Diagnosis of Faults in the transformer windings by Sweep Frequency Response Analysis (SFRA)

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A project report
submitted in partial fulfillment
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(With Specialization in Power System Engineering)

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Candidate's Declaration

I hereby declare that the work which is being presented in this report entitled "Diagnosis of faults in the transformer windings by Sweep Frequency Response Analysis (SFRA)" submitted in the partial fulfillment of the requirement for award of the Degree of Master of Technology in Electrical Engineering with specialization in Power System, from Indian Institute of Technology, Roorkee under the supervision of Dr. Ganesh Kumbhar,Associate Professor of Department of Electrical Engineering, Indian Institute of Technology, Roorkee, is an authentic work carried out during the period of January, 2019 to April, 2019. The matter presented in the seminar has not been submitted by me for award of any other degree of this institute and any other institute.

Date: Priyanshi Aggarwal
Place: Enrollment Number : 17529010

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Abstract

Power transformers, one of the vital elements of the power system network, are exposed to different types of winding faults, radial and axial deformation continuously. Monitoring at regular interval should be done in a way that will minimize(i.e take less time) its affect due to power outage on consumers. Sweep frequency response analysis is one such method. But it requires expert supervision in differentiating visual data records at normal and faulty condition. This work presents interpretation of data records by calculating statistical parameters which help in analyzing the location of fault in the winding and to differentiate between different faults. Faulty conditions were created artificially in the winding at differnt locations by shorting the tappings. Simulation data can be obtained with the help of MATLAB and Ltspice programming. For this parameters of the winding should be known which can be calculated if dimensions of the winding are known. Different type of faults show changes in different frequency bands and hence value of parameters changes.

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Chapter 1

Introduction

1.1 General

High voltage transformers, one of the expensive elements of transmission and distribution networks, work under different mechanical, electrical and environmental conditions. Its performance in the network directly affects the reliability of the network. They may be subjected to various defects during operation. It is very difficult to repair or replace them immediately after failure. Temporary exit or outage of the power transformer results in power outage for customers and heavy losses for the power sector [1].

The internal condition of transformer degrades with the transformer usage and increases the risk of failure. It is very important to detect the problems before it fails due to its high cost. So, there is a need to detect the internal faults in the power transformer due to winding displacement and deformations without opening the unit so that time which was required for de-assembling the unit for fault clearance and assembling it again can be utilized in some other useful work [2].

This report aims at a diagnostic technique, Sweep frequency response analysis used for detecting faults, winding deformation and displacements during transportation, turn to turn shorts with the help of statistical parameters such as correlation coefficient. Graphical analysis needs expertise and experience of different people. But statistical parameters make work easy and do not require expert supervision. Correlation parameters can also tell the type of fault i.e series or shunt fault.

1.2 Literature Survey

Power system protection schemes can not differentiate between the inter-turn faults and faults due to other abnormal operating conditions like magnetic inrush, over voltage and faults at other components in the system. Differential protection scheme used in the power system network will operate for inter-turn faults but one can not differentiate whether the fault has ocuured due to some other internal faults or shorting of turns. Also location of fault can not be estimated by this method. So, a new method known as Sweep Frequency Response Analysis (SFRA) is proposed which is simple and elegant method for fault detection.

Mechanical defects occur due to flow of short circuit currents in the transformer windings, careless transportation of transformer between sites, earthquakes, explosion of accumulating gases in the transformer oil [2].

They include

- Winding deformation due to radial or axial forces
- Buckling (forced as well as free buckling)
- Shorted turns
- Faulty grounding of cores
- Broken clamping structure

Various methods were proposed to monitor the fault in the winding [3],[1]. Some are

1. Measuring temperature
2. Dissolved gas analysis- DGA
3. Partial discharge analysis
4. Measurement of short circuit inductance- SCI
5. Frequency response of stray losses
6. Frequency response analysis
    (a) Low-voltage impulse-LVI
    (b) **Swept frequency response analysis-SFRA**

In SCI method , leakage inductance is measured and is compared to the name plate value. If the change is more than $\pm 3\,\%$ then it indicates winding deformation. But this method was not so good. Leakage inductance value changes with the distance between LV and HV winding. Moreover, high value of leakage inductance results in high voltage drop and less value affects short circuit current [2].

DGA method can detect internal faults but cannot detect mechanical deformations in the winding [1].

Frequency response analysis is better than other methods due to its high sensitivity. In this method, change in impedance of transformer takes place due to winding deformation or displacement which further modifies its frequency response [3].

In LVI method, a low voltage impulse signal with sufficient steepness is given to transformer winding. It is a time domain method. To convert it into frequency domain, fast fourier transform (FFT) is done. The steepness of voltage signal should be adjusted so as to provide wide frequency band. This frequency band is compared with the corresponding reference fingerprint of the transformer [3], [4], [5].

1.2.1 Sweep Frequency Response Analysis(SFRA)

In SFRA method, a sinusoidal sweep voltage signal of fixed magnitude with frequency varying from 20 Hz-10 MHz is applied to one of the windings of transformer. The transfer function of transformer winding is determined and plotted as a function of frequency as shown in Figure 1 & 2 [3], [4]. This is compared with the reference fingerprint of the transformer which is taken when no fault is present in the winding. If there is difference between the two graphs then there is fault in the transformer [4].

FRA measurements are taken on isolated transformer and disconnected from the power system network i.e it is an offline method. This is done to neglect the effect of bus capacitances which are variable and depends on the location. Advantages of SFRA over LVI method [5]

- In LVI, measurements are affected by ambient noise. So, it is not preferred.
- Less requirement of measurement equipment.
- Higher signal to noise ratio

The only disadvantage of SFRA method over LVI method is that measurements are taken at various discrete frequencies so takes relatively long time. Open circuit self impedance/admittance can also be used instead of transfer function for comparison purpose. But the magnitude plot of transfer function is more sensitive to small displacements/deformations. The transfer function of transformer depends on the type of the winding and its connection, tap positions etc [5].

The frequency response magnitude 'K' is given by (in terms of decibels) [2]:

$$K = 20\,log\frac{V_{out}}{V_{in}} \tag{1.1}$$

where $Vout$ is the output voltage of transformer, Vin is the sinusoidal sweep signal injected at the terminals of the transformer.

1.2.2 Equivalent Circuit of Transformer

A simplified equivalent circuit diagram of a winding using cascaded π sections is drawn. The model consists of 8 sections, having equal number of turns.

Figure 1.1 represents the equivalent circuit of transformer winding where R is series resistances, Ls1-Ls8 are self inductances, Cg is ground capacitance, Cs is series capacitance, K12,K13.....so on, are mutual coupling coefficients. In a winding, there exists a capacitance between adjacent sections or discs, adjacent turns within a disc or section, capacitance to ground, capacitance to other windings. Similarly there exists self and mutual inductances with other sections. Both are distributed in nature but considered as lumped for practical purpose [6].

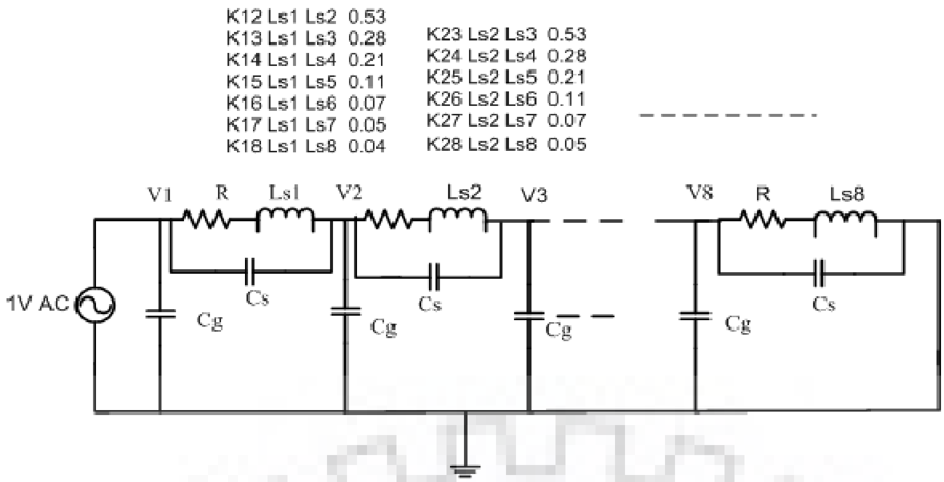


Figure 1.1: Equivalent circuit diagram

1.2.3 SFRA Characterstics

The reference curve of a transformer is obtained at various discrete frequencies after its manufacturing so that it can be used for further comparisons. Figure 1.2 shows the typical SFRA characteristic which is also known as fingerprint of the transformer response. Any deviation from this response indicates some type of fault in the winding.

The frequency response is divided into three regions: low frequency region, mid frequency region and high frequency region. In low frequency region, resonance is between magnetizing inductance and the capacitance of the winding. In mid frequency region, resonance is between the inductances and capacitances of the winding. In high frequency region, resonance is affected by the bushing capacitances, lead inductances and stray capacitances [5].
Change in the frequency response occur in different frequency bands for different types of faults. For example short circuit fault affects the low and medium frequency region and no change occur at high frequency. Axial displacement and radial deformation show changes in middle frequency band and high frequency region respectively [1].

