Improved Methods for measurement of Electrical Conductivity of Liquids

A THESIS

Submitted in partial fulfillment of the requirement of the award of the degree of

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CERTIFICATE

This is to certify that the project titled “**Improved Methods for measurement of Electrical Conductivity of Liquids**” being submitted to the Indian Institute of Technology Madras by **Ginjala Sphoorti Reddy (EE15B089)**, in partial fulfillment of the requirements for the award of the degrees of **Bachelor of Technology in Electrical Engineering and Master of Technology in Electrical Engineering** is a bona fide record of work carried out by her under my supervision. The contents of this project report, 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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Acknowledgement

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Finally, I would like to thank all my friends who made my institute life memorable. Also, words cannot express how grateful I am to my beloved parents for their unconditional support.

- **G. Sphoorti Reddy**

ABSTRACT-

Conductivity is defined as the ability of a substance to conduct electric current. Electrical Conductivity of liquids is an important analytical measurement in many industrial processes. Most industrial interest is in the conductivity measurement of liquids. It offers a fast, reliable, nondestructive, inexpensive and durable means of measuring the ionic content of any solvent sample. This conductivity can be measured quite easily by electronic means, and this offers a simple test which can tell much about the quality of a liquid, or the makeup of the solution. We have a broad line of conductivity equipment to measure liquids ranging from low conductivity to concentrated high conductivity liquids.

In our work, we focus specifically on the conductivity measurement of water which is extremely necessary to estimate its TDS level or obtain salinity. The paper we discuss here talks about the drawbacks in the conventional methods of measuring electrical conductance and come up with an improved method to build conductivity meters immune to contamination, corrosion and polarization. We try to understand this by building a self balancing signal conditioning circuit and doing simulations in LT Spice.

Certain block level changes are contemplated in the circuit for better accuracy in conductivity measurement. A prototype of the design is developed to increase the reliability of the measurement. Simulations are run in LT Spice for a better understanding of the two new prototypes we discuss here. This ensures us to use it effectively in many areas of practical applications in galvanizing plants, beverage bottling plants, pharmaceutical productions, power stations, etc.

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ABBREVIATIONS

FET- *Field effect Transistor*

OA- *Operational Amplifier*

MOSFET- *Metal Oxide Semiconductor Field effect Transistor*

EC- *Electrical Conductivity*

AF- *Area due to Fringe Effect*

INA- *Instrumentation Amplifier*

VCCS- *Voltage Controlled Current Source*

IC- *Integrated Circuit*

VT1- *Voltage at terminal 1 as shown in the fig 7*

VT2- *Voltage at terminal 2 as shown in the fig 7*

Vx1- *Voltage at node 1 connected to capacitor Cx1 as shown in the fig 7*

Vx2- *Voltage at node 2 connected to capacitor Cx2 as shown in the fig 7*

TDS- *Total Dissolved Solids*

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CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Electrical Conductivity of liquids reflects its quality, chemical properties and its effectiveness to be used in any process. We specifically are more inclined to appreciate that of water due to the information it provides and acts as an indicator in various applications. Pure water has very low conductivity while sea water has a much higher conductivity. Different types of water need to be measured for various reasons. For instance, the measurement of the electrical conductivity of water is very important for numerous industrial applications.

Conductivity of water is important as it tells you how much dissolved minerals, concentration of substances and chemicals are present in the water**.** Higher amounts of these impurities will lead to a higher conductivity. A small amount of salts and chemicals dissolved can heighten the conductivity of water. For example, if we are in charge of a waste water treatment facility and if we observe some significant changes in the conductivity of water, it might indicate that a pollutant has entered the water. There is also a possibility of a sewage leak too. Hence, knowing about the electrical conductivity of water helps us understand its scope and extent of application.

The electrical conductivity of water is a term that refers to how well the water is able to conduct electricity. Higher Electric Conductivity of water implies that the electricity is more attracted to water, therefore it is dangerous to use a smart phone while taking a bath or to go swimming during a thunder. Pure water has an extremely low electrical conductivity due to the lack of impurities in it. There must be ions contained in the water to conduct electricity properly.

Chemicals and salts when dissolved in the water, turn into negatively charged and positively charged ions. The positively charged ions that can affect water include potassium, magnesium, and sodium. Whereas, the negatively charged ions include carbonate, chloride, and sulfate. A higher amount of a substance like sulfate can cause damage to the boilers and other pieces of industrial equipment. For environmental and industrial applications, measuring the electrical conductivity of water is an easy and inexpensive method for identifying the number of ions are present in the water. These measurements taken is an indicator for the water to be properly treated ,if necessary.

Its important to understand that the electrical conductivity of water should be measured for a variety of different reasons. The main measurements of electrical conductivity are ***uS/cm and mS/cm.*** In the case of drinking water, the electrical conductivity should be less than 1 mS/cm. Seawater has large amounts of salt and other chemicals which makes its conductivity to be typically in between 45-72 mS/cm. Whereas in the pharmaceutical industry, the Electric Conductivity of water will need to be even less and lower than 1 uS/cm.

Whatever the application we use it for, measuring the electrical conductivity of your water will allow you to identify whether the Electrical Conductivity levels are either too high or too low**.** Appropriate measurements are needed for practical purposes that will address the changes.

Ability to effectively measure the electrical conductivity of water is extremely essential in many industries and for numerous applications. In the case of fish, they can only tolerate a specific electrical conductivity range and hence knowing the conductivity of water is very beneficial for fisheries. Some of the other applications that call for the measurement of the Electrical Conductivity of water include environmental monitoring, the monitoring of chemical concentration, boiler protection, and the monitoring of reverse osmosis**.** In order to create an ideal measurement, you should obtain a conductivity sensor that matches the specific application you need it for. Water can be filtered for a better reading or its temperature can be changed based on the EC readings.

1.2 PROBLEM STATEMENT

Design a prototype that effectively measures the conductivity of liquids. We particularly do it for computing electrical conductivity of water.

1.3 OBJECTIVE

To implement the method as mentioned in the paper "***Conductivity Measurement Using Non-Contact Potential Electrodes and a Guard Ring***", identify the shortcomings and further build a new circuit taking them into consideration.

1.4 CHALLENGES

Measuring conductivity simply detects the presence of ions in solution and is therefore a non-specific measurement. Conductivity applications encompass for instance monitoring of water purity, drinking water and process water quality. It is also a rapid and inexpensive way of determining the ionic strength of a solution. The principle drawback of conductivity is that it is a nonspecific measurement; it cannot distinguish between different types of ions, giving instead a reading proportional to the combined effect of all ions present. Therefore it must be applied with some pre-knowledge of the solution composition or used in relatively pure single solute solutions to be successful.

CHAPTER 2

LITERATURE SURVEY

2.1 BACKGROUND

2.1.1 THEORY OF CONDUCTIVITY -

Conductivity is a measure of water's capability to pass the electrical flow. This is directly related to the concentration of ions in the water . These ions which conduct come from dissolved salts and inorganic materials. Ions are formed when salts, acids, or alkalis dissolve. In metals, the movement of electrons that causes the current flow. In aqueous solutions, ions take over the charge transport.

Compounds that dissolve into ions are also known as electrolytes. The more ions that are present, the higher is the measured conductivity of water. Similarly, fewer ions indicate that the water is less conductive. Distilled water can act as an insulator due to its very low conductivity value while sea water, on the other hand has a very high conductivity.

Ions get the ability to conduct electricity due to their positive and negative charges. When electrolytes dissolve in water, they split into positively charged cations and negatively charged anion particles. As the dissolved substances split in water, the concentrations of each positive and negative charge don't change. Even though the conductivity of water increases with added ions, it remain electrically neutral.

How well an aqueous solution conducts electricity depends on a number of factors:

- **Concentration -**

  Higher the concentration of ions, higher the conductivity will be.

- **Mobility of ions -**

  Mobility is inversely related to its concentration and hence decreases the conductivity as it increases.

- **Valence of ions -**

  Valence electrons per atom present in metals describes the electric conductance of it. Conduction increases with the valence of ions due to more charged particles.

- **Temperature -**

  Conductivity measurements are temperature dependent, if the temperature increases, conductivity increases.

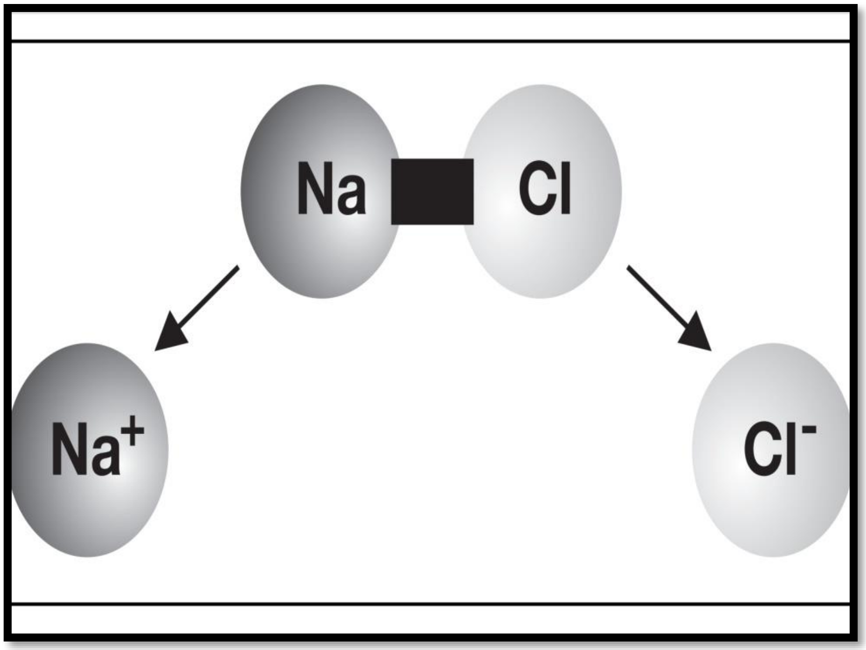


Fig 1: Salts dissociating into positive and negatively charged ions when dissolved [19]

The conductance or conductivity is of paramount importance in quality assessment of liquids such as water which expresses how well a material conducts an electric current. This relationship between the ion concentration and the ability to conduct the electric current makes the conductivity an interesting process variable in water analysis. It is especially suited for determining the concentration of dissolved salts. It is an essential parameter to obtain the salinity or total dissolved solids (TDS) level. The TDS corresponds to the total weight of cations, anions and the undissociated dissolved species in one litre of water. This is the measure of the total concentration of ionic species of a sample. Its magnitude is relative to the standard solution used to calibrate the meter while salinity is a measurement without unit corresponding to the weight of dissolved salts in seawater. Salinity is a measurement without unit corresponding to the weight of dissolved salts in seawater. The salinity is calculated from an empirical relationship between the conductivity and the salinity of a seawater sample.

The result of a conductivity measurement is quoted as a conductivity value in S/m (siemens per meter). In practice, the units µS/cm and mS/cm are used commonly.

2.1.2 CONDUCTIVITY MEASUREMENT OF WATER-

2.1.2.1 Cell Constant-

The cell constant (K) is defined as the ratio of the distance between the electrodes (d) to the active electrode area (A)

$$K = \frac{d}{(A + AF)}$$

Where AF is the fringe-field effect which alters the electrode area.

