IMPEDANCE MONITORING THROUGH MAGNETIC COUPLING

A THESIS

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CERTIFICATE

This is to certify that the thesis title "***IMPEDANCE MONITORING THROUGH MAGNETIC COUPLING***", submitted by **Debasrita Kar**, an **exchange** student from NIT Agartala, to the Indian Institute of Technology, Madras, for the award of the degree of **Bachelor of Technology** in Electrical engineering, is a bonafide work carried out by her, under my supervision and guidance. The contents of this project thesis, in full or in parts, have not been submitted to any other University/Institute for the award of any Diploma or Degree.

Place: Chennai-36

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ABSTRACT

Impedance measurement is very important to know characteristics of a material and its electrical properties. But as compared to the contact impedance measurement, the non-contact type of impedance measurement has many advantages. This is because in this method of measurement, the electrical properties do not get altered due to direct contact and there is no risk of electric shock or damage to the test specimen.

This thesis investigates a simple method to find impedance through a magnetically coupled approach. This method includes measurement of the impedance of a test specimen by developing a proper impedance model and thereby extracting the data for further manipulation using the modern measuring technique: Virtual Instrument. A prototype of the measurement system has been developed and tested. Virtual Instrument developed directly gives the magnitude and phase of impedance.

Keywords-Impedance Measurement, Phase sensitive Detector, Virtual Instrument.

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ABBREVIATIONS

ac	Alternating Current
LabVIEW	laboratory Virtual Instrument Engineering Workbench
VI	Virtual Instrument
PSD	Phase sensitive detector

LIST OF NOTATIONS

B	Magnetic field
I	Current flowing
μ	Magnetic permeability of the material
μ_0	permeability of free space
N	Number of turns
l	length of the inductor
φ	magnetic flux
λ	total flux through the helical windings
R_{ac}	AC resistance per unit length
ρ	Resistivity of the material
A_{eff}	Effective area of the conductor
Y_{meas}	Measured admittance
Y_{sensor}	Sensor admittance
Y_{load}	load admittance
V_L	voltage across inductor
C	Capacitance
L	Inductance
R	Resistance
M	Mutual inductance
k	Geometry dependent Coupling Coefficient
f	Frequency
Z	Impedance

1. INTRODUCTION

1.1 Introduction

Human skin impedance measurement is the basically the measurement of the electrical impedance of the skin. Human skin impedance measurement is required for getting the information about the physiological, biological and chemical properties of the human body, skin and body fluids [1]. A skin impedance model is therefore required to eventually used in many applications such as to determine the electrical properties of the skin for drug delivery [2], blood glucose monitoring [3], [4], cancer cell detection[5]-[8], characterization of heart rate electrodes [9], measurement of oedema in irritant skin [10]. It is also used to find out the signal level for activating the motor neurons underneath the skin surface.

There are two ways to measure the electrical impedance - a) contact type and b) Non-contact type.

Contact type measurement involves direct contact of the electrodes with the skin to measure the skin impedance. Here voltage is directly applied to the skin through the electrodes and allows current to pass through the human body. This is the conventional way of impedance measurement. The disadvantage of this method of measurement is that it can generate certain amount of shock which can damage the tissues.

Due to the above mentioned reasons the preferred form of measurement is the non-contact type measurement. Here there is no direct contact between the human body and the sensor. The proposed scheme is to measure the impedance of a material or in that place a human skin by non-contact method. A virtual instrument developed in LabVIEW environment is employed for this purpose of measurement.

1.2 Objective and Scope of the Project

The aim of this project is to design and develop a virtual instrumentation based impedance measuring system that can measure the impedance of different materials through a magnetically coupled approach.

1.3 Organization of the Thesis

Chapter 1 of this thesis deals with the introduction about need of the measurement of Human skin impedance and different ways of impedance measurement. It also describes the scope and objective of the reported work and gives a proper brief outline of the thesis.

Chapter 2 present the literature review of the thesis and the different properties, effects involved related to the thesis.

Chapter 3 comprise the block diagram description of the work reported, theory and operation of architecture, design procedure all major circuits are explained. Mathematical algorithms and its LabVIEW implementation of automatic calculation of Impedance measurement of various test specimen. Simulation studies of validation of scheme are also presented. Theory and VI implementation of new method of impedance measurement is explained in the end of the chapter.

Chapter 4 has been emphasized on different experiments and measurements conducted on proposed impedance measurement. Snapshots of experimental and test results are given in this chapter.

Chapter 5 conclusions and scope of the future work has been presented.

2. NON-CONTACT IMPEDANCE MEASUREMENT

2.1 Human skin impedance measurement

The conventional human skin impedance model as derived by Cole *et al* [11] describes electrical conduction on biological tissues that include a parallelly connected RC network in series with a linear resistor R_s as shown in figure 1(a) for the lower amplitude signals.

Later on, it is seen that the skin impedance is non-linear when excitation of higher amplitude signals is applied. Therefore, the impedance model is modified as in [12]. In this model the linear resistor is replaced by R_p and capacitor C_p in Figure 1(a) with a variable resistor and polarized capacitor as can be seen from the figure1 (b).

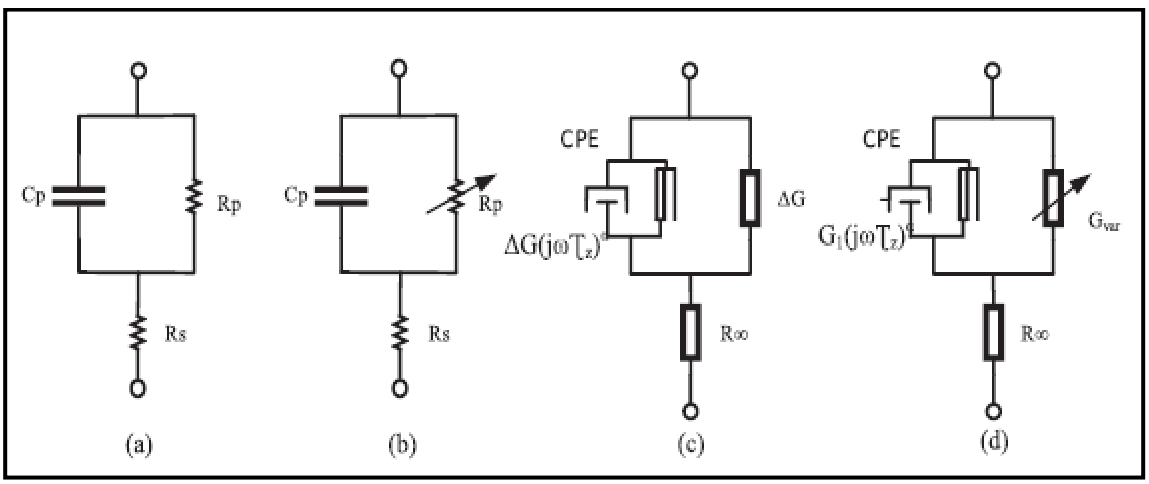

Fig. 2.1(a) Cole skin impedance model. (b) Modified skin impedance model for nonlinear history dependent dynamic of the skin impedance. (c) When the ideal capacitor replaced by a CPE with frequency dependent components in the Cole Circuit. (d) Non-Cole Impedance Model [16]

