COMBINED CONTACT AND CAPACITIVELY COUPLED CONDUCTIVITY MEASUREMENT SUBMITTED TO IITM

A THESIS

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CERTIFICATE

This is to certify that the thesis titled **COMBINED CONTACT AND CAPACITIVELY COUPLED CONDUCTIVITY MEASUREMENT,** submitted by **Bijoy K P**, to the **Indian Institute of Technology Madras**, Chennai for the award of the degree of **Master of Technology** (Control and Instrumentation) in Electrical Engineering, is a bona fide record of the research work done by him under my supervision and guidance. The contents of this project thesis, in full or in parts, have not been submitted to any other Institute/University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: conductivity measurement probe, capacitive coupling.

The combined contact and capacitively coupled conductivity measurement method measure resistance and hence conductivity of water in an insulating tube through contact and capacitively coupled electrodes. The probe combines the advantages of contact type and capacitively coupled method. The probe has three contact electrodes (exciting electrode, receiving electrode and dummy electrode) and two capacitively coupled voltage electrodes. The contact type electrodes act as the current electrodes, capacitively coupled electrodes act as the potential electrodes. Dummy electrode is to ensure that current in the surrounding water does not find its way in the measurement. The insulated voltage electrodes are metal electrodes coated with a dielectric material. Thus a capacitance C_x is formed between the metal electrode and the outer surface of water in the tube. The capacitive coupling overcomes the problems of electrode polarization and contamination associated with conventional contact based approach of conductivity measurement of water

A signal conditioning circuit suitable for conductivity measurement is proposed. The circuit developed is capable of providing a linear output over the range of values between 20 mS/cm to 70 mS/cm. The prototype of the sensor is fabricated using five copper rings (3 contact and 2 non-contact) in a tube fabricated using 3D printing.

The hardware testing is done by implementing the signal conditioning circuit on the NI ELVIS board. LabVIEW software is used for data acquisition and implementing an indicator which helps in easy read out after doing appropriate mathematical calculations.

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ABBREVIATIONS

TDS	Total Dissolved Solids
EMI	Electro-Magnetic Interference
NI	National Instruments
ELVIS	Electronic Laboratory Virtual Instrumentation Suite
LabVIEW	Laboratory Virtual Instrumentation Electronic Workbench
LPF	Low Pass Filter
FEM	Finite element method
XOR	Exclusive OR gate
SPDT	Single-pole, double-throw
LCD	Liquid Crystal Display
VI	Virtual Instrument
ADC	Analog-to-digital converter
AI	Analog Input
DAQ	Data Acquisition

NOTATIONS

C Capacitance

HV Insulated voltage electrode (after excitation electrode)

LV Insulated voltage electrode (Next to HV electrode)

C_{x1} capacitance formed between the HV metal electrode and the outer surface of water in the tube

C_{x2} capacitance formed between LV metal electrode and outer surface of water in the tube

R_{x1} Resistance of water column between exciting electrode and HV

R_{x2} Resistance of water column between HV and LV

R_{x3} Resistance of water column between LV and receiver electrode

F Frequency

Hz Hertz

CHAPTER 1

INTRODUCTION

1.1 CONDUCTIVITY

Conductivity of water is an essential parameter to obtain the salinity or total dissolved solids (TDS) level. The conductivity σ is computed by multiplying the measured conductance with the cell constant *K*.

$\kappa = G \cdot K$

κ = conductivity (S/cm),G = conductance (S), where G = 1/R

K = cell constant (cm^{-1}) ratio of the distance (d) between the electrodes to the area (a) of the electrodes.

Conductivity measurement is an extremely widespread and useful method, especially for quality control purposes. Surveillance of feed water purity, control of drinking water and process water quality, estimation of the total number of ions in a solution or direct measurement of components in process solutions can all be performed using conductivity measurements. The high reliability, sensitivity and relatively low cost of conductivity instrumentation make it a potential primary parameter of any good monitoring program.