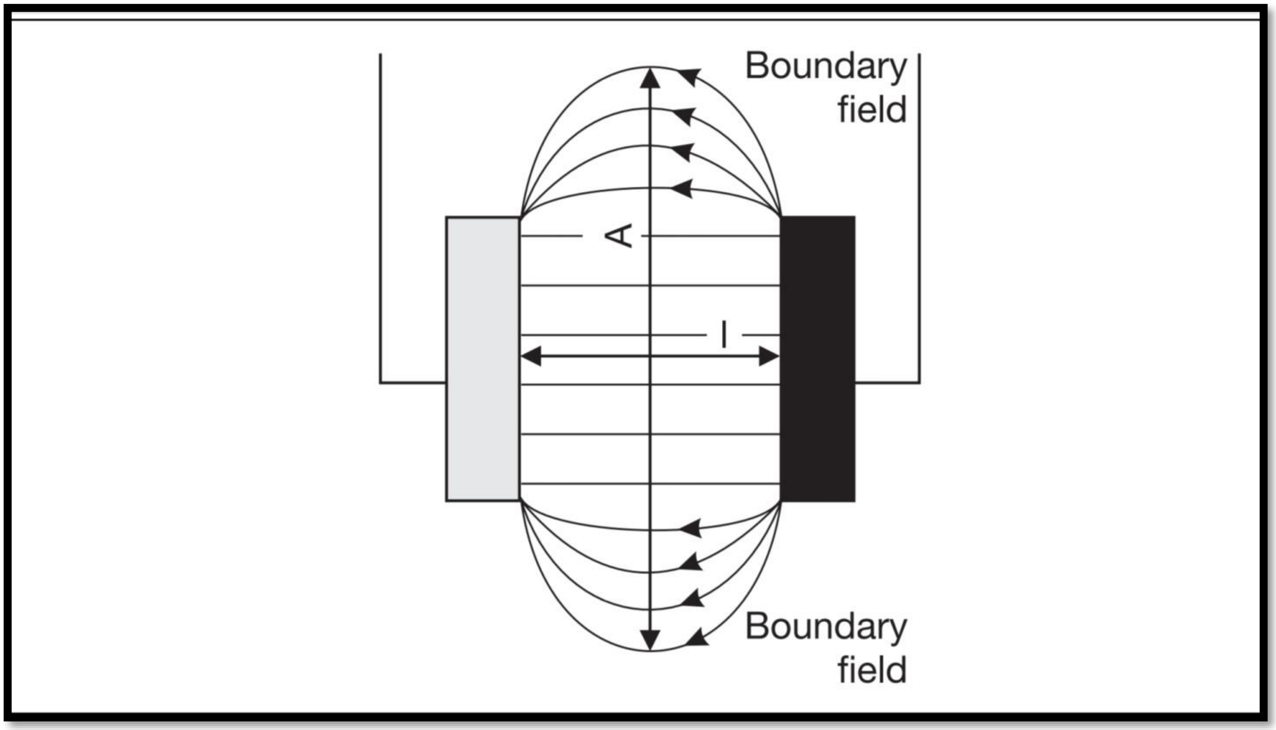


Fig 2 : Schematic Representation of the active electrode area **[19]**

2.1.2.2 Conductance-

Resistance of an object is the measure of its opposition to the electric current flow. The inverse quantity is called Conductance that quantifies the ease with which an electric current passes.

$$R = \frac{V}{I} \qquad G = \frac{1}{R} = \frac{I}{V}$$

Where V=Voltage across the object’s electrodes (in volts), I=Current flowing through the object (in amperes),
R= Resistance of the object (in ohms) and G= Conductance of object (in seimens).

The conductivity of a liquid, σ is given by the product of measured conductance G with the cell constant K.

$$\sigma = G \times K$$

With a short length of conductor the electrodes are close together. The smaller the distance between the electrodes, the lower is the resistance of the measured solution. The influence of the electrodes on the ions increases. A large conductor surface area is synonymous with large electrode surface areas. The bigger the surface area of the electrodes, the smaller is the resistance of the measured solution. As the surface area increases, more and more ions come within the range of influence of the electrodes. The surface area of the electrical conductor is normally larger than the electrode surface area. The electrodes not only affect ions that are directly between the electrode surfaces, but also those in the boundary fields. The influence of the electrode boundary fields on the ions decreases with the distance. The boundary fields can be limited by the construction of the cell or the location, e. g. pipe internal diameters. These influences are taken into account in the cell constant.

The specific electrical conductivity is therefore a substance-specific variable, which does not depend on geometric factors, as opposed to the conductance G,. The precise value of the cell constant is obtained from a calibration with a reference solution that has a known temperature-dependent conductivity.

Units of conductivity-

The main measurements of electrical conductivity are uS/cm and mS/cm, the former of which is considered to be less than the latter. The uS/cm unit stands for micro-Siemens, 100,000 of which make a standard SI unit of S/cm.

2.2 EXISTING METHODS OF CONDUCTIVITY MEASUREMENT–

2.2.1 CONTACT TYPE CONDUCTIVITY METER –

Contact type conductivity meters use a four electrode conductivity probe in which the two outer electrodes serve as current electrodes and the inner electrodes pick up the potential drop across a fixed liquid column.

The contamination or corrosion of the current terminals of the four terminal conductivity probe do not affect the conductivity measurement as long as the excitation source is able to drive the required current through the liquid column to be measured. However, any corrosion or contamination of the potential electrodes affect the measurement of conductivity severely. If the probe is to be immersed in the liquid, additional error will be introduced in the measurement due to current flow outside of the probe, and coupled to the potential electrodes.

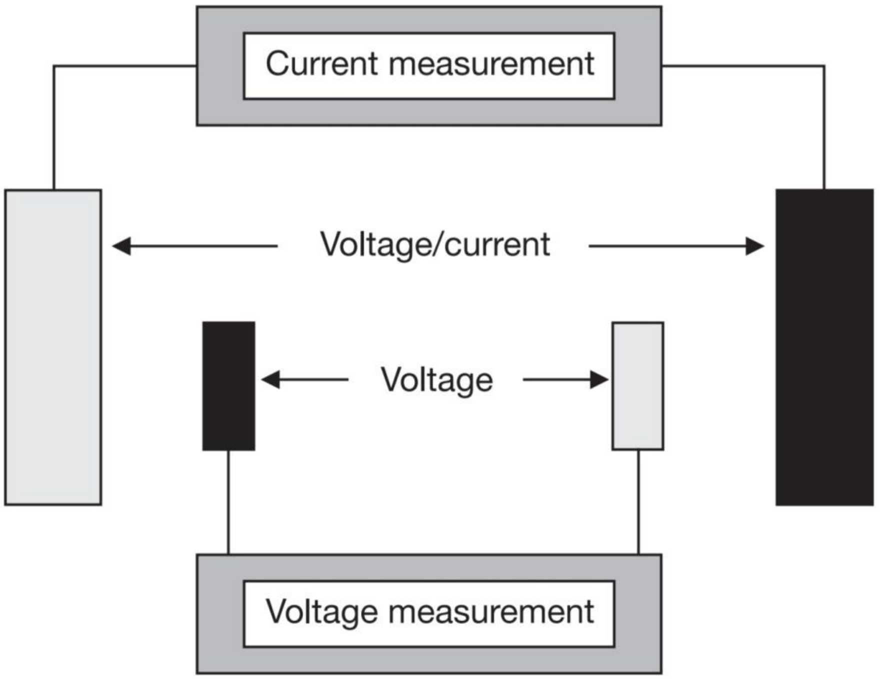


***Fig 3: 4-electrode Contact type Conductivity Cell* [19]**

2.2.2 INDUCTIVE TYPE CONDUCTIVITY METER-

In this cell, the electrodes are replaced by two coils. One of the coils is the exciter coil. An AC current flows in this coil, producing a magnetic field in the vicinity of the coil. The measured solution is in the core of the coil. The current flow which is required for the measurement is induced in the measured solution by the magnetic field of the coil. The current flowing in the measured solution generates its own magnetic field. This magnetic field induces an AC current in the receiver coil with the appropriate voltage. The voltage in the receiver coil is dependent on the current flowing in the medium directly, i.e; on the conductivity. As the magnetic field can act through a plastic pipe, there is no requirement of direct contact between the coils and the measured medium. There are advantages of this non-contact measurement technique. Measurement of aggressive media such as acids or alkalis can be made without any problems. High conductivities cannot cause polarization effects and consequent low readings. Hence, they are immune to contamination/corrosion/polarization.

But Inductive type conductivity meters due to un-confined current path gets induced with errors. Current spreads out in all directions to an extent dictated by the electrical properties of the liquid.

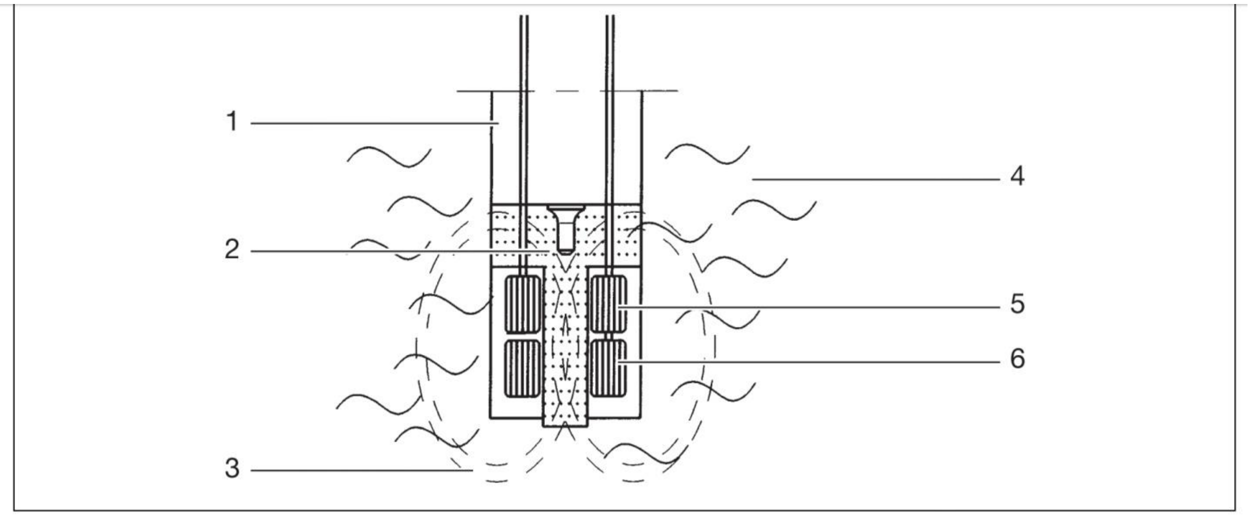


Fig. 6: **Diagram of an inductive measuring cell**

1 PVDF or PEEK body
2 T-shaped flow-through channel
3 Liquid loop subjected to measuring current
4 Measured solution
5 Receiver coil
6 Exciter coil

Fig 4: Inductive type Conductivity Cell **[19]**

2.2.3 RING TYPE ELECTRODES-

The ring type electrodes make the current path confined but suffer from error due to the assumption that half of the current flows between the transmitter and receiver electrodes along the specified liquid column and other half flow through the external path. This assumption will also lead to additional errors when liquid has suspended particles or contamination of electrodes occurs.