In [13], it can be seen that the skin impedance loci is forming a circular arc in the complex plane. The centre of the impedance loci can be seen depressed from the real axis through the skin impedance loci. This behaviour can be represented by the Constant Phase Element Model (CPE). Hence by replacing the polarized capacitor in figure 1(b) with CPE a new skin impedance model has been proposed as shown in figure 1(c). But, since the CPE admittance is proportional to parallel conductance, therefore we can say that the parallel conductance of Cole model is not an independent parameter [13]. Another skin impedance model in which the linear parallel conductance in Cole model is replaced by variable conductance and is shown in figure 1(d).

The above mentioned models consider that the human skin is only a single layered structure. However, the human skin consists of several tissue layers, and each layer can again divided into sub layers. In [1], skin impedance with this kind of layered structure has been reported and is considered to be a new approach. In this approach, the skin is considered to contain several layers and these layers are called as extra cellular medium, intra cellular medium and lipid bilayer. Each layer is then represented as RC network. Therefore the whole human skin can be said to be a cascaded RC circuit.

The important quantities for determining the impedance of a material are conductivity and permittivity of that material.

The major drawback of this model is it does not say anything about the Mutual Inductance between the sensor part and the load part.

2.2 Inductive Coupling or Magnetic Coupling

When two conductors are placed in proximity to each other and the change in current passing through one conductor will bring about a change in voltage across the other conductor through electromagnetic induction, then these two conductors are said to be inductively or magnetically coupled. Here the primary and the secondary coils are not connected directly but magnetically. And the energy transfer from one circuit to another is through Mutual Induction as shown in Fig. 2.2.

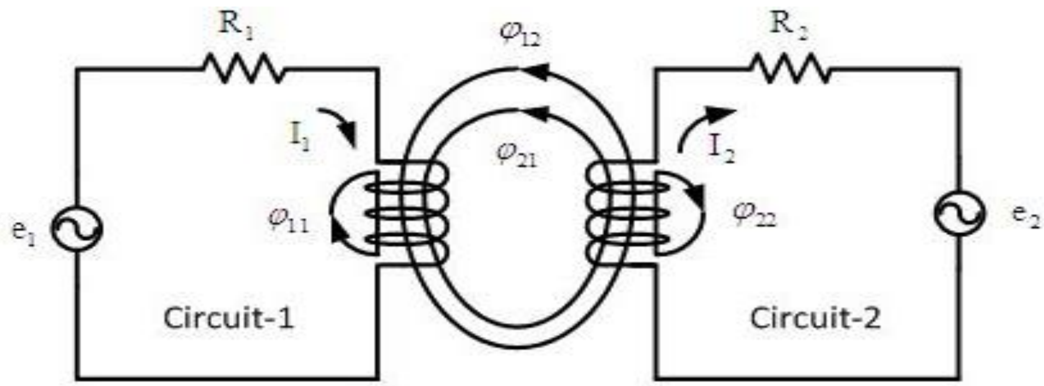

Fig. 2.2. Magnetic Coupling (*Courtesy: www.assignmentpoint.com*)

2.3 Eddy current

Eddy currents are the currents which in circular loop in the surface of the conductor as shown in Fig. 2.3. It is created either due to change in magnetic field where the conductor is placed or by moving the conductor in a constant magnetic field. This eddy current will then give rise to an opposing magnetic field opposite to the source magnetic field.

The amount of eddy current produced is proportional to the amount of magnetic field, the area of the loop and the rate of change of magnetic flux, and inversely proportional to the resistivity of the conductor.

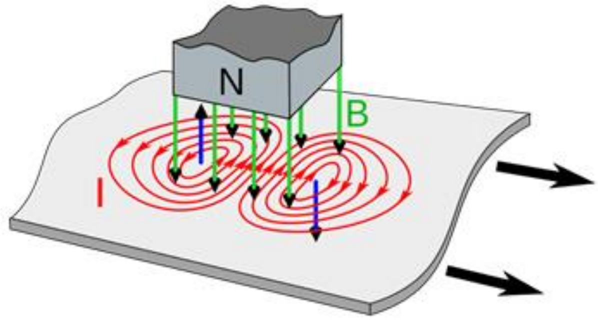

Fig. 2.3. Eddy current (Courtesy: www.magcraft.com)

2.4 Planer Inductor parameters:

Ideally an inductor can be modelled as a pure inductance. But practically in comparatively high frequency, it can be modelled as a combination of inductance, resistance and capacitance. This capacitance is the stray capacitance that is due to the proximity of the coil windings. The resistance is the winding resistance that changes with the changing frequency due to the skin effect. So the inductive reactance will increase and the capacitive reactance will decrease with the increasing frequency. Therefore, at the frequencies higher the resonant frequency the inductance will be acting as capacitance.

2.4.1 Calculation of Self inductance

Self inductance is the property of that particular coil to resist the change in the current flowing through the conductor. When there is a fall or increase in the amount of current flowing through the conductor, the inductor produces an opposite self-induced emf to oppose the flow of the fall or increase in the current flow.

Let the magnetic field produced is given by:

$$B = \frac{\mu N I}{l} \tag{2.1}$$

The magnetic Flux for one of the loop:

$$\Phi = BA = \frac{\mu_0 NIA}{l} \tag{2.2}$$

The total flux through the windings which has N turns, is

$$\lambda = N\,\Phi = \frac{N^2\mu_0 IA}{l} \tag{2.3}$$

Therefore, the self inductance of the coil is

$$L = \frac{\lambda}{I} = \frac{N^2\mu_0 A}{l} \tag{2.4}$$

2.4.2 Parasitic Capacitance

The parasitic capacitance is due to the turn to turn capacitance as the planar inductor we are using is having only one layer.

