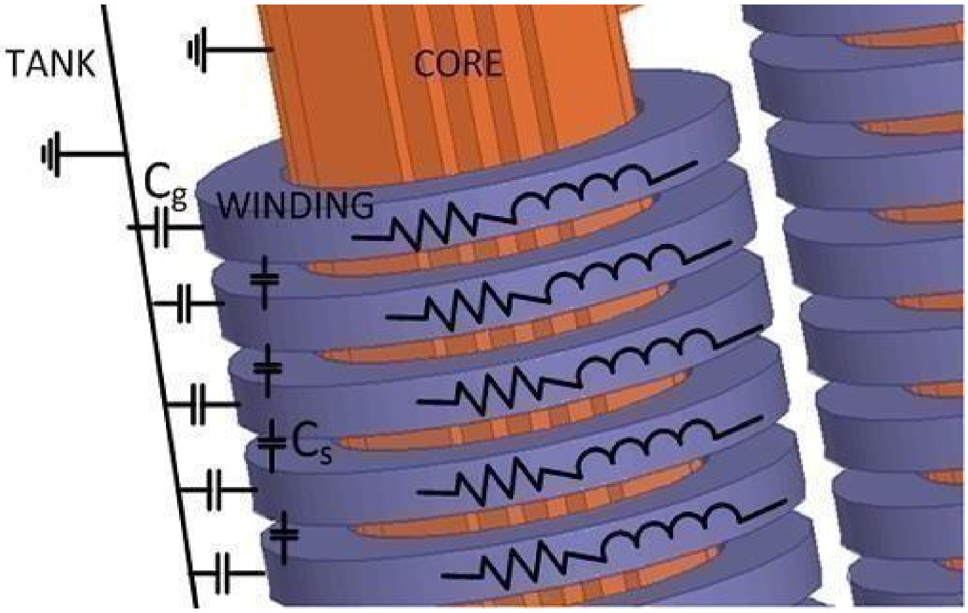

Fig. 2.6 Electrical parameter representation of transformer winding [3]

These alterations can be detected by analyzing the frequency response, which highlights even minor changes within the network.

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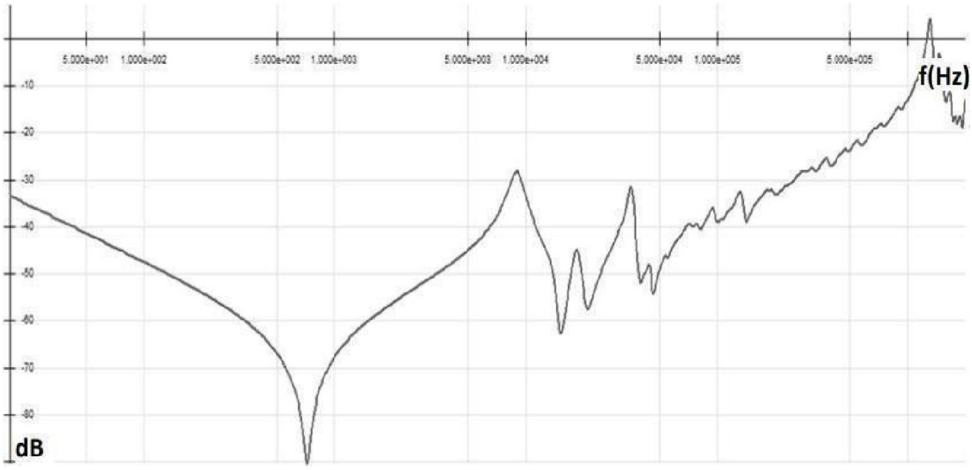

Figure 2.7: Typical SFRA plot [13]

Figure 2.7 shows a typical SRFA plot for HV winding. The frequency range is between 20 Hz and 2 MHz.

2.5 Significance of SFRA

(SFRA) involves measuring the response of transformer windings across a wide range of frequencies. The resulting data is then compared to a reference set. Discrepancies between the measurement and the reference may indicate damage to the transformer. Further investigation using other techniques or an internal examination can be performed to diagnose the problem.[8] ructive testing method. This versatility allows SFRA to be performed on transformers in various states, including with or without oil, under normal operation, or even in faulty conditions. Throughout a transformer's lifecycle, SFRA has proven its usefulness at every stage.

2.6 SFRA Theory

During SFRA testing of a transformer, the leads are set up to utilize four terminals. These four terminals can be grouped into two distinct pairs: one for the input and another for the output. The configuration can be modeled as a two-terminal pair or a two-port network. Figure 01 depicts a two-port network, where Z11, Z22, Z12, and Z21represent the open-circuit impedance parameters.

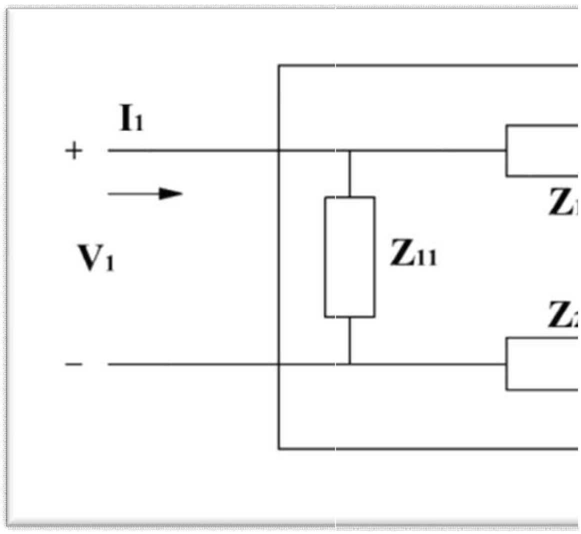

Figure 2.8: Two port networks [13]

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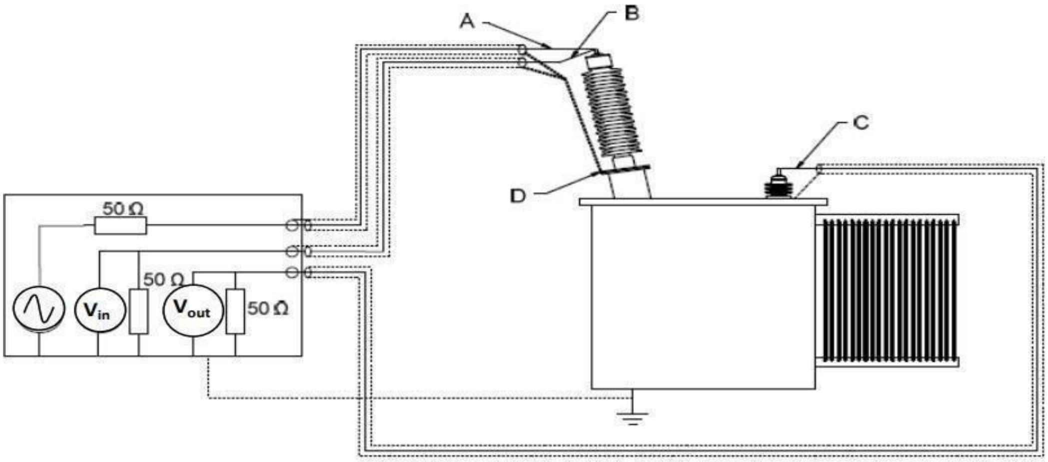
The transfer function of the network is represented in the frequency domain by the Fourier variable H(jω). The term (jω) indicates a frequency-dependent function, where ω is equal to 2πf. Equation 2.1 describes the Fourier relationship between the input and output transfer function.

'$H(jw) = Voutput(jw) / Vint(jw)$ (3.1)

2.6.1 SFRA measurement method

A low voltage signal is introduced to one terminal of the test object relative to the tank. This initial voltage serves as the baseline signal. A second voltage signal (the response signal) is recorded at a different terminal relative to the tank. The response voltage is measured across an impedance matching the input impedance of the response measuring channel, which is set at 50 Ω. For accurate ratio measurements, the reference and response measurement channels and leads must be identical.