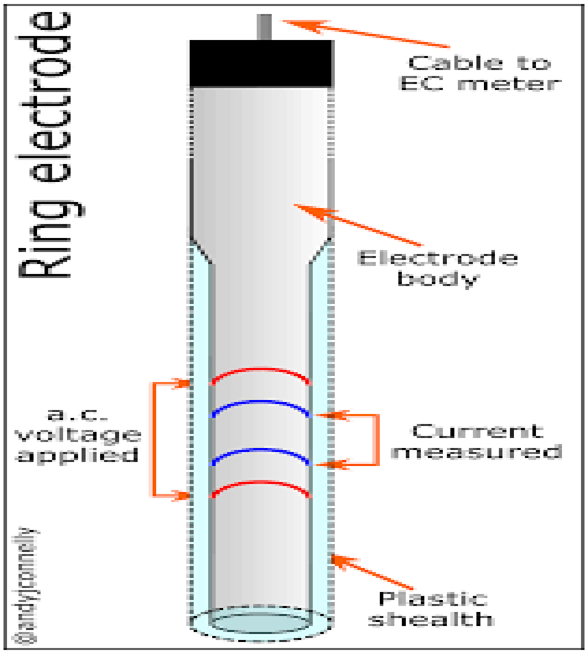


Fig 5: Ring Type Electrode **[4]**

The problem of electrode contamination and polarization can be handled by using capacitive coupled electrodes that avoid the electrodes coming in direct contact with the liquid. Such a system will not suffer from polarization and electrode contamination, possess all the advantages of the inductive type meter and will have the added advantage that the current path is confined similar to ring type four-electrode conductivity meters.

However conductivity measurement probe with capacitive coupled electrodes operated by an auto-balancing signal conditioning circuit suffers from errors introduced by current flow external to the probe.

2.3 PROTOTYPE OF THE MEASUREMENT PROBE MENTIONED IN THE REFERENCE PAPER *"Conductivity Measurement Using Non-Contact Potential Electrodes and a Guard Ring"*

2.3.1 NECESSITY FOR AN IMPROVED METHOD FOR CONDUCTIVITY MEASUREMENT

The paper presents us a new conductivity measurement probe that uses contact type current terminals as well as insulated, ring type potential terminals. Use of insulated potential electrodes eliminates the problems of contamination and corrosion while the use of ring type electrodes make sure that the measurement is made on a pre-fixed column of the liquid. So, the probe has the advantages of both contact type and non-contact type conductivity measurement. Apart from the current and potential electrodes, we also have a fifth electrode, in the probe functions as a guard ring which eliminates the current flow external to the probe. This ensures that conductivity can be measured either by the flow-through or immersion type methodologies.

2.3.2 DESIGN OF THE CONDUCTIVITY PROBE AS IN THE REFERENCE PAPER

The conductivity measurement probe here is made of an insulating cylindrical tube with five circular electrodes embedded in it. Three of these electrodes, that is, the excitation electrode TE, the Return electrode TR and the Guard ring TG are into the inner surface of insulating tube and so are in contact with the liquid. The potential electrodes T1 and T2 are laid within the walls of the insulating tube and hence do not come into contact with the liquid, even if the probe is immersed in the liquid. If the probe is to be immersed in the liquid, then the probe arrangement as shown above is inserted into a second insulating cylindrical tube of higher diameter so as to ensure the liquid outside of the probe does not get coupled either to the liquid inside the probe nor to the electrodes.

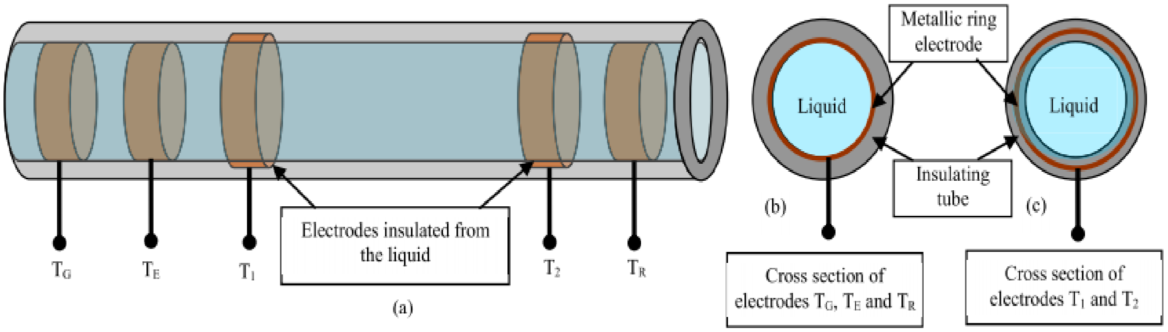


Fig. 1. (a) Proposed conductivity measurement probe with five electrodes. (b) Cross section of electrodes T_G, T_E and T_R. (c) Cross section of electrodes T_1 and T_2.

Fig 6A: Five electrode conductivity measurement probe [1]
Fig 6B: Cross section of electrodes Tg, Te, Tr [1]
Fig 6C: Cross section of electrodes T1, T2 [1]

The equivalent circuit of the above probe as in Fig. 6 is shown in Fig. 7. The insulation between the liquid and electrode T1 acts like a capacitance Cx1 and capacitance Cx2 between the liquid and electrode terminal T2. The resistance of water column between exciting electrode and insulated voltage electrode TE as in the figure 7 is taken as Rx1. The resistance between insulated voltage electrode T1 and T2 is named as Rx, as in the Fig.7. Whereas the resistance between insulated voltage electrode T2 and return electrode TR is Rx2 and the resistance between excitation electrode and guard electrode is RGE. The external resistance between the guard ring and return electrodes is Rex. The voltage at terminal TG is assumed to be at ground potential and the voltage of terminal T1 is taken as vT1 while that of T2 is taken as vT2.

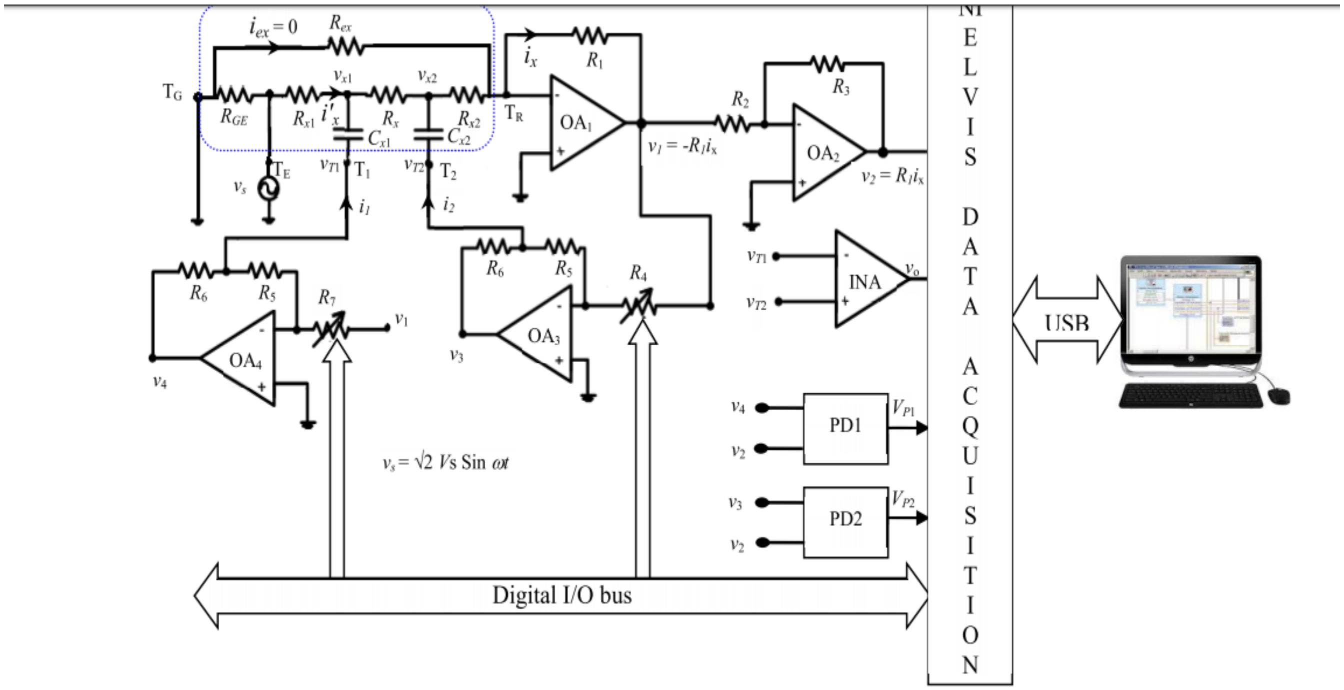
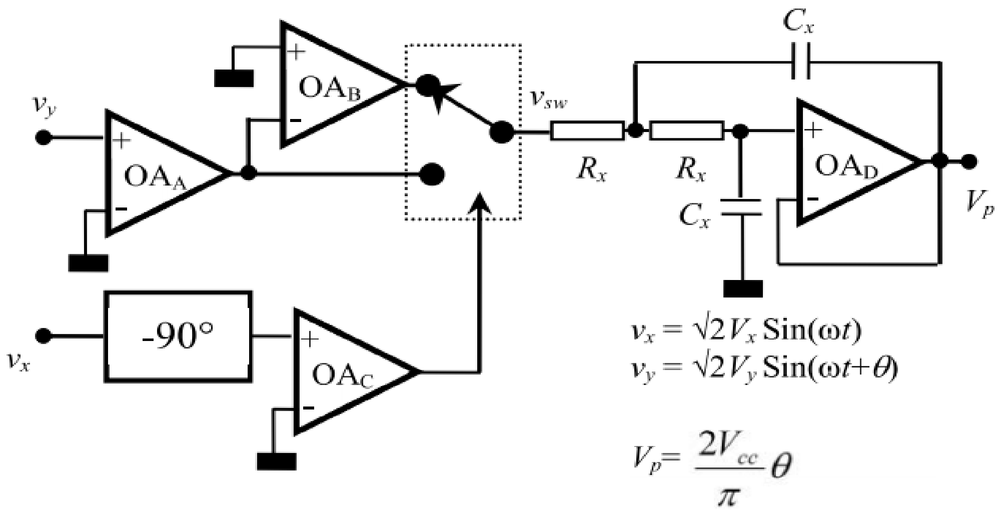


Fig. 4. Signal conditioning circuit for capacitive coupled conductivity measurement probe.

Fig 7: Signal Conditioning Circuit for Capacitive coupled Measurement probe **[1]**



$$v_x = \sqrt{2}V_x\,\mathrm{Sin}(\omega t)$$
$$v_y = \sqrt{2}V_y\,\mathrm{Sin}(\omega t+\theta)$$
$$V_p = \frac{2V_{cc}}{\pi}\theta$$

Fig. 5. Block diagram of the phase detector.

Fig 8: Phase detector Circuit **[1]**

2.3.3 SIGNAL CONDITIONING CIRCUIT OF NON-CONTACT CONDUCTIVITY MEASUREMENT

Rx can be easily determined by measuring the voltages vx1, vx2 and the current ix through Rx . As the voltages vx1 and vx2 are accessible only through capacitances Cx1 and Cx2, a dedicated signal conditioning circuit is designed to measure vx1, vx2 and the current ix and we get to calculate Rx from there .