2.4.3 Calculation of the AC resistance

Under the influence of skin effect phenomenon, the resistance increase with the frequency. The magnetic field generated at the centre of the conductor increases by increasing the frequency. So the current density also gets increased on the conductor surface [14], [15]. The variation of the resistance with frequency of a conductor depends on its conductivity and magnetic permeability.

The AC resistance per unit length of a conductor from [16] is

$$\frac{R_{ac}}{\rho l} = \frac{\rho}{A_{eff}} \tag{2.5}$$

3. THE IMPEDANCE MODEL AND THE MEASUREMENT APPROACH

This chapter describes about the theory, design, working and the development of the impedance model for measuring the impedance of any test specimen. The functional block diagram is given below. The whole setup can be broadly classified into two sections, hardware and software parts. The hardware part deals with the source generation for excitation of the circuit, the impedance measuring unit and an Analog Discovery Kit which helps in interfacing the whole circuit with the PC (and acts as an oscilloscope). The software part consists of Virtual Instrument Instrumentation in LabVIEW which ultimately gives the value of the impedance of the test specimen.

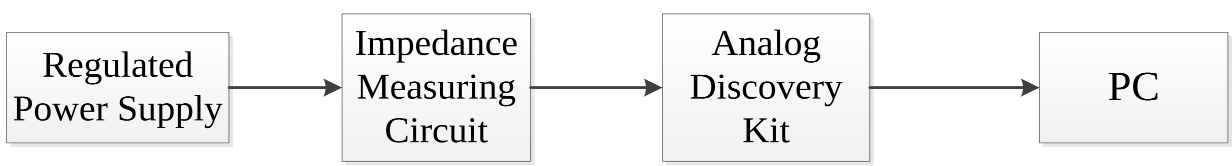

Fig. 3.1Block diagram of the Experimental Setup

The hardware part consists of the following functional blocks:

1. **Regulated Power supply**
2. **Impedance measuring Circuit**
3. **Analog Discovery Kit**

3.1 Regulated Power Supply

The supplied AC voltage was 10Vp-p and was applied to the circuit at a frequency of 1MHz which was found to be convenient for the proper functioning of the circuit and get the output out of it.

3.2 First Impedance Mode

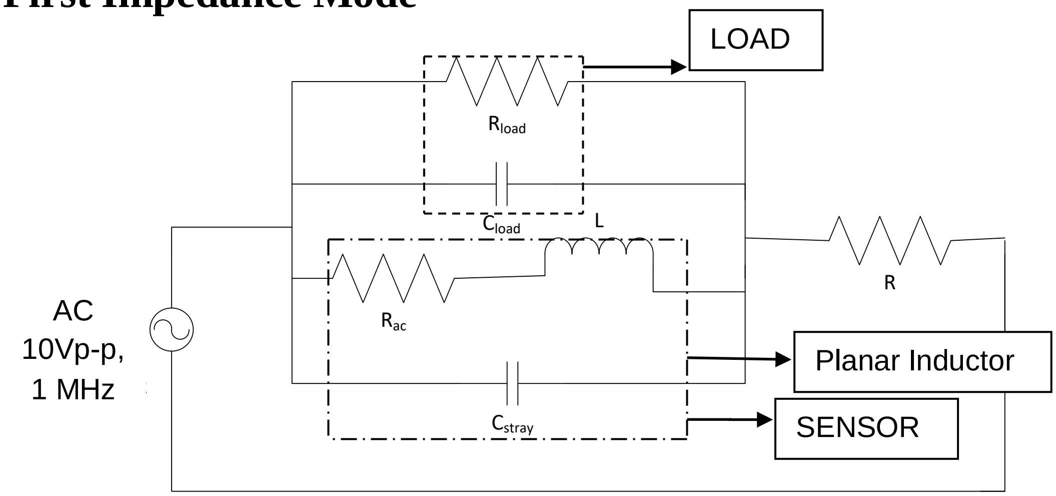

Fig. 3.2 Impedance Model

The above impedance model shown in Fig. 3.2 is good for working in high frequency. The load is considered to a magnetically coupled parallel-connected RC circuit. Electrical conductivity is being represented by $1/R_{load}$ component and electrical permittivity is being represented by C_{load}.

3.2.1 Calculation of load

Let admittance of the sensor be denoted as Y_{sensor} and the combination of the sensor and the load be denoted as Y_{meas}.

So the admittance of the load is

$$Y_{meas} = Y_{load} + Y_{sensor} \tag{3.1}$$

As the parameters of the sensor are known to, so we can calculate the sensor admittance as

$$Y_{sensor} = \frac{1}{R_{ac} + j\omega L} + j\omega C_{stray} \tag{3.2}$$

So the admittance of the Load can be calculated as –

$Y_{load} = Y_{meas} - Y_{sensor}$

$$= \frac{I_{ac}}{V_{ac}} - \left(\frac{1}{R_{ac} + j\omega L} + j\omega C_{stray} \right)$$

$$= j\omega C_{load} + \frac{1}{R_{load}} \qquad (3.3)$$

The R_{load} and C_{load} represent the real and the imaginary components of the Y_{load}, the load resistance and the load capacitance is expressed as

$$R_{load} = \frac{1}{Re\{Y_{load}\}} \qquad (3.4)$$

$$C_{load} = \frac{Im\{Y_{load}\}}{\omega} \qquad (3.5)$$

Here the value of external resistance that has been used to measure the current is **61.6Ω.**

3.3 Analog Discovery Kit

This instrument is a multifunction instrument from Digilent. A snapshot of the instrument is given in Fig. 3.3. Here in our experiment it has been used as an Oscilloscope. Sampling rate is kept at 100 MHz. From the oscilloscope we found Voltage across the Inductor, the current Flowing through the circuit.

Then WAVEFORM software is used to acquire the signal and to read the required data. This data has been transferred and manipulated in LabVIEW.

Fig. 3.3 Snapshot of Analog Discovery Kit

3.4 Virtual Instrument Instrumentation in LabVIEW

After the whole circuit being interfaced with the PC through Digilent Analog Discovery Kit, the waveform software transfers the data for further manipulation in LabVIEW software package. Here the total Impedance of the test specimen is calculated.

