NON CONTACT MEASUREMENT OF AC VOLTAGE USING CAPACITIVE SENSITIVE TECHNIQUES

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **NON CONTACT MEASUREMENT OF AC VOLTAGE USING CAPACITIVE SENSITIVE TECHNIQUES**, submitted by **ARJUN RAVEENDRANATH**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Date: 6th June 2014

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ABSTRACT

KEYWORDS: Capacitive sensing; Non contact measurement; AC Voltage.

There is no end to the need of voltage measurement in any industry. It is the cornerstone of applications like manufacturing processes and automated factory lines. Calibration of sensors is an irreplaceable requirement and a majority of sensor outputs are voltages. Many cases require this voltage measurement to be made by unobtrusive and discreet methods. There lies the importance of non contact measurement.

A measurement set up for performing non contact voltage measurements of conductive media such as wires is described. Wherein, the method of sensing employed is capacitive. The sensors are made to couple with the measurand via electric fields and suitable signal processing methods generate the required measurement. The system involves a reference source at a different frequency from that of the unknown voltage source to be measured. The reference current that flows is thus used to measure the coupling capacitance with the sensor electrodes. The coupling capacitance and the voltage set up by the source is manipulated to correctly measure the unknown source voltage. Some amount of manual intervention is required to calibrate an offset output voltage.

The system is designed to be independent of spacial placement of sensor plates, geometry of conductor, its material as well as the medium surrounding it.

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ABBREVIATIONS

IITM	Indian Institute of Technology, Madras
CS	Cross Sectional
VS	Vertical Sectional
gnd	Ground potential
opamp	Operational Amplifier
INA	Instrumentation Amplifier
E Field	Electric field

NOTATION

r	Radius, cm
h	Height, cm
ϵ	Relative permittivitty
σ	Conductivity

CHAPTER 1

INTRODUCTION

Measurement of voltage is a requirement that can have a wide range of applications particularly-industrial, scientific or military. This voltage could be the output of a sensor or some intermediate signal between two systems. Therefore, it is important to accurately measure voltage. Sometimes the voltage of a conductor or signal source needs to be measured for better understanding or extracting more information regarding the system. In such cases, the measurement needs to be carried out without obtruding the working of system. This is where non contact measurement becomes significant.
In this thesis, the author has focussed on remote measurement of voltages of conductive cable like media. Voltage and current measurements are important for such conductors to effectively compute the power drawn from a source.

1.1 Traditional and commonly prevalent techniques:

1.1.1 Electrometers:

Electrometers measure the electrostatic force. Force either between the unknown wire and a charged plate, or between two charged plates that are brought into close proximity to the unknown wire is measured.
Disadvantages:
Since these methods rely on measuring the mechanical deflection of charged plates, they are sensitive to undesirable error sources such as gravitational effects, temperature effects and susceptibility to low-frequency vibration, making them unsuitable for portable or handheld use. Also, their reading varies with variations in coupling capacitance between the unknown wire and the sensing apparatus. Since this capacitance varies with orientation, wire and sensor geometries, and dielectric constants, the readings are merely proportional to voltage on the unknown wire, rather than conveying an accurate absolute voltage measurement. The size of existing electrometers makes them too large to be used to measure voltages in tight quarters.

1.1.2 Using electrostatic force transducers:

A conducting membrane is coupled to a force transducer like microphone. The membrane is driven with an AC reference voltage as shown in Fig. 1.1, creating alternating attractive and repulsive electrostatic forces caused by the difference in potential between the membrane and the conductor. The transducer generates a signal having the same frequencies as the forces on the membrane, and the amplitudes of the A.C. components are proportional to the unknown voltage on the conductor. By dividing the amplitude of the AC components, an accurate determination of the unknown voltage is calculated.(Libove *et al.*, 2002)

Disadvantages:

Microphones cannot respond beyond a frequency range, hence by the proposed algorithm, only signals of frequency upto half the bandwidth of microphones can be measured.

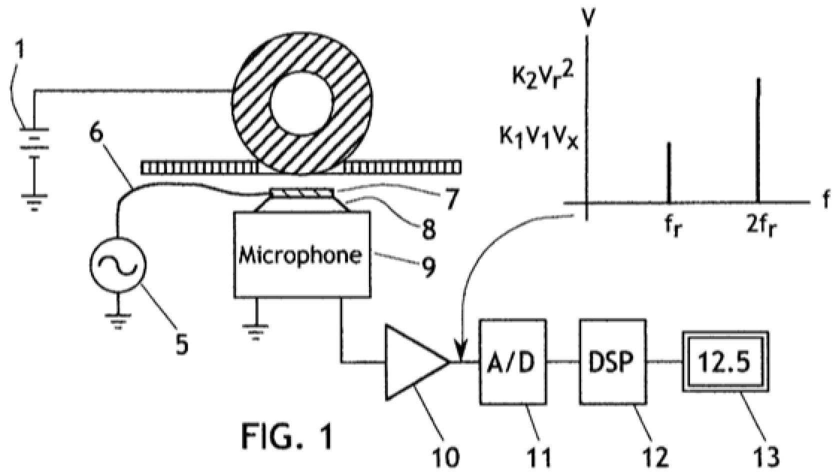

Figure 1.1: Electrostatic force transducer method. Figure courtesy Libove *et al.* (2002)

1.1.3 Electric field balancing technique:

This method has an object and a potential controller which is electrically connected to the electrode as shown in Fig. 1.2. The potential controller changes a reference potential applied to the electrode to a final value such that the E field between object and electrode disappears. The electric potential is determined from the final value. (Makuth *et al.*, 2014)

Disadvantage:

Reference should be in phase with the signal voltage to be measured.

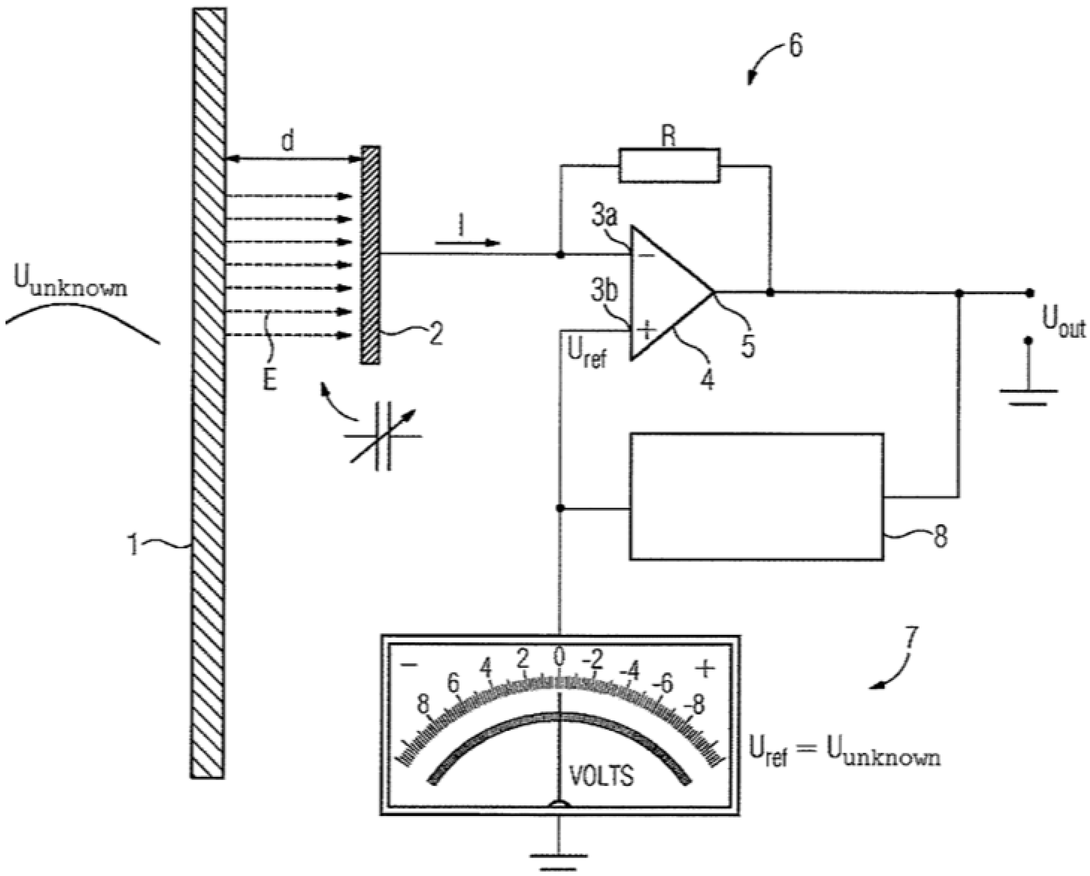

Figure 1.2: Field balancing technique. Figure courtesy Makuth *et al.* (2014)

1.2 Incorrectness of Electric field based measurement:

This author had begun this work with the motive to sense voltage from measured E field values (Razavipour *et al.*). The E field distribution depends on charge density which again depends on voltage to which the conductor is charged. By measuring E field and substitution in the E field distribution should theoretically help in deduction of conductor voltage. E field could be calculated by measuring the potential between two electrodes placed in the field. However, as seen from the comsol simulation, Fig. 1.3 and Fig. 1.4, there is a slight disturbance in the field pattern when two plates are introduced in the field. This renders the voltage between them to follow non linear relationships. Hence measuring this voltage does not conclusively aid in deduction of voltage.