To get this, the probe is excited using a sinusoidal voltage source Vs connected between terminals TE and ground. Terminal TR is connected to an I-to-V converter realized using opamp OA1 with its feedback resistor R1 as shown in the signal conditioning circuit above. The i-to-v converter ensures that terminal TR is at virtual ground. As one end i.e; terminal TG of Rex is at ground(zero) potential and the other end i.e; terminal TR is at virtual ground, no current can flow through Rex . This makes Rex not to have any effect on the operation of the probe.

The output voltage of the current to voltage converter is v1 = ix R1. It is given to an inverting amplifier with gain K1 , where K1 = −R3/R2 is realized using opamp OA2 to obtain the voltage v2. The output v1 of the current to voltage converter is given as input to a couple of variable inverting amplifiers which are realized using opamps OA3 and OA4 to obtain voltages v3 and v4 respectively. The gain of OA3 is varied by changing the input resistances R4 and the gain of OA4 is varied with the help of variable resistance by the opamp OA7. The variable resistors R4 and R7 are digitally controlled resistors.

The terminal voltage vT1, of T1 is set as K2v4, where K2 = R5/ (R5 + R6) . Similarly, terminal voltage vT2, of T2 is set as K2v4. The voltages vT1 and vT2 are fed as input to the instrumentation amplifier (INA) with a gain of 5 , and output being

$$v_{INA} = 5(v_{t2} - v_{t1})$$

Phase detector PD1 detects the phase angle θ1 between the output v2 of OA2 and v4 of OA4 and the phase detector PD2 detects the phase angle θ2 between the output v2 of OA2 and v3 of OA3, where θ1 and θ2 varies from −90◦ to +90◦.

Inputs of the PDs are taken as- $v_x = \sqrt{2}\, V_x\ Sin(\omega t)$ and $v_y = \sqrt{2} V_y\ Sin(\omega t + \theta)$.

The output of opamp OAA will be:

$$V_{CC}\ Sgn\,(\sqrt{2}\ Vy\ Sin(\omega t + \theta\,))$$

The output of OAC will be:

$$V_{CC}\ Sgn\,(\sqrt{2}\ Vx\ Sin(\omega t + 90^{\circ}))\ ,$$

where Vcc is the magnitude of the positive and negative supply voltages of the opamps and Sgn is the signum function defined by Sgn (x) is −1 for x < 0 and +1 for x > 0.

The output vsw of the single pole double throw switch is:

$$v_{sw} = V_{CC} Sgn \sqrt{2Vy} Sin (\omega t + \theta)$$

The output VP of the phase detector is:

$$v_{ph} = \frac{2V_{CC}}{\pi} \theta$$

Thus the output VP1 of phase detector PD1 will be 2Vccθ1/π and the output of phase detector PD2 will be 2Vccθ2/π. The digital control unit made of a data acquisition system plugged into a PC the heart of the conductivity measurement technique. This acquires the voltages VP1, VP2, v2 and vo and computes the conductivity from these .

Firstly, the data on VP1 is obtained. If vT 1 > vx1 then the current i1 will be leading and hence VP1 > 0. In this case the digitally controlled resistor R7 needs to be incremented till VP1 = 0. If vT 1 < vx1 then i1 will be lagging and hence VP1 < 0 and the digitally controlled resistor R7 needs to be decremented till VP1 = 0. Once VP1 = 0, then VP2 is acquired and we do as the above. Here ,digitally controlled resistor R4 is appropriately varied till VP2 = 0. These both loops are repeated till both VP1 and VP2 are zero. If both the voltages VP1 and VP2 are zero, then angles θ1 and θ2 are zero and hence the sinusoidal voltages v3 and v4 are in phase with the current ix . Only if currents i1 and i2 are zero are the voltages v3 and v4 being in phase with the current ix. If currents i1 and i2 are zero, then drop of voltage across Cx1 and Cx2 are zero implying that vT1 = vx1 and vT2 = vx2.

Once i1 and i2 are zero, then ix’ = ix and hence-

$$i_x = \frac{v_s}{R_{x1} + R_x + R_{x2}} = \frac{R_2}{R_1 R_3 v_2}$$

$$v_1 = -i_x R_1$$

$$v_2 = \frac{R_1 R_3}{i_x R_2}$$

$$v_3 = v_1 \frac{R_5 + R_6}{R_4}$$

$$v_4 = v_1 \frac{R_5 + R_6}{R_7}$$

$$v_0 = v_{t2} - v_{t1} = v_{x2} - v_{x1}$$

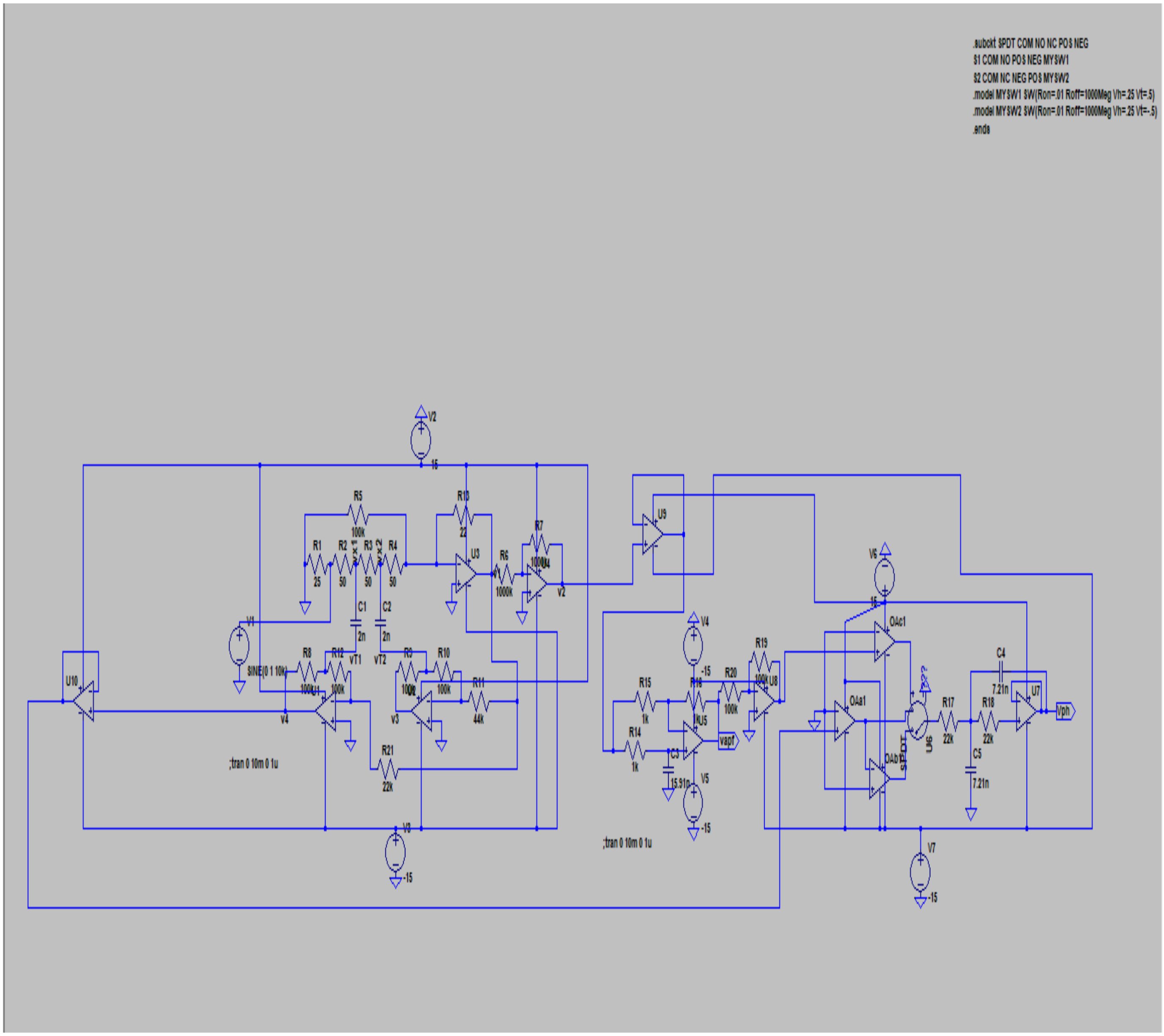
With these conditions, the conductance of the liquid column is:

$$G_x = \frac{1}{R_x} = \frac{I_x}{v_{x2} - v_{x1}} = \frac{K_1 R_2 v_2}{R_1 R_3 v_0}$$

Vo and V2 are the rms values of sinusoidal voltages vo and v2 respectively. After the conductance is determined, the conductivity σ (S/m) of the liquid is calculated as:

$$\sigma = K G_x = K \frac{K_1 R_2 v_2}{R_1 R_3 v_0}$$

where K is the cell constant determined from the dimensions of the probe derived from calibration.



```
.subckt SPDT COM NO NC POS NEG
S1 COM NO POS NEG MYSW1
S2 COM NC NEG POS MYSW2
.model MYSW1 SW(Ron=.01 Roff=1000Meg Vh=.25 Vt=.5)
.model MYSW2 SW(Ron=.01 Roff=1000Meg Vh=.25 Vt=-.5)
.ends
```

Fig 9: Partial Schematic Representation of the of the Signal Conditioning Circuit with one Phase Detector Circuit in LT Spice

2.3.4 CALCULATION OF UNKNOWN RESISTOR VALUES FOR A GIVEN Rx.

In the balanced condition for the circuit above, the voltages on either side of the capacitances Cx1 and Cx2 are equal . Vx1 and Vt1 are equal as well as the pair of voltages Vx2 and Vt2. Here, we consider the values of Rx ,Rx1, Rx2 to be **50 Ω**.
We consider Vs to be 1V.

$$v_{x1} = v_{t1},\ \ v_{x2} = v_{t2} \quad \text{--------------------} \quad Eq\ 3.1\&3.2$$

But in balanced condition,

$$v_{x1} = v_s \frac{R_x + R_{x2}}{R_x + R_{x1} + R_{x2}}$$

$$v_{x2} = v_s \frac{R_{x2}}{R_x + R_{x1} + R_{x2}}$$

But as we have already deduced in the previous section,

$$v_{t1} = -v_1 \frac{R_5}{R_7}$$

$$v_{t2} = -v_1 \frac{R_5}{R_4}$$

and $v_1 = -R_1 \times i_x$

Where $i_x = \dfrac{v_s}{R_x + R_{x1} + R_{x2}}$

Therefore, v_{t1} **= 670 mV** and v_{t2} **= 335 mV**

From equations 3.1 and 3.2, we get
R_7 **= 22k Ω ,** R_4 **= 44k Ω**

2.3.5 SPECIFICATIONS OF THE PROTOTYPE

2.3.5.1 DETERMINING CIRCUIT COMPONENTS AND THEIR VALUES-

According to the reference paper, below are the components and their specified values.

Given : Cx1, Cx2 = 2nF

Frequency of operation, f = 10kHz

R1 = 22 Ω, R2 = R3 = R4 = R5 = R6 = 1MΩ

The second order sallen-key low-pass filter in the Phase Detector circuit is implemented with low cut off frequency of 7Hz using IC LF347.