3.4.1 LabVIEW and Features

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a graphical programming environment which is developed by National Instruments Corporation (NI). It is a programming language which is used for developing projects graphically, also called as Application specific Development Environment (ADE) [17]. It is used for developing applications like virtual instruments for measurements, control, real-time embedded system etc. Here the programme is developed in graphical method rather than text based programming like Fortran COBOL, C etc. It can be easily interfaced with any data acquisition system so that we can get real-time measurement, control and simultaneously its manipulation can be done. Because of its user friendly nature one can easily develop graphical programs in it. The VI has two parts, the 'Block diagram Panel' and the 'Front Panel'. The Block Diagram Panel is where the actual programming part of VI takes place which is a graphical source code is depicted as data flow concept in text based programming language. On the other hand, Front Panel consists of Graphical User Interface (GUI) where all graphical indicators, control knobs etc. appears.

3.4.2 Determination of the impedance of test specimen

I. Firstly the excitation voltage is measured by acquiring the signal through one channel of the analog discovery kit.

II. Then the voltage across the external resistance (V_R) is acquired through the second channel. From there by use of PSD (Phase Sensitive Detector) again, magnitude of the particular voltage is found out.

III. The voltage across the inductor (V_L) is calculated by subtracting the voltage across external resistance from the excitation voltage. Then by use of PSD the magnitude of this voltage is found out.

IV. Then the angle between VL and current flowing through the circuit is found out by the use of PSD.

3.4.2.1 Working of PSD (Phase Sensitive Detector)

The PSDs are of two types- a) Multiplier Type and b) Synchronous Switching type.

Here we have used the Multiplier type PSD to find out the magnitude and phase of the signal. In this type of PSDs the signal is multiplied with a reference signal and passed through a low pass filter. The output that we get is either the

Inphase component or the **Quadrature** component of the signal depending upon the reference signal that is being multiplied. A snapshot of PSD developed in LabVIEW is given in fig. 3.4.

3.4.2.2 Calculation of the Magnitude and Phase of Signal

Considering that the signal to be measured is $\sqrt{2}V\sin(\omega t+\theta)$.

The Inphase component of the signal is $X= V\cos\theta$

The Quadrature component of the signal is $Y= V\sin\theta$.

So the magnitude of the signal can calculated as $\sqrt{(V\cos\theta)^2 + (V\sin\theta)^2}$

And the phase can be calculated as

$$\theta = \tan^{-1}(Y/X)$$

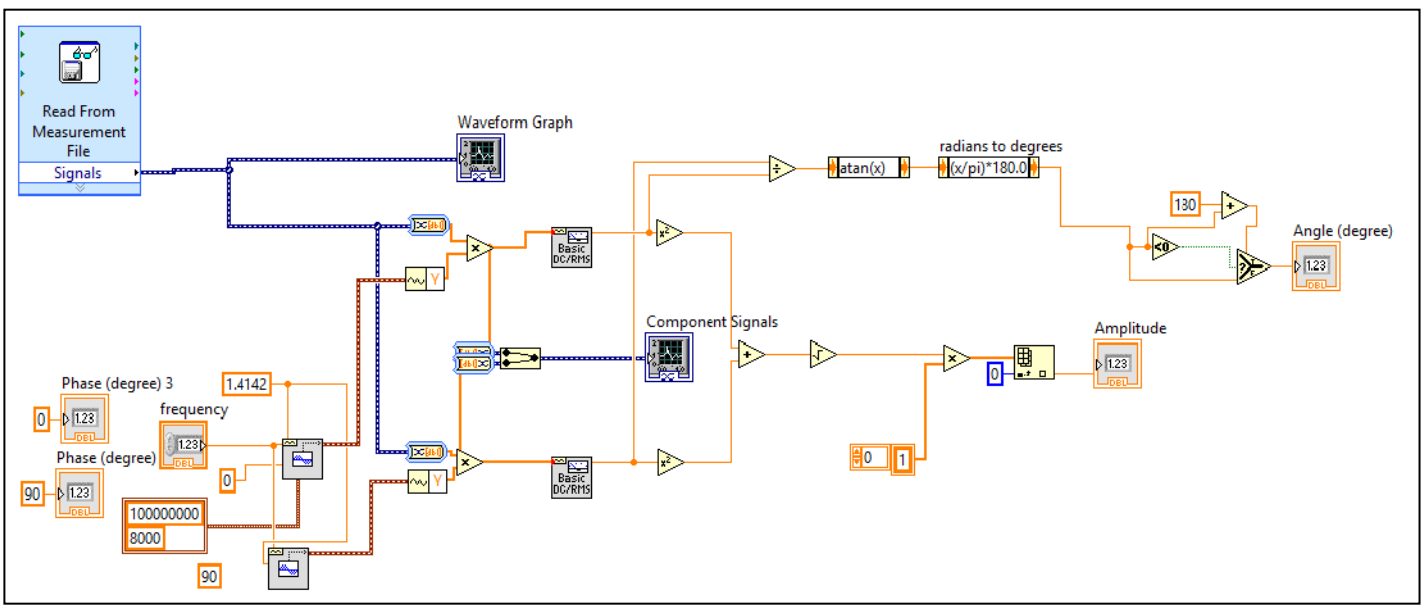

Fig. 3.4A snapshot of the Block diagram panel of sub VI of PSD

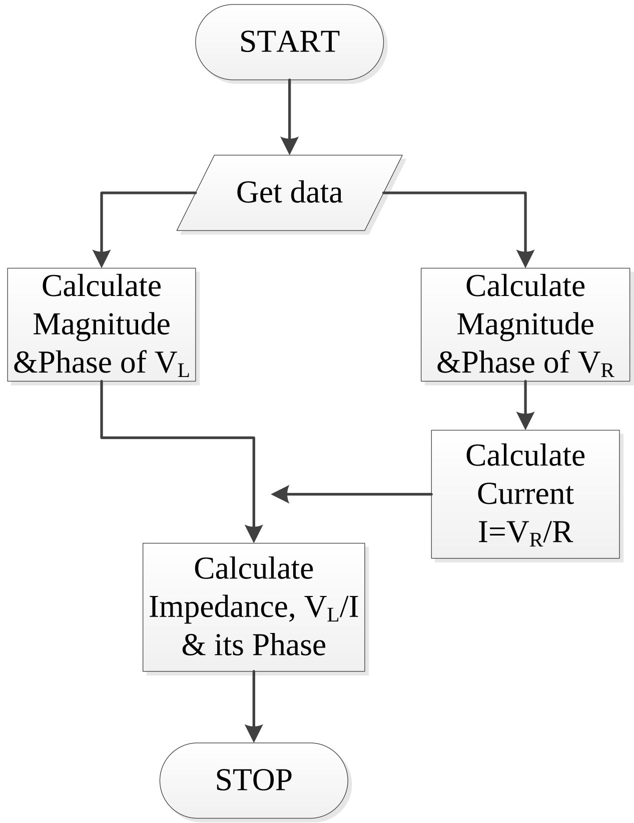

Fig.3.5 Flowchart of the program that calculates the impedance and its phase.