1.2 CONDUCTIVITY MEASUREMENT EXISTING METHODS

Conductivity can be measured using contact type electrode conductivity meter or the non-contact type inductive conductivity meter. There are two types of electrode conductivity meters. They are two electrode conductivity meter and four electrode conductivity meter. With Inductive Conductivity (also called Toroidal or Electrodeless), the sensing elements (electrode coils) of an inductive sensor do not come in direct contact with the process.

- **Contacting conductivity**

Contacting conductivity uses a cell with two metal or graphite electrodes in contact with the electrolyte solution. An AC current is applied to the electrodes by the conductivity meter, and the resulting AC voltage is measured. This technique can measure down to pure water conductivity. Its main drawback is that the cell is susceptible to coating and corrosion, which drastically decreases the reading. In strongly conductive solutions there can also be polarization effects, which result in non-linearity of measurements.

- **Two electrode measurement**

The analyzer applies an alternating voltage to the electrodes. The electric field causes the ions to move back and forth producing a current. Because the charge carriers are ions, the current is called an ionic current. The analyzer measures the current and uses Ohm's law to calculate the resistance of the solution. The conductance of the solution is the reciprocal of the resistance

- **Four electrode measurement**

In the four electrode measurement, the analyzer injects an alternating current through the outer electrodes and measures the voltage across the inner electrodes. The analyzer calculates the conductance of the electrolyte solution from the current and voltage. Because the voltage measuring circuit draws very little current, charge transfer effects at the metal-liquid interface are largely absent in four-electrode sensors.

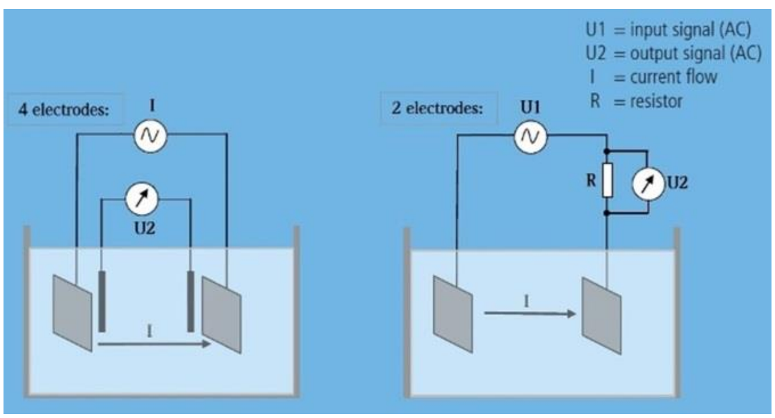


Figure 1.1 Two electrode and four electrode conductivity measurement.

- **Toroidal "Inductive" conductivity**

A toroidal conductivity measurement is made by passing an AC current through a toroidal drive coil, which induces a current in the electrolyte solution. This induced solution current, in turn, induces a current in a second toroidal coil, called the pick-up toroid. The amount of current induced in the pick-up toroid is proportional to the solution conductivity. The main advantage of toroidal conductivity is that the toroidal coils are not in contact with the solution. They are either encased in a polymeric material or are external to a flow through cell. One of the main disadvantages of toroidal conductivity measurements is that it lacks the sensitivity of contacting measurement.

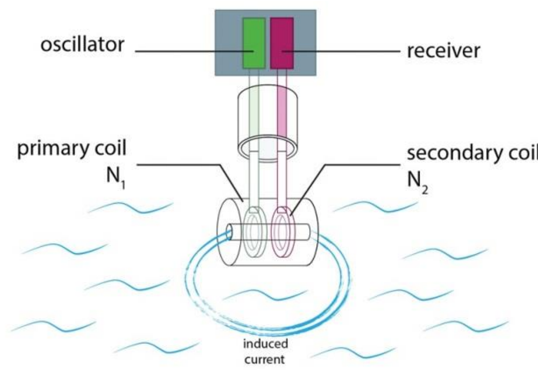


Figure 1.2 Toroidal conductivity measurement.