This implies that - $\boldsymbol{tan^{-1}\, 2\pi f C R = \frac{\pi}{4}}$

The set of values fitting the above equation are **22 kΩ** and **7.21nF** respectively, which are the resistor and capacitors values in the Phase Detector Circuit. *(as in fig 9)*

Based on the available lab sensors, we consider the resistance of water Rx, Rx1, Rx2 to be 50Ω.

For opamps OA1 to OA6, we use the IC LF347. The comparators used in PD circuit are also IC LF347.

Digitally controlled resistors R4 and R7 are implemented using AD5241.

The instrumentation amplifier, which quantifies the difference between terminal voltages of the electrode, is realized using INA2126 to measure Vo.

TABLE 1 :SPECIFICATIONS OF THE CONDUCTIVITY MEASUREMENT PROTOTYPE

S.no	PARAMETER	DIMENSION
1	Inner diameter of insulating tube	2.5 cm
2	Thickness of the tube	0.3 cm
3	Insulation thickness of terminal T1 and T2	10 um
4	Length of insulating tube	17 cm
5	Width of electrodes	1.5 cm
6	Distance between insulated voltage electrodes	3.5 cm
7	Distance between Te and Tr electrodes	11 cm
8	Distance between Tg and Te electrodes	1.5 cm

2.3.5.2 CONDUCTIVITY DEDUCTION *(FOR THE ABOVE PARAMETERS)*

$$\sigma = \frac{l}{Rx*A} \quad ,$$

Where l= length between the insulated voltage electrodes = 3.5 cm,

A= area of the tube containing the liquid = $\pi * 0.5d * 0.5$d (d = inner diameter of insulating tube = 2.5 cm)

The resistivity of water considering Rx to be 50 ohms = 70 ohm_m.

The conductivity of water = **1.426S/m**.

In order to get accurate values, we need to be able to dynamically change the resistances wrt the output voltages of the phase detectors so that it finally boils down to zero. The determining resistance corresponding to these variable resistances is more accurate.

2.4 RESOLUTION OF Rx WRT VARIABLE RESISTORS R4 & R7

Consider the opamps OA4 and OA3. As the positive terminals of both the opamps are grounded, the negative terminals should also be so. Therefore, current through opamp OA4 = v1/R7 which makes

$$v_{t1} = -v_1 \frac{R_5}{R_7}$$

Similarly, current through opamp OA3 = $\frac{v_1}{R_4}$ & $v_{t2} = -v_1 \frac{R_5}{R_4}$

$Vx1 - Vx2 = Vt1 - Vt2 = R5[(\frac{1}{R7}) + (\frac{1}{R4})]$

Resistors R4, R7 are varied digitally in steps of $\partial R4, \partial R7$ respectively which makes below the immediate potential value

$$v_{t2} - v_{t1} = v_{x2} - v_{x1} = R_5 \left[\frac{1}{R_7 \pm \Delta R_7} + \frac{1}{R_4 \pm \Delta R_4} \right]$$

$ix = \frac{v1}{R1}$ and $ix = \frac{Vx1 - Vx2}{Rx}$

So, $R_x = R_1 R_5 \left[\frac{1}{R_7} - \frac{1}{R_4} \right]$ & $R_x \pm \Delta R_x = R_1 R_5 \left[\frac{1}{R_7 \pm \Delta R_7} - \frac{1}{R_4 \pm \Delta R_4} \right]$

$$\Rightarrow \Delta R_x = R_1 R_5 \left[\frac{\Delta R_7}{R_7 \pm \Delta R_7} - \frac{\Delta R_4}{R_4 \pm \Delta R_4} \right]$$

The immediate next value what Rx can take while calculating is-

$$R_x^{'} = R_1 R_5 \left[\frac{1}{R_7 \pm \Delta R_7} - \frac{1}{R_4 \pm \Delta R_4} \right]$$

Therefore, the calculated value of Rx increases in the steps of $Rx' - Rx$.
Hence, the resolution in the calculation of Rx approximately is

$$\Delta R_x = R_1 R_5 \left[\frac{\Delta R_7}{R_7} - \frac{\Delta R_4}{R_4} \right]$$

Hence, we can't obtain the exact value of Rx as R4 and R7 can't change the values continuously.

CHAPTER 3

DEVELOPMENT OF EFFICIENT CIRCUIT DESIGNS FOR CONDUCTIVITY MEASUREMENT

3.1 CIRCUIT DESIGN IMPLEMENTATION OF METHOD "A"

As we have seen in the previous section, values of resistors are being increased in quantized steps. Inorder to get accurate values, we need to be able to dynamically change the resistances wrt the output voltages of the phase detectors so that it finally boils down to zero. The determining resistance corresponding to these variable resistances is more accurate. To do so, we come up with the usage of Voltage Controlled Resistors using n-fets.

3.1.1 NFET -

The field-effect transistor is a type of transistor which uses an electric field to control the flow of current. FETs are devices having three terminals namely source, gate, and drain. FETs control the flow of current by the applying some voltage to the gate, which regulates the conductivity between the drain and source.

***Fig 10: Field-effect Transistors* [20]**

The FET controls the flow of electrons from the source to drain by affecting the size and shape of a conductive channel created and influenced by voltage applied across the gate and source terminals. The above conductive channel generated is the stream where electrons flow from source to drain. NFET or an n-channel FET is a field-effect transistor whose source and drain terminals are negative i.e, doped with donor impurities.

3.1.2 NFET CHARACTERISTICS-

The Field Effect Transistor or FET uses the voltage that is applied to their input terminal, called the Gate to control the current flowing through them resulting in the output current being proportional to the input voltage whereas the Gates to source junction of the FET is always reversed biased. Their operation relies on an electric field which is due to field effect generated by the input Gate voltage. This makes the Field Effect Transistor a "VOLTAGE" operated device.

We understand the characteristics by simply getting to know the variations in the drain-source current with the gate-source voltage.

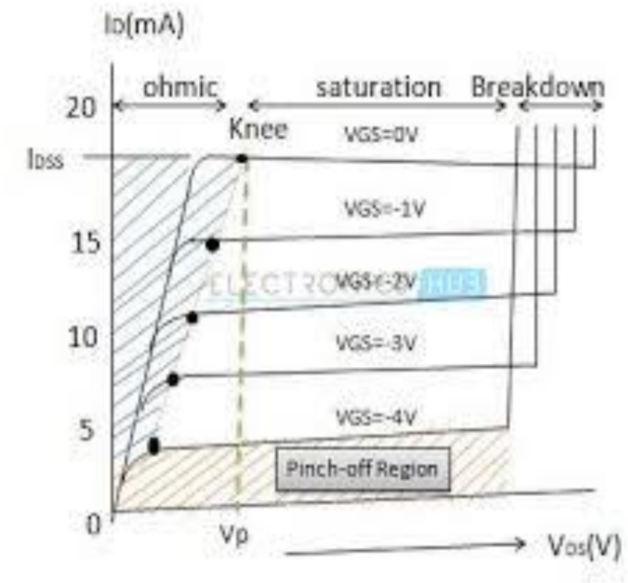


Fig 11: Characteristics of Field Effect Transistors and Regions of Operation **[10]**

3.1.3 REGIONS OF OPERATION:

The characteristics curves example shown above, shows the four different regions of operation and these are given as:

Ohmic Region-When VGS is beyond a threshold, the depletion layer of the channel is very small and the FET acts like a voltage controlled resistor till a particular drain-source voltage.

Cut-off region- This is also known as the pinch-off region were the Gate Voltage, Vgs is sufficient to cause the FET to act as an open circuit as the channel resistance is at maximum.

Saturation or Active Region – The FET becomes a good conductor and is controlled by the Gate-Source voltage, (Vgs) while the Drain-Source voltage, (Vds) has little or no effect.

Breakdown Region-The voltage between the Drain and the Source, (VDS) is high enough to causes the FET’s resistive channel to break down and pass uncontrolled maximum current.

In response to small applied voltage from drain to source, then n-type bar acts as simple resistor, and the drain current increases linearly with Vds. As there is an increase in Id, the ohmic voltage drop between the source and the channel region reverse biases the junction. This makes the conducting position of the channel begins to remain constant. The Vds now is called “pinch of voltage”. If the gate to source voltage (Vgs) is applied so as to provide additional reverse bias, the pinch off voltage is decreased.

In the circuit we build below, we utilize the ohmic region properties where the drain current, Id, has a linear response to changes in the drain-source voltage, Vds, which mimics the linear response obtained from Ohm's Law.
The drain current Id depends on the drain-source voltage Vds. In the beginning of the curve, when Vds is small, the drain current Id varies nearly linearly with Vds. This the region where the FET is beginning to resist. It acts like a variable resistor.

The Ohmic Region is the only region on a FET Characteristics curve where there is a linear behaviour in current from changes in the voltage. In this region, it behaves like a voltage-controlled resistor. It mimics ohm's law, where current is seen to have a linear response to changes in voltage (I=V/R).

3.1.4 VOLTAGE CONTROLLED RESISTORS -

VCR is a three-terminal active device with one input port and two output ports with the input-port voltage controlling the value of the resistor between the output ports most often built with FETs. The input-port voltage controls the value of the resistor between the output ports. VCRs are most often built with field-effect transistors .

Two types of FETs are often used: the JFET and the MOSFET. There are two types of VCRs i.e; floating-voltage controlled resistors and grounded floating resistors. Floating VCRs are to be placed between two passive or active components whereas the Grounded VCRs which is the more common and less complicated design, requires one port of the voltage controlled resistor to be grounded. Linearity of resistance developed across the FET with respect to its voltage driven in the Ohmic region is the principle behind the VCR design block. It dynamically changes the resistor values wrt to the output voltages of Phase detectors so that it approaches 0.

In our circuit, we build voltage controlled resistors using nfets.

3.1.5 CIRCUIT MODELLING FOR METHOD “A”

In the paper mentioned in the literature survey, the output of the phase detectors PD1 & PD2, i.e, Vp1 and Vp2 respectively are made zero by comparing their absolute value with 0 and making corresponding changes in the variable resistor values. Instead of this, here we build voltage controlled resistors where the controlling voltage is the output of the phase detectors PD1 & PD2 (Vph) by making use of the ‘nfet’ properties in the ohmic region.

$$V_{ph} = \frac{2V_{CC}}{\pi}\,\theta\ ,$$

where θ is the phase angle between v2 and v3/v4 for PD2 and PD1 respectively and the range of Vph is between –Vcc to +Vcc where Vcc is the supply voltage.

To be able to dynamically alter the values of resistors, we need to design the feedback circuit in such a way that the resistive values sensitively change wrt their corresponding outputs of Phase detectors . For the resistances to obtain a larger value, the magnitude of the gate voltage should be sufficiently small.

So, we place a voltage divider from Vph in order to reduce its range for it to directly influence the resistance of the nfet J2 *as in figure 19*. This voltage is acted as a source for VCCS such that when Vph is +ve, node (drain of nfet J1) voltage increases which ultimately increases the gate voltage of J2 and hence the resistance it brings. This resistance increase decreases the value of Vph and this further progresses to make its value to be 0 as discussed previously. Same thing happens in the opposite way if Vph is –ve. When Vph attains the value 0, there is no change in the nodal voltage which fix the gate voltage of J2 and therefore it’s corresponding resistance.