A	Source Lead
B	Reference Lead
C	Response Lead
D	Earth Connection

Figure 2.9: Schematic of the frequency response measurement circuit (Source IEC 60076-18)

2.7 Measurement types

The Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC) both recommend three basic types of measurements for performing (SFRA) on transformers: Open Circuit Measurement, Short Circuit Measurement, and Inter- Winding Measurement. [4]

1. Open-Circuit Measurement
2. Short -Circuit Measurement
3. Inter winding inductive test
4. Inter winding capacitive test

2.8 Characteristics of SFRA plot

2.8.1 Regions of the SFRA plot

Different frequency response characteristics exist for various transformer types due to the inherent link between a transformer's response and its core and winding structure. Experience suggests that specific internal components dominate different frequency bands. This allows the frequency response to be segmented into three main regions based on the dominant component within each band.

• The low-frequency region is influenced by the core.

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• The mid-frequency region is influenced by the interactions between the windings.

• The higher frequency region is controlled by the individual winding structure and internal connections.

For analysis and diagnostics, the high-frequency range can be further divided into sub- regions, resulting in a total of four. These regions are illustrated using a frequency response from the HV open winding of a three-phase power transformer (Figure 2.10)

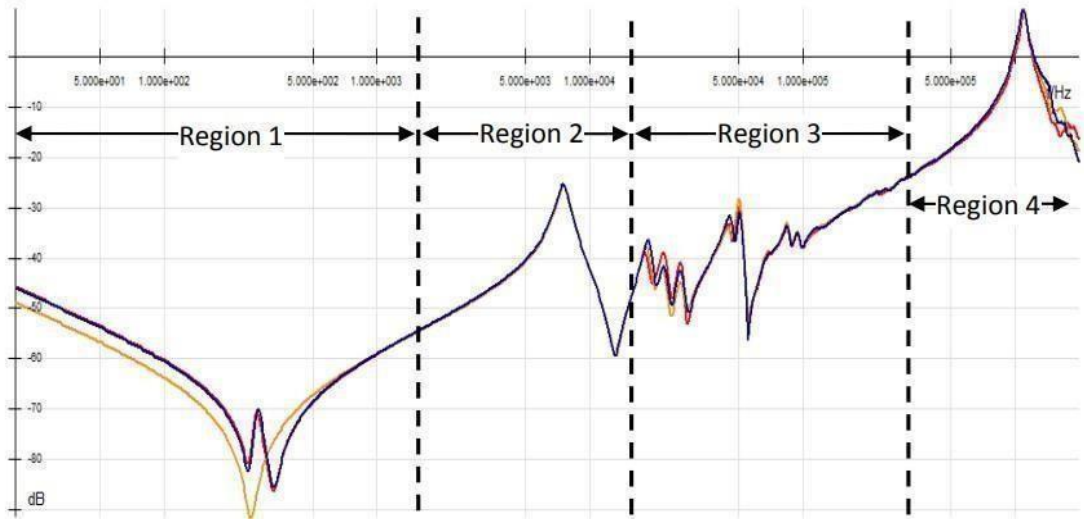

Figure 2.10: Separation of the regions [13]

2.8.2 Behavior of the SFRA plot

The SFRA measurement of a transformer winding exhibits a complex response with decreasing and increasing magnitude relative to frequency. Various resonances (peaks) and anti-resonances (dips) arise from the electrical characteristics of the winding. These characteristics can be modeled by an equivalent circuit containing resistance, inductance, and capacitance elements. The inductance and capacitance values depend on the winding's structure, geometry, insulation layout, and clearances.

Transformer windings exhibit capacitive behavior at high frequencies. This results in a rising magnitude trend with a linear slope in the end-to-end SFRA response as frequency increases. Higher capacitance leads to a greater increase in magnitude.

The combination of inductance and series capacitance within the windings creates a parallel circuit of inductance (L) and capacitance (C). This parallel LC circuit generates a parallel anti-resonance at a specific frequency, effectively blocking the signal at that point. This phenomenon manifests as a local anti-resonance dip in the magnitude response at that particular frequency.

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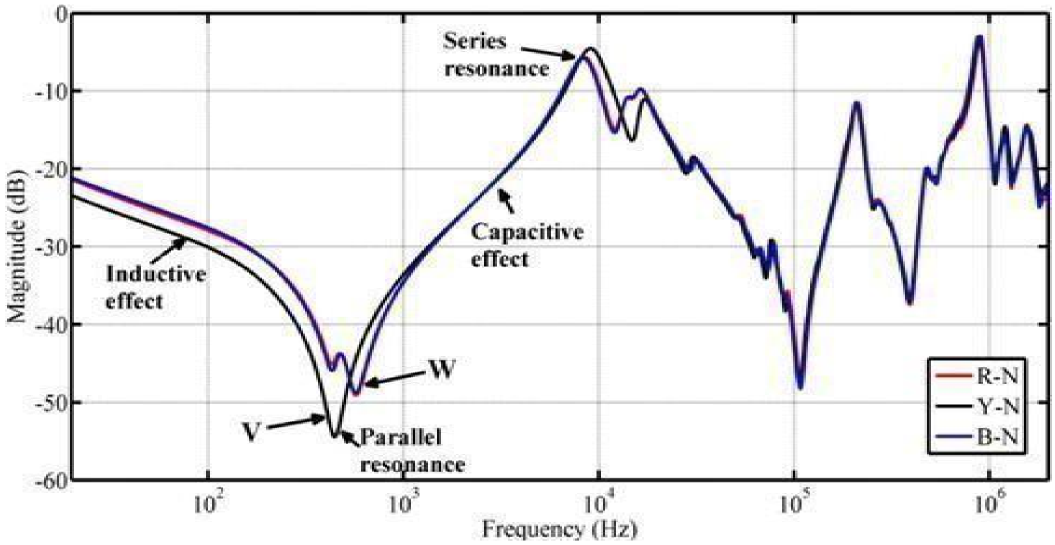

Figure 2.11: Parallel and series resonant point [3]

Resistance affects resonances and anti-resonances by attenuating (smoothing) their sharpness.

2.9 Failure versions of SFRA

These violent events can sometimes lead to compounded failuremodes. Below lists are the failure modes which can be detected by SRFA.

- Core Defects
- Contact Resistance
- Winding Turn to Turn Short Circuit
- Open Circuited Winding
- Winding Looseness

Region	Frequency Sub Band	Component	Failure Sensitivity
1.	< 2 kHz	core and winding inductance	Core deformation, open circuit, shorted turns
2.	2 kHz – 20 kHz	Bulk winding and shunt impedances	Bulk winding movement between windings and clamping structure
3.	20 kHz – 400 kHz	Main windings and tap windings	Deformation within the main or tap windings
4.	400 kHz – 2 MHz	Main winding and tap winding leads, internal leads	Movement of the main & tap windings/ leads, ground impedance variations

Table 1: Frequency sub band sensitivity [8]

III. SFRA OF LUMPED PARAMETER

3.1 Introduction

Traditionally, transformer models rely on estimates of key parameters based on physical dimensions and winding arrangements. These estimates often involve simplifying the actual winding geometry. However, with advancements in technology,finite element analysis can now be used to compute these parameters more accurately, without sacrificing geometric details. In both methods, it's crucial to consider how the frequency of the signal affects the behavior of the transformer's components, including the insulation. This frequency dependence is especially important when performing a (SFRA) test.