1.3 Advantages of capacitive sensing:

Capacitive coupling is a purely Electric field based phenomenon, which has no temperature, ionic concentration or corrosion effects, and thus provides unprecedented measurement fidelity.Also,ultra-high impedance feedback techniques can be implemented in a capacitive sensor to enhance measurement fidelity even further. Thus, using the techniques proposed in this thesis, an accurate determination of the unknown voltage may be made, regardless of changes and uncertainties in the coupling capacitance that may be due to differences in wire geometry, variations in dielectric constant, and other factors which can affect coupling capacitance. Also, it is possible to measure voltage on the centre conductor of an insulated wire without the need to pierce the insulation.

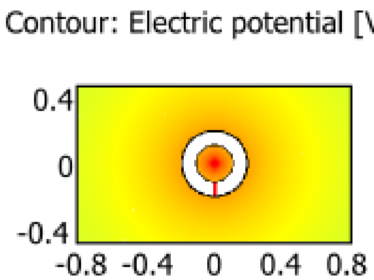

Figure 1.3: Contour with two sensor plates

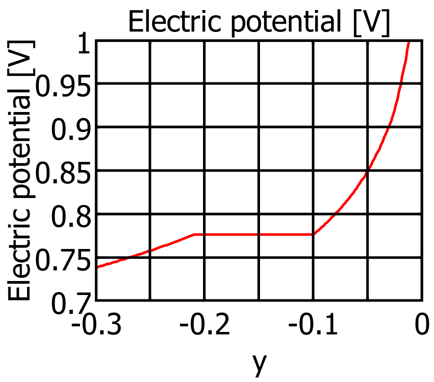

Figure 1.4: Radial voltage variation in Fig. 1.3

1.4 Objective of the work:

The aim of this work is to develop a virtual instrument based measurement system that can be used for measurement of ac voltage of cable like conductors in a non contact fashion. The type of sensing chosen is capacitive due to the various drawbacks of existing techniques as described previously. The system also requires to be insulated to errors resulting from slight movements of conductor, type of metal in its composition, and also the medium surrounding it.

1.5 Organisation of thesis:

Chapter 1- Introduction to non contact voltage measurement and different prevalent methods.

Chapter 2 -Description and design of the capacitive coupled techniques, wherein two independent strategies are discussed.

Chapter 3- FEA analysis using COMSOL. A simulation model of sensor and conductors is created, and the techniques proposed are checked for validity and accuracy.

Chapter 4: The two proposed sensing and measurement techniques are implemented on hardware, using a prototype built for the same purpose. Hardware validation and results obtained are discussed. Different probable conditions of error are incorporated and performance is checked under these situations.

Chapter 5: Thesis is concluded here and steps that need to be taken for application to a particular area are proposed.

CHAPTER 2

NON CONTACT VOLTAGE MEASUREMENT USING CAPACITIVE TECHNIQUES

As is seen in the previous chapter, placement of electrodes in the field to be measured slightly disturbs the E field pattern and therefore the measurement results will be erroneous.

Underlying principle: In the techniques described in this principle, an external known load is introduced to deliberately load the system and to generate an output voltage/current which bears a relation to the known load. As we know, a conductor carrying a voltage will form a capacitance with any other conductor placed in its E field. Since the measurement is not dependent on accuracy of E field, it is of no concern to us.

2.1 Technique 1 Methodology:

For the remaining part of the discussions, the unknown voltage on the conductor is termed Source Voltage (V_x) of frequency f_s. In this technique, we make use of a simple opamp I-V converter shown in Fig. 2.1. Meaning, the sensed current flowing through C is converted into a voltage at the output of the opamp as per the equation(2.1)

$$vo = j2\pi f_s R_F C_x v_x \tag{2.1}$$

Now, if a sensor electrode E1 is placed in the E field of the conductor, a capacitance, C_x, is established between the two. This capacitance is dependent on the geometries of the conductors and sensor electrodes as well as the separation between them. This unknown capacitance establishes an unknown current through it which is made to flow through the resistance R and appears as output voltage of opamp (eq. 2.5).

Now, this opamp voltage is dependent on two unknowns, V_x and C_x, the only known quantity is source frequency f_s. This is a 2 unknown 1 equation scenario. It would be advantageous if we could send a known voltage and frequency signal through the

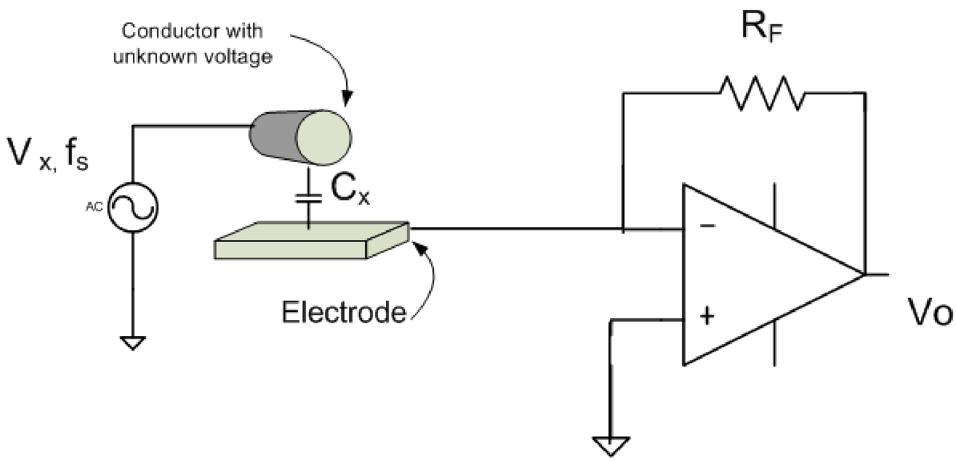

Figure 2.1: I to V Converter

conductor to measure this unknown C_x .That is the essence of this technique. Basic idea of this strategy is reported in (Libove and Singer, 1995).

Another sensor electrode E2 is introduced into the system. This is also connected to the non inverting terminal of the I-V converter opamp. By the negative feedback virtual grounding property of the opamp, there exists no voltage difference between E1 and E2 as they are at the same potential. Now, a known voltage is connected to E2 which will henceforth be termed as Reference voltage V_r of frequency f_r. To ensure the proper I-V functionality for source voltage, the non inverting terminal should be at ground. To ensure these criteria, we select f_r to be different from f_s. Ideally, they should be spectrally as far away as possible. Now, this creates an impression of a known voltage applied to the conductor under test.Thus the system now encompasses two equations and two unknowns, which can easily be solved.

2.1.1 Mathematical formulation

Since the two signals are at different frequencies, superposition theorem splits the output into additive linear outputs for each independent signal. It follows that,

$$v_x = V_{xm}sin(2\pi f_s t) \quad (2.2)$$

$$v_r = V_{rm}sin(2\pi f_r t) \quad (2.3)$$

$$i_{cap}(x) = C_x d(v_x)/d(t) \quad (2.4)$$

$$vo_r = 2\pi f_r R C_x V_{rm} cos(2pif_r t) + v_{off} \quad (2.5)$$

$$vo_x = 2\pi f_s R C_x V_{xm} cos(2pif_s t) \quad (2.6)$$

$$vo = vo_x + vo_r \quad (2.7)$$

From eq.(2.4) C_x can be obtained. Substituting it in eq. (2.5) v_x is obtained.

2.1.2 Offset correction

As seen in eq. (2.4), an offset voltage v_{off} is seen at the opamp output even when no C_x is present. During hardware testing, the same residual offset voltage was observed. The reason for this offset voltage is not fully known to the author and is believed to be caused by a parasitic capacitance C_p of the nature shown in Fig.2.6. This prompted slight modifications in the circuit. The reference voltage is now supplied through a resistive network comprising of R1, R2 and R3.These serve so as to minimise the offset voltage to zero. If offset can't be negated completely by adjusting these resistor values, it needs to be subtracted from the voltage due to reference. This is clear from the phasor diagram 2.3,
where, X-axis $Angles$ refers to Phase angles.
The modified circuit as well as equivalent circuits for the frequencies f_s and f_r are depicted in figures 2.2, 2.5 and 2.6 respectively.

2.2 Technique 2 :

In this technique, an external load is added in series to the unknown capacitance C_x. The source voltage V_x gets thus shared between C_x and the load. The voltage across the load is then measured. Since C_x is purely capacitive, it is ideal to use capacitive loads rather than resistive as to avoid phase considerations in equation solving. This is