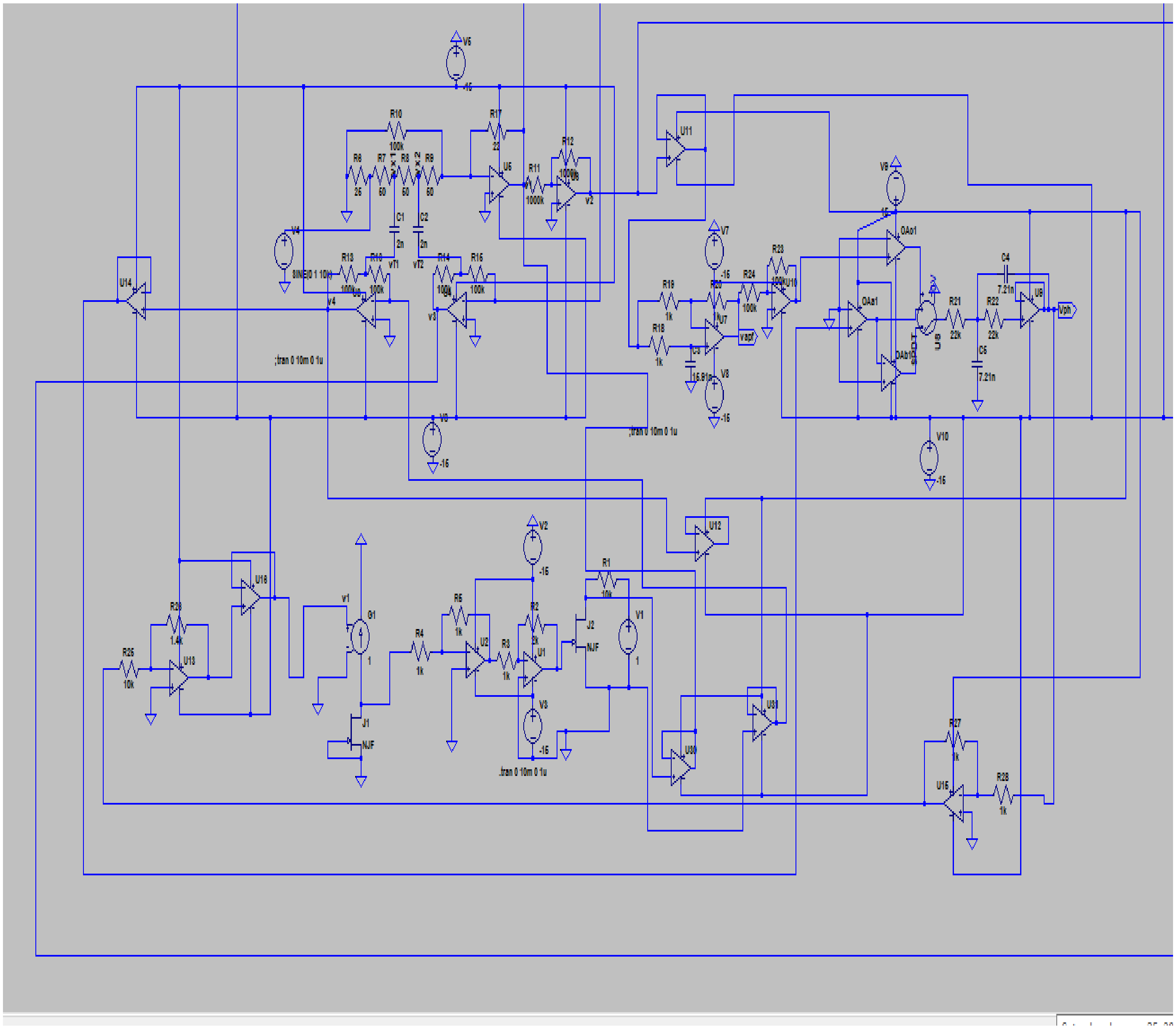


Fig 12: Schematic Representation of the modified Signal Conditioning Circuit in Method "A"

But the problem with the above circuit is that the node measuring v1 drives both the voltage controlled resistors. Due to the heavy load, the voltage at v1 drastically reduces with its phase intact. Though it doesn't affect the final output we require, it does alter voltages at some nodes.

3.2 CIRCUIT DESIGN IMPLEMENTATION OF METHOD “B”

In the previous **method “A**”, we came up directly utilizing the variations in the gate-source voltage of nfet due to the phase detector circuit output and connecting it between the output of OA1 and OA3/OA4 inplace of variable resistors R4 and R7 respectively. Due to this, the output node of OA1 gets driven by heavy load. Though this might not have any impact on the final output of the whole circuit as the phase of v1 doesn’t change, the magnitude of v1 reduces drastically.

To avoid this, we come up with an Electronic Gain Control circuit model wherein we scale down the phase detector’s output voltage and feed it as input to the gate of nfet. Instead of directly connecting the output of OA1 to the drain of the nfet, we connect it to the terminal VIN shown in the *figure 20* below.

3.2.1 ELECTRONIC GAIN CONTROL CIRCUIT

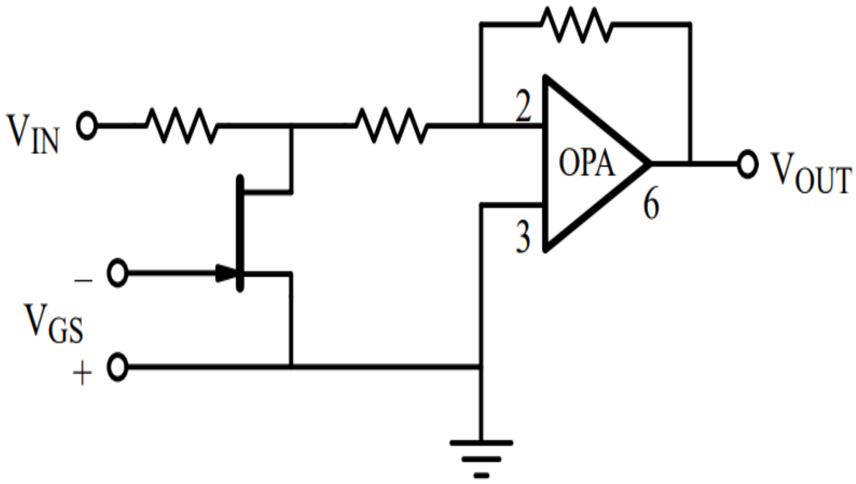


***Fig 13: Electronic Gain Control Circuit* [15]**

3.2.2 CIRCUIT MODELLING FOR METHOD “B”

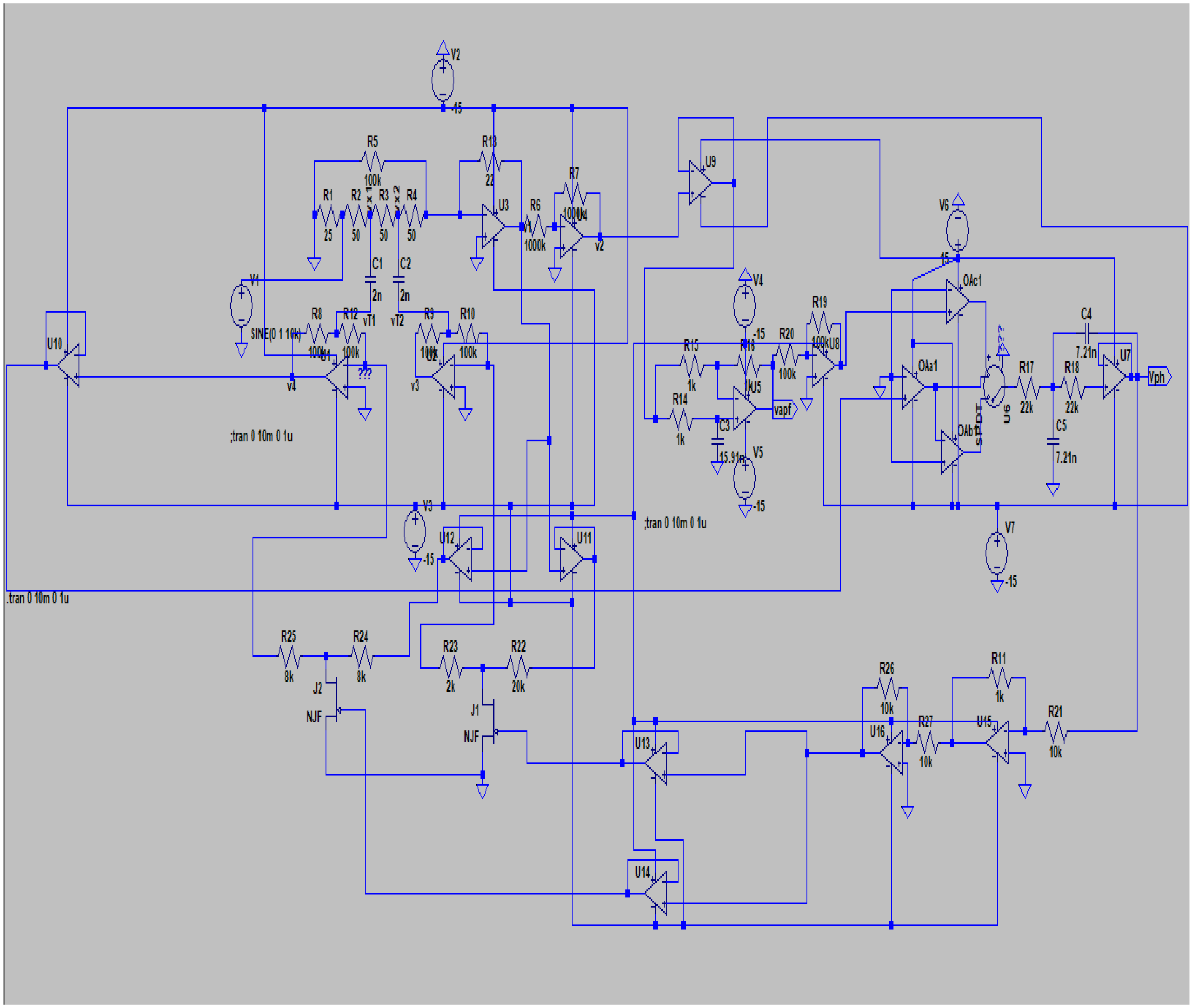


Fig 14: Schematic Representation of the modified Signal Conditioning Circuit in Method “B”

Here, the resistances of the nfets are being varied by their gate-source voltages(Vgs) such that the effective resistance between the VIN terminal and terminal 2 changes. As Vgs alters, the resistance of the nfet also does, overall affecting the effective resistance which tracks it down to the appropriate values.

This increase in the effective resistance decreases the value of Vph and this further progresses to make it’s value to be 0 as discussed in the previous section .