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During an SFRA test, a low-voltage AC sine wave with a variable frequency (ω) is injected into one end of a transformer winding. The response is then measured at another end of the same winding, or on a different winding entirely. The transformer's winding impedance dictates how this input signal is transferred, and this relationship iscaptured by the transformer transfer function, denoted as T(ω). In essence, the transferfunction is the ratio of the output voltage wave to the applied voltage (Vin). It's directlyinfluencedby the transformer's impedance (Z), which is a complex value combining resistance (R), inductance (L), and capacitance (C). Since these components exhibit frequency- dependent behavior, the transformer's impedance also varies with frequency

3.2 Creating a winding Model

In recent decades, transformer modeling has relied on various analytical methods. While some simpler methods are used for analyzing deformed windings, they may not capture the intricacies of real-world transformer geometry. To achieve the thesis goal need to identify suitable methods for calculating key parameters. This thesis focuses on the frequency range of 20 Hz to 2 MH

3.3 Model by Lumped Parameter.

It's important to note that directly analyzing a real transformer's transient response is highly complex. To overcome this, engineers use a simplified model called the lumped parameter model. This model represents the transformer's windings as a series of discrete sections, typically modeled as inductors, capacitors, and resistors. The accuracy of this model heavily relies on how these sections are defined.

A lumped parameter model can be thought of as a simplified circuit containing three basic elements: resistors (R), inductors (L), and capacitors (C). These components represent the electrical properties of a system. In this specific model, there are three capacitors: a series capacitance (Cs), a shunt capacitance to ground (Cg), and a self-inductance.[1]

IV. SIMULATION & RESULT

4.1 General Overview

Understanding basic electrical components (resistors, inductors, and capacitors) and their combinations is crucial for SFRA, as a transformer winding can be simplified as a combination of these elements. In real-world measurements, a 50-ohm cable connects the FRA instrument to the transformer to minimize high-frequency signal reflections. However, for this study, we're neglecting the 50-ohm resistance to focus solely on the isolated responses of the individual components.[1]

A MATLAB code simulates this response, plotting the driving point impedance (20log|Z|) across a range of frequencies.

4.2. Single circuit element: Resister–Capacitor- Inductor

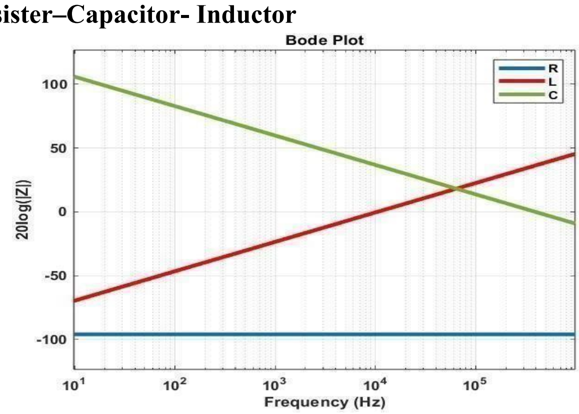

Fig. 4.1 Simulated Response of a R-L-C

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Unlike resistors, which consistently oppose current flow regardless of frequency (resulting in a flat decibel response), inductors and capacitors react differently to varying frequencies. Inductors become more stubborn against changes in current at higher frequencies, causing their response to rise by 20 decibels per decade (dB/decade). In contrast, capacitors become more permissive for current flow at higher frequencies, leading to a response that dips by 20 dB/decade

4.3 Series R-L-C circuit

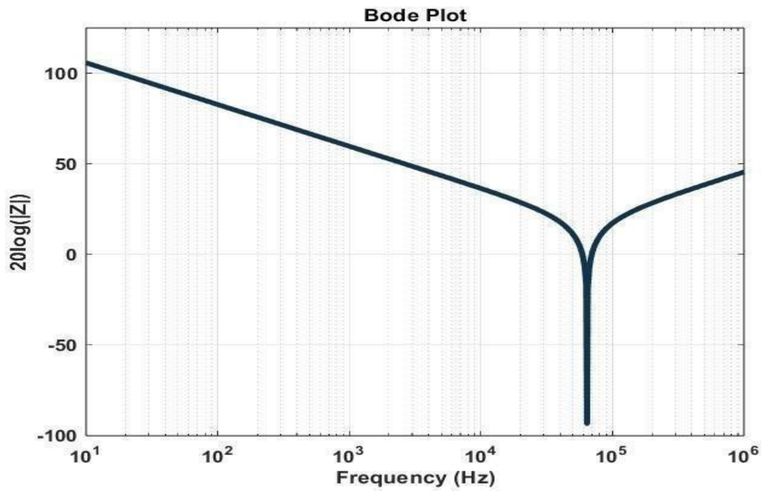

Fig. 4.2 Simulated Response of a series RLC circuit

In this scenario, we take into account the values of R = 8.3×10−4-ohm, L = 1.845×10−4 H, and C = 3.3383×10−8 F. Consider a circuit where the resistor (R), inductor (L), and capacitor (C) are connected in series. In this configuration, the capacitor (C) and inductor (L) significantly affect the circuit's response at low and high frequencies. Specifically, they cause slopes of -20 dB/decade and +20 dB/decade in those regions, respectively.

4.4 C in parallel with series

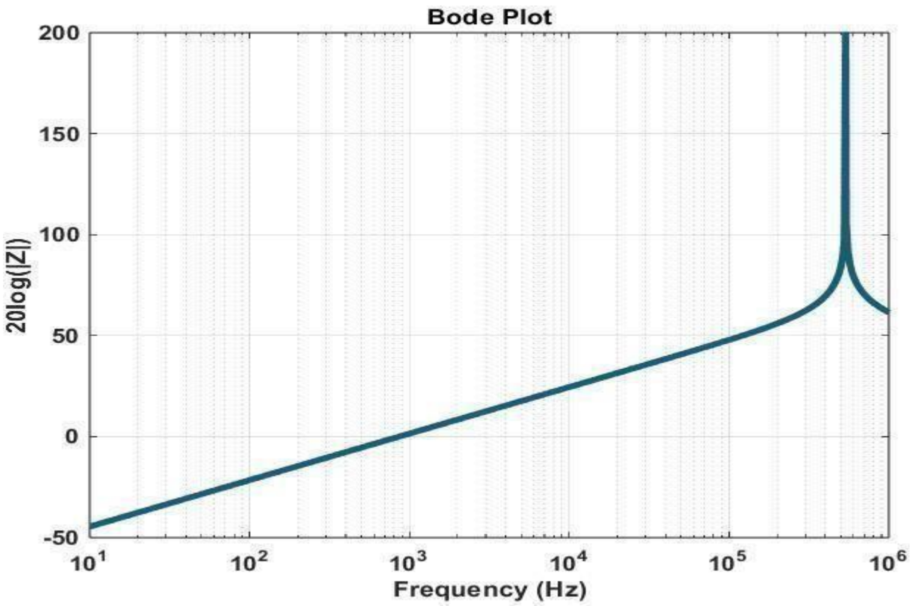

Fig. 4.3 Simulated Response of a Parallel RLC circuit

In the circuit (refer to Figure 5), the inductor (L) dominates at lower frequencies. This results in a rapid 20 dB increase in signal strength with each tenfold rise in frequency (20 dB per decade). However, at the resonant frequency, the capacitor (C) becomes more influential. Beyond this point, the capacitor causes a rapid decrease of 20 dB per decade.