4. EXPERIMENTAL SETUP AND RESULTS

In the experimental setup, all the circuit blocks were separately wired on the bread board and tested properly. A prototype of the impedance model and a Virtual Instrument that performs automated impedance measurement of different test specimens are developed and tested. Snapshots of the experimental setup is taken and given below in Figure 4.1, 4.2, 4.3 respectively.

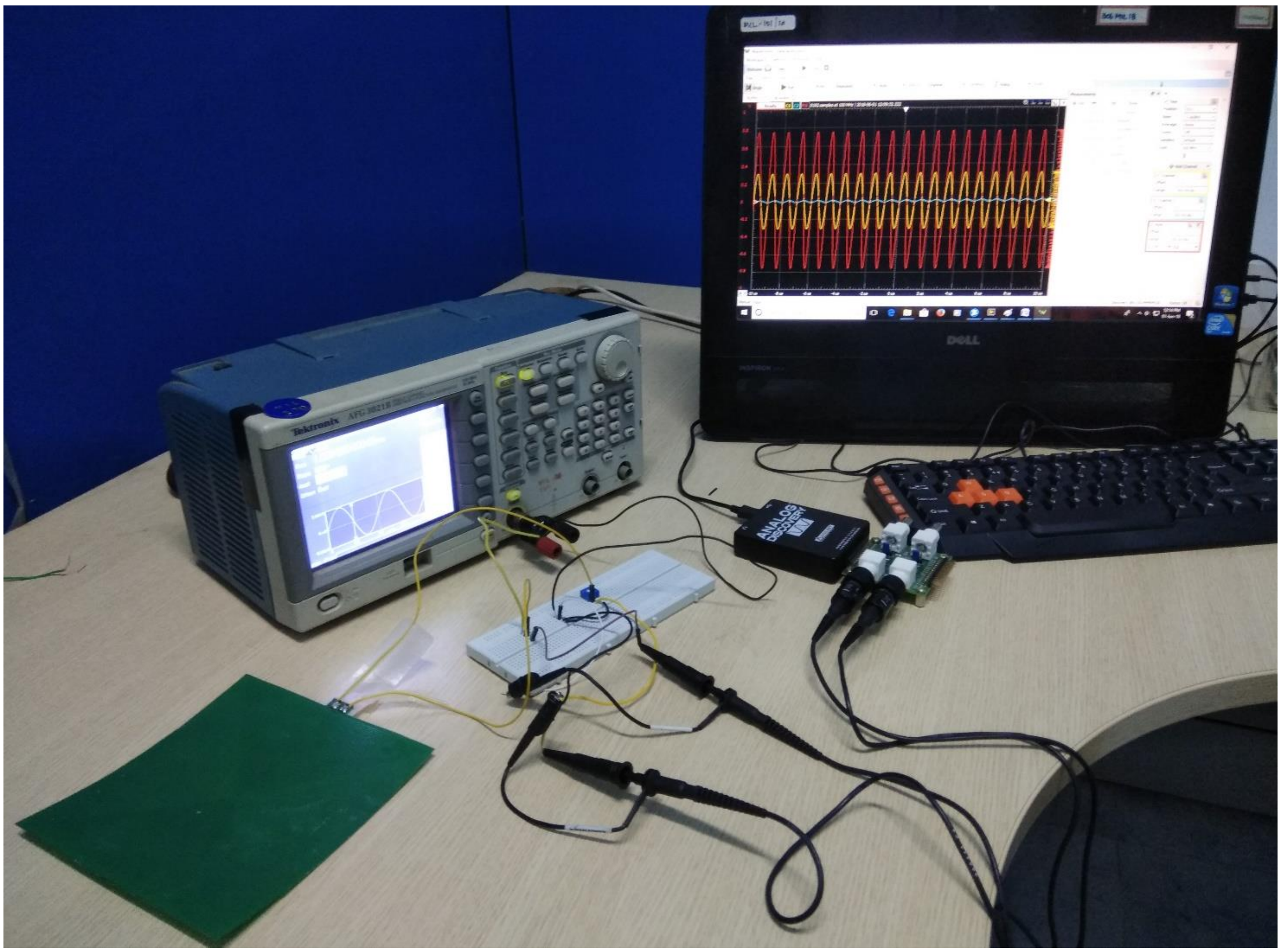

Fig. 4.1 Snapshot of the Experimental Setup for measurement of impedance when there is no load