CHAPTER 4

RESULTS AND CALCULATIONS

4.1 GRAPHS OBTAINED BY IMPLEMENTATION OF THE CIRCUIT IN THE REFERENCE PAPER

i) On Y-axis are plotted Vx1 and Vt1 as in the schematic implemented in the paper with time

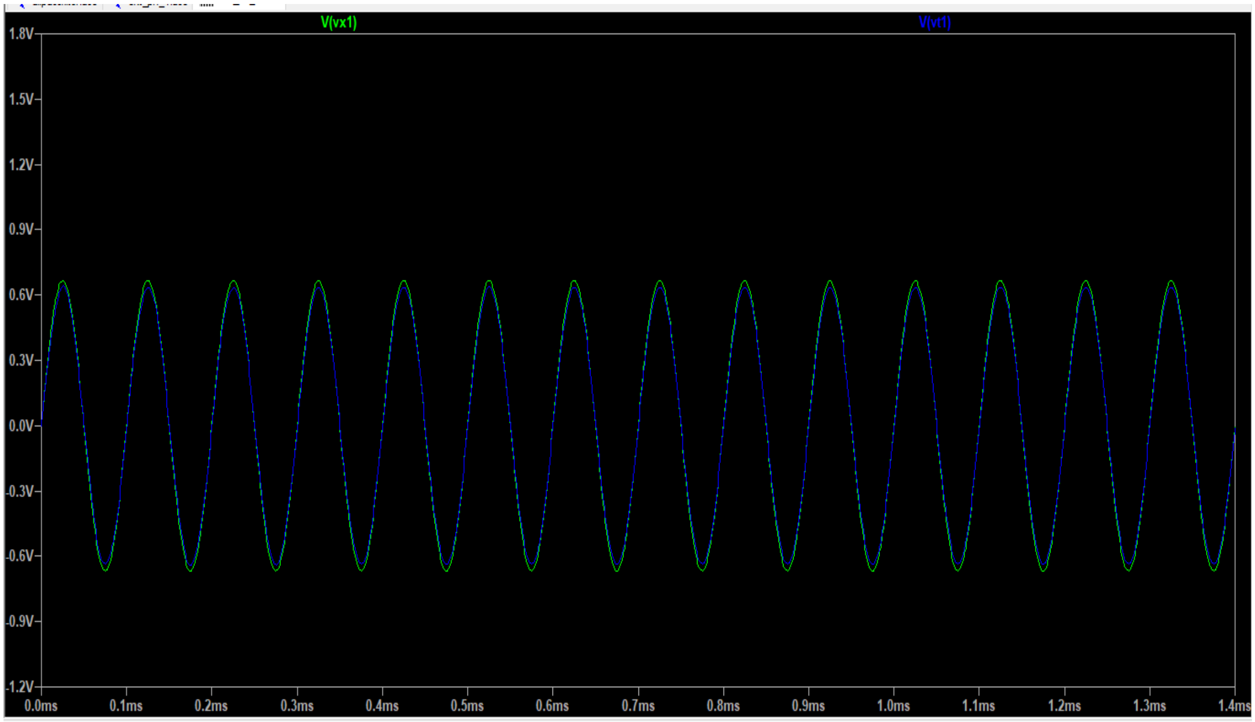


Fig15A : The above graph plots the voltages across first capacitive terminal with time

ii) On Y-axis are plotted Vx2 and Vt2 as in the schematic implemented in the paper with time

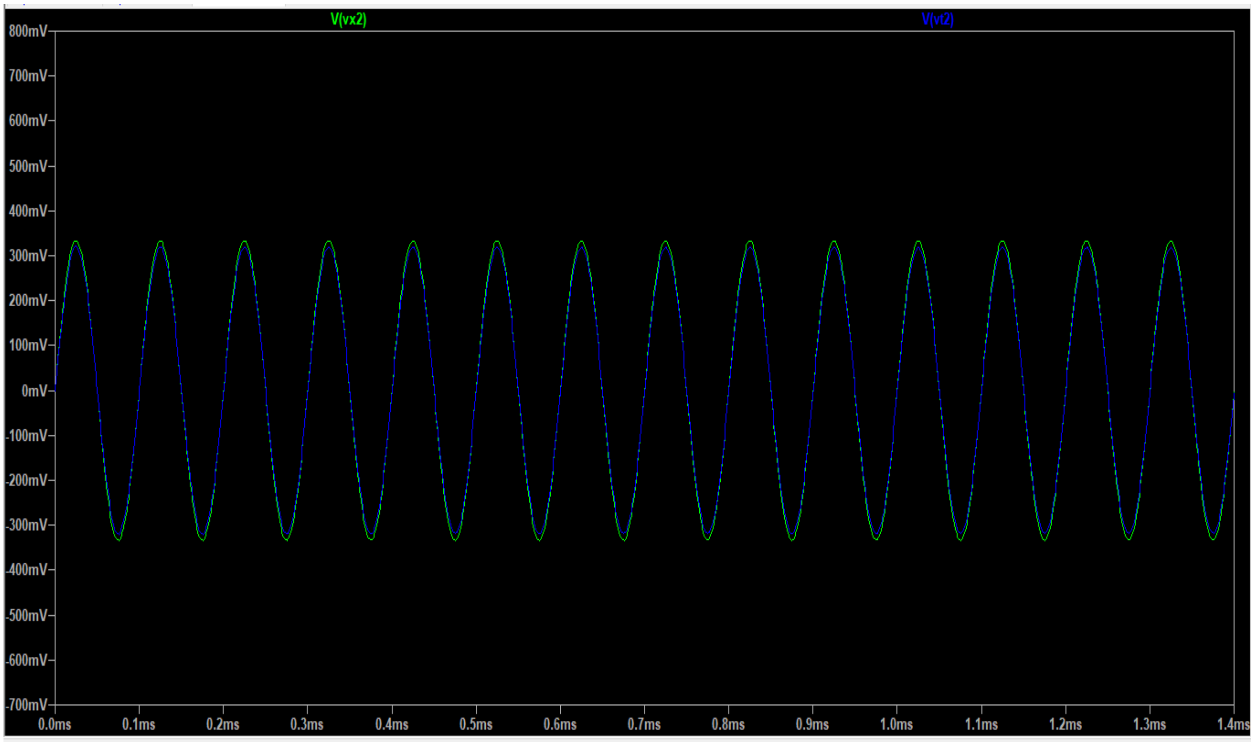


Fig15B: The above graph plots the voltages across second capacitive terminal with time

iii) On Y-axis is plotted the output of Phase Detector Circuit as in the schematic implemented in the paper with time

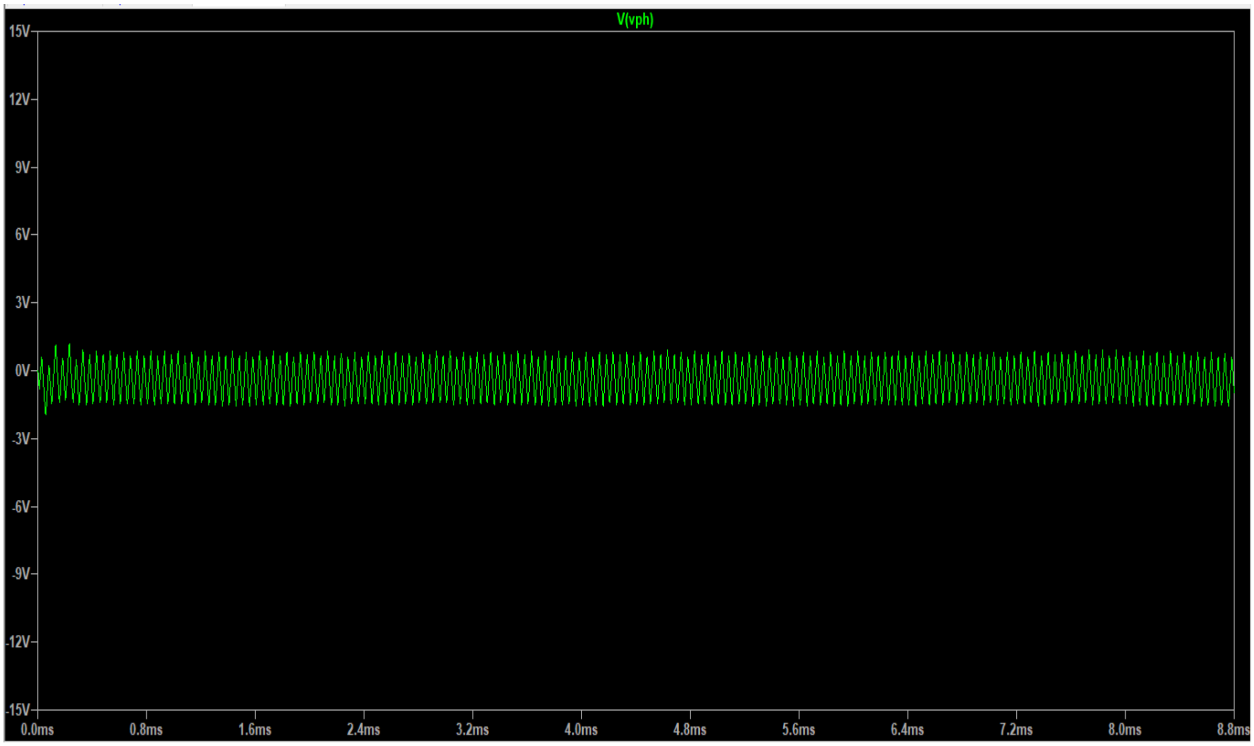


Fig15C: The above graph plots the voltage of phase detector circuit with time

4.2 GRAPHS OBTAINED BY IMPLEMENTATION OF THE CIRCUIT AS IN THE METHOD “A”

i) On Y-axis are plotted Vx1 and Vt1 as in the schematic implemented in the method “A” with time

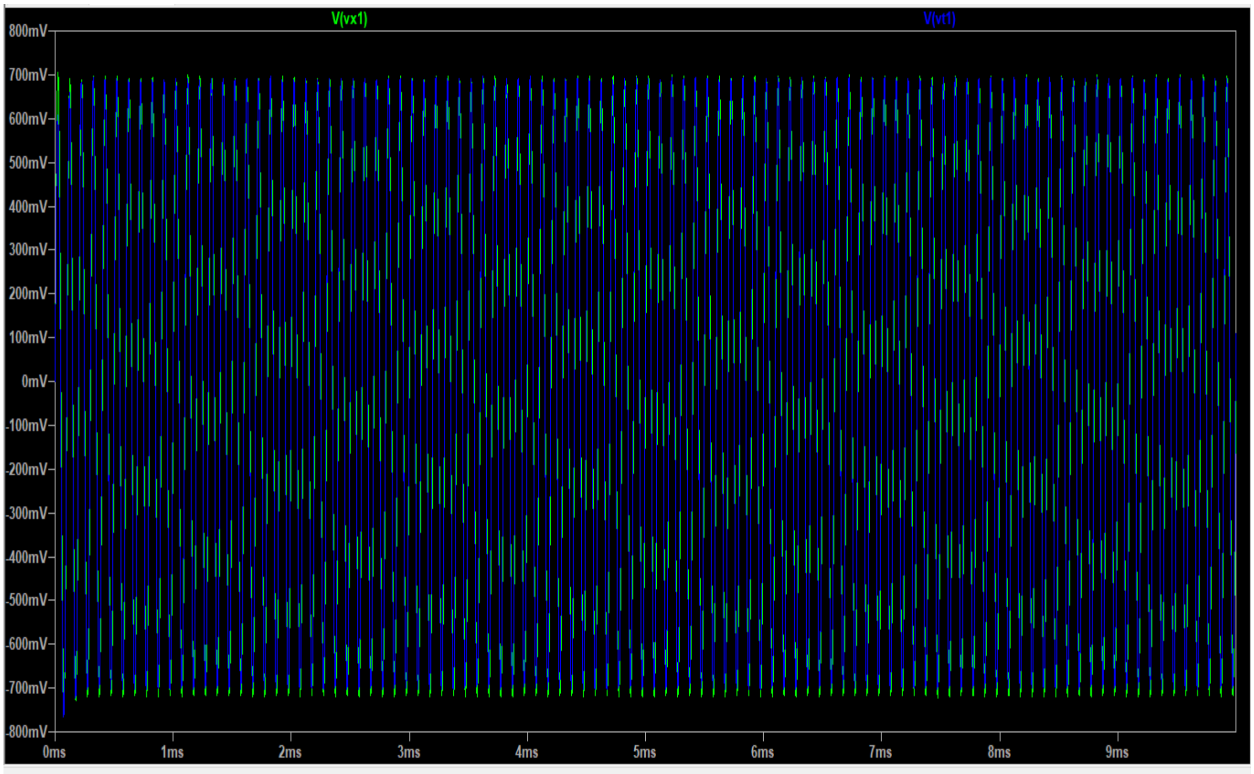


Fig16A : The above graph plots the voltages across first capacitive terminal with time

ii) On Y-axis are plotted Vx2 and Vt2 as in the schematic implemented in the method “A” with time