4.5 One section

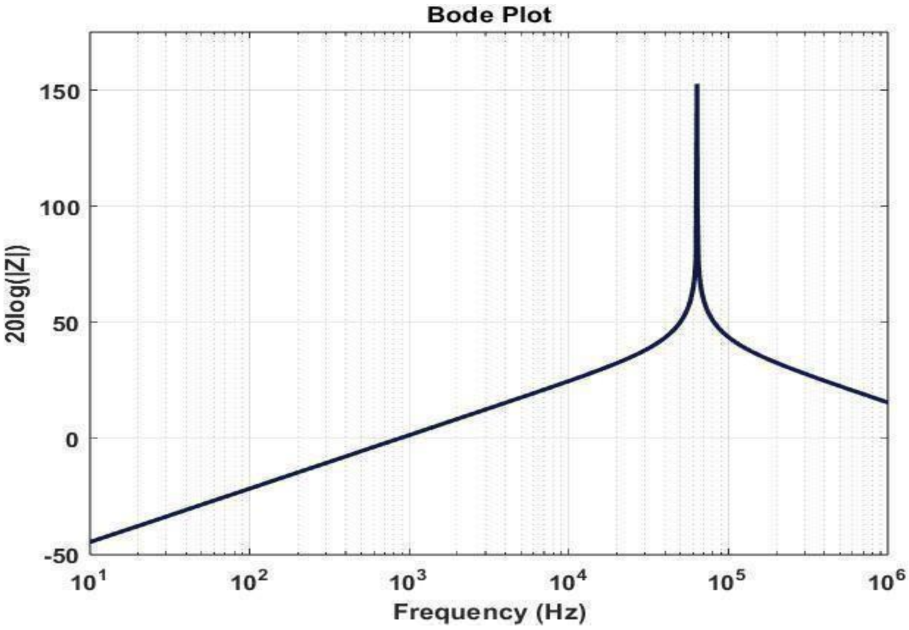

Fig. 4.4 Simulated Response of one Section

4.6 Two Sections

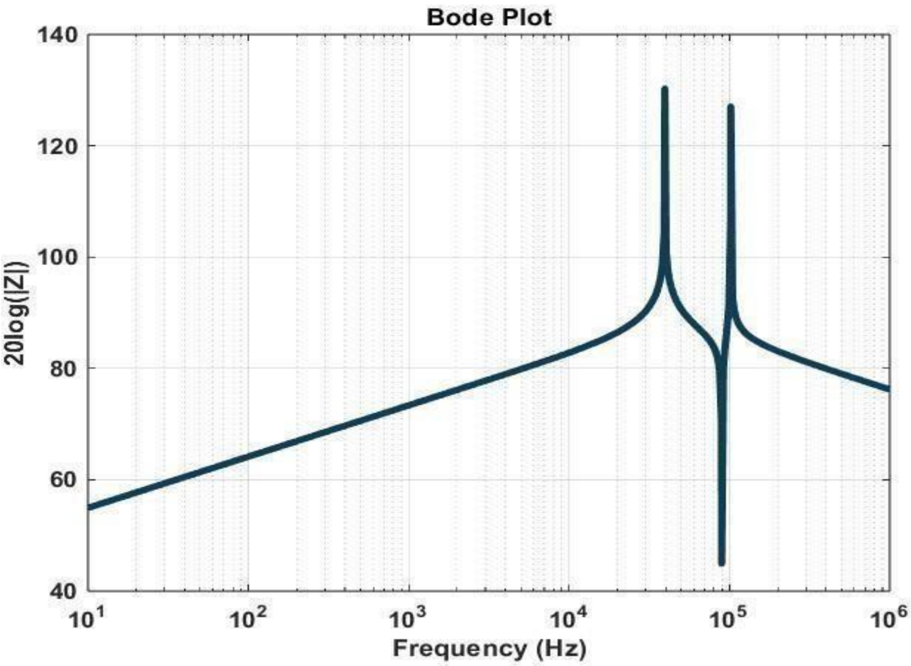

Fig. 4.5 Simulated Response of two section

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4.7 Eight Section

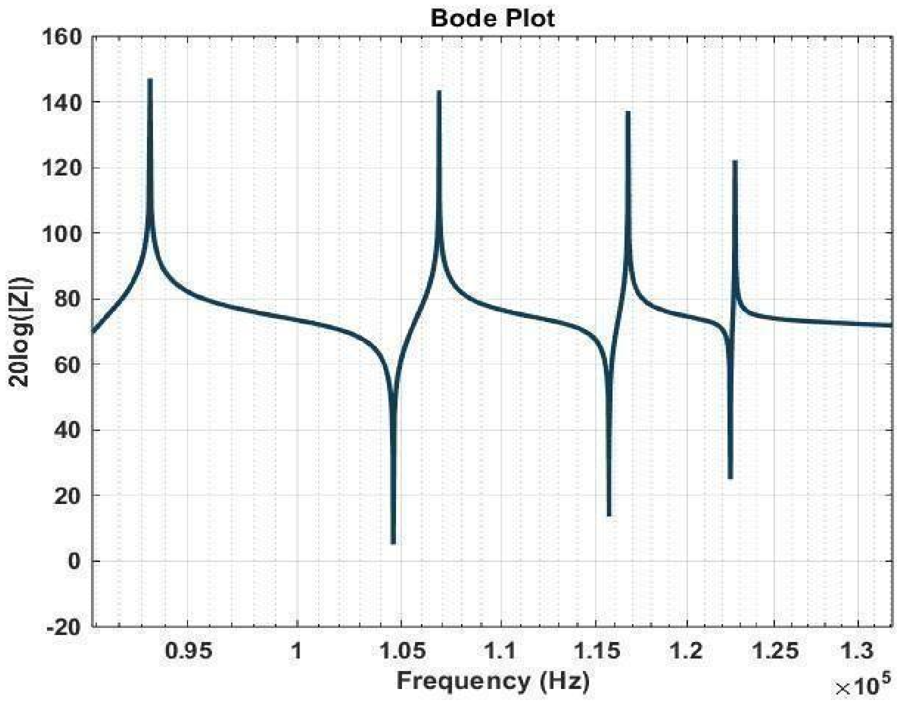

Fig. 4.6 Simulated Response of Eight section

A transformer winding can be represented by dividing it into multiple sections, each consisting of a combination of a resistor, an inductor, a series capacitance (Cs), and a ground capacitance (Cg). The circuit parameters for each section are as follows: R = 8.3×10−4-ohm, L = 1.845×10−4 H, Cg = 3.3383×10−11 F, and Cs = 4.768×10−10 F.

Figures 5 and 6 show the simulated responses for different winding configurations. Figure 5 depicts the general case. Figure 6 illustrates the specific case of an eight- section winding. As the number of sections increases, the effective inductance and capacitance values rise. This rise causes the frequencies at which the first pole and zero occur to decrease. Additionally, mutual inductances between the sections are observed.

4.8 Variation of parameter

This study investigates the impact of varying circuit parameters (capacitances Cs and Cg, resistance R, and inductance L) on the frequency response of a winding with a fixed section count.[1]

1. Capacitance:
• Lower Cs or Cg values lead to a higher natural frequency, and vice versa.
• For frequencies below 100 kHz, the frequency response remains relatively constant regardless of Cs or Cg. However, at higher frequencies, changes in these capacitances significantly impact the response.
• Increasing either capacitance shifts the frequency response towards lower frequencies, and vice versa.
2. Inductance
• It lowers the first natural frequency of the system.
• The peak values of both poles and zeros are impacted by the magnitude of L.
• L significantly affects the frequency response at frequencies below 100 kHz. This influence diminishes for frequencies above 1 MHz. However, in the range between 100 kHz and 1 MHz, both L and capacitance (C) play a role in shaping the response, including the placement of resonant and anti-resonant frequencies.
3. Resistance
• Resistance introduces damping, affecting the magnitude of poles and zeros in a system. Higher resistance translates to lower pole/zero magnitudes, and conversely, lower resistance leads to higher magnitudes.

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V. CASE STUDY

This section explores case studies involving power transformers of various capacities and voltage classes. We'll examine transformers ranging from small-scale prototypes to powerful 150MVA units deployed in field substations across diverse locations. The following details the transformers subjected to testing.