1.3 OBJECTIVE AND SCOPE OF THE WORK

The main objective of the work described in this thesis is to design a prototype of conductivity measurement probe which will sense the conductivity of sea water and display it on a display unit. The sensor is affordable and apart from having the sensitivity of four electrodes method has the added advantages of reduced corrosion area due to capacitive coupled electrodes. The usage of dummy electrodes results in no external current finding its way in the measurement. Further there is no effect of polarisation and sensor is less expensive compared to four electrode probe and weighs less compared to inductive type probe.

1.4 ORGANIZATION OF WORK

A brief introduction to conductivity measurement is presented in Chapter-1. Chapter-2 deals with design of the conductivity sensor and its fabrication technique. Chapter-3 explains the working of signal conditioning circuit used in conductivity measurement. Chapter-4 provides experimental results of the combined contact and capacitively coupled conductivity measurement probe. The conclusion of the work carried out and its future scope is provided in Chapter-5.

CHAPTER 2

SENSOR DESIGN AND FABRICATION

2.1 INTRODUCTION

The combined contact and capacitively coupled conductivity measurement probe has five electrodes and combines the advantages of contact type and capacitively coupled method. The probe has three circular contact type electrodes (exciting electrode, receiving electrode and dummy electrode) and two circular capacitively coupled voltage electrodes. The contact type electrodes act as the current electrodes, capacitively coupled electrodes act as the potential electrodes. When the exciting electrode is excited, the current will start flowing into the water and collected by the receiver electrode. Dummy electrode will make sure that current in the surrounding water does not find its way in the measurement. The insulated voltage electrodes are metal electrodes coated with a dielectric material. Thus a capacitance C_x is formed between the metal electrode and the outer surface of water in the tube.

Fig. 3.8 Phase correction circuit to compensate the parasitic capacitances.

3.4 PHASE DETECTION

The phase detection circuit is implemented by passing the voltages whose phase difference is to be measured to a comparator (LM311). The output of the comparator is given to an Ex-OR gate implemented using analog multiplexers (CD405xB). The Ex- OR gate pulses are averaged using a sallen key LPF. The LPF output is acquired using Analog Input pins in ELVIS and is used to control the Digital Potentiometer(X9C104P).

3.5 DATA ACQUISITION WITH LabVIEW

The ability to pull in data from an outside source, process the data, and send signals back out to control devices is what sets LabVIEW apart from numerous other software products that can be used to analyse data. The goal of *data acquisition* is to capture data from one or more laboratory instruments on a computer so that it can be analysed, stored and displayed.

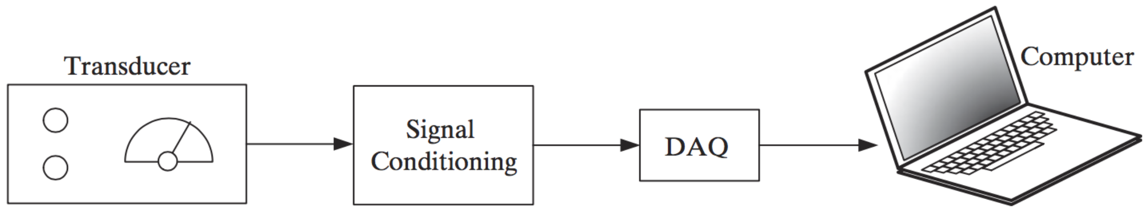
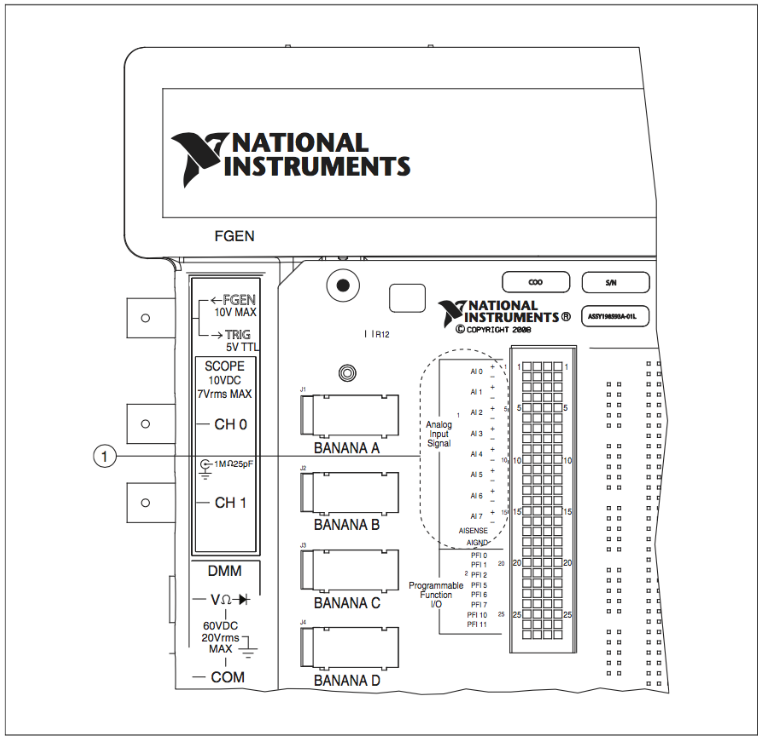