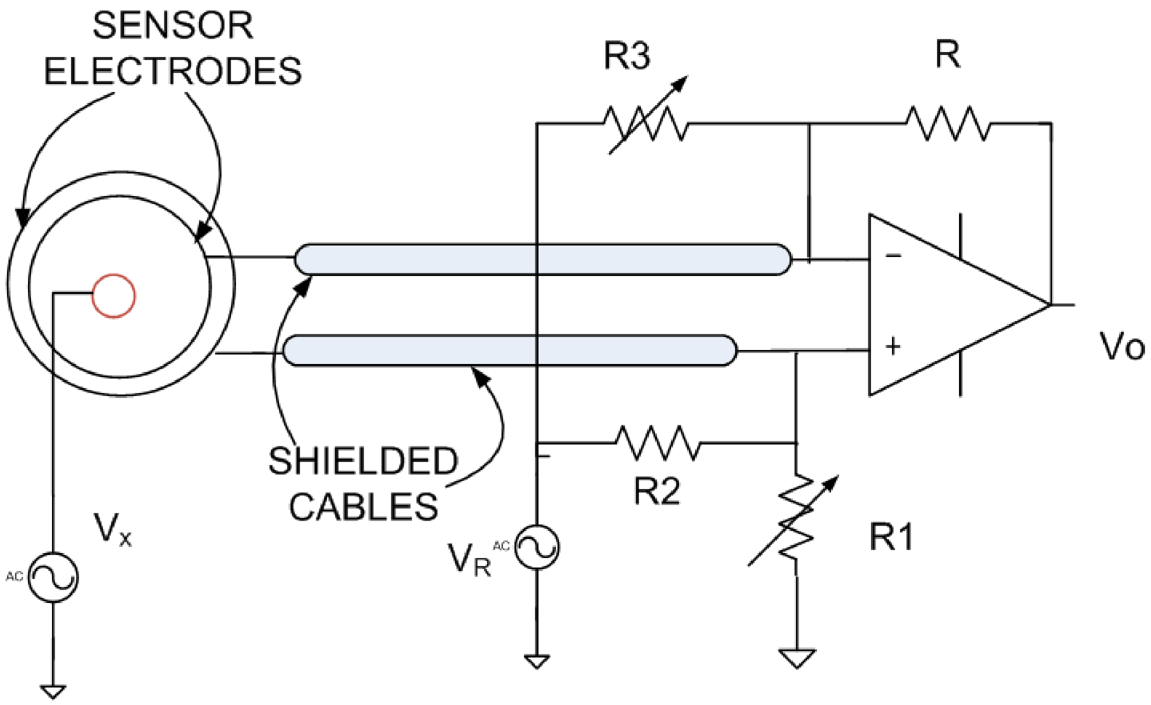

Figure 2.2: Full circuit with offset compensation

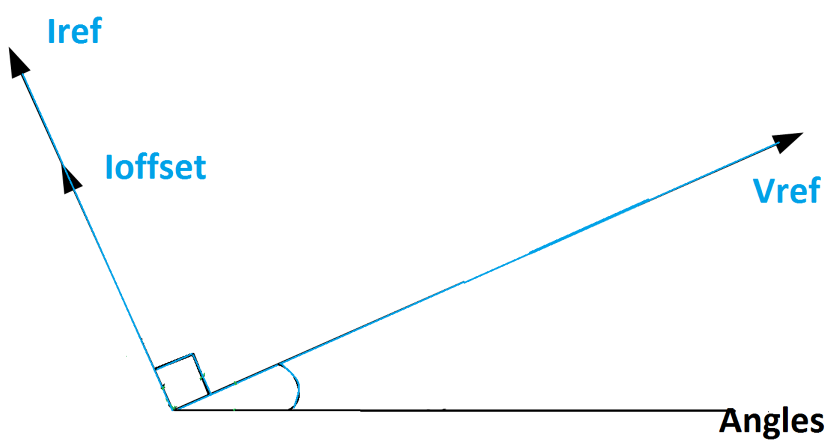

Figure 2.3: Phasor diagram for reference signal

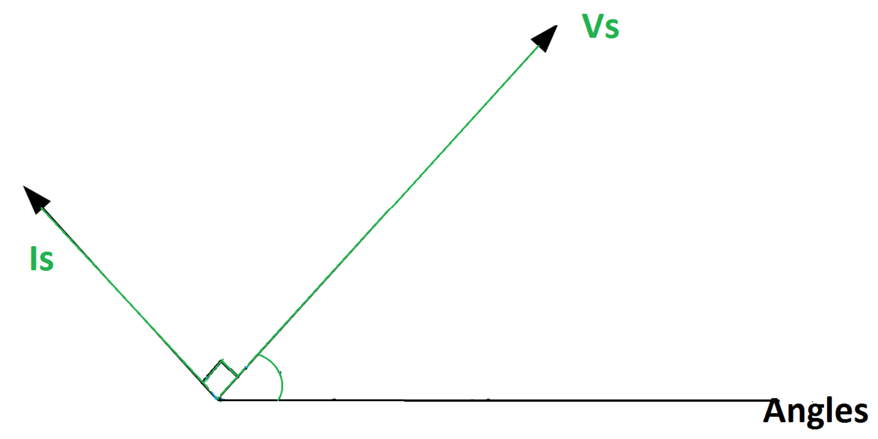

Figure 2.4: Phasor diagram for source signal

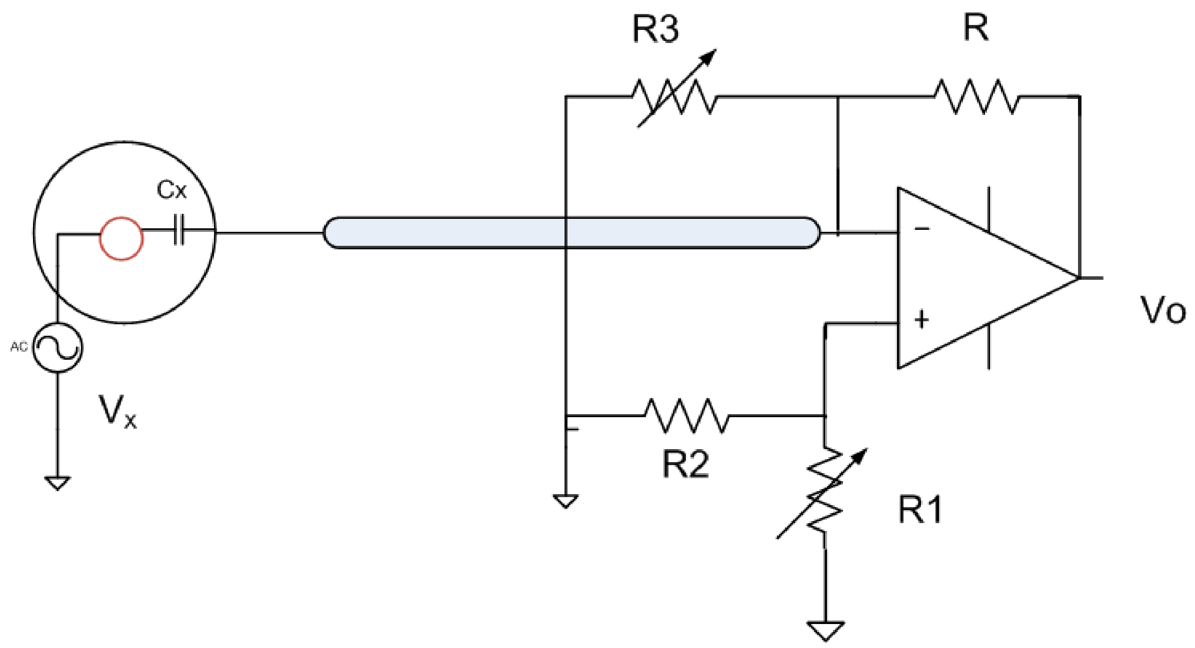

Figure 2.5: Equivalent circuit for source signal

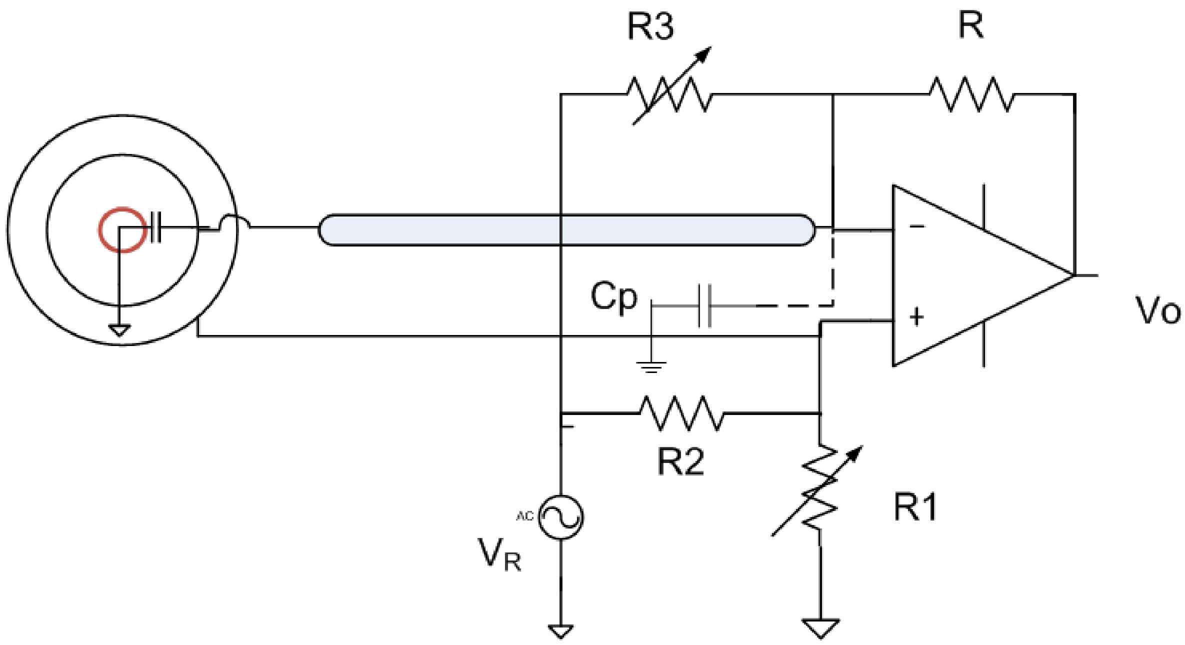

Figure 2.6: Equivalent circuit for reference signal

because the voltage of this capacitive network becomes independent of frequency. To invoke two equations to solve for two unknowns, two different capacitances or sets of capacitors can be used suitably switched. This is perfectively fine as long as one takes care of any inherent switching capacitors. Another issue is the resolution available to the measuring DAQ system. To get sufficiently resolved sets of voltage readings depends a lot on the sizes of load capacitor as compared to C_x.