- 132/11kV, 12.5 MVA, three phase 2 winding,
- 220/132kV, 100 MVA, three phase 2 winding,
- 66/11kV, 15 MVA, three phase 2 winding,
- 11/3.3kV, 1 MVA, Single phase 2 winding.

To validate the proposed methodology for transformer condition monitoring using SFRA, several case studies will be conducted. These studies will demonstrate the application of the method and provide evidence for the weights and scores assigned to various indices discussed in Chapter 3. Ultimately, these case studies will help confirm the effectiveness of the methodology in assessing transformer health

5.1 Case Study 1

Table 1. Basic design detail for the Test Transformer

Rated power	12.5MVA
Voltage Rating	HV – 132 KV LV-11 KV
Location	Chiloda (Before - 19/04/2019) / Chiloda (After – 21/04/2021)
Rated Frequency	50 Hz
Phases	3
winding	2
Company	GETCO
Manufacture	BHEL

This particular instance examines data obtained from a 12.5 MVA transformer with 3 phases and 2 windings. The manufacturer is BHEL company, and the transformer is currently stationed at the Chiloda substation. The transformer is specifically configured to function at 132 KV on its high voltage (HV) winding, while the low voltage (LV) winding operates at 11 KV.

An analysis will be conducted to compare and contrast information on the transformer's state before it was commissioned and after it tripped. Examining data from these two periods will reveal any changes or problems that might have happened during operation. This analysis will provide insights into the transformer's performance and identify potential improvements to guarantee its reliability and efficiency.

1. HV winding (R-Y) Phase - LV winding SHORT

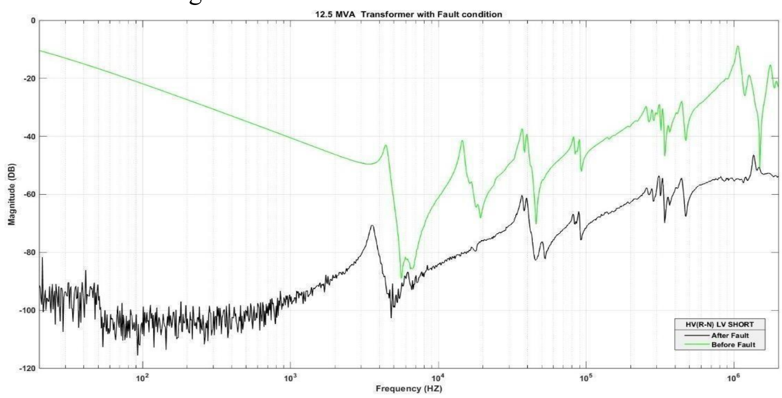

Fig. 1 HV (R-N) Green before fault and Blue after fault comparison (21/04/2021)

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The process begins with a short circuit test. The first measurement is taken between the high voltage (HV) winding (R-N) phase and the open low voltage (LV) winding. The green trace in the resulting signature represents the pre-fault condition, while the blue trace shows the post-fault comparison.

Figure 1 illustrates how the short circuit test significantly impacts the lower frequency range, particularly below 1 KHz. This region is closely linked to core defects like core lamination issues, multiple grounding problems, joints, and dislocations.

2. HV winding (R-N) Phase - LV winding OPEN

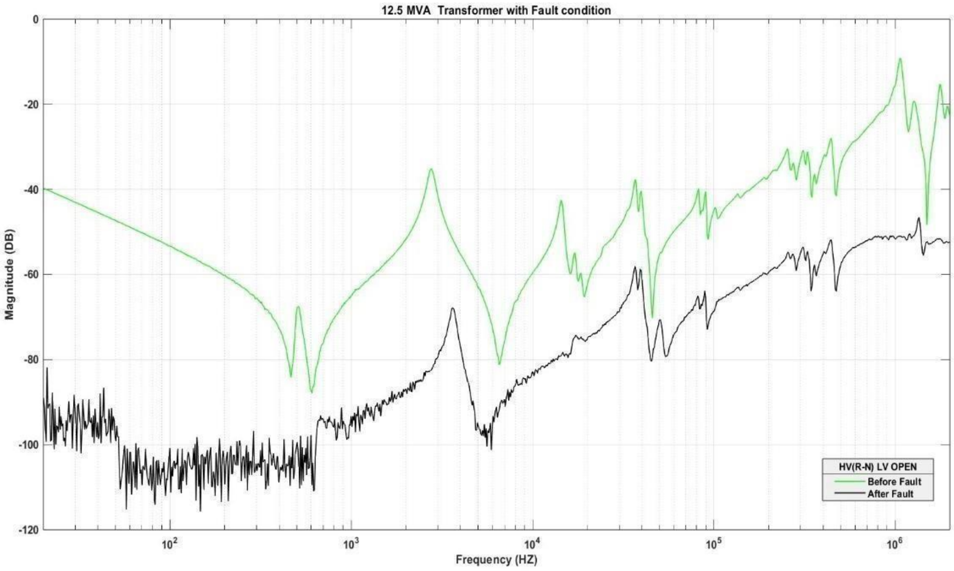

Fig. 2 HV (R-N) Green before fault and Blue after fault comparison (21/04/2021)

The next open circuit test involves measuring between the HV (R-N) phase with the LV open circuit test involves measuring between the HV (R-N) phase with the LV winding left open. As illustrated in Figure 2, the core defect appears to have a similar impact on the lower frequency region during this test.

As we can see in the fig.3, Measurement taken between LV(R-N) phases, it is observed that a resonance shift becomes noticeable towards the lower frequency range (less than 1 KHz). This shift in resonance signifies a significant change in the characteristics being analyzed.

3. LV winding (R-N) Phase

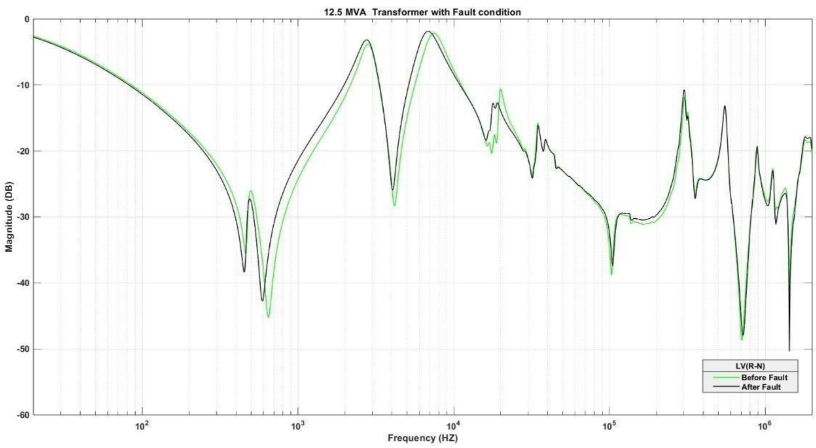

Fig. 3 LV (R-N) Green before fault and Blue after fault comparison (21/04/2021)

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Conclusion from Data Analysis:

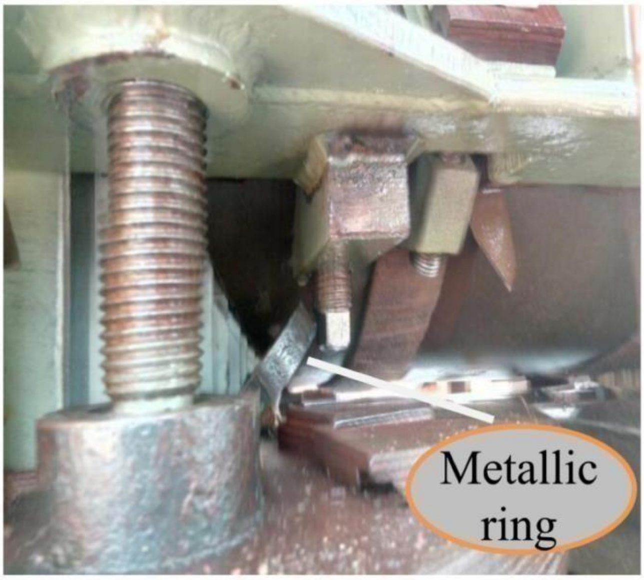

Fig. 7.4 metallic ring used for mechanical support was dislocated

The SFRA was conducted and compared to the available base signature. Although the HV winding was found to be normal, some disturbances were observed in the core area.