Figure 3.9 Data acquisition system with external signal conditioning.

After the required signal conditioning, which helps to adjust the signal type and range of the output signal to align with the requirements of the data acquisition system, data can be collected. The computer driving the data acquisition system will need to know what signal(s) to measure, how often to take readings and how many readings to collect, or how long to continue reading the signal(s)

The data acquisition process is configured by providing this required information prior to collecting data. The LabVIEW approach is to create a data acquisition *task* that contains this information. The collected data is available to the computer system and can be displayed, modified, analysed, or simply stored.

The heart of most data acquisition systems is an analog-to-digital converter (ADC) that can receive an analog signal and convert it to a digital form that can be used and stored on a computer system. The sensor's analog signals are connected to an analog input (AI) as shown in figure 3.9(b). Many data acquisition systems provide several AIs (called *channels*) that share a single ADC by means of a multiplexer.



1 Analog Input Connections

Figure 3.9(b) Analog Input connections on prototyping board.

The LabVIEW operates the data acquisition system and a request for a data acquisition device to collect one or more data values is called a *task*. Once we define a data acquisition task, the following questions are to be answered. The questions include which data acquisition device will be used, which AI channel(s) will be used, how often will each channel be sampled and how many samples should be collected?

This task can be defined from inside LabVIEW using the DAQ Assistant VI or from outside of LabVIEW using National Instruments Measurement and Automation Explorer.

The task for data acquisition and control of Digital Potentiometer was created in LabVIEW. The Digital outputs D_0, D_1 and D_2 were used to control the Digital Potentiometer (X9C104P) which minimizes the phase difference between v_{02} and $v_{ph1.}$ The block diagram for data acquisition and control of Digital Potentiometer is as shown in figure 3.9(c).