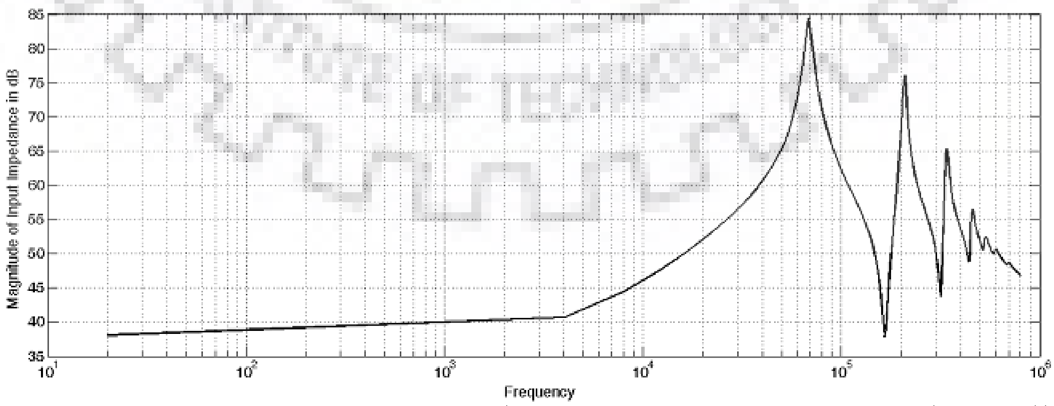


Figure 1.2: Typical SFRA signature (magnitude in dB & frequency in Hz(log scale)))

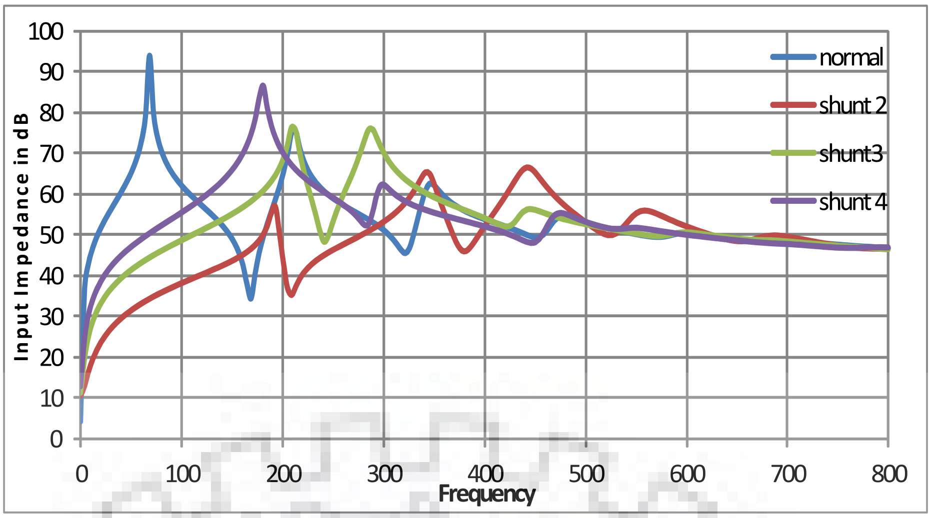


Figure 1.3: Comparison between shunt fault and healthy condition in different frequency band

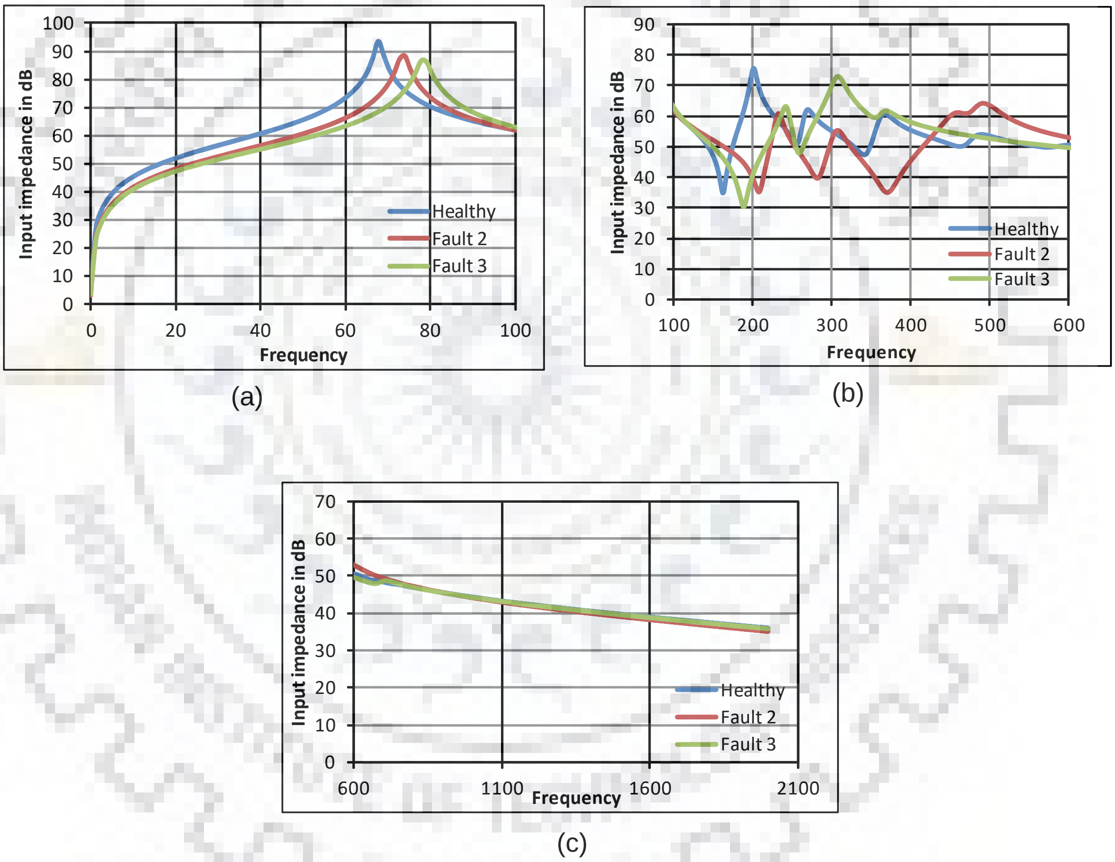


Figure 1.4: Comparison between series fault and healthy condition (a) low frequency (b) middle frquency range (c) high frequency

From figure 1.3, it is clear that frequency response deviates from the healthy condition in the frequency range upto 600kHz and above it there is no change in healthy and fault condition. Also as the section at which shunt fault occur changes the curve shifts upward. From the figure 1.4, it is clear that in the low frequency i.e upto 100kHz there is slight right shift in the frequency response of series fault as compared to healthy state. In medium frequency range i.e 100-600kHz deviation is high at the time of fault while at high frequency there is no change in the response.

Chapter 2

Problem Formulation

- To propose a method to detect the inter-turn faults using **SFRA** (Sweep Frequency Response Analysis) by comparing actual results with the simulated results obtained by MATLAB and Ltspice modelling.
- To analyze location and type of fault with the help of statistical parameters such as correlation coefficient.

2.1 Simulation of winding in frequency domain

The network model of the transformer winding used for the simulation purpose consists of 8 sections. The parameters i.e resistance(R), inductance(L,self and mutual), series capacitance(Cs) and the ground capacitance(Cg) of the winding affects the frequency response of the transformer. Simulated results are obtained by analysing node and mesh equations of the network model.

2.1.1 MATLAB Simulation

For programming, nodal and mesh equations of the network model of the transformer winding are the primary tool. For a winding of n sections, 2n equations are formed of which n are nodal and rest are voltage equations. This will form a two 2n by 2n matrix which are further solved to obtain impedance of the circuit for a required frequency range. Here, we have considered a 8 sections winding model as shown in figure 2.1.

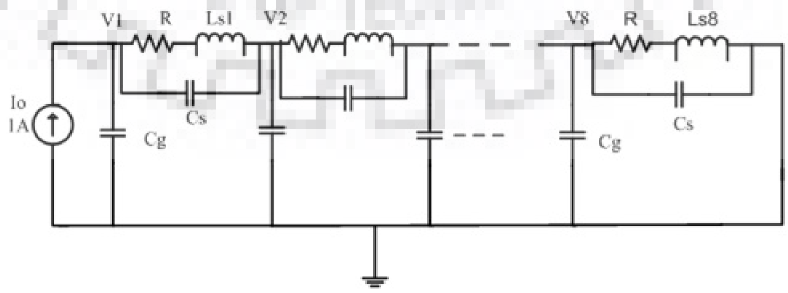


Figure 2.1: Network model of transformer winding

Equations formed are as below:
At node V_1,

$$I_0 = I_{LS1} + C_s \frac{d\,(V_1 - V_2)}{dt} + C_g \frac{dV_1}{dt} \tag{2.1}$$

At node V_2,

$$I_{LS1} + C_s \frac{d(V_1 - V_2)}{dt} = I_{LS2} + C_s \frac{d(V_2 - V_3)}{dt} + C_g \frac{dV_2}{dt} \tag{2.2}$$

Similarly for nodes upto V_8. Rearranging equations we get

$$\begin{aligned}
I_{LS1} + (C_g + C_s)\frac{dV_1}{dt} - C_s \frac{dV_2}{dt} &= I_0 \\
I_{LS2} - I_{LS1} - C_s \frac{dV_1}{dt} + (2C_s + C_g)\frac{dV_2}{dt} - C_s \frac{dV_3}{dt} &= 0 \\
&\vdots \\
I_{LS8} - I_{LS7} - C_s \frac{dV_7}{dt} + (2C_s + C_g)\frac{dV_8}{dt} &= 0
\end{aligned} \tag{2.3}$$