Here, the author aims to mitigate above mentioned problems. As in Technique 1, a reference frequency is introduced into the circuit as shown in the figure 2.7. The advantage being that the amplitude of this reference signal can control the output voltage and hence provide better resolution.

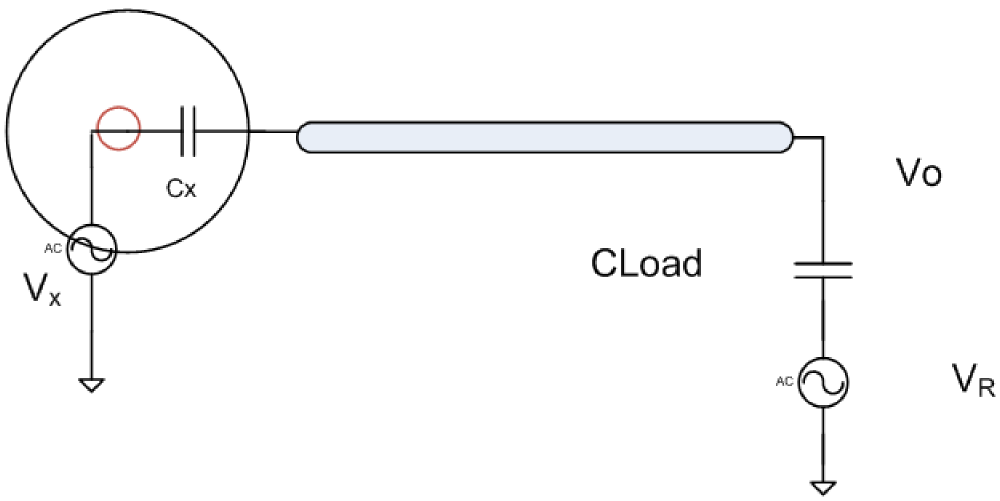

Figure 2.7: Measurand with the Load

2.2.1 Bias current issue:

Measurement of voltages involves an opamp or an INA that offers high input impedance to the measurand. For proper working of opamps, the input transistors need to draw a small bias current for being operational. This DC current should therefore have a path to ground. Otherwise, the DC current flows into the capacitive terminals causing the opamp output to drift and finally get saturated. The system under consideration being an all capacitive network does not offer a DC path to gnd.Usually, this path is provided by a high resistor (several M ohms) connected from the opamp terminal to gnd. For our purposes, the capacitances involved are too small (pico-femto) range and frequencies low (<100) making their impedances large. These therefore form a voltage divider network with the resistance and shunt most of the signal to gnd. Several techniques have been proposed to mitigate this aforementioned issue, out of which, here explored is the one described in (Krupka, 2006).

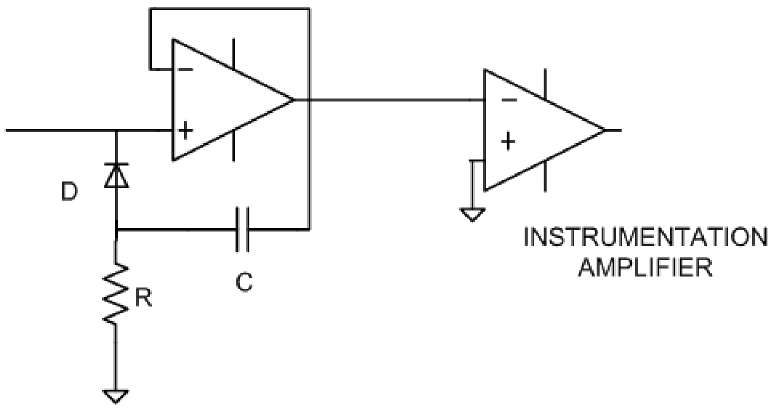

Figure 2.8: Bias current compensation circuit

The circuit 2.8 has a buffer as input stage, to the output of which, the INA is connected. R and C is designed as a high pass filter of cut off freq approx. 1Hz. DC bias current flows through the reverse biased diode and R to gnd to set up a DC voltage at input of buffer. Thus the DC voltage and AC signal at input of buffer gets reflected to its output. Out of this, only the AC signal is passed through by the high pass. Thus at both ends of the diode, there appears the same AC signal, making it an infinite impedance to AC. Thus, the two requirements of resistive path to gnd as well as high impedance for the signal are now satisfied.

Note: At low frequencies such as 50 Hz and very low coupling capacitance values, the impedance of capacitive network is comparable to opamp input terminal impedances. In such cases, the R_{in},C_{in} (opamp input impedances) parallel combination and their phase induced needs to be accommodated for accurate results.

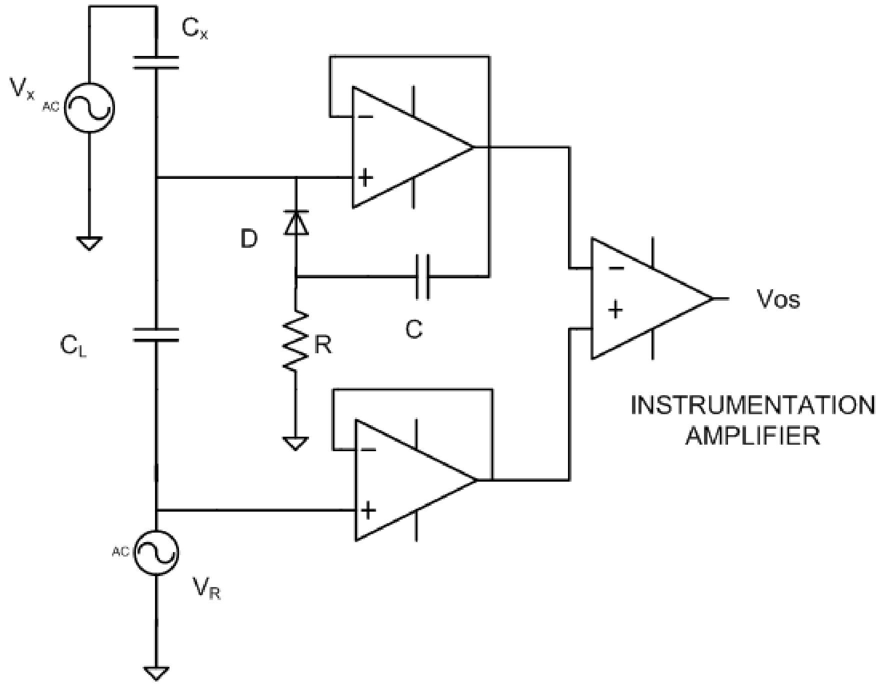

Figure 2.9: Circuit diagram for second technique

2.2.2 Mathematical formulation:

The entire circuit is as seen in figure 2.9. The equations governing above can be summarised as follows,

$$vos_x = v_x A(X_{Ls})/(X_{Ls} + X_{Xs}) \tag{2.8}$$

$$vos_r = v_r A(X_{Lr})/(X_{Lr} + X_{Xr}) \tag{2.9}$$

$$X_{Ls} = 1/j2\pi f_s C_L \tag{2.10}$$

$$X_{Xs} = 1/j2\pi f_s C_X \tag{2.11}$$

$$X_{Lr} = 1/j2\pi f_r C_L \tag{2.12}$$

$$X_{Xr} = 1/j2\pi f_r C_X \tag{2.13}$$

Where,

A- INA gain

C_X- Sensor to conductor capacitance

C_L- Known Load capacitance

X_{Xr}- Impdeance of C_X at f_r

X_{Xs}- Impdeance of C_X at f_s

X_{Lr}- Impdeance of C_L at f_r

X_{Ls}- Impdeance of C_L at f_s

From eq. (2.8), X_{Xr} is calculated. Now, substituting in eq. (2.12), C_X can be calculated. Similarly substituting C_X in eq. (2.10), X_{Xs} is obtained.Finally from eq. (2.7),v_x can be found.

2.2.3 Advantages of Technique 2:

- Output is independent of frequency, no requirement to choose higher reference frequency for better output
- Better control over resolution as output proportional to amplitude of reference signal.This is better than loading two times with an external load.

CHAPTER 3

FEA STUDIES

Finite Element Analysis is performed here with the tool called COMSOL. COMSOL Multiphysics is a finite element analysis, solver and simulation software for various physics and engineering applications, especially coupled phenomena, or multiphysics.It utilizes Finite element methods to find the solutions to boundary value problems involving partial differential equations.It is particularly advantageous to put into use in Electrostatics/ Electrodynamic problems concerning complex geometries/ objects.

The author, here in this project, has concerned himself with Comsol ver. 4.3 and in particular only the following three physics:

- Electrostatics-This interface simulates electric fields in dielectric materials with a fixed charge present.
- Electric currents-This interface simulates the current in a conductive and capacitive material under the influence of an electric field.
- Electric circuits-This interface has the equations for modeling electrical circuits with connections to a physical model and is capable of solving for the voltages, currents, and charges associated with the circuit elements.

3.1 COMSOL modelling of the measurement system

The entire measurement system, the element with the measurand (voltage) as well as the sensor configuration is modelled here.The geometrical model is then further excited to carry out steady state as well as transient analysis.Electric circuits physics enable measurement of output currents/voltages.