An internal inspection was scheduled to be conducted, during which the total oil was drained and the active part of the transformer was removed for further examination. Subsequently, a thorough inspection of the active part was performed to ensure its proper functioning and maintenance.

6.2 Case Study 2

Rated power	150 MVA
Voltage Rating	HV – 220 KV LV- 132 KV
Location	RANASAN (Before - 16/01/2015) / RANASAN (After – 24/10/2016)
Rated Frequency	50 Hz
Phases	3
winding	2
Company	GETCO
Manufacture	T&R

Table 1. Basic design detail for the Test Transformer

In this particular instance, Examine the data obtained from a Transformer with a capacity of 150 MVA, featuring 3 phases and 2 windings. The manufacturer of this Transformer is T&R company, and it is currently stationed at the Ranasan substation. The transformer is specifically configured to function at 220 KV on its high voltage (HV) winding, while the low voltage (LV) winding operates at 132 KV.

An analysis will be conducted to compare information about the transformer before it was commissioned and after it tripped. By examining data from these two distinct periods, valuable insights can be gained into any changes or problems that might have occurred during the transformer's operation.

This analysis will help better understand the performance of the transformer and identify any potential improvements that can be made to ensure its reliability and efficiency.

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1. HV winding (Y-N) Phase - LV winding SHORT

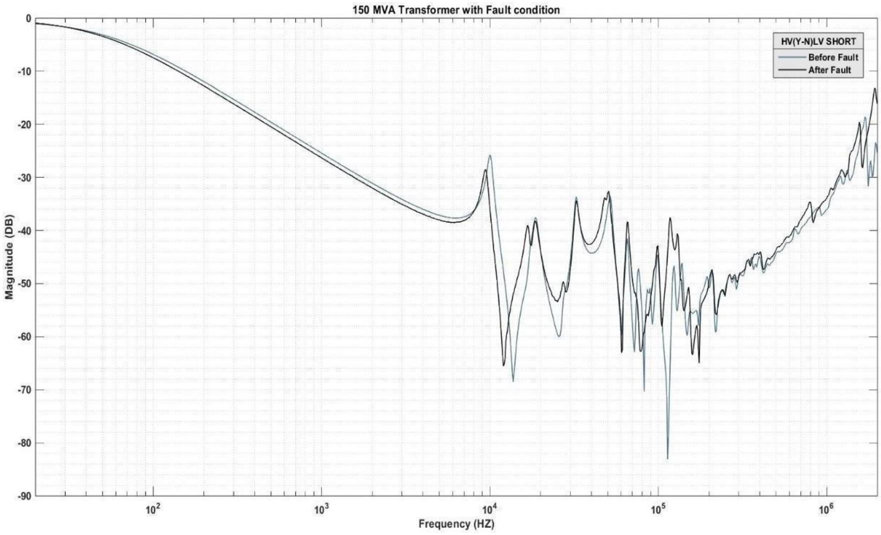

Fig.7.5 HV (Y-N) Blue before fault and Black after fault comparison (24/10/2016)

Initially, a short circuit test is performed, during which the first measurement is taken between the high voltage (HV) winding (Y-N) phase with the LV winding kept short. The Blue trace in this signature indicates the condition before the fault occurred, while the Black trace represents the comparison after the fault has occurred.

From the fig 1, it is observable that the resonance points have shifted with respect to each other. Higher frequency region (10 KHz to 1 MHz) is affected which correspond to the leads and terminal failure.

The 150 MVA transformer, which has been in operation since 1980, recently experienced an issue with its taps becoming stuck. As a result, it was necessary to change the tap position during the Sweep Frequency Response Analysis (SFRA) test. This adjustment, however, may lead to a slight shift in resonance within the low frequency range that is typically associated with core defects.

2. HV winding (Y-N) Phase- LV winding OPEN

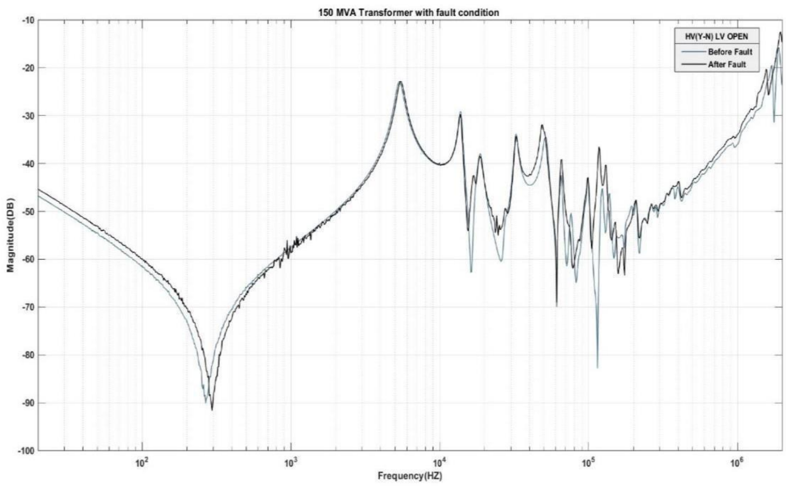

Fig.7.6 HV (Y-N) Blue before fault and Black after fault comparison (24/10/2016)

In the next open circuit test, the measurement is taken between the HV (Y-N) phase while keeping the LV winding open. From the fig 6. In the high frequency region (10 KHz to 1 MHz), a noticeable variation becomes apparent during the open circuit test. The Blue trace in this signature indicates the condition before the fault occurred, while the Black trace represents the comparison after the fault has occurred. This variation in the high frequency region during the open circuit test indicates that there may be some impedance mismatch or other factors affecting the performance of the

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circuit. It is important to further investigate and analyze this variation to determine the root cause and make any necessary adjustments to ensure optimal performance.

3. HV Winding (Y) Phase – LV winding (Y) Phase

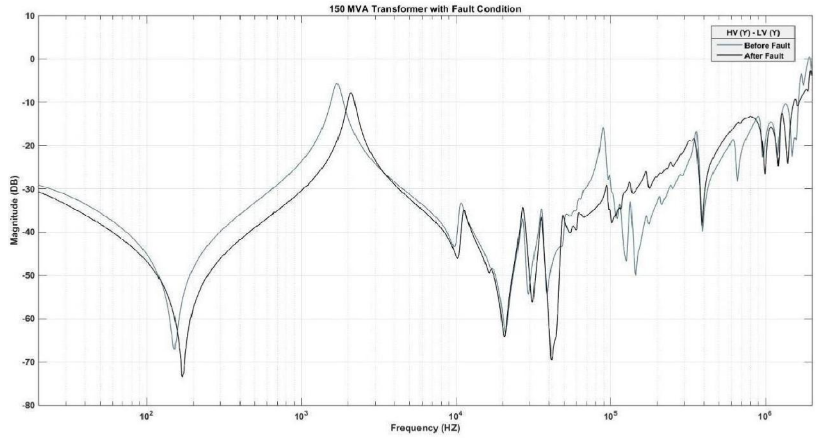

Fig.7.7 HV (Y) – LV (Y) Blue before fault and Black after fault comparison (24/10/2016)