Also, 8 voltage difference equations formed are as below:

$$\begin{aligned}
V_1 - V_2 &= I_{LS1}R + L_{S1}\frac{dI_{LS1}}{dt} + L_{12}\frac{dI_{LS2}}{dt} + L_{13}\frac{dI_{LS3}}{dt} + \cdots + L_{18}\frac{dI_{LS8}}{dt} \\
V_2 - V_3 &= I_{LS2}R + L_{21}\frac{dI_{LS1}}{dt} + L_{S2}\frac{dI_{LS2}}{dt} + L_{23}\frac{dI_{LS3}}{dt} + \cdots + L_{28}\frac{dI_{LS8}}{dt} \\
&\vdots \\
V_8 &= I_{LS8}R + L_{81}\frac{dI_{LS1}}{dt} + L_{82}\frac{dI_{LS2}}{dt} + L_{83}\frac{dI_{LS3}}{dt} + \cdots + L_{S8}\frac{dI_{LS8}}{dt}
\end{aligned} \tag{2.4}$$

Rearranging equations:

$$\begin{aligned}
V_2 - V_1 + I_{LS1}R + L_{S1}\frac{dI_{LS1}}{dt} + L_{12}\frac{dI_{LS2}}{dt} + L_{13}\frac{dI_{LS3}}{dt} + \cdots + L_{18}\frac{dI_{LS8}}{dt} &= 0 \\
V_3 - V_2 + I_{LS2}R + L_{21}\frac{dI_{LS1}}{dt} + L_{S2}\frac{dI_{LS2}}{dt} + L_{23}\frac{dI_{LS3}}{dt} + \cdots + L_{28}\frac{dI_{LS8}}{dt} &= 0 \\
&\vdots \\
-V_8 + I_{LS8}R + L_{81}\frac{dI_{LS1}}{dt} + L_{82}\frac{dI_{LS2}}{dt} + L_{83}\frac{dI_{LS3}}{dt} + \cdots + L_{S8}\frac{dI_{LS8}}{dt} &= 0
\end{aligned} \tag{2.5}$$

All these equations are combined to form a single equation in the form shown below:

$$[A]\frac{dX}{dt} + [B]X = [P] \tag{2.6}$$

where X denotes both voltage and current and both A and B matrices are of 16 by 16. For convenience A and B matrices are divided into four 8 by 8 matrices.

$$[A] = \begin{bmatrix} a & c \\ c & b \end{bmatrix} \tag{2.7}$$

$$[B] = \begin{bmatrix} c & d \\ e & f \end{bmatrix} \tag{2.8}$$

where

$$[a] = \begin{bmatrix} C_g + C_s & -C_s & 0 & 0 & 0 & 0 & 0 & 0 \\ -C_s & C_g + 2C_s & -C_s & 0 & 0 & 0 & 0 & 0 \\ 0 & -C_s & C_g + 2C_s & -C_s & 0 & 0 & 0 & 0 \\ 0 & 0 & -C_s & C_g + 2C_s & -C_s & 0 & 0 & 0 \\ 0 & 0 & 0 & -C_s & C_g + 2C_s & -C_s & 0 & 0 \\ 0 & 0 & 0 & 0 & -C_s & C_g + 2C_s & -C_s & 0 \\ 0 & 0 & 0 & 0 & 0 & -C_s & C_g + 2C_s & -C_s \\ 0 & 0 & 0 & 0 & 0 & 0 & -C_s & C_g + 2C_s \end{bmatrix} \tag{2.9}$$

$$[b] = \begin{bmatrix} L_{S1} & L_{12} & L_{13} & L_{14} & L_{15} & L_{16} & L_{17} & L_{18} \\ L_{21} & L_{S2} & L_{23} & L_{24} & L_{25} & L_{26} & L_{27} & L_{28} \\ L_{31} & L_{32} & L_{S3} & L_{34} & L_{35} & L_{36} & L_{37} & L_{38} \\ L_{41} & L_{42} & L_{43} & L_{S4} & L_{45} & L_{46} & L_{47} & L_{48} \\ L_{51} & L_{52} & L_{53} & L_{54} & L_{S5} & L_{56} & L_{57} & L_{58} \\ L_{61} & L_{62} & L_{63} & L_{64} & L_{65} & L_{S6} & L_{67} & L_{68} \\ L_{71} & L_{72} & L_{73} & L_{74} & L_{75} & L_{76} & L_{S7} & L_{78} \\ L_{81} & L_{82} & L_{83} & L_{84} & L_{85} & L_{86} & L_{87} & L_{S8} \end{bmatrix} \tag{2.10}$$

$$[d] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{2.11}$$

$$[e] = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \tag{2.12}$$

$$[f] = \begin{bmatrix} R & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & R \end{bmatrix} \tag{2.13}$$

and $[c]$ is 8 by 8 zero matrix.

$$[P] = \begin{bmatrix} I_0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ \vdots \\ 0 \\ 0 \end{bmatrix}_{16\times1} \tag{2.14}$$

Converting the equations in frequency domain, we get

$$[A]\, j\omega X(\omega) + [B]\, X(\omega) = P(\omega) \tag{2.15}$$

Separate the voltage and current values (represented by X) into real and imaginary parts, we get

$$j\,[A]\,\omega\,(X_r(\omega) + jX_i(\omega)) + [B]\,(X_r(\omega) + jX_i(\omega)) = P(\omega) \tag{2.16}$$

$$j\,[A]\,\omega X_r(\omega) - [A]\,\omega X_i(\omega) + [B]\,X_r(\omega) + j\,[B]\,X_i(\omega) = P_r(\omega) + jP_i(\omega) \tag{2.17}$$

$$[B]\,X_r(\omega) - [A]\,\omega X_i(\omega) = P_r(\omega) \tag{2.18}$$

$$[A]\,\omega X_r(\omega) + [B]\,X_i(\omega) = P_i(\omega) \tag{2.19}$$

$$\begin{bmatrix} [B] & -[A]\,\omega \\ [A]\,\omega & [B] \end{bmatrix} \begin{bmatrix} X_r(\omega) \\ X_i(\omega) \end{bmatrix} = \begin{bmatrix} P_r(\omega) \\ P_i(\omega) \end{bmatrix} \tag{2.20}$$

$$\begin{bmatrix} X_r(\omega) \\ X_i(\omega) \end{bmatrix} = \begin{bmatrix} [B] & -[A]\,\omega \\ [A]\,\omega & [B] \end{bmatrix}^{-1} \begin{bmatrix} P_r(\omega) \\ P_i(\omega) \end{bmatrix} \tag{2.21}$$

$X_r(\omega)$, $X_i\ (\omega)$ represents real and imaginary values respectively of voltages and currents.

Both the matrices $X_r\ (\omega)$, $X_i\ (\omega)$ are of 16 by 16. Hence,

$$\begin{aligned} V_1 &= complex\left(X_r\left(1\right), X_i\left(1\right)\right) \\ V_2 &= complex\left(X_r\left(2\right), X_i\left(2\right)\right) \\ &\vdots \\ V_8 &= complex\left(X_r\left(8\right), X_i\left(8\right)\right) \end{aligned} \tag{2.22}$$

Similarly,current in all branches can be calculated.

$$\begin{aligned} I_{LS1} &= complex\left(X_r\left(9\right), X_i\left(9\right)\right) \\ I_{LS2} &= complex\left(X_r\left(10\right), X_i\left(10\right)\right) \\ &\vdots \\ I_{LS8} &= complex\left(X_r\left(16\right), X_i\left(16\right)\right) \end{aligned} \tag{2.23}$$

For required frequency range input impedance can be calculated.

$$Z = \frac{V_1}{I_T} \tag{2.24}$$

where, I_T is the sum of currents through series capacitance, ground capacitance and current through inductance.

$$I_{T1} = I_{LS1} + I_{Cg} + I_{Cse} \tag{2.25}$$

$$I_{Cg} = j\omega C_g * V_1 \tag{2.26}$$

$$I_{Cse} = j\omega C_s * (V_2 - V_1) \tag{2.27}$$

This is the process which is followed in calculating simulated data of normal network model of winding through matlab.

Fault in the winding can be simulated by slight modification in the circuit and hence the equations formed. Short circuit at any section is equivalent to connecting very low resistance. So, for fault, equation 2.8 will be modified to

$$[B] = \begin{bmatrix} g & d \\ e & f \end{bmatrix} \tag{2.28}$$

For series and shunt faults $[g]$ will be different. For series fault,$[g]$ is as equ 2.29 when the series fault is present at section 1 and eqn 2.30 for fault at section 2. Similarly for fault at other sections this matrix can be easily calculated.

$$[g] = \begin{bmatrix} {}^{1}/_{R_f} & {}^{-1}/_{R_f} & 0 & 0 & 0 & 0 & 0 & 0 \\ {}^{-1}/_{R_f} & {}^{1}/_{R_f} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.29}$$

$$[g] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {}^{1}/_{R_f} & {}^{-1}/_{R_f} & 0 & 0 & 0 & 0 & 0 \\ 0 & {}^{-1}/_{R_f} & {}^{1}/_{R_f} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.30}$$

In case of shunt faults, only one diagonal element is present and it will change as the position of fault changes.$[g]$ is as per eqn 2.31.

$$[g] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & {}^{1}/_{R_f} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.31}$$

2.1.2 Ltspice Simulation

Ltspice is a spice simulation software and is widely used as a waveform viewer. Ltspice programming is done to obtain the simulated result.

In Ltspice programming, we need to tell the position of all the elements present in the network model along with their numeric value. After running the program graph related to any parameter can be calculated.Element name, position of connection (i.e to and from node number) and element value are written in the code. For example, C10 1 0 0.5e-9 means C10 capacitance is connected between nodes 1 & ground of value 0.5e-9.

Simulated data was obtained through MATLAB as well as Ltspice and both the data were compared with experimental data. Figure 2.2 shows that MATLAB and Ltspice simulation gives the same result and validate the correctness of the matlab programming.