Geometry specifications: Conductor, whose voltage is to be measured, is modelled as a cylinder of r=3cm and h=15cm.Two sensor electrodes, one placed on inside and the other outside a cylindrical framework of insulator/dielectric having r=4cm and h=18cm.An air volume, also cylindrical is included, to accurately capture fringing fields. The size of this volume is arbitrarily fixed initially and then varied until the solution remains unaffected.

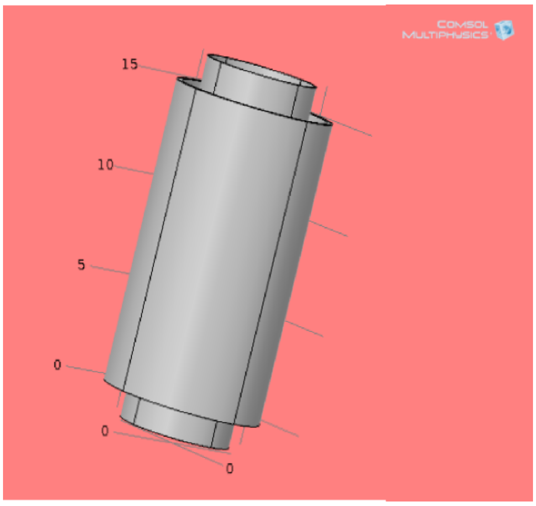

Figure 3.1: Sensor arrangement along with the conductor whose voltage is to be measured.

Materials: All metal parts, the conductor and inner and outer electrodes are assigned as Copper(ϵ =1, σ = 5.96 e 7). The dielectric framework is assigned to glass. Remaining part of geometry is filled as air.

3.2 Analysis of Technique 1

3.2.1 Steady state analysis:

Steady state analysis is done to find out the capacitance between the conductor and electrode. For measuring capacitance, the conductor is excited by supply of 1V DC. Now the integral of surface charge density over the electrode is computed, which gives a measure of the capacitance.

3.2.2 Transient Analysis:

As seen from the equation(2.4), such a transfer function is difficult to implement without the virtual ground property of an opamp.Unfortunately, these elements are not supported by COMSOL now.The author here has attempted a work around by measuring the capacitive current on excitation by a sinusoidal signal $(5sin(2\pi1000t))$, and then multiplying it with R (4.87e6 ohm) value to get corresponding voltages. Also alongside

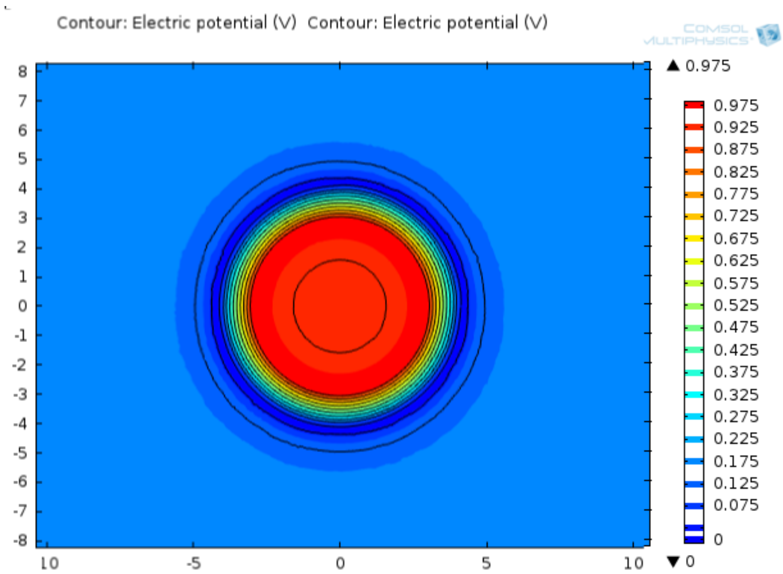

Figure 3.2: Cross sectional view: Electric potential contour

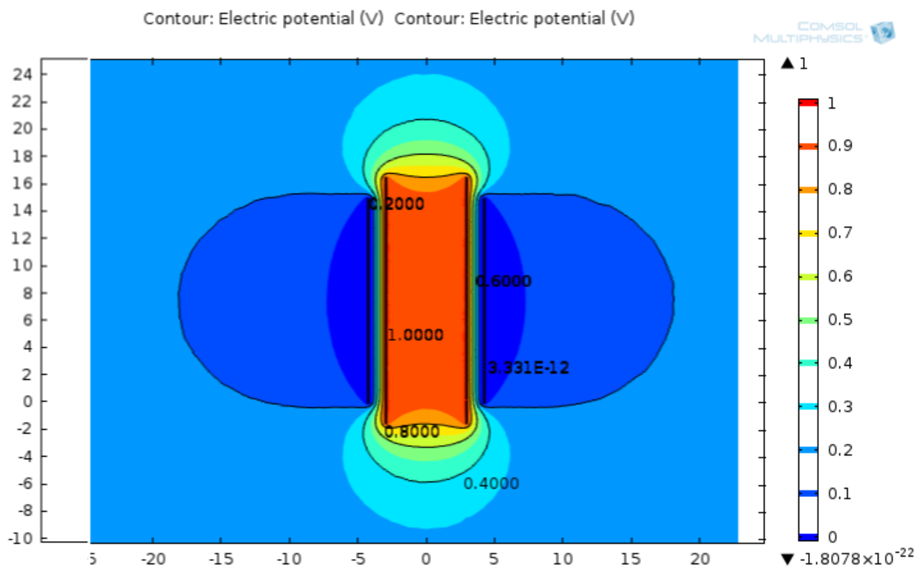

Figure 3.3: Vertical sectional view: Electric potential contour

plotted is the theoretical voltage waveform, obtained as:

$$V_o = 2\pi 1000RC5cos(2\pi ft) \tag{3.1}$$

Where C (32.81p)is obtained from steady state analysis carried out above.

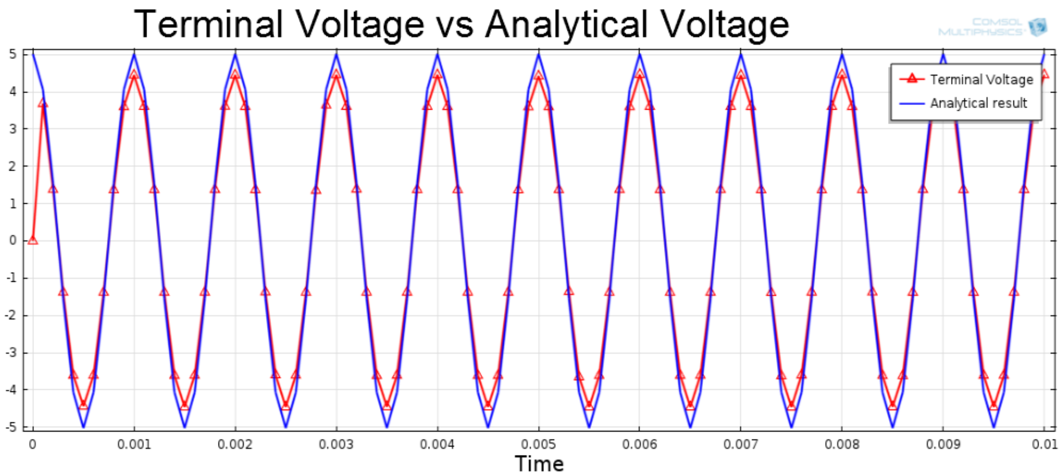

Figure 3.4: Transient vs Analytical response : Technique 1

3.3 Analysis of Technique 2

3.3.1 Steady state analysis:

Steady state analysis to find out the capacitance between the conductor and electrode follows the procedure described in subsection (3.2.1).

3.3.2 Transient Analysis:

Here, an external capacitance $C2$ (20pF) is connected in series with the sensor capacitance. This is made possible by the 'External I terminal' module in Electric circuits physics. The conductor is excited by a sinusoidal signal $(5sin(2\pi 1000t))$ and the voltage developed across the capacitance $C2$ is plotted. Also, the theoretical voltage waveform across capacitor $C2$ is calculated and plotted as per the equation.