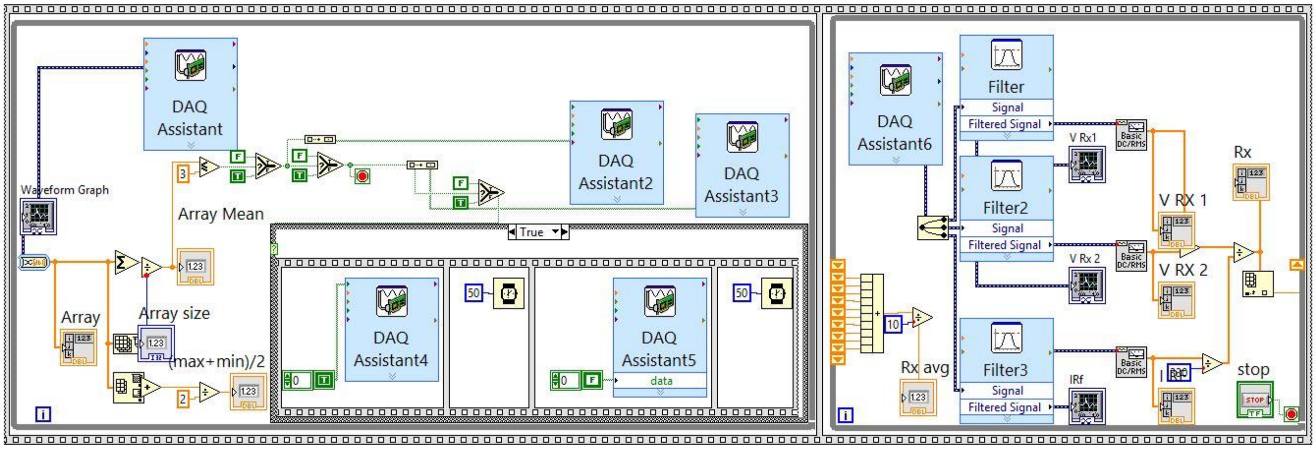
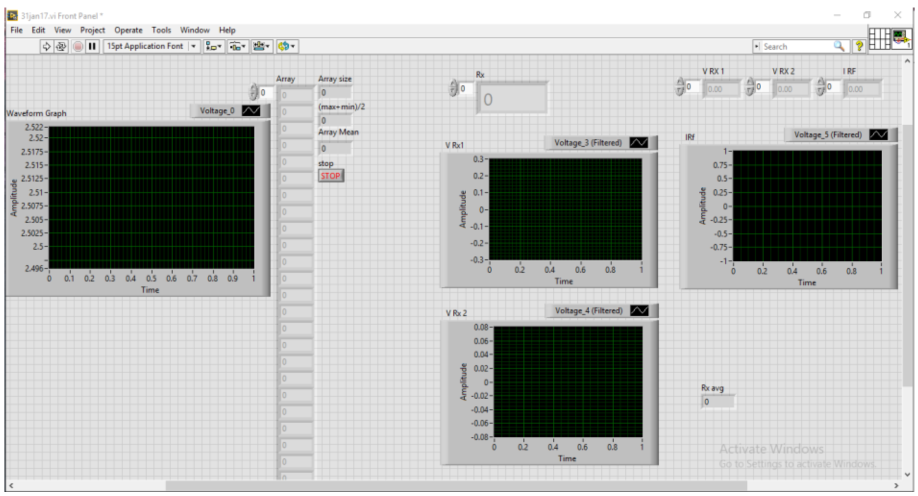


Figure 3.9© LABview code for resistance measurement.