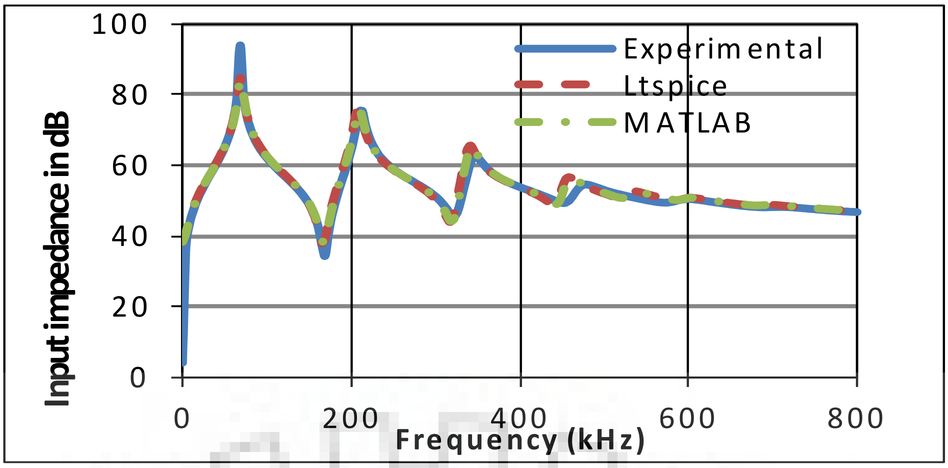


Figure 2.2: Comparison of simulated data with experimental data for normal case

2.2 Statistical Parameter for Analysis

2.2.1 Correlation Coefficient(CC)

It is calculated for a frequency range. It is given by:

$$CC_{X,Y} = \frac{\sum_{i=1}^{N} X_i Y_i}{\sqrt{\sum_{i=1}^{N} X_i^2 \sum_{i=1}^{N} Y_i^2}} \tag{2.32}$$

where X_i and Y_i are the i_{th} elements of the fingerprint and measured FRA traces respectively. N is the total number of elements. Absolute value of CC lies between -1 and 1, [8]. It is sensitive to shift in existing resonant peaks, creation or deletion of resonant frequencies, non constant amplitude difference. But it will remain same when the change in shape is characterized by constant difference,[3]. The positive value of CC indicates that 2 variables will act in same direction, negative value indicates opposite direction relation and zero value indicates no relation.

2.2.2 Min-Max Ratio(MM)

It is defined as the ratio of minimum and maximum value of the 2 compared samples.It compares the similarity of data sets. Ideally its value is 1 for similar data sets.It is sensitive to changes in shape related to amplitude variations,[3]. It can be calculated as:

$$MM = \frac{\sum\limits_{i=1}^{N} \min(X_i, Y_i)}{\sum\limits_{i=1}^{N} \max(X_i, Y_i)} \tag{2.33}$$

2.2.3 Absolute Difference(DABS)

It refers to the average of the absolute difference of data points of 2 compared sets. Ideally, its value should be 0. It is sensitive to large number of amplitude variations which may be due to shifting, creation or deletion of resonant frequencies, [3],[4]. It is given by:

$$DABS_{(X,Y)} = \frac{\sum_{i=1}^{N} |Y(i) - X(i)|}{N} \tag{2.34}$$

2.2.4 Standard Deviation(SD)

It measures the dispersion of a data set relative to another data set. Less value of SD indicates that curves are more similar. It is given by:

$$SD = \sqrt{\frac{\sum_{i=1}^{N} (X_i - Y_i)^2}{N}} \tag{2.35}$$

Chapter 3

Experimental Measurements

3.1 Network Model

The network model of the transformer winding used for the simulation purpose consists of parameters i.e resistance(R), inductance(L,self and mutual), series capacitance(Cs) and the ground capacitance(Cg). These parameters are calculated by LCR meter.

3.1.1 LCR Meter

As the name itself indicates L means inductance, C means capacitance and R means resistance. This instrument is basically used for measuring these parameters and work at high frequency range also. This is also used for measuring quality factor and impedance of the circuit for a large frequency range. Figure 3.1 shows the LCR meter.

Figure 3.1: LCR meter

3.1.2 Measurement of parameters

3.1.2.1 Resistance

It is measured by applying dc voltage between phase and neutral through LCR meter. Measured value of resistance is equal to 10 Ω.

3.1.2.2 Inductance

Self and mutual inductances of the winding is measured by removing all external series and shunt capacitances connected. As the internal capacitance of the winding is negligible so to consider the effect of capacitance in the FRA, they are connected externally. Figure 3.2 shows the connection for measuring inductance where L11 is the self inductance of a section of the winding, M12-M18 are the mutual inductances. Self inductance is measured for every section and then the average value obtained is used for simulation. Mutual inductances are calculated as:

$$M_{12} = \frac{L_{12} - L_{11} - L_{22}}{2} = \frac{L_{12} - 2L_s}{2} \tag{3.1}$$

As self inductance of all sections is equal, therefore L_{11}=L_{22}=L_s. Similarly,mutual inductances for all other sections can be calculated.

$$M_{13} = \frac{L_{13} - 3L_s - 4M_{12}}{2} \tag{3.2}$$

$$\vdots$$

$$M_{18} = \frac{L_{18} - 8L_s - 14M_{12} - 12M_{13} - 10M_{14} - 8M_{15} - 6M_{16} - M_{17}}{2} \tag{3.3}$$

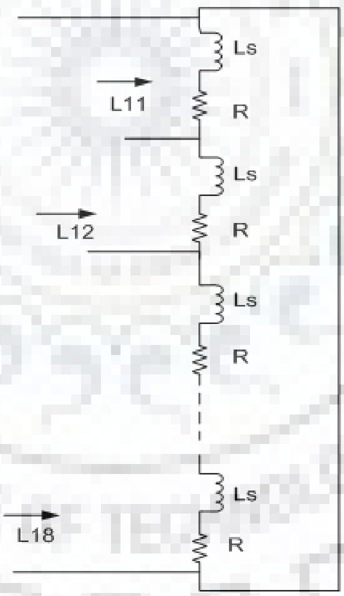


Figure 3.2: Network model for measuring self and mutual inductances

Inductances can be calculated by LCR meter only if tappings are provided in the transformer winding. Normally tappings are not present. So, this method can not be used. FEMM(Finite element method magnetics) ,used for solving 2D planar and axialsymmetric problems is an effective tool for measurement of inductance of a coil. Knowing the dimensions of the winding (i.e inner diameter of coil, height of coil, diameter of the conductor, number of turns per section), model is drawn and a steady current of 1A is given. Total magnetic energy is calculated which gives the value of self and mutual inductances.

Table 3.1: Self and mutual inductances(in mH)

	L_{exp}	L_{FEMM}
L_s	0.127	0.1176
M_{12}	0.067	0.0606
M_{13}	0.03356	0.0317
M_{14}	0.02667	0.01925
M_{15}	0.01397	0.01246
M_{16}	0.00889	0.00843
M_{17}	0.00635	0.0058
M_{18}	0.00508	0.00376

Measured values obtained from LCR meter and FEMM simulation are shown in table 3.1. Values obtained are approximately same and will give the same results.

3.1.2.3 Series Capacitance

Total series capacitance of the winding is measured through LCR meter at high frequency. Series capacitance of a section of winding is obtained by multiplying the total capacitance with the number of sections. Output terminal of the winding(i.e last section of the winding) is open circuited to neglect the effect of ground capacitance. At high frequency, inductive reactance is very high so the branch can be considered as open and will not affect the measurement of series capacitance. Figure 3.3 shows the set up used for measuring total series capacitance.

Total series capacitance measured is equal to 0.125 nF. Hence, for one section it is equal to 1 nF(8×0.125 nF).

3.1.2.4 Shunt Capacitance

Total shunt capacitance is measured at high frequency and by short circuiting the first and last section of the winding to neglect the effect of inductances and series capacitance respectively. Figure 3.4 shows the connection used for measurement.
From the figure, it can be seen that all ground capacitances will be in parallel. Hence, for one section it is calculated by dividing the total measured value by the number of sections.

Total ground capacitance= 4.0 nF

For one section Cg= 0.5 nF

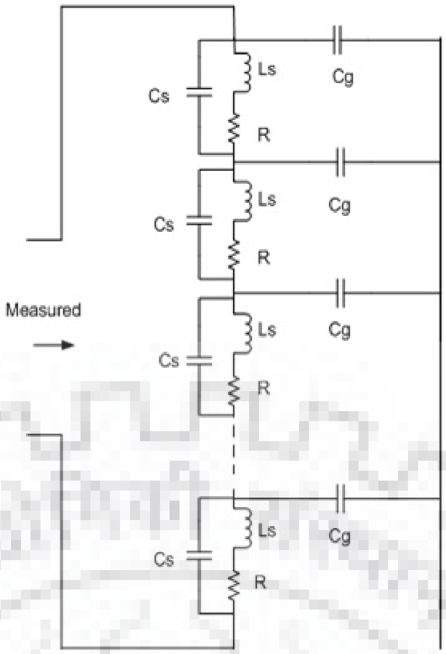


Figure 3.3: Measurement of series capacitance

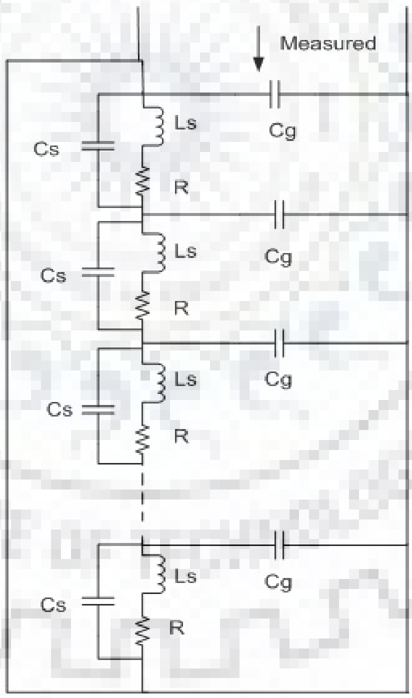


Figure 3.4: Measurement of shunt capacitance

3.2 Experimental Setup

An 8-section model winding is used to estimate FRA at normal and fault at different sections. The winding consists of single layer 18 SWG insulating wire wound on an air former. Height and diameter of former is 225 mm and 175 mm respectively. It consists of 160 turns and