$$V_o = 5sin(2\pi 1000t)(C/(C+C2)) \tag{3.2}$$

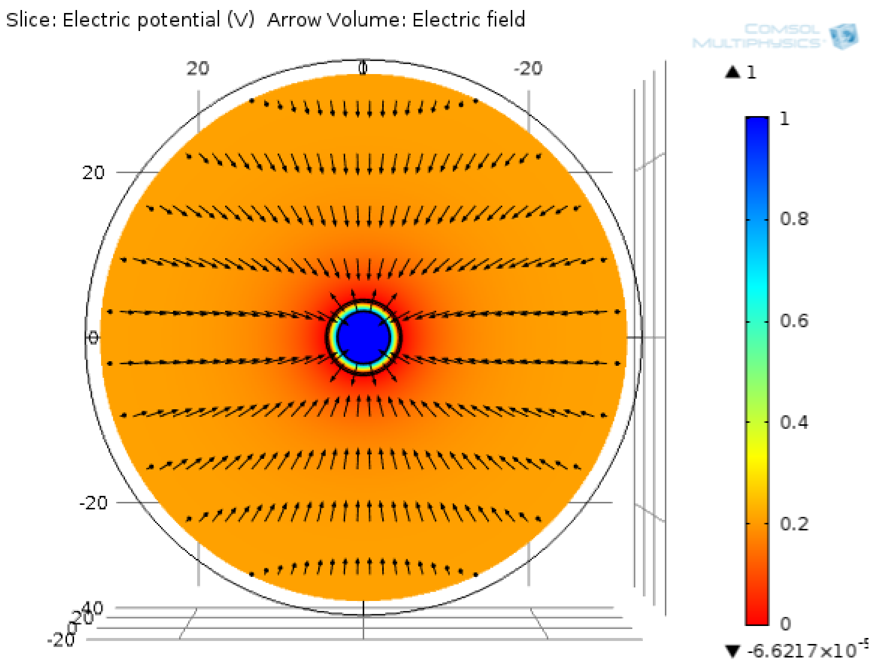

Figure 3.5: CS view : Electric field lines

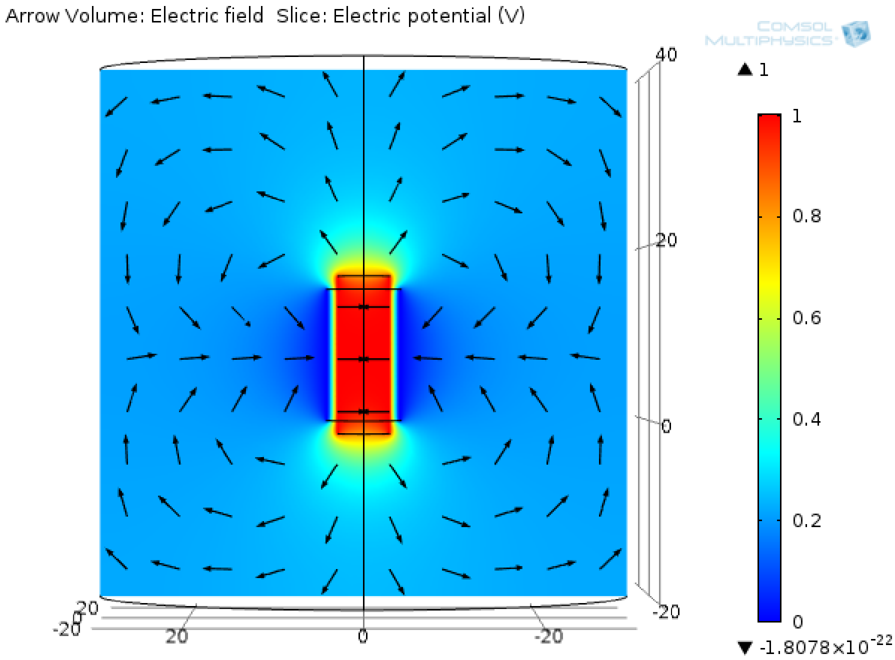

Figure 3.6: VS view : Electric field lines

Where C is obtained from steady state analysis carried out above.

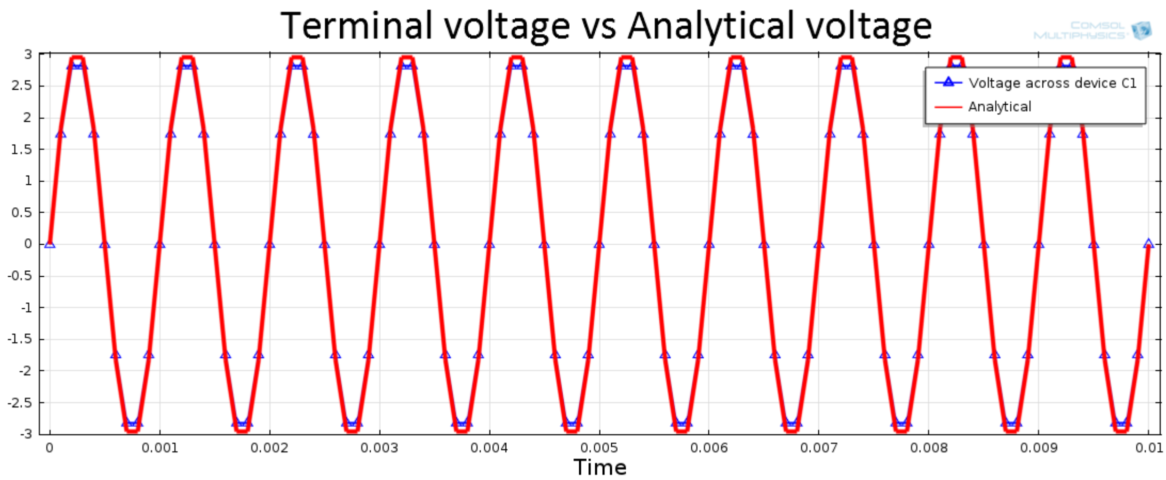

Figure 3.7: Transient vs Analytical response : Technique 2

3.4 Conclusions :

From the above studies it can be shown that:

- This conductor sensor arrangement works well in FEA studies. Hence, the model has been validated and can be fabricated for hardware based tests.
- The shape of electrode that should be fabricated, in order to minimise error in signal capture, is arrived at.
- Steady state and transient performance of the system is satisfactory and mimics closely, a real life prototype.
- The two methods arrived at for measurements have been validated to be working and dependable.

CHAPTER 4

HARDWARE IMPLEMENTATION AND RESULTS

4.1 Data acquisition and signal processing

The author, for this project, has entirely depended on the Data acquisition system supplied by National Instruments for signal acquisition and processing.
NIELVIS The NI Educational Laboratory Virtual Instrumentation Suite (NI ELVIS) modular platform delivers a hands-on lab experience. NI ELVIS features an integrated suite of commonly used instruments such as Scope, Function Generator, Digital Multimeter and so on. The NIELVIS also has the added advantage of interface ability with LabVIEW using inbuilt DAQ cards.
LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a system-design platform and development environment for a visual programming language from National Instruments.Moreover, it can be interfaced with **MATLAB**.

4.1.1 Hardware descriptions

As is seen from the circuit diagrams of Technique 1 and Technique 2, very few discrete components are required:
TL064 - Opamp used for I-V Converter and Buffer stages
INA129 - Instrumentation amplifier
Passive and active components.

4.1.2 Labview VIs:

Since no hardware filter stages are plausible to be accommodated, signals are acquired to Labview platform after buffer stages and all data processing is done within Labview. Some of the important labview VIs used are:

- DAQ Assistant

- Filter
- Tone measurements
- Amplitude and Level measurements
- Mathscript script window

The process followed is elucidated in the block diagram of Fig.4.1.

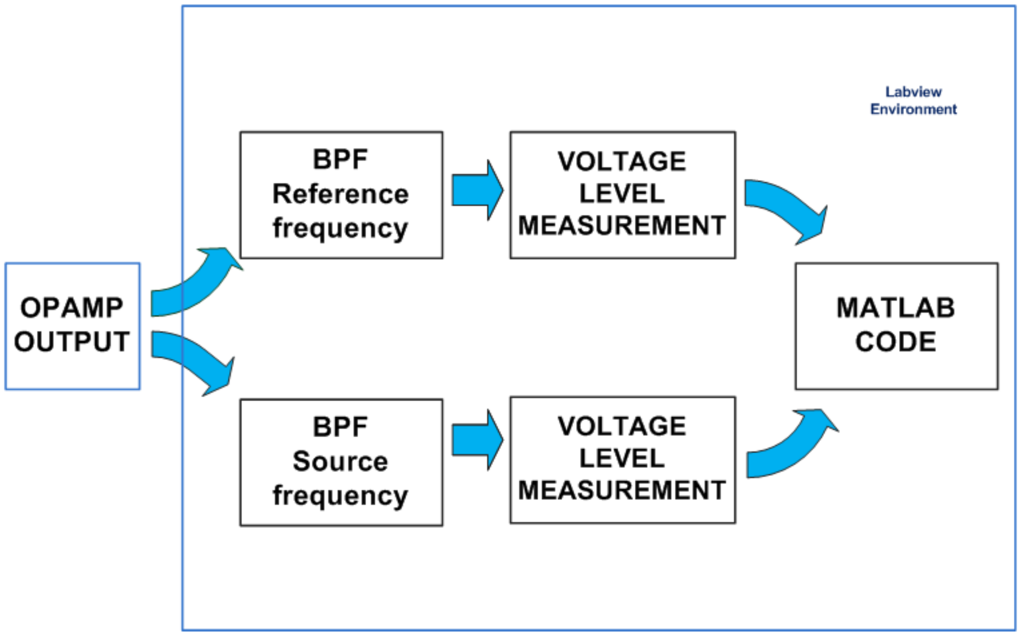

Figure 4.1: Block diagram of implementation

4.2 Shielding:

Since the range of capacitances that is dealt with is very small, (order of 10 pF), it is important to ensure proper signal collection from the electrodes. Two key issues are:

- A connection wire accumulates a capacitance along it, specifically when they are long. That is measurand and the measurement circuits are far off from one another. This can act as a shunt path for signal to ground, thereby reducing available signal strength.
- External disturbances, most prominently the power line frequency can couple through these capacitances and affect the measurement. Since the power line frequency voltages and fields are usually higher than the measurand, there is a good chance of input stage opamps to get saturated.

4.2.1 Electric field isolation:

To isolate the measurement set up (Fig. 4.3) from ambient external electric fields, the entire prototype measurement equipment (sensor electrodes and conductor) is housed within a metal cabinet. This metal cabinet is more than 20 times the radius of conductor and is maintained at ground potential. This ensures that no external Electric field lines enter the cabinet and affect the measurand.