CHAPTER 4

EXPERIMENTAL SETUP AND RESULTS

4.1 INTRODUCTION

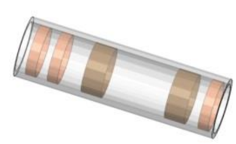


Fig 4.1 Sensing unit

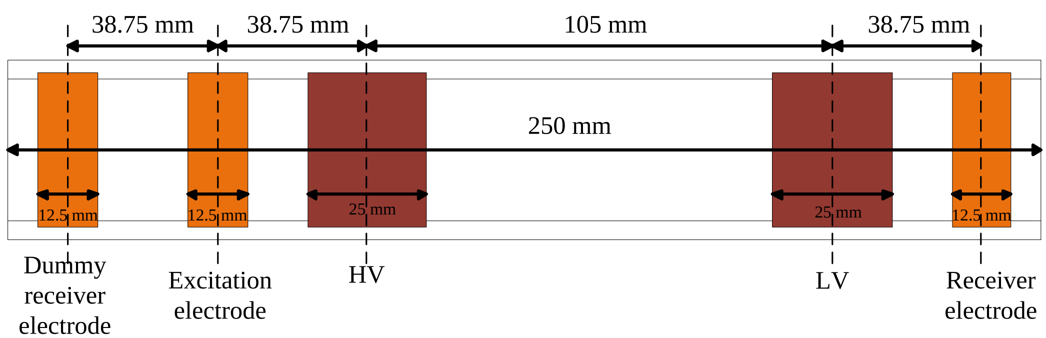


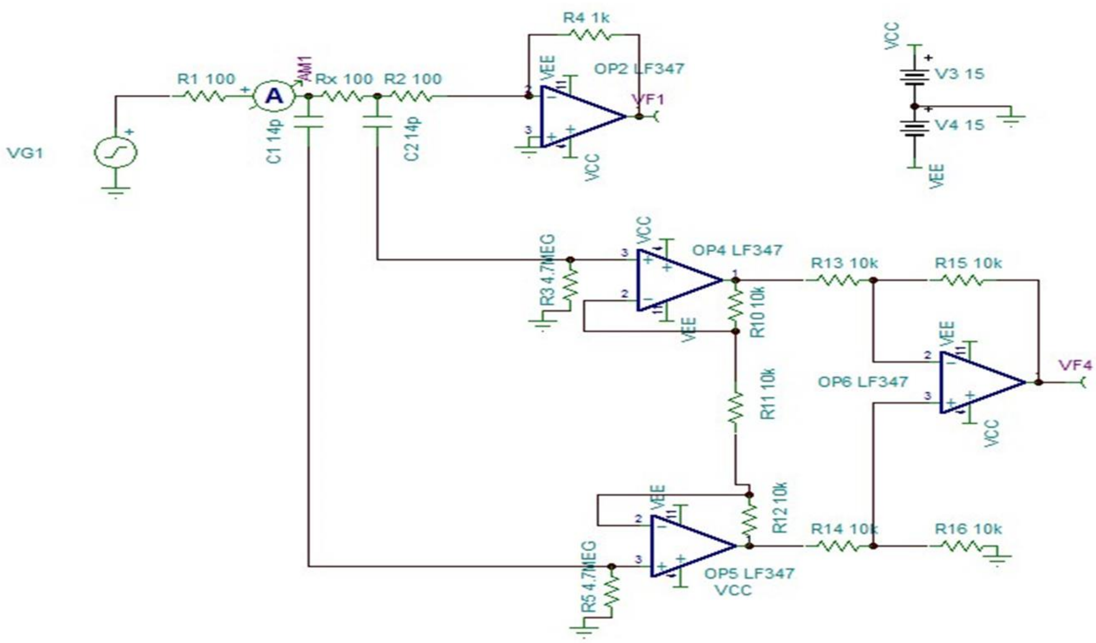
Fig. 4.2 Sensing unit longitudinal sectional-view geometry.

A prototype of the proposed sensor and the signal conditioning circuit is built and tested in the laboratory. The insulating tube has outer diameter of 2.5 cm, inner diameter of 2.1 cm. Fig.4.2 shows the dimensions of the sensor geometry. The contact type electrodes are made of copper and non-contact type coils are made of transformer coil with thin dielectric material. The excitation electrode is given supply from a voltage source v_{in} taken from a function generator available in the National instruments NI ELVIS II data acquisition unit. The frequency of operation f is chosen to be 60 kHz. For op amps OA_1 to OA_6, wide band-width IC LF347 was used. Values of components used were R_1 = R_2=

R_3 = 1 MΩ, R_f = 330 Ω, C_3 = C_4 = 1 nF, R_4 = R_5 = 43 kΩ. R_C is a digital potentiometer implemented using X9C104P. The comparators in phase detection circuit are implemented using high speed comparator IC LM311P, XOR gate together with SPDT switch are implemented using CD4052BE, and second order sallen-key low-pass filter is implemented with lower cut-off frequency of 7 Hz using IC LF 347. The values of v_{X1}, v_{X2}, v_{01}, V_1 are fed to the LabVIEW program and depending on the value of V_1 the digital pot R_C is adjusted to bring down V_1 to zero. When V_1 becomes zero then the value of resistance R_{X2} is calculated using (18). From (18) the conductivity of the water is calculated using (19).