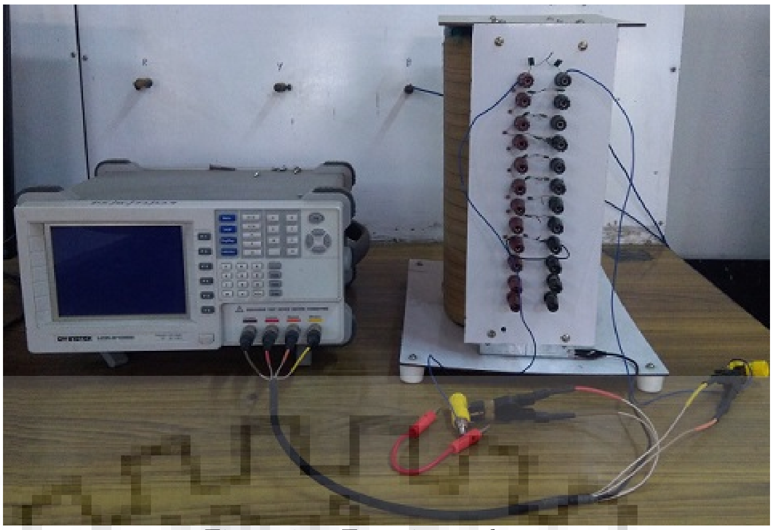


Figure 3.5: Experimental setup

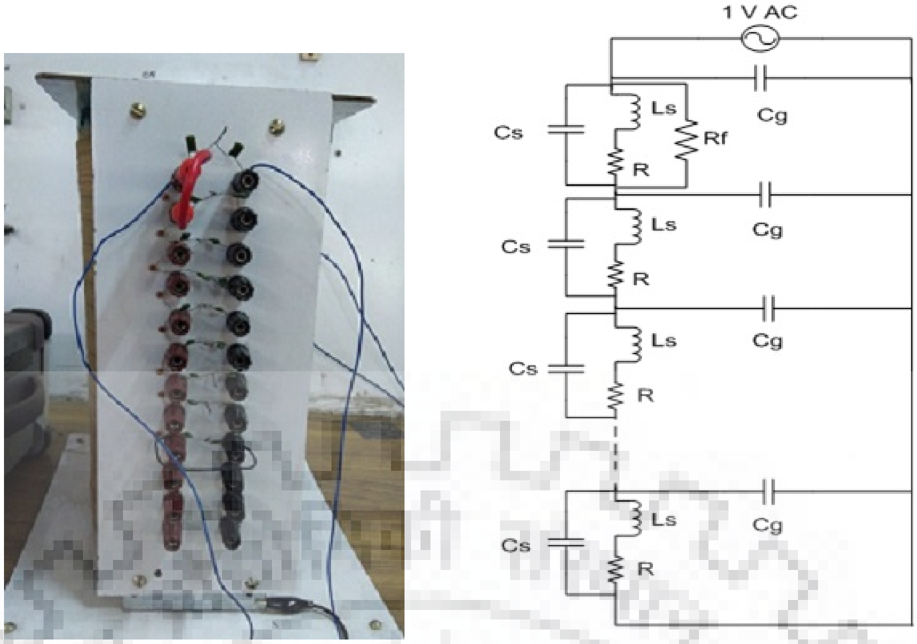
taps are brought out at 20 turns to form 8 sections. Capacitances of 1 nF and 0.5 nF are externally connected in series and shunt respectively to consider the effect of capacitances in the frequency response. Figure 3.5 shows the experimental set up. In the winding, right side pins(black color) are grounded and left side pins(red colour) are at positive side of supply. Experiment is performed for both shunt and series faults at different sections of the winding so that fault location can be estimated by the change in FRA obtained and also series and shunt faults can also be differentiated.

3.2.1 Series Fault

This fault is basically turn to turn short and reduces the number of turns/sections in the winding. With the change in position of series fault frequency response also changes and by calculating statistical parameters one can easily detect fault position. Experimental setup and network model for series fault at section 1 are shown in figure 3.6(a) and 3.6(b). Section 1 is shorted by connecting 1st & 2nd positive terminals.

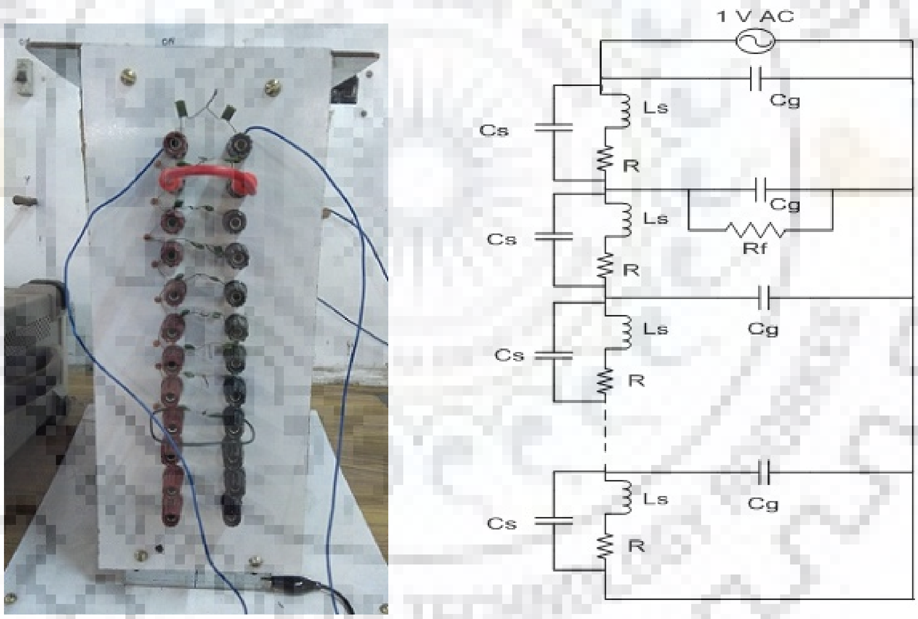
3.2.2 Shunt Fault

Experimental setup and network model for shunt fault at section 2 are shown in figure 3.7(a) and 3.7(b). For ground fault at section 2, positive terminal is connected to adjacent ground terminal.



(a) (b)

Figure 3.6: (a) Experimental setup (b) Network model for **series** fault at section 1



(a) (b)

Figure 3.7: (a) Experimental setup (b) Network model for **shunt** fault at section 2

Chapter 4

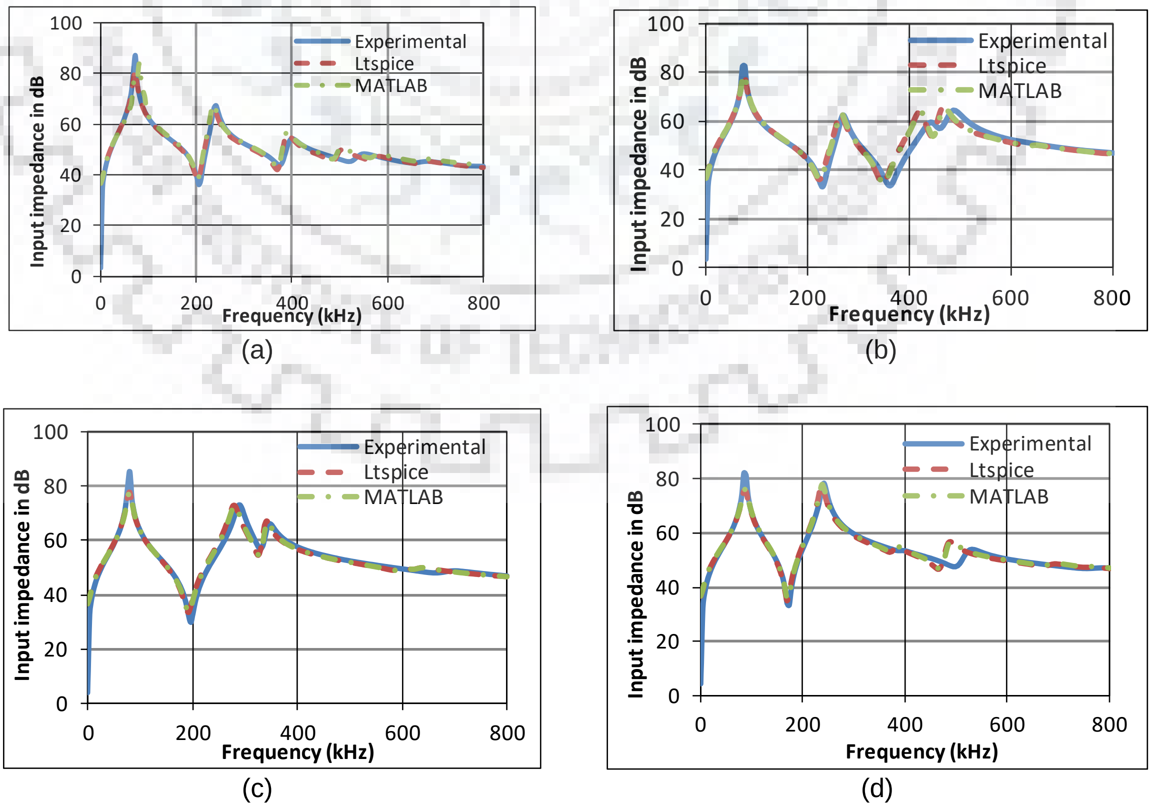
Results and Discussions

4.1 Series Fault

Experimental data obtained for series fault at different sections is compared with the simulated data(using ltspice). For simulation, a low value of series resistance is connected across the section at which fault is supposed to happen. Connecting low resistance across the section will not change the number of nodes.