4.2.2 Shielded cables:

The connections from the sensor electrodes are taken via shielded cables. Shielded cables have an additional wire along with usual sensing wire. This wire, called shield, develops a capacitance with respect to sensing wire. Only one end of the shield wire is connected, whereas the other end is left free. Depending on where the shield is connected, they are of two types:

- **Passive shielding:** Shield is connected to gnd. Here any calculations must take into consideration the capacitance of shield.
- **Active shielding:** Here, shield is maintained at the same potential as sensing wire so as to negate the capacitance between them. This is done by connecting shield to output of a buffer, whose input is the sensing wire. In the hardware testing, active shielding was employed by the author. In technique 1, shield was connected to non inverting terminal in Fig. 2.2 whereas in technique 2, shield was connected to output of buffer in Fig.2.9

4.3 Sensor electrode design:

Since the sensor electrodes are made of metal, they form an equipotential surface throughout its body. The sensor plates should be made such that they have geometry same as that of the equipotential lines. From CS and VS view from fig 3.2 and fig 3.3 , it is clear that the sensor plates should be cylindrical or part of a cylinder. For better coupling, author has incorporated entire cylindrical structure for electrodes in this project, as shown in fig. It comprises of two electrodes E1 and E2 held firmly by a cylindrical PVC structure, one to the inner surface and the other on the outer surface. The plates by themselves are double side conducting copper foil tape as seen in Fig. 4.2

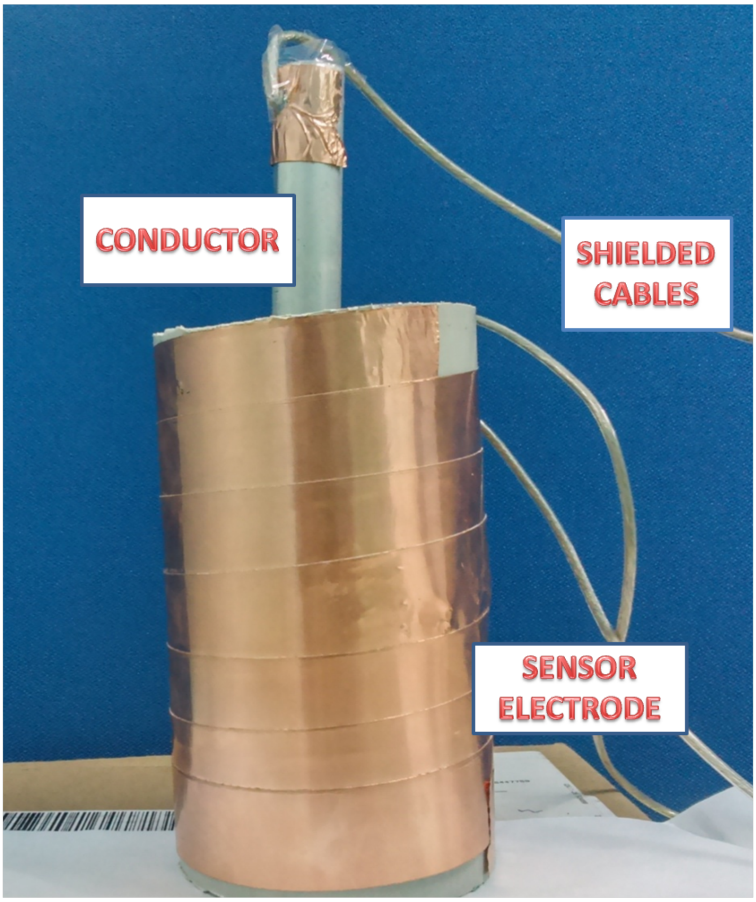

Figure 4.2: Sensor electrodes along with conductor

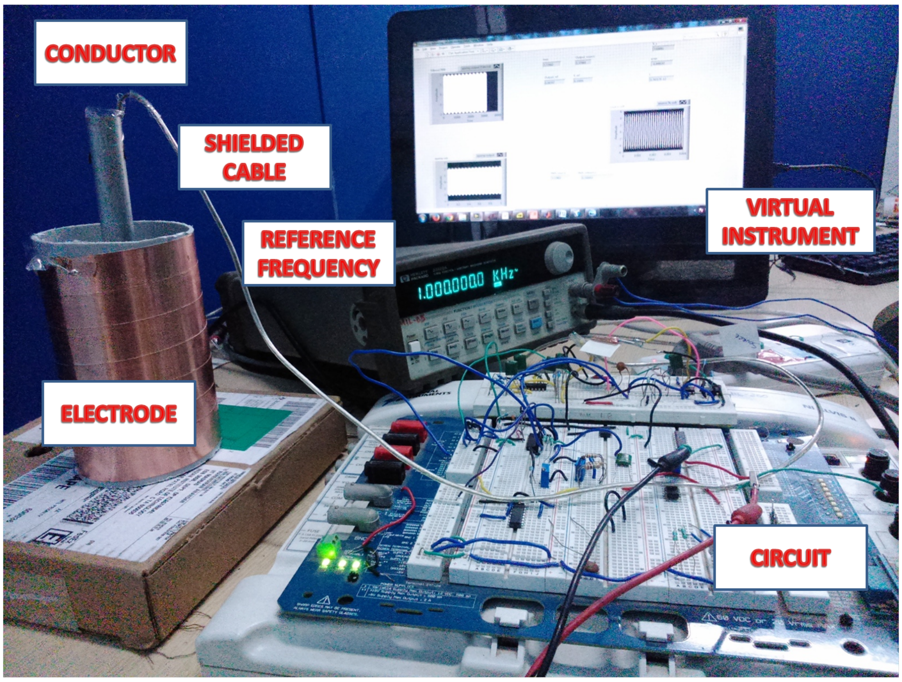

Figure 4.3: Entire measurement setup

4.4 Measurement steps

- The output of I to V converter is balanced by varying pots R1 and R3 in Fig. (2.6) until zero offset is obtained or a minimum offset voltage at a phase of 90 degrees is obtained as in Fig. 4.4. The offset voltages so obtained are furnished in table (4.1).
- A set of readings is taken with conductor exactly positioned concentrically (Fig. 4.5)to the sensor electrodes and results collected in Table 4.2.
- A set of readings is taken with conductor positioned off centre (Fig. 4.5) to the sensor electrodes and results collected in table 4.3.
- Table 4.2 results are further plotted as graph on (Fig. 4.6)
- Same conductor voltage (5V) is measured at different reference signals and results tabulated in Table 4.4.

4.5 Input conditions

v_r has a frequency, f_r=400Hz and v_x has a frequency, f_s=7000Hz

R= 4.87e6 ohm

Even though choice of f_s and R are not important, here these values have been chosen to maximise the vo_x as it is applied to inverting terminal.

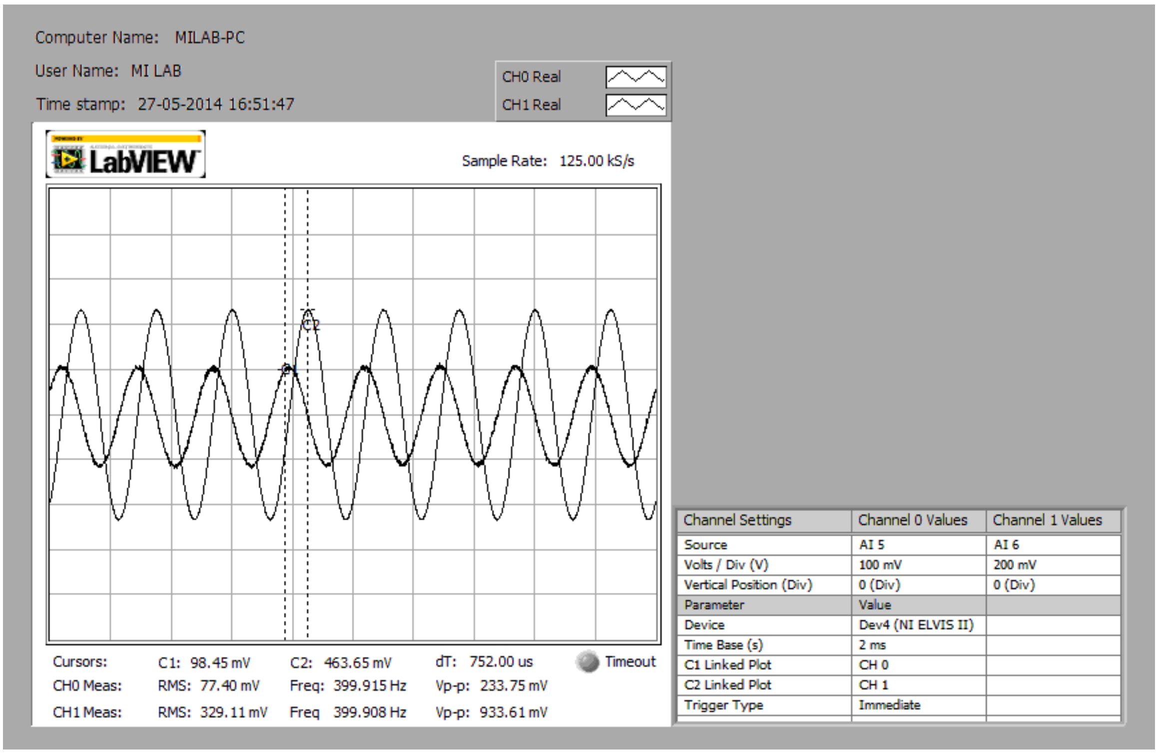

Figure 4.4: 90 deg phase difference between v_r and v_{off}

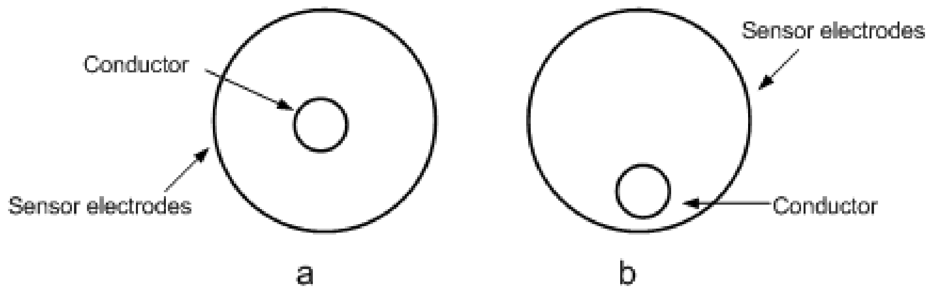

Figure 4.5: Conductor placed at centre (a) and off centre (b)with respect to sensor electrodes.