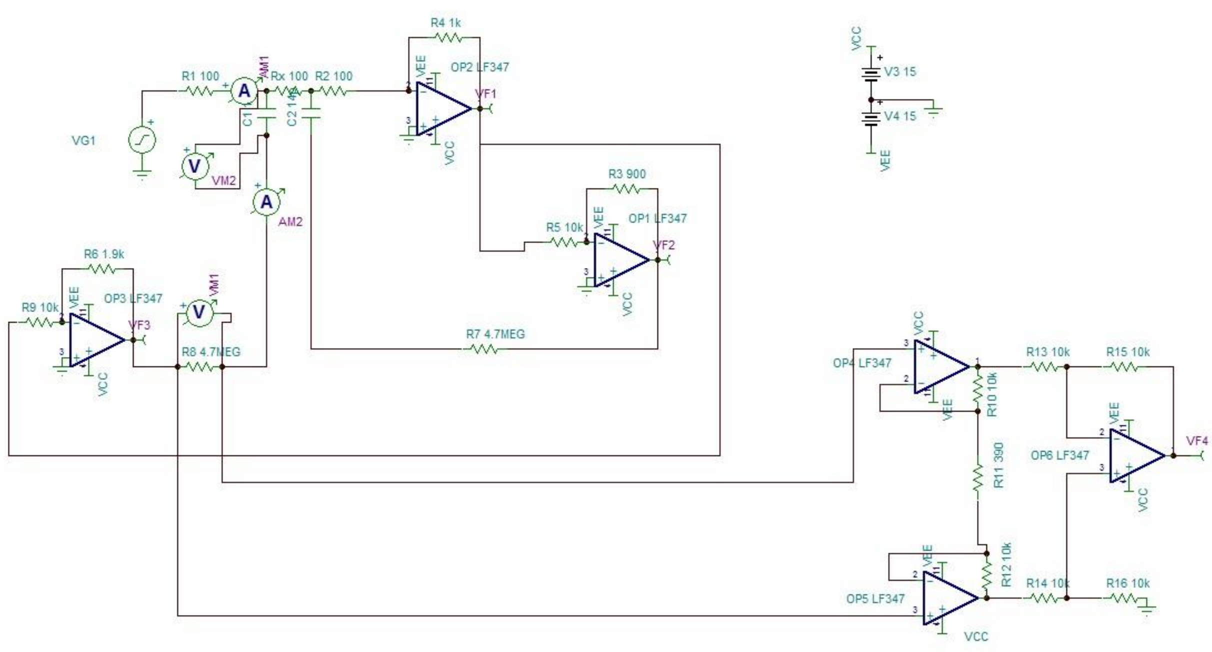
4.2 EXPERIMENT RESULTS

One end of the probe (Receiver Electrode end) was closed, the solution whose conductivity was to be measure was poured into the probe and conductivity measured. The full scale error with linear curve fit is maximum of 1% and with second order polynomial the error is 0.5% maximum. The range of conductivity measured was between 20 mS/cm to 70 mS/cm.



Rx actual	Rx meas	% error

10.4	13.46002741	29.42334048
27.2	34.38136135	26.40206379
39.3	46.88752855	19.30668843
51.2	59.13933303	15.50650982
62	71.26395614	14.94186475
75	82.24394701	9.65859601
82.3	85.63544998	4.052794626
91.5	92.41845592	1.003776957
100	98.98949292	-1.010507081