Figure 3.6(b) represents the equivalent circuit used for simulation purpose and the fault is shown by connecting Rf at section 1 whose value is 0.001 Ω.

Simulation and experimental data are compared for normal and fault at different sections. Similarity between the graphs shows that location of fault can be estimated by comparing the FRA of transformer winding with the various simulated FRA graphs. Various statistical parameters such as correlation coefficient,DABS,standard deviation,MM ratio etc are calculated to show their senstivity to frequency variations and to locate the fault position easily.



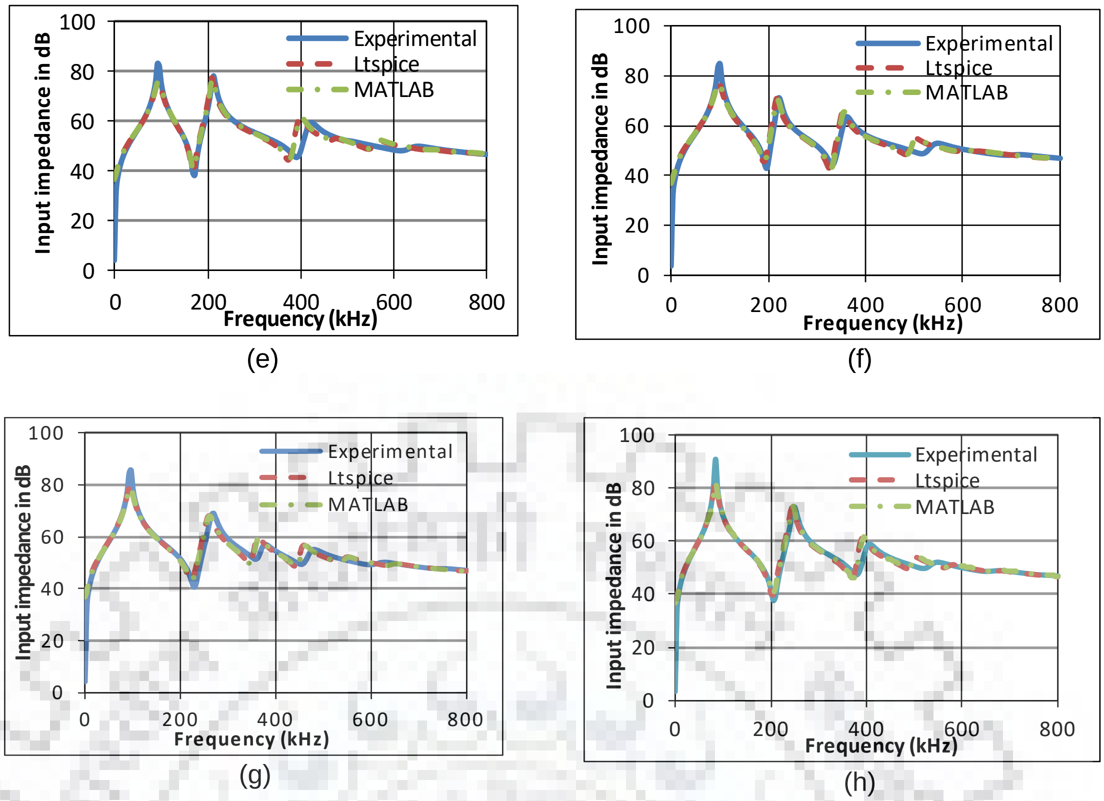


Figure 4.1: comparison between experimental and simulated data for faults at different sections: (a) 1-2 fault (b) 2-3 fault (c) 3-4 fault (d) 4-5 fault (e) 5-6 fault (f) 6-7 fault (g) 7-8 fault (h) 8-0 fault

Figure 4.1 shows the resemblance in simulated data with the experimental one. However at high frequency there is slight variation. This is due to change in resistance at high frequency, stray capacitances, change in inductance with frequency. These effects can't be considered in simulation program.

Table 4.1-4.4 shows the statistical parameters CC,MM ratio, DABS, SD values respectively for comparing simulated data with the experimental one. These values will directly tell us degree of simmilarity between the experimental response obtained and all simulated data present and it is easy to locate the fault position. These parameters make the process of estimating fault position easy as it did not require expert supervision.The slight shifts in the resonant frequencies which are not easily visible can be analyzed by these parameters.

Table 4.1: Correlation coefficients for series fault at different sections

		Experiment								
		Nrml	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-0
Ltspice	Nrml	0.9410	0.6019	0.2554	0.4056	0.6781	0.7170	0.5757	0.4203	0.4790
	1-2	0.6484	0.9417	0.5089	0.6334	0.7171	0.5955	0.6845	0.6346	0.8417
	2-3	0.3149	0.6163	0.8942	0.4756	0.3087	0.3509	0.3665	0.5965	0.6288
	3-4	0.5126	0.6897	0.4113	0.9442	0.7044	0.4690	0.5607	0.6799	0.7455
	4-5	0.7349	0.7005	0.2577	0.5923	0.9399	0.7988	0.6715	0.5499	0.7209
	5-6	0.7436	0.5979	0.3157	0.3637	0.7681	0.9135	0.7073	0.5715	0.6096
	6-7	0.7016	0.6327	0.2414	0.5196	0.6883	0.7584	0.9245	0.6497	0.6473
	7-8	0.4747	0.7329	0.5425	0.6887	0.6380	0.5987	0.7458	0.9256	0.8254
	8-0	0.5423	0.8975	0.5274	0.7103	0.7909	0.6369	0.7321	0.7452	0.9346

Table 4.2: Min-Max ratio for series fault at different sections

		Experiment								
		Nrml	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-0
Ltspice	Nrml	0.97918	0.9014	0.8821	0.9093	0.9214	0.9263	0.9194	0.9027	0.9077
	1-2	0.9128	0.9774	0.8853	0.8923	0.8984	0.8949	0.9049	0.8932	0.9153
	2-3	0.8961	0.8975	0.9557	0.9006	0.8829	0.8930	0.8937	0.9024	0.9153
	3-4	0.9193	0.8970	0.8868	0.9732	0.9256	0.9112	0.9128	0.9286	0.9346
	4-5	0.9349	0.8970	0.8778	0.9195	0.97264	0.9353	0.9210	0.9313	0.9335
	5-6	0.9362	0.8995	0.8840	0.9061	0.9300	0.9686	0.9385	0.9244	0.9381
	6-7	0.9366	0.8970	0.8819	0.9098	0.9249	0.9337	0.9707	0.9363	0.9261
	7-8	0.9131	0.8969	0.8930	0.9233	0.9266	0.9295	0.9417	0.9711	0.9485
	8-0	0.9144	0.9186	0.8974	0.9258	0.9355	0.9314	0.9344	0.9384	0.9757

Table 4.3: DABS values for series fault at different sections

		Experiment								
		Nrml	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-0**
	Nrml	**1.1296**	**5.3848**	**6.6186**	**5.0824**	**4.3889**	**4.1061**	**4.5122**	**5.4883**	**5.1964**
	1-2	**4.7349**	**1.1463**	**6.2165**	**5.8918**	**5.5558**	**5.7591**	**5.1891**	**5.8604**	**4.5948**
	2-3	**5.7949**	**5.5230**	**2.3599**	**5.5151**	**6.5725**	**5.9763**	**5.9359**	**5.4262**	**4.6747**
Ltspice	**3-4**	**4.5033**	**5.6207**	**6.324**	**1.4489**	**4.1303**	**4.9758**	**4.8825**	**3.9651**	**3.6193**
	4-5	**3.6091**	**5.6286**	**6.8706**	**4.4832**	**1.48627**	**3.5864**	**4.4135**	**3.8181**	**3.6902**
	5-6	**3.5390**	**5.4913**	**6.5070**	**5.2734**	**3.8926**	**1.7137**	**3.4040**	**4.2193**	**3.4265**
	6-7	**3.5142**	**5.6361**	**6.6316**	**5.0523**	**4.1830**	**3.6785**	**1.598**	**3.5316**	**4.1218**
	7-8	**4.8787**	**5.6445**	**5.9730**	**4.2679**	**4.0869**	**3.9224**	**3.2238**	**1.576**	**2.8394**
	8-0	**4.8030**	**4.4030**	**5.7171**	**4.1237**	**3.5772**	**3.8156**	**3.6406**	**3.4111**	**1.3225**

Table 4.4: SD values for series fault at different sections

		Experiment								
		Nrml	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-0**
	Nrml	**2.9478**	**8.1482**	**10.347**	**9.1310**	**6.7196**	**6.1340**	**7.3564**	**8.5709**	**8.2660**
	1-2	**7.4947**	**2.8888**	**8.3734**	**7.7212**	**6.9922**	**7.9165**	**7.0719**	**7.4837**	**5.6062**
	2-3	**9.7090**	**7.4917**	**4.0366**	**8.7389**	**9.9470**	**9.4480**	**9.2093**	**7.3843**	**7.2083**
Ltspice	**3-4**	**8.0883**	**7.3211**	**9.2948**	**3.0625**	**6.4848**	**8.4347**	**7.5632**	**6.4517**	**5.8626**
	4-5	**5.9572**	**7.2919**	**10.346**	**7.626**	**3.126**	**5.2064**	**6.503**	**7.588**	**6.1023**
	5-6	**5.7983**	**8.0887**	**9.8121**	**9.3158**	**5.7194**	**3.5246**	**6.0573**	**7.2792**	**7.0877**
	6-7	**6.1999**	**7.7799**	**10.211**	**8.0908**	**6.53211**	**5.6118**	**3.2381**	**6.549**	**6.7055**
	7-8	**8.0935**	**6.9596**	**8.0885**	**6.6056**	**6.9834**	**7.1100**	**5.6136**	**3.224**	**4.8284**
	8-0	**7.7253**	**5.3627**	**8.3399**	**6.4545**	**5.4677**	**6.8965**	**5.8416**	**5.6898**	**3.0942**

From the statistical parameters following points were observed:

- While comparing normal with normal & faulty cases with faulty cases(diagonal elements), we get maximum values for CC & MM ratio and minimum values for DABS & SD. These values are comparable to the ideal values of the parameters and hence indicates the similarity of the curves.