Table 4.1: Offset output voltages for $v_{reference}$ at f_r=400 Hz

$v_{ref}(pk)$	Vo_{offset}(mV)
1	77.8
2	155.6
3	233.2
4	311
5	389.6

Table 4.2: Measured value vs true value when conductor placed at centre with v_{ref}=2V pk-pk

True voltage pk(V)	Capacitance (pF)	True voltage rms(V)	Measured voltage rms(V)	error percent
1	1.77	0.739	0.70	-2.3
2	1.79	1.482	1.41	-3.5
3	1.79	2.276	2.18	-3.3
4	1.79	2.966	2.85	-3.2
5	1.76	3.73	3.65	-1.6

Table 4.3: Measured value vs true value when conductor placed away from centre with v_{ref}= 2V pk-pk

True voltage pk(V)	Capacitance (pF)	True voltage rms(V)	Measured voltage rms(V)	error percent
1	1.866	0.739	0.705	-4.5
2	1.849	1.482	1.425	-3.8
3	1.844	2.276	2.193	-3.6
4	1.837	2.966	2.868	-3.2
5	1.857	3.733	3.548	-4.8

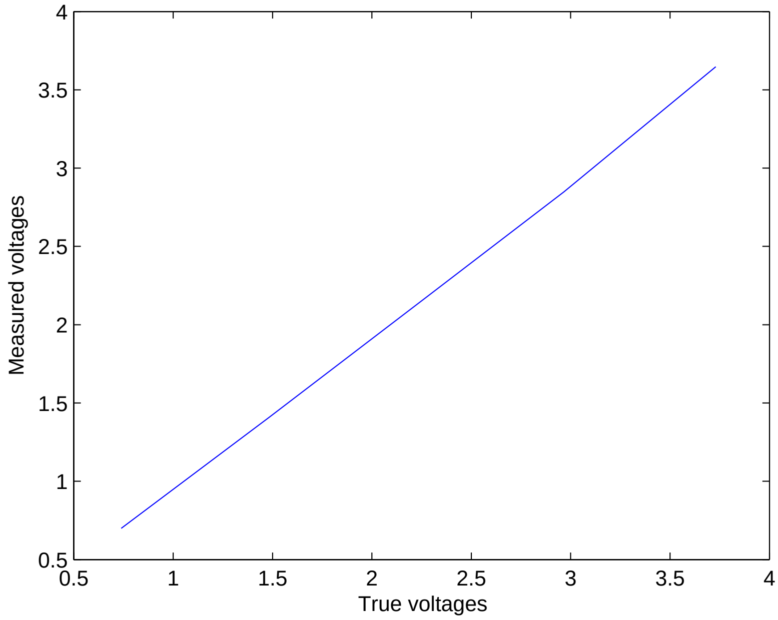

Figure 4.6: Measured value vs True value

Table 4.4: 5V measured with different values of v_{ref}

Offset voltage pk(V)	True voltage pk(V)	True voltage rms(V)	Measured voltage rms(V)	error percent
2	5	3.73	3.548	-4.8
4	5	3.73	3.604	-3.3
6	5	3.73	3.556	-4.6
8	5	3.73	3.59	-3.7
10	5	3.73	3.568	-4.3

CHAPTER 5

CONCLUSIONS:

5.1 Summary of work carried out:

A measurement system capable of measuring voltage of cable like conductive media has been proposed, simulated, tested and presented in this thesis. It was found to give measurement readings within and below an error of 5 percentage. This, being dependent on capacitive coupling technique, is arguably the cheapest method available. Two alternative techniques for implementing the same philosophy are also elaborated. It is also shown that measured values of voltages are independent of the radial positioning of the sensors, though closeness to the conductor ensures better coupling. Provided that a disturbance free environment is given and a DAQ system of good resolution is available, the system can be said to be entirely independent of sensor positioning. Testing results are available only up to 10V peak source voltages owing to non availability of higher voltage generators. Choosing sensor positioning and resistance R value wisely, theoretically this technique can be used over a large range of voltages and frequencies.Thus, an accurate determination of the unknown voltage may be made, regardless of changes and uncertainties in the coupling capacitance that may be due to differences in wire geometry, variations in dielectric constant, and other factors. In addition, it is also possible to measure voltage on the centre conductor of an insulated wire without the need to pierce the insulation.

5.2 Scope for future work:

A possible extension of this technique could be to effectively measure the power line voltages remotely from ground. The author had attempted the same, however unsuccessfully. One of the key issues would be to create a set up that is isolated from ambient power line frequency noise. Generating higher voltages at frequencies other than power line frequencies will also be a challenge. Also care should be taken that,

- The voltage contours are not exactly radial due to the presence of ground under the transmission line. Hence, the sensor plates should be geometrically designed in such a way that they are part of a contour line.

- The equivalent circuit when only reference frequency is considered is quite different. The source voltage is not exactly short to gnd, but instead has a transformer winding impedance path to the gnd.This has to be taken care in the model.

APPENDIX A

LABVIEW VI

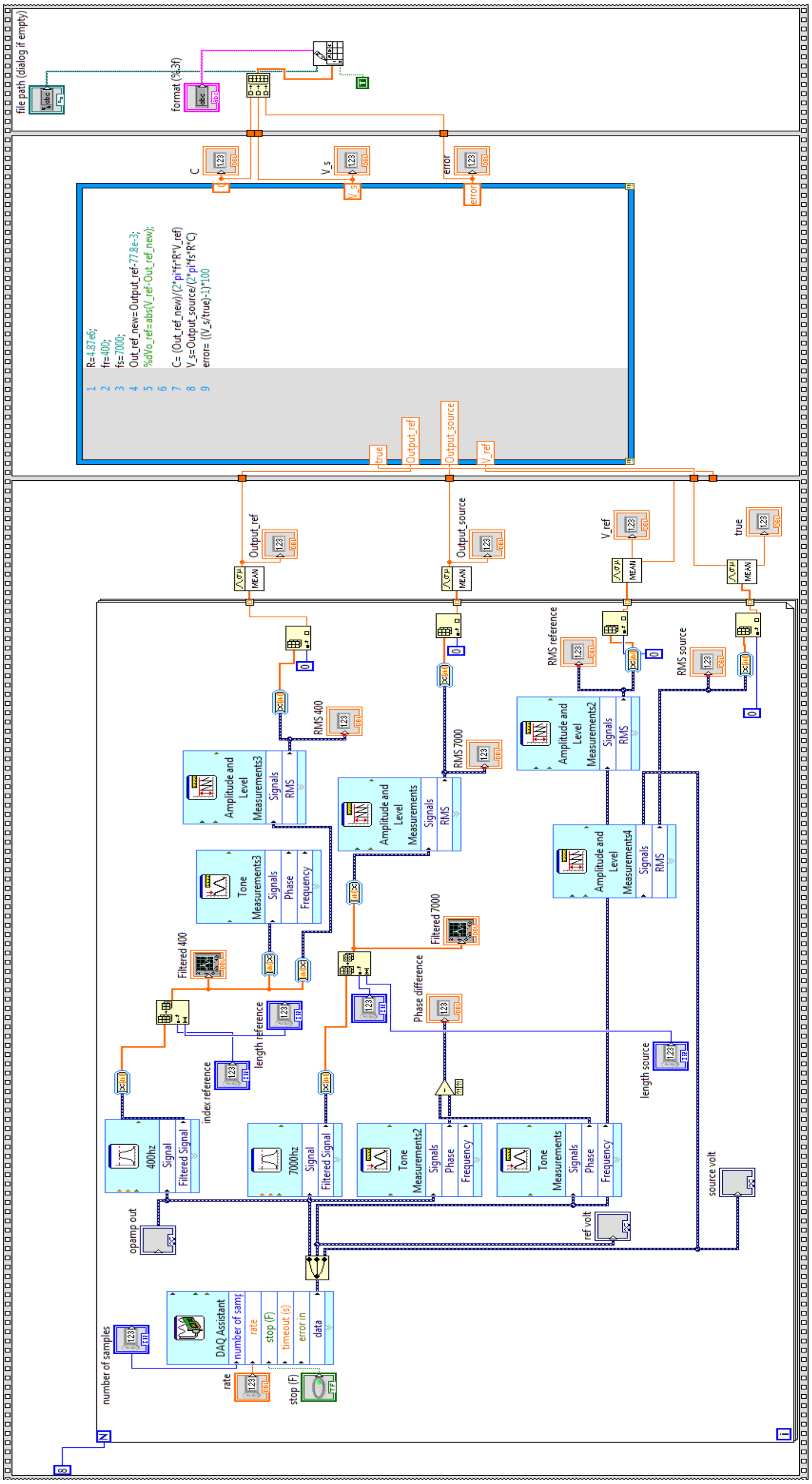

Figure A.1: A screenshot of Labview VI employed.

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