4. Winding (Y-N) Phase

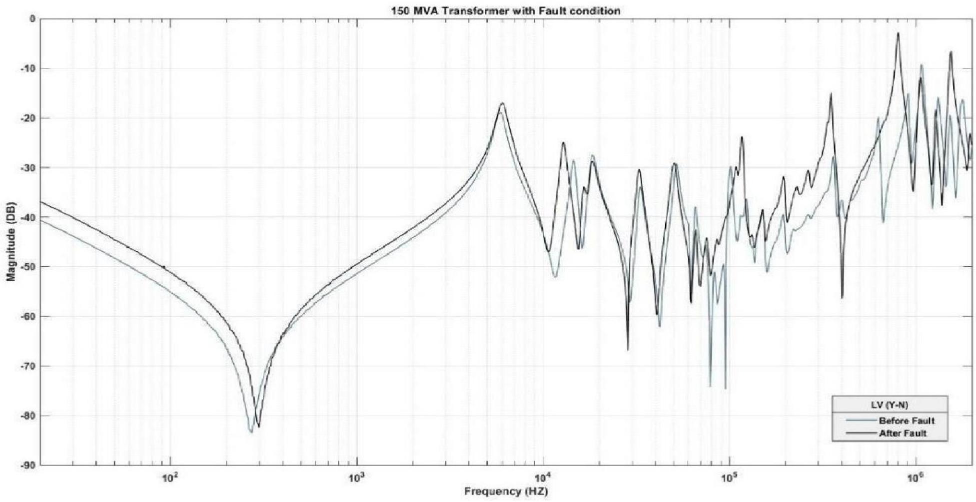

Fig.7.8 LV (Y-N) Blue before fault and Black after fault comparison (24/10/2016)

This noticeable difference in the high frequency region between the LV (Y-N) phase is indicative of potential issues with the insulation system. The voltage measurement between the HV (Y) phase and LV (Y) phase, which shows a significant impact on the high frequency region, suggests that there may be a fault or breakdown in the insulation between these phases.

In this case, the measurement between the HV (Y) phase and LV (Y) phase indicates the largest difference. The high frequency region experiences a significant impact, which is easily observable and ultimately results in the failure of leads. The significant impact on the high frequency region suggests that the insulation is not effectively blocking or attenuating the high frequency signals, leading to potential issues with the system's performance and reliability.

To further investigate the insulation condition, another measurement is taken between the LV (Y-N) phase. The noticeable difference in the high frequency region is appear, which result in leads and terminal failure.

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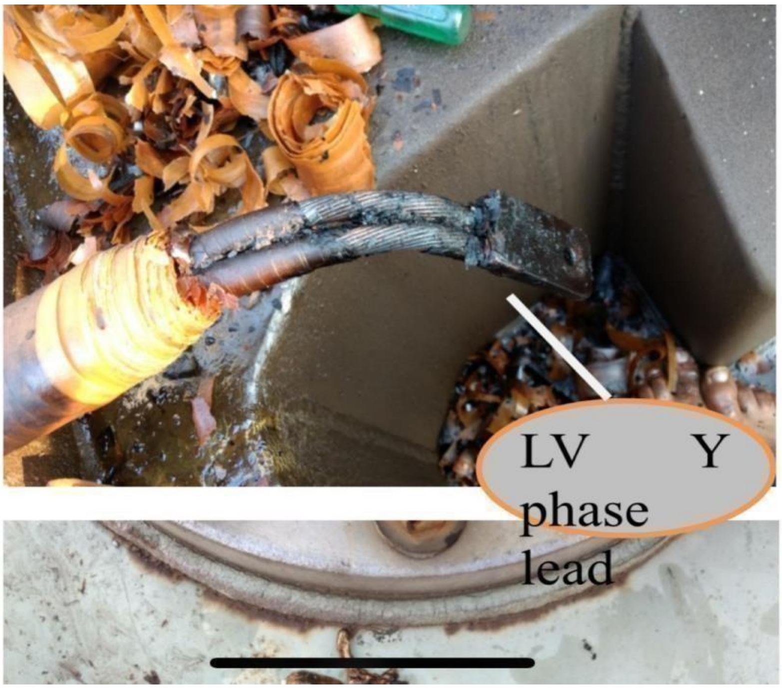
Conclusion from Data Analysis:



6.9 lead found loose and burnt from braising.

The testing results, which included SFRA and tan delta, indicated normal conditions. Upon analyzing the DGA major key gases, it was observed that C2H2 and H2 levels had increased, suggesting possible arcing inside the transformer. Consequently, an internal inspection of the transformer was conducted. During the inspection, copper particles were discovered in the selector switch on the LV Y-phase main lead that was connected to the selector switch. Additionally, it was observed that this lead was loose and had been burnt due to braising.

Following the removal of burnt insulating papers and thorough cleaning of the lead, new insulation was applied to ensure its proper functioning.

Case Study 3

Rated power	15 MVA
Voltage Rating	HV – 66 KV LV- 11 KV
Location	BHAT (Before - 27/06/2013) / BHAT (After – 8/12/2017)
Rated Frequency	50 Hz
Phases	3
winding	2
Company	GETCO
Manufacture	ATLANTA

Table 1. Basic design detail for the Test Transformer

In this specific case, we'll analyze data gathered from a Transformer with a 15 MVA capacity, comprising 3 phases and 2 windings. The Atlanta company manufactured this Transformer, which is presently located at the Bhat substation. It's designed to operate at 66 KV on its high voltage (HV) winding and 11 KV on its low voltage (LV) winding.

The data concerning the transformer will be analyzed and compared from two distinct time periods: before it is commissioned and after a trip event. This examination aims to identify any changes or issues that might have emerged during the transformer's operation.

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This analysis is designed to yield a deeper understanding of the transformer's performance. By examining its capabilities, potential areas for improvement can be identified, ultimately ensuring its reliability and efficiency.

1. HV(R-Y) LV OPEN

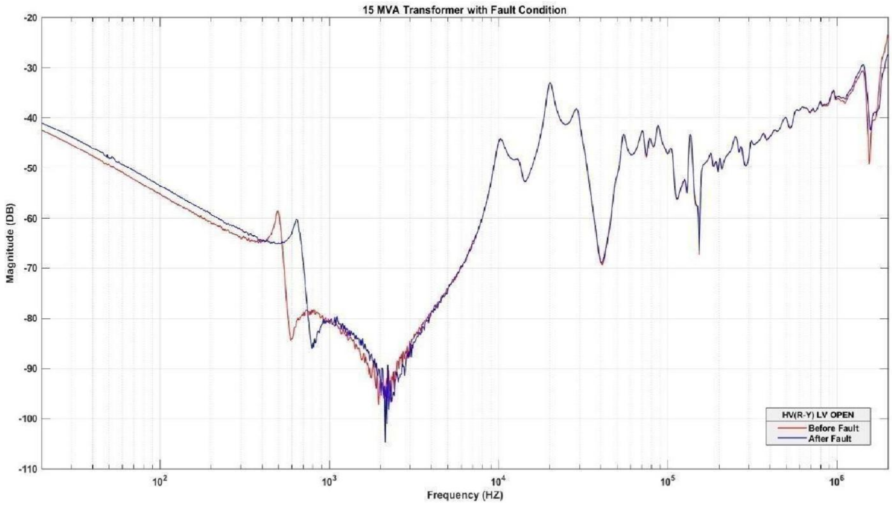

Fig.7.8 HV (R-Y) RED before fault and Blue after fault comparison (8/12/2027)

In the next open circuit test, the measurement is taken between the HV (R-N) phase while keeping the LV winding open. From the fig 1. In the high frequency region (10 KHz to 1 MHz), a Slight variation noticeable during the open circuit test. Through the visual inspection of the SFRA plot collected for this transformer, from the fig.1 we can see that the plot of the R phases deviates from each other at the low and Middle frequency regions which is influenced by Core and winding deformation respectively. The affected winding cause difference between phase or previous result.