- When faulty cases compared with normal these parameters show large deviations from its ideal value. This is true even when different faulty cases are compared i.e 1st section fault with 2nd section fault. Large deviation is due to large shifts in resonance frequencies as well as its amplitude in case of fault.

- Only MM ratio can not differentiate between the faults and normal case. As there is small deviation between the values. For normal-normal comparison, MM value is 0.97918 while for normal-4-5 section fault its value is 0.92. Hence, sometime it may give wrong results.

- Among all parameters correlation coefficient gives the best result to differentiate between fault locations.For normal-normal i is 0.94 and for normal-fault it is less than 0.72.

- There may be a frequency range where there is contant amplitude shift between normal and faulty case and as the CC is insensitive to changes in shape due to constant amplitude differences,so CC may give bad interpretation of result.

- For amplitude variation DABS and standard deviation will provide the best result.

- Hence to analyze the shape and amplitude variations both at a time, it is better to validate the results with more than one parameter.

4.2 Shunt Fault

This fault is also analyzed by connecting low resistance across the ground capacitance as shown in figure 3.7(b). For fault at different sections simulated data is comapared with experimental data as shown in figure 4.2.

From table 4.5-4.6,following observation were made:

- CC for shunt fault is maximum for normal-normal and fault-fault cases. Its value is nearly equal to 1 which indicates that the experimental response obtained is largely same as that of the simulated response of that case only.

- For normal-fault cases,CC values are less than 0.5 . So, this will tell the location of shunt fault.

- From table 4.6, we can estimate the type of fault i.e series or shunt fault. On comparing experimental and simulated responses for the same cases CC is very high and for all other cases it is less or negative.

- When series fault data with the shunt fault CC is negative for some cases. For normal-2-0 fault CC is -0.23,normal-3-0 fault CC is -0.33 etc.

- From the figure 4.2, there is slight variation in the experimental and simulated result in the frequency range 400-600kHz. This is because the effect of stray capacitance, chnange in resistance at high frequency is not considered.

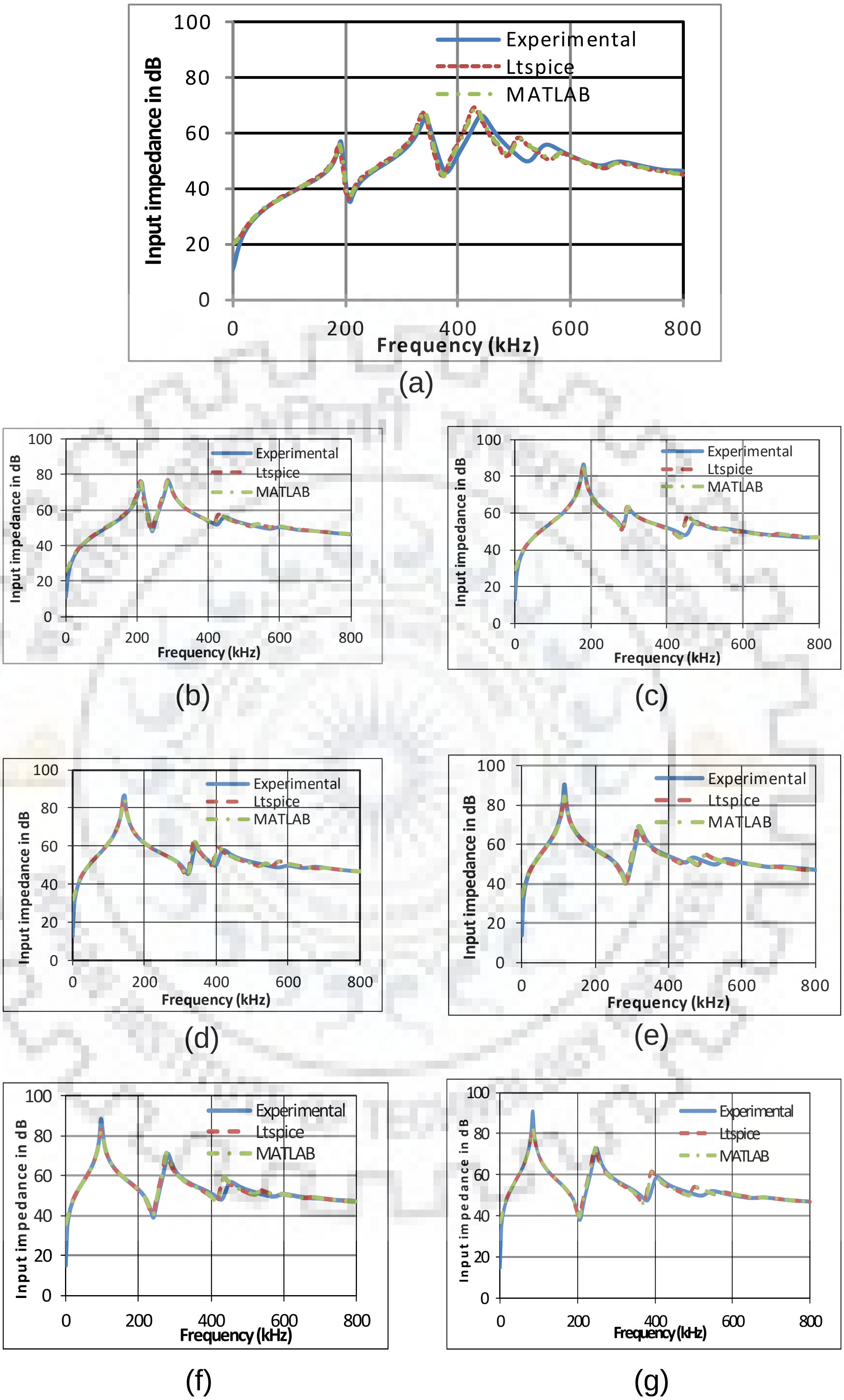


Figure 4.2: comparison between experimental and simulated data for faults at different sections : (a) 2-0 fault (b) 3-0 fault (c) 4-0 fault (d) 5-0 fault (e) 6-0 fault (f) 7-0 fault (g) 8-0 fault

Table 4.5: Correlation coefficients for shunt fault at different sections

		Experiment							
		Nrml	**2-0**	**3-0**	**4-0**	**5-0**	**6-0**	**7-0**	**8-0**
	Nrml	**0.94097**	**-0.228**	**0.19085**	**0.23605**	**0.3025**	**0.3815**	**0.39801**	**0.4856**
	2-0	**-0.1971**	**0.9608**	**0.54094**	**0.25313**	**0.1138**	**0.0413**	**-0.013**	**-0.0444**
	3-0	**0.19544**	**0.5349**	**0.98438**	**0.70859**	**0.438**	**0.2603**	**0.36429**	**0.1094**
Ltspice	**4-0**	**0.21273**	**0.2577**	**0.7138**	**0.97795**	**0.7474**	**0.5722**	**0.39856**	**0.2167**
	5-0	**0.30695**	**0.0967**	**0.40949**	**0.73632**	**0.9706**	**0.7493**	**0.5194**	**0.4224**
	6-0	**0.34979**	**0.0104**	**0.27291**	**0.57652**	**0.7104**	**0.9712**	**0.6711**	**0.4803**
	7-0	**0.38459**	**-0.015**	**0.33209**	**0.35022**	**0.5332**	**0.6351**	**0.96213**	**0.6891**
	8-0	**0.54231**	**-0.173**	**0.06835**	**0.21091**	**0.3967**	**0.4771**	**0.61548**	**0.9536**