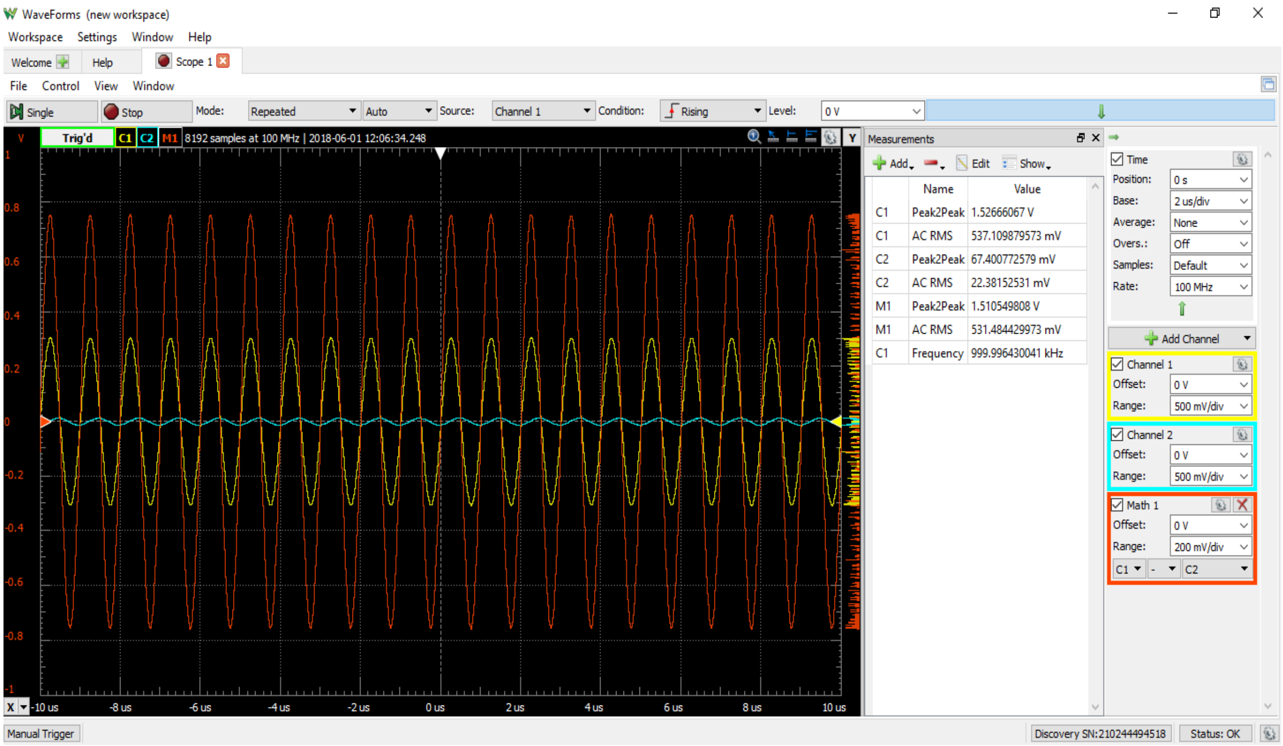

Fig. 4.2 Snap shot of the front panel of WAVEFORM software when there is no load

4.1Design and Development of Impedance Model

In this impedance model, the planar inductor is used as the sensor part and the measurement is carried out at 1 MHz frequency. The Analog Discovery kit is used for the interfacing the circuit with the PC using software named WAVEFORMS which worked as an oscilloscope. For providing the excitation voltage function generator Tektronix AFG 3021B is used. Then the data is being extracted from the WAVEFORMS software to LabVIEW for further manipulation and finding out the value of Impedance and its phase.

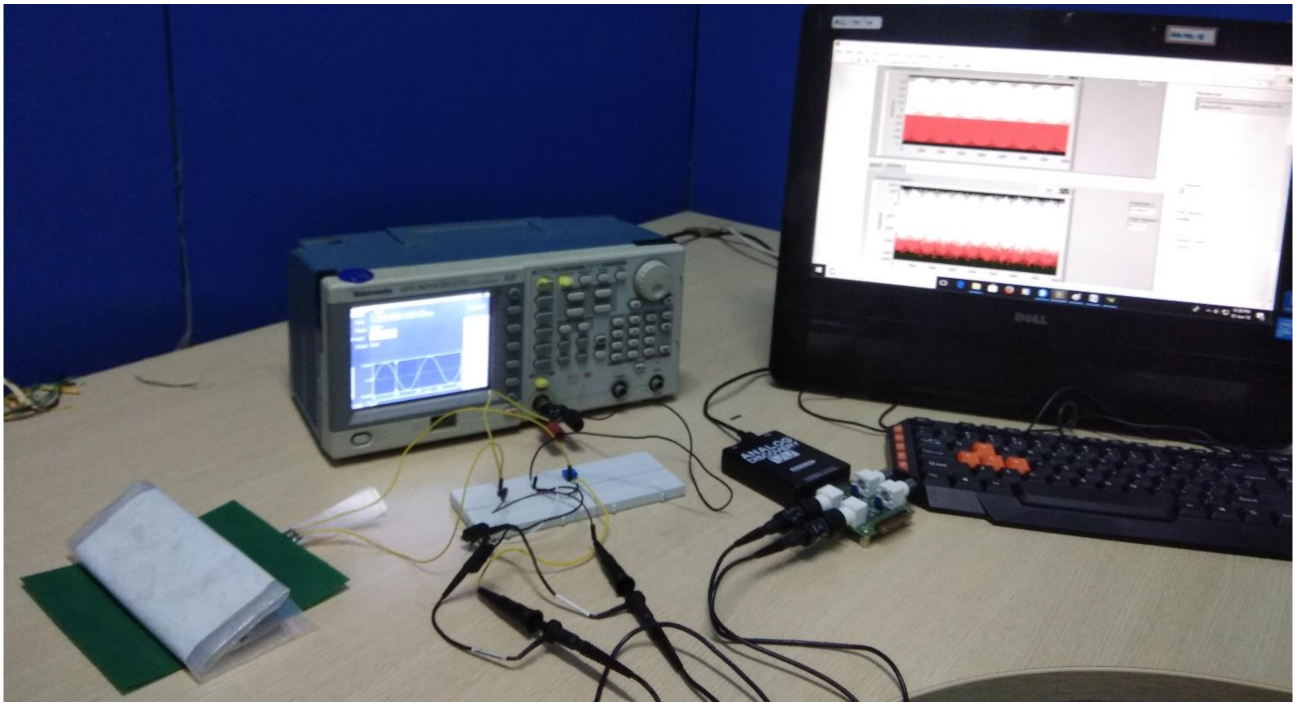

Fig. 4.3 Snapshot of the Experimental setup when there is load

4.2Impedance Measurement Results

Firstly, measurement is done when there is no load and reading is noted down. Then dry paper, wet paper, wet paper with salt and then conductive plates are kept over the planar inductor as a load respectively. Then measurement is done and readings are noted down. The inductance magnitude and phase is calculated and accordingly comparison is made.

The results are noted down in table 4.1.

Test Specimen	**LabVIEW Data**			**WAVEFORM Data**			**Impedance (Ω)**
	V_L(mV)	V_R(mV)	θ(deg.)	V_L(mV)	V_R(mV)	θ(deg.)	
No load	531.873	21.59	76.77	531.86	21.62	77.76	1517.46
Dry paper	532.95	21.32	76.72	532.99	21.33	75.6	1539.48
Wet paper	530.257	20.09	72.81	530.25	20.14	71.28	1625.5
Wet paper having salt	532.745	18.82	74.49	532.16	18.82	75.6	1743.36
Conductive plates	511.19	43.90	71.21	511.82	43.11	67.32	717.205

Table 4.1 Impedance Measurement Results

4.3 Errors in the above mentioned Method

From the above values we can see that the impedance values increases in ascending order from No load condition to dry paper to wet paper to wet paper having salt. But normally the impedance value should decrease in this order. So we can say that the result we are getting is erroneous which may be due to other effects that affected the measurements.