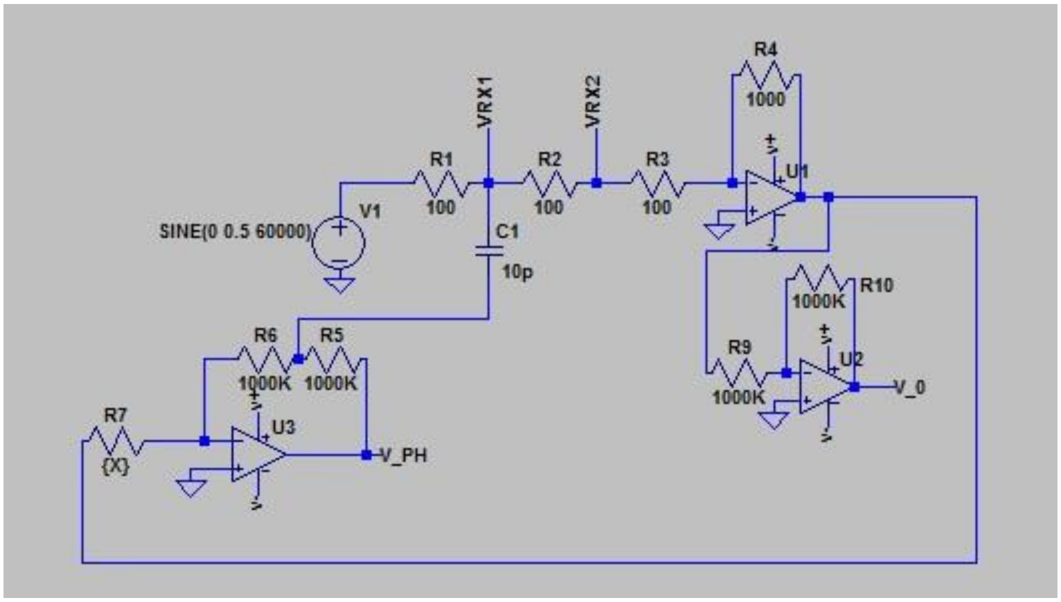
Capacitance	Rx Actual Ohm	Gain of Inv Amp(G1)	Gain of Inv Amp(G2)	Rx Measured
1nf	100	0.1958	0.0985	97.3
681pf	100	0.1885	0.0969	91.6
66pf	100	0.1610	0.0809	80.1
22pf	100	0.1265	0.0614	65.1
14pf	100	0.0900	0.0500	40

At 14pf and below minimum INA o/p doesn't imply min current in path of 4.7 M ohm And capacitor.

No similarity between the simulated and actual results.

Frequency increased from 3 KHz to 60 KHz to reduce reactance of 14 pf capacitor didn't provide desired output.

POSSIBLE DIRECTIONS FOR FUTURE WORK



REFERENCES

[1] Doebelin E.O., *Measurement Systems – Application and Design*, McGraw-Hill Publications, Fifth Edition, 2004.

[2] Neubert, Hermann K.P., *Instrument Transducers: An Introduction to their Performance and Design*, Oxford University Press, Second Edition, 2003.

[3] CD405xB analog multiplexers and demuliplexers are digitally-controlled analog switches http://www.ti.com/lit/ds/symlink/cd4052b.pdf

[4] Dual and Quad 70MHz, 1000V/µs Op Amps http://www.analog.com/en/products/amplifiers/operational-amplifiers/high-speed-op-amps-bandwidth-greaterthanequalto-50mhz/lt1365.html

[3] The LM111, LM211, and LM311devices are single high-speed voltage comparators http://www.ti.com/lit/ds/symlink/lm211.pdf

[4] X9C102, X9C103, X9C104, X9C503 are Intersils' digitally controlled (XDCP) potentiometers https://www.intersil.com/content/dam/intersil/documents/x9c1/x9c102-103-104-503.pdf

[5] LF347 Op Amp IC datasheet http://www.ti.com/lit/ds/symlink/lf347.pdf

[6] MAX4708 8:1 single fault protected Multiplexer IC datasheet https://www.maximintegrated.com/en/products/analog/analog-switches-multiplexers/MAX4708.html/tb_tab0

[7] NI ELVIS II datasheet *www.ni.com/datasheet/pdf/en/ds-394*

[8] NI ELVIS II user manual *www.ni.com/pdf/manuals/374629c.pdf*

[9] Ronald W Larsen – "*LabVIEW for Engineers*"

[10] www.ni.com/ni-elvis

[11] Getting started with TINA TI - http://www.ti.com/tool/tina-ti

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