Table 4.6: Comparison of CC with shunt and series faults

		Experiment															
		nrml	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-0S**	**2-0**	**3-0**	**4-0**	**5-0**	**6-0**	**7-0**	**8-0**
	nrml	**0.94**	**0.60**	**0.26**	**0.41**	**0.68**	**0.72**	**0.58**	**0.42**	**0.48**	**-0.23**	**0.19**	**0.24**	**0.30**	**0.38**	**0.40**	**0.49**
	1-2	**0.65**	**0.94**	**0.51**	**0.63**	**0.72**	**0.60**	**0.68**	**0.63**	**0.84**	**-0.33**	**-0.03**	**0.16**	**0.35**	**0.43**	**0.54**	**0.86**
	2-3	**0.31**	**0.62**	**0.89**	**0.48**	**0.31**	**0.35**	**0.37**	**0.60**	**0.63**	**-0.05**	**-0.15**	**-0.06**	**0.18**	**0.19**	**0.49**	**0.64**
	3-4	**0.51**	**0.69**	**0.41**	**0.94**	**0.70**	**0.47**	**0.56**	**0.68**	**0.75**	**0.06**	**0.25**	**0.00**	**0.17**	**0.29**	**0.64**	**0.76**
	4-5	**0.73**	**0.70**	**0.26**	**0.59**	**0.94**	**0.80**	**0.67**	**0.55**	**0.72**	**-0.13**	**0.30**	**0.25**	**0.26**	**0.35**	**0.45**	**0.73**
	5-6	**0.74**	**0.60**	**0.32**	**0.36**	**0.77**	**0.91**	**0.71**	**0.57**	**0.61**	**-0.15**	**0.36**	**0.40**	**0.46**	**0.51**	**0.54**	**0.62**
	6-7	**0.70**	**0.63**	**0.24**	**0.52**	**0.69**	**0.76**	**0.92**	**0.65**	**0.65**	**-0.21**	**0.21**	**0.36**	**0.61**	**0.64**	**0.62**	**0.66**
Ltspice	**7-8**	**0.47**	**0.73**	**0.54**	**0.69**	**0.64**	**0.60**	**0.75**	**0.93**	**0.83**	**-0.13**	**0.19**	**0.34**	**0.53**	**0.63**	**0.86**	**0.84**
	8-0S	**0.54**	**0.90**	**0.53**	**0.71**	**0.79**	**0.64**	**0.73**	**0.75**	**0.93**	**-0.17**	**0.07**	**0.21**	**0.40**	**0.48**	**0.62**	**0.95**
	2-0	**-0.20**	**-0.17**	**0.04**	**0.18**	**-0.01**	**-0.03**	**-0.12**	**-0.03**	**-0.02**	**0.96**	**0.54**	**0.25**	**0.11**	**0.04**	**-0.01**	**-0.04**
	3-0	**0.20**	**0.02**	**-0.05**	**0.27**	**0.32**	**0.38**	**0.20**	**0.30**	**0.12**	**0.53**	**0.98**	**0.71**	**0.44**	**0.26**	**0.36**	**0.11**
	4-0	**0.21**	**0.19**	**-0.01**	**0.05**	**0.23**	**0.38**	**0.37**	**0.35**	**0.23**	**0.26**	**0.71**	**0.98**	**0.75**	**0.57**	**0.40**	**0.22**
	5-0	**0.31**	**0.39**	**0.16**	**0.17**	**0.28**	**0.47**	**0.59**	**0.51**	**0.43**	**0.10**	**0.41**	**0.74**	**0.97**	**0.75**	**0.52**	**0.42**
	6-0	**0.35**	**0.45**	**0.21**	**0.34**	**0.37**	**0.51**	**0.63**	**0.62**	**0.48**	**0.01**	**0.27**	**0.58**	**0.71**	**0.97**	**0.67**	**0.48**
	7-0	**0.38**	**0.58**	**0.57**	**0.65**	**0.49**	**0.59**	**0.64**	**0.90**	**0.68**	**-0.01**	**0.33**	**0.35**	**0.53**	**0.64**	**0.96**	**0.69**
	8-0	**0.54**	**0.90**	**0.53**	**0.71**	**0.79**	**0.64**	**0.73**	**0.75**	**0.93**	**-0.17**	**0.07**	**0.21**	**0.40**	**0.48**	**0.62**	**0.95**

Chapter 5

Conclusions

Sweep frequency response analysis (SFRA) is a simple and elegant method to detect the internal winding fault which can not be detected by differential relays and restraining relays. Usefulness of SFRA in detecting the type and location of fault was discussed. Frequency response for a range of 20Hz-800kHz was plotted in terms of input impedance (magnitude in dB) of the circuit when the output terminal is short circuited. Transfer function can also be plotted instead of impedance.
As the location of fault changes, variation in frequency response such as peak magnitudes, appearance and disappearance of peaks/dips, frequencies at which peaks and troughs occur are observed. To validate the results from the graph, statistical parameters such as DABS (absolute difference), CC (correlation coefficient),MM ratio, standard deviation etc are calculated. Their values in required frequency band shows the same results as obtained from the frequency response curve.

Simulated data for normal and all possible fault locations (series & shunt) can be stored by MATLAB and Ltspice programming. Whenever there is a need to check whether a fault has occured or not and if it has occured then location and type of fault can estimated by comparing the frequecy response of the concerned transformer with all the simulated data present. Statistical parameters will give instant result and there is no need of expertise in the field.But result is more reliable if more than one statistical parameter is used. Sometime, one parameter can overestimate or underestimate the variation for a specific range. So, sensitivity of 2 or 3 parameters for a frequency band will provide accurate result.
This method can be extended to three phase transformer to determine which phase is faulty. Also this will be a good method to detect the fault due to mechanical deformation of winding (buckling), core imbalance in transformers and rotating machines.

Appendix A

Matlab Programming

Simulated data of the frequency response of the transformer winding is obtained with the matlab as well as the Ltspice programming. Both the simulated data were compared to check the correctness of the code.

MATLAB Code

```
clc
clear all

cs=1.0e-9;   %series capacitance
cg=0.5e-9;   %shunt capacitance
%Inductance matrix
l=[0.127 0.067 0.03556 0.02667 0.01397 0.00889 0.00635 0.00508]*1e-3;
n=8;    %no of sections
rs=10;  %ohm   %series resistance

A=zeros(2*n,2*n);
B=zeros(2*n,2*n);
a=zeros(n,n); b=zeros(n,n); c=zeros(n,n); d=zeros(n,n);
e=zeros(n,n); f=zeros(n,n);

% [a] matrix
for i=1:n
   for j=1:n
      if i~=1
         if i==j
             a(i,i)=2*cs+cg;
         end
         if i~=j
           a(i,i-1)= -cs;
             if i~=8
               a(i,i+1)= -cs;
             end
         end
      end
      if i==1
         if i==j
```

```
            a(i,i)=cs+cg;
         end
         if i~=j
           a(i,i+1)= -cs;
         end
      end
   end
end

%[b] matrix
z=1;
 while z<n
    for i=1:n
       for j=1:n
         if abs(i-j)==z
            b(i,j)=l(1,z+1);
         end
       end
    end
  z=z+1;
 end

% [f],[d],[e] matrix
for i=1:n
  for j=1:n
     if i==j
      f(i,i)=rs;
      d(i,i)=1;
      b(i,i)=l(1,1);
      e(i,i)= -1;
     end
   end
end

i=1;
while i<n
 d(i+1,i)= -1;
 e(i,i+1)=1;
 i=i+1;
end

A=[a c; c b];
B=[c d; e f];
fx=20:4000:800000;
```

```
n1=max(size(fx))
w=2*pi*fx;
for i=1:n1
w1=w(1,i);
A1=w1*A;
Cr=zeros(2*n,1); Ci=zeros(2*n,1);
Cr(1,1)=1; C=[Cr;Ci];
X=[B  -A1;  A1  B];
x=inv(X)*C;
xr=x(1:2*n,1);  xi=x(2*n+1:4*n,1);

j=1;
while j<=n
format long
v(j,1)=complex(xr(j),xi(j));
il(j,1)=complex(xr(n+j),xi(n+j));
ig(j,1)=sqrt(-1)*w1*cg*v(j,1);
j=j+1;
end
for k=1:n
format long
 if k~=n
  is(k,1)=sqrt(-1)*cs*w1*(v(k,1)-v(k+1,1));
 end
 if k==n
  is(k,1)=sqrt(-1)*cs*w1*v(k,1);
 end
end
 it=il+ig+is;
 za(i)=v(1,1)/it(1,1);
end
%graph plot
figure;
%plot(fx,20*log10(abs(za)))          %simulation
xlabel('freq')
ylabel('magnitude in dB')
```

Appendix B

Ltspice Model

Ltspice is a spice simulation software and is widely used as a waveform viewer. Ltspice programming is done to obtain the simulated result.
Program for FRA of the normal case of transformer winding is shown below.

FRA netlist for network model

```
VIN 1 0 AC 1

* shunt capacitance
C10    1    0     0.5e-9
C20    2    0     0.5e-9
C30    3    0     0.5e-9
C40    4    0     0.5e-9
C50    5    0     0.5e-9
C60    6    0     0.5e-9
C70    7    0     0.5e-9
C80    8    0     0.5e-9

* series capacitance
C12    1   2    1.0e-9
C23    2   3    1.0e-9
C34    3   4    1.0e-9
C45    4   5    1.0e-9
C56    5   6    1.0e-9
C67    6   7    1.0e-9
C78    7   8    1.0e-9
C89    8   0    1.0e-9

* Resistance
R12    1   13    10
R23    2   14    10
R34    3   15    10
R45    4   16    10
R56    5   17    10
R67    6   18    10
R78    7   19    10
R89    8   20    10
```

```
* Self Inductance
L12    13   2    0.127e-3
L23    14   3    0.127e-3
L34    15   4    0.127e-3
L45    16   5    0.127e-3
L56    17   6    0.127e-3
L67    18   7    0.127e-3
L78    19   8    0.127e-3
L89    20   0    0.127e-3

* Mutual coupling coefficients
K_1_2    L12   L23    0.53
K_1_3    L12   L34    0.28
K_1_4    L12   L45    0.21
K_1_5    L12   L56    0.11
K_1_6    L12   L67    0.07
K_1_7    L12   L78    0.05
K_1_8    L12   L89    0.04

K_2_3    L23   L34    0.53
K_2_4    L23   L45    0.28
K_2_5    L23   L56    0.21
K_2_6    L23   L67    0.11
K_2_7    L23   L78    0.07
K_2_8    L23   L89    0.05

K_3_4    L34   L45    0.53
K_3_5    L34   L56    0.28
K_3_6    L34   L67    0.21
K_3_7    L34   L78    0.11
K_3_8    L34   L89    0.07

K_4_5    L45   L56    0.53
K_4_6    L45   L67    0.28
K_4_7    L45   L78    0.21
K_4_8    L45   L89    0.11

K_5_6    L56   L67    0.53
K_5_7    L56   L78    0.28
K_5_8    L56   L89    0.21

K_6_7    L67   L78    0.53
K_6_8    L67   L89    0.28
```

```
K_7_8    L78   L89    0.53

*RF    5   6    1e-6       (command added when simulated for fault)

.ac  lin  200  20  800e3
```

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