2. HV (Y-B) LV OPEN

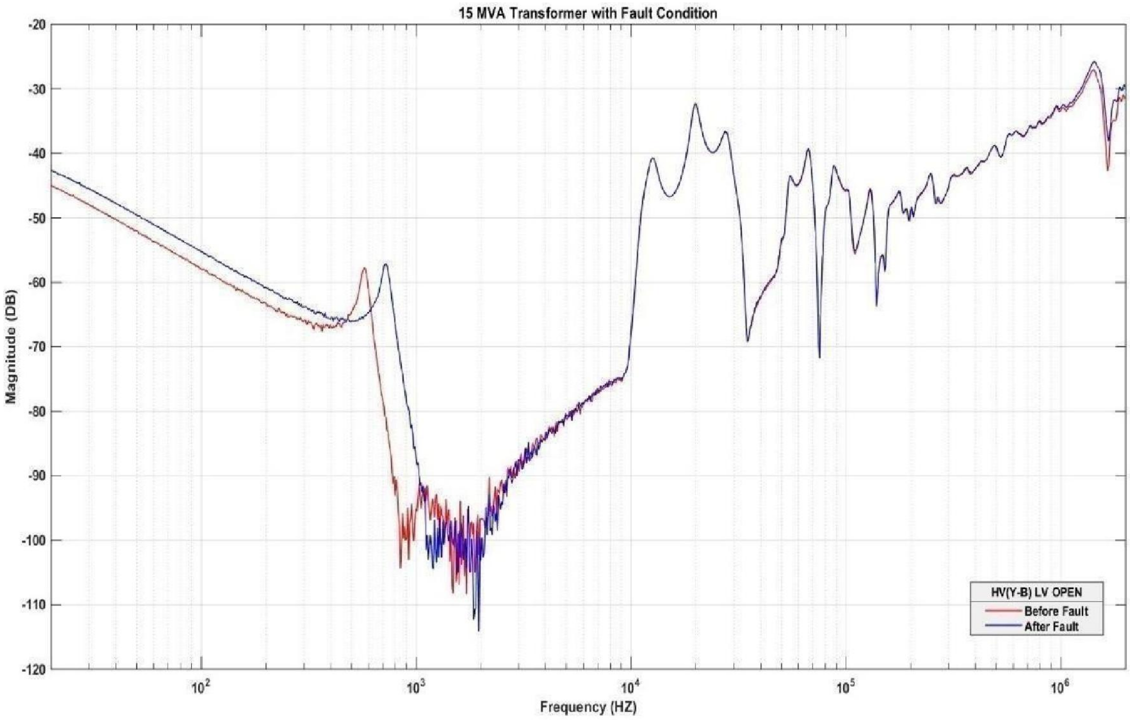

Fig.7.8 HV (Y-B) RED before fault and Blue after fault comparison (8/12/2027)

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3. HV(B-R) LV OPEN

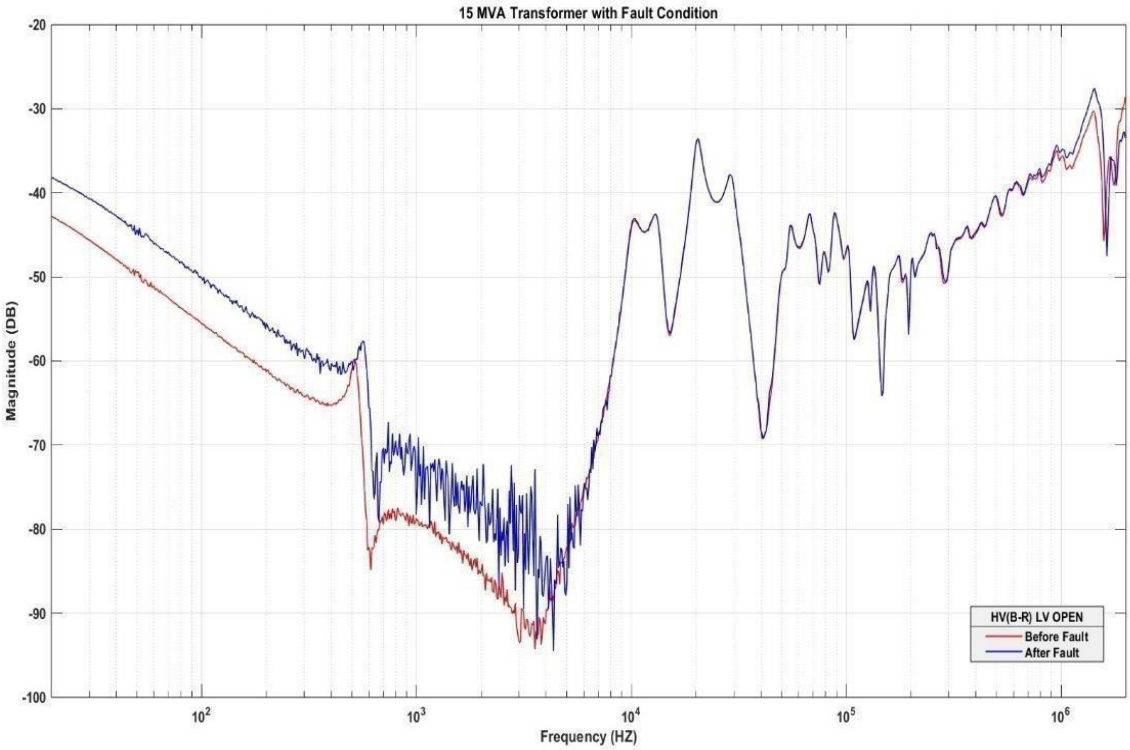

Fig.7.8 HV (B-R) RED before fault and Blue after fault comparison (8/12/2027)

Conclusion from Data Analysis:
Turns on HV Winding disc number 21 have been identified as damaged and punctured as a result of a fault on the LV side and excessive axial force on the core. Furthermore, this force has caused deformation, altering the disc's original shape.

VI. CONCLUSION AND FUTURE WORK

6.1 Conclusion

This Chapter concludes the research work summary and significant contributions of the thesis and provides a few suggestions for further research work in this area. This thesis has deal with deformation diagnostics of power transformer winding. the work primary focused on following aspects.
A lumped parameter circuit of transformer winding has been carried out to understand the nature of FRA. Which consist the 8 Disc and the response is simulated through a code written in MATLAB, which plots the driving point impedance, viz. 20log|Z|, as afunction of frequency. which clarify the response of Ideal R-L-C, their series and parallel combination as well as section wise simulation. Also gives understanding of transformer winding characteristics and enhance their ability to design and analyse transformer circuits with precision and accuracy.
The case study involved conducting an SFRA experiment on a single-phase transformerat IITRAM. The experiment aimed to:
The experiment aimed to showcase the practical use of SFRA in diagnosing thehealth of transformers.
The effectiveness of SFRA in identifying turn-to-turn faults was evaluated duringthe experiment.

6.2 Future Work

Based on the investigations conducted in this thesis, the following aspects are recommended for future research:

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• This thesis proposes interpreting SFRA tests using phase shift differences between regions. Similar to how dB difference rules are established, a phase difference matrixcan be developed for SFRA analysis based on these phase shifts. This approach offersan alternative method for analyzing SFRA data.

• The interpretation of SFRA responses is critical for assessing both mechanical and electrical integrity of winding's.. However, the primary factor that governs the SRFA responses across low, medium and high frequency regions is the construction of the winding. A more in depth understanding of this influence can be achieved through transformer winding circuit modelling, which could provide a clearer insight into the relationship between the winding structure and SRFA behaviour

• Adaptive resonance theory based Self-Learning Neural Network can be used to predictthe faults by pattern recognition technique.

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