Result from the experiment-

Impedance value increases in the order-

Conductive plates <No load< Dry paper< Wet paper< Wet paper having salt

The ideal result would be-

Conductive plates < Wet paper having salt< Wet paper< No load< Dry paper

Considering the factors, hence a modified impedance model is developed and explained below.

4.4 Modified Impedance Model

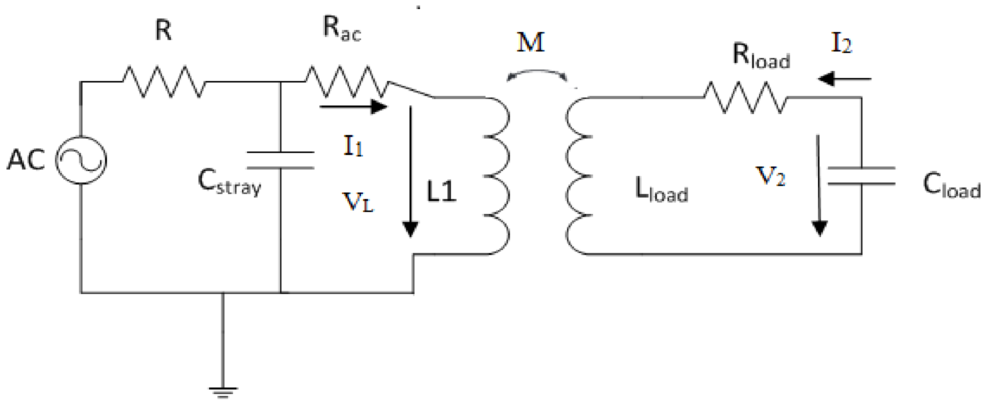

Fig. 4.4 Equivalent Circuit Diagram of the Modified Impedance Model

This modified impedance model given in Fig. 4.4 is based on the concept that any test specimen comprises of three parameters L_{load}, C_{load} and R_{load}. Accordingly these parameters changes depending on the test specimens [18].

There is **mutual inductance** between the two coils L1 and L_{load} which also changes according to the test specimen used. This change ultimately affects the Impedance value concerned with that test specimen.

That's why this effect of mutual inductance explains the increase in the impedance value in the above model.

4.4.1 Analytical Model

The analytical model of this modified impedance model can be derived using the well-known transformer equations for harmonic oscillations with the frequency '*f*':

$$V_L = RI_1 + j\omega L1I_1 + j\omega MI_2 \qquad (4.1)$$

$$V_2 = R_{load}I_2 + j\omega L_{load}I_2 + j\omega MI_1 \qquad (4.2)$$

Here V_L, V_2, I_1, I_2 are shown in figure 4.4

The Mutual inductance M of the coupled coils can be written as

$$M = k\sqrt{L_1 L_{load}}$$

(4.3)

k =geometry-dependent coupling coefficient with a value between 0 (no coupling) and ∓1.

$$I_2 = -j\omega C_{load} V_2$$

(4.4)

The equivalent impedance of the across the inductor of the read out coil is derived by using 4.1, 4.2 and 4.3 (considering that the effect of R_{ac} and C_{stray} is negligible).

$$Z_L = j\omega L_1 - \frac{\omega^2 M^2}{R_{load} + j\left(\omega L_{load} - \frac{1}{\omega C_{load}}\right)} \quad (4.5)$$

5. CONCLUSIONS

5.1 Summary of the work done

A proper approach for finding the impedance of any test specimen is found out. This work mainly focuses on the non-contact impedance measurement of the any material so that any damage due to direct contact can be eradicated. If there is direct contact between the test specimen and the sensor, then there is a possibility of modification of the electrical properties of the test specimen which will not allow us to know the characteristics of that material.

So we opted for the non-contact impedance measurement taking mutual induction in consideration which actually explains the variation of the measured results from the expected results.

Modular programming technique was adopted for VI development and each sub VI is tested separately to ensure its effectiveness.

Adequate number of simulation studies has been conducted to ensure that there is no error in the measurement and to validate the Vis and make it accurate.

5.2 Scope for Future Work

In the modified Impedance model, the unknown values R_{load}, C_{load}, L_{load}, and M are yet to be found. A method will be developed in future to measure the parameters accurately.

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APPENDIX

The front panel and the Block diagram Panel developed in Virtual Instrument are given below:

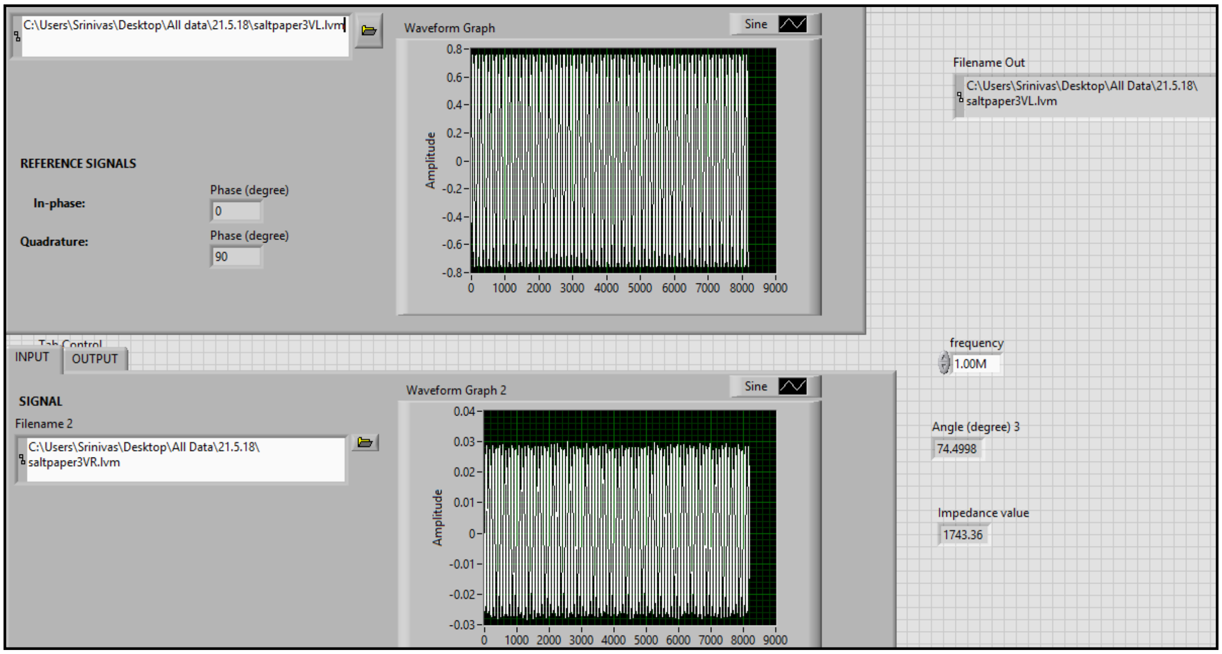

Fig. A1 Snapshot of the Front Panel of the input when there is load

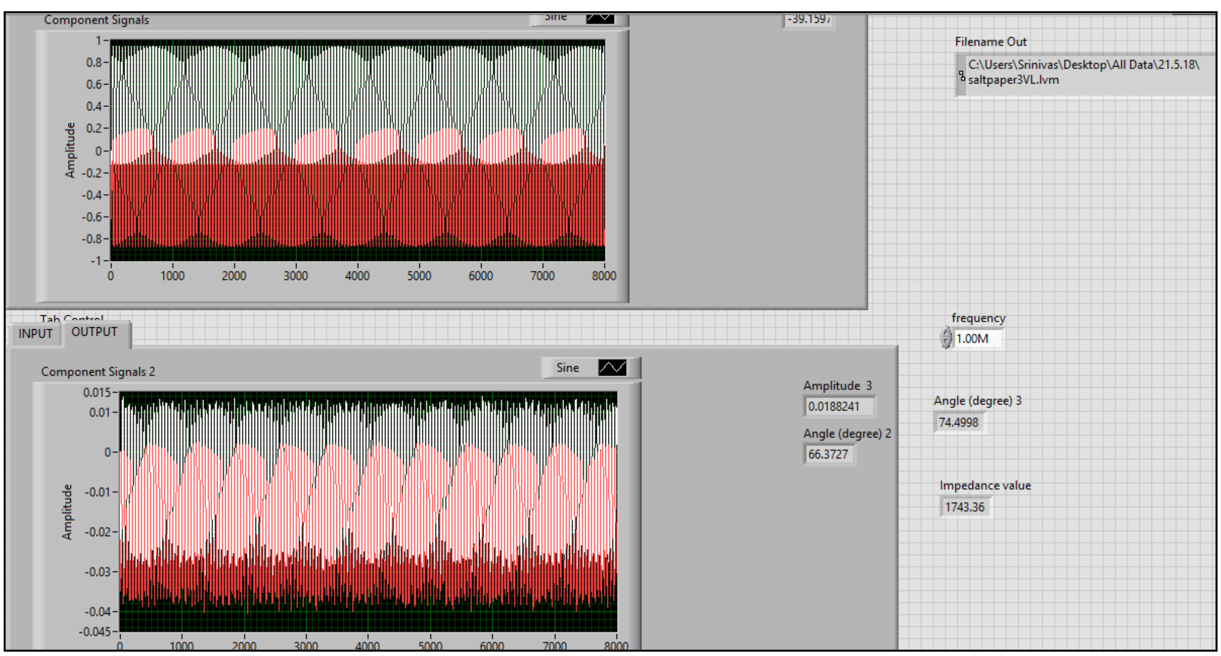

Fig. A2 Snapshot of the Front panel of the output when there is load

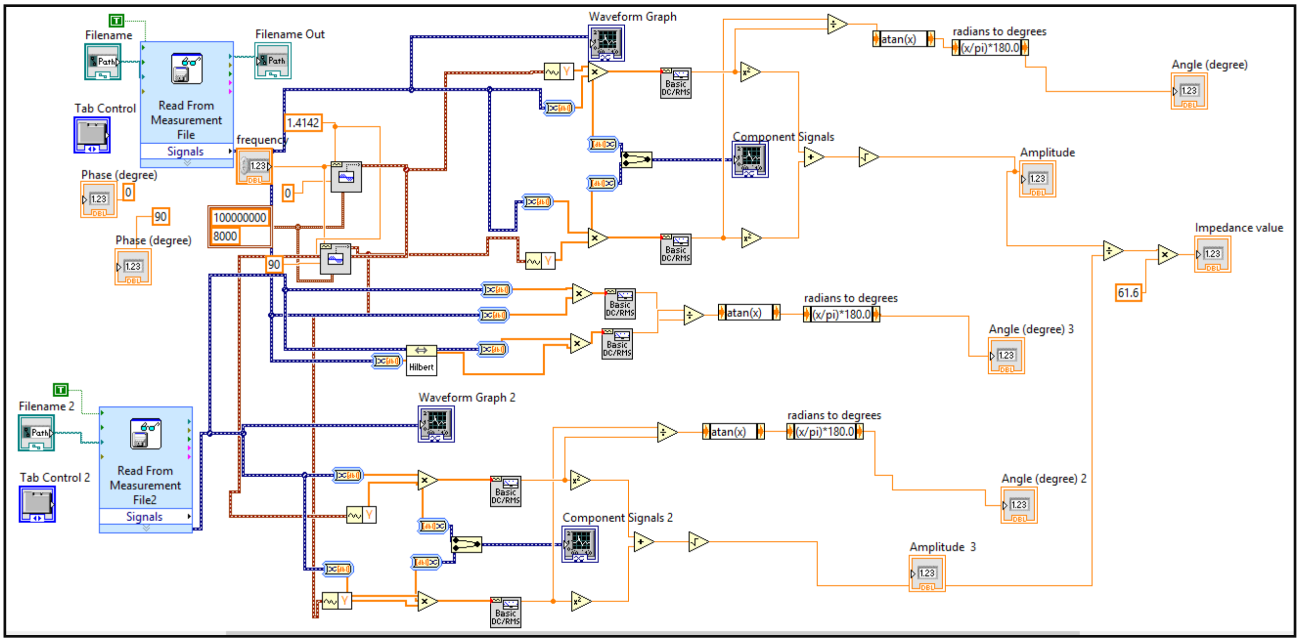

Fig. A3 A snapshot of the Block diagram panel for measurement of Impedance

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