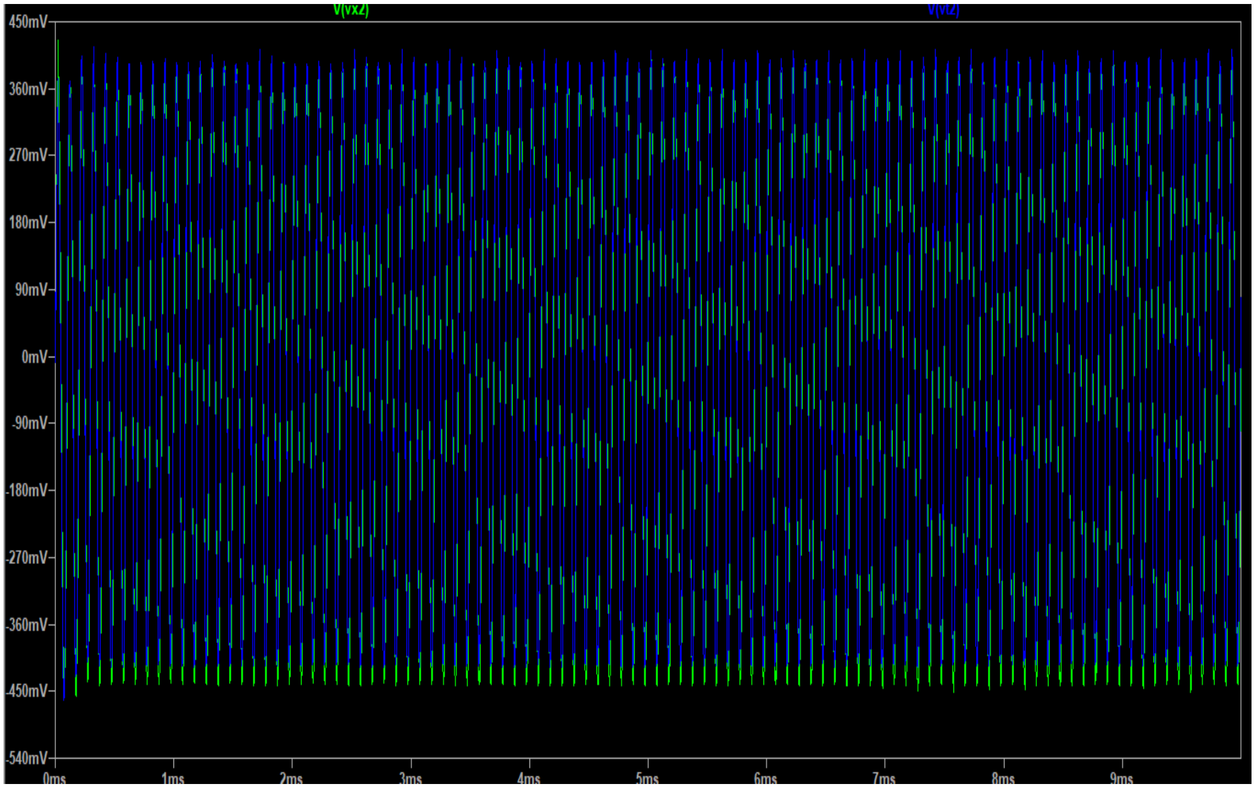


Fig16B: The above graph plots the voltages across second capacitive terminal with time

iii) On Y-axis is plotted the output of Phase Detector Circuit as in the schematic implemented in the method "A" with time

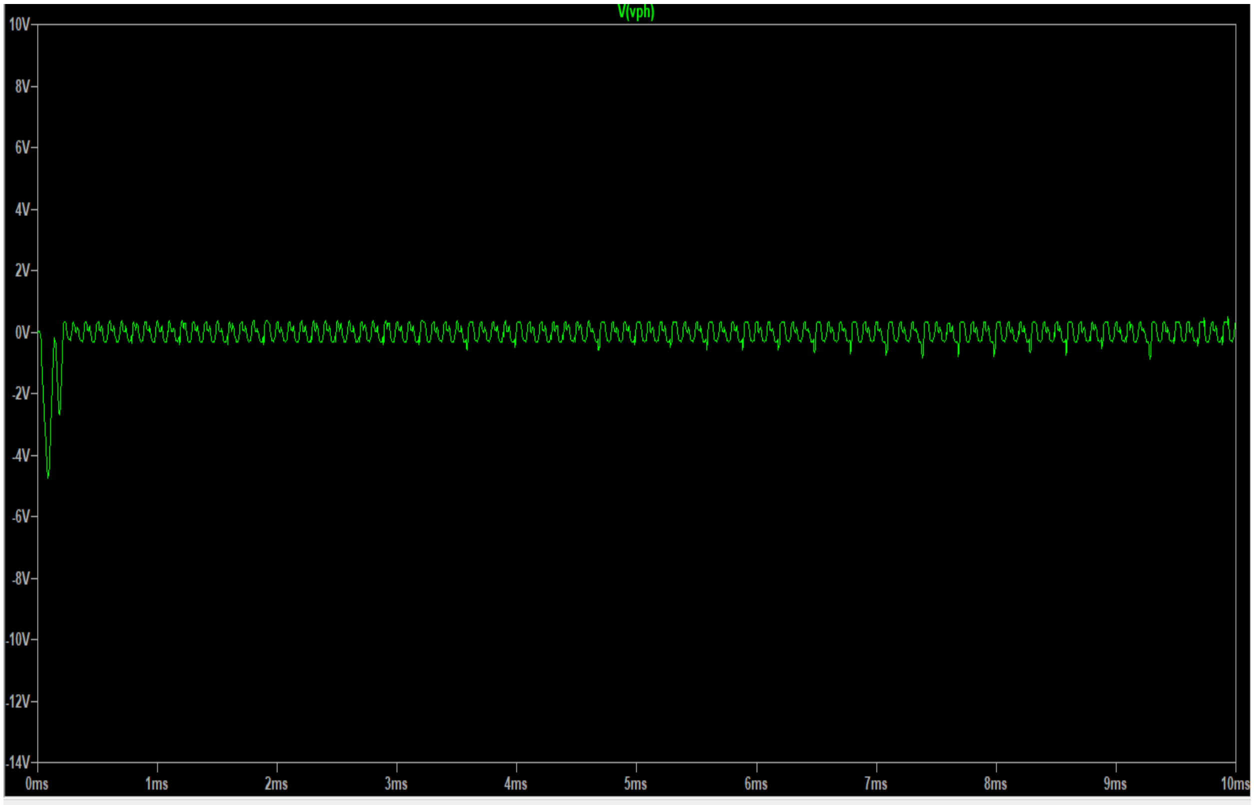


Fig16C: The above graph plots the voltage of phase detector circuit with time

4.3 GRAPHS OBTAINED BY IMPLEMENTATION OF THE CIRCUIT AS IN THE METHOD “B”

i) On Y-axis are plotted Vx1 and Vt1 as in the schematic implemented in the method “B” with time

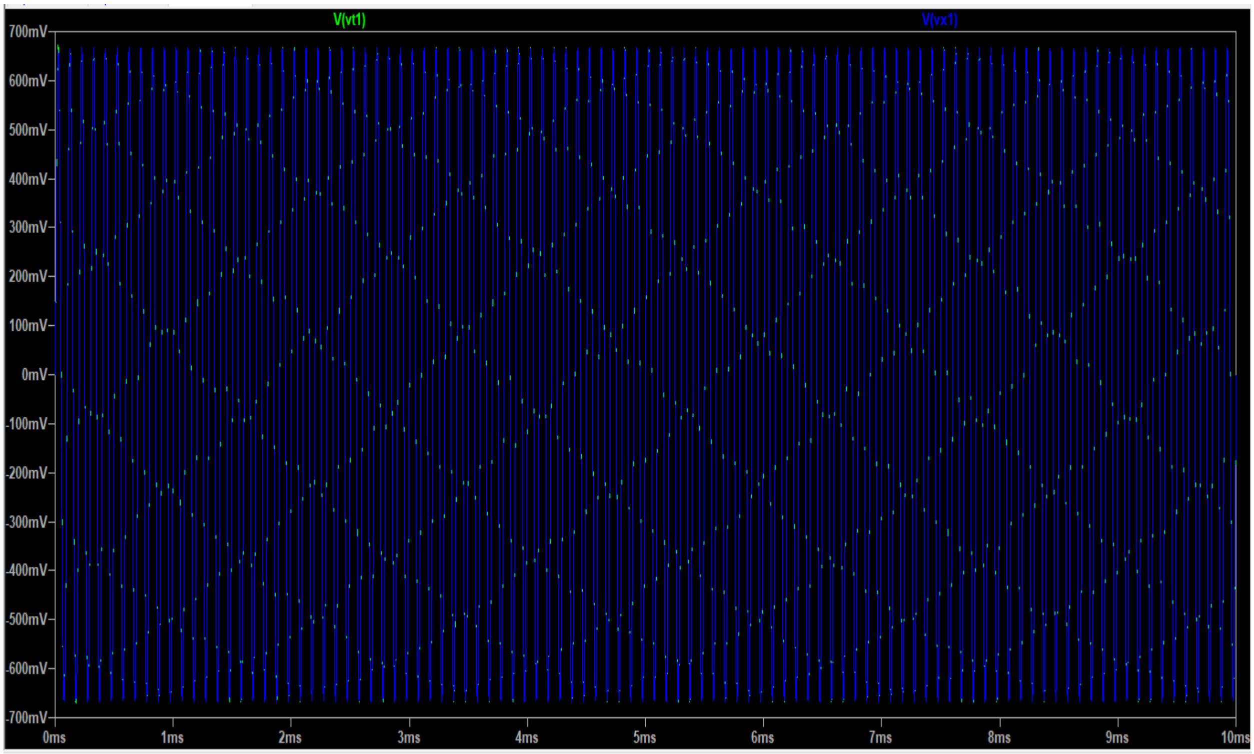


Fig17A : The above graph plots the voltages across first capacitive terminal with time

ii) On Y-axis are plotted Vx2 and Vt2 as in the schematic implemented in the method “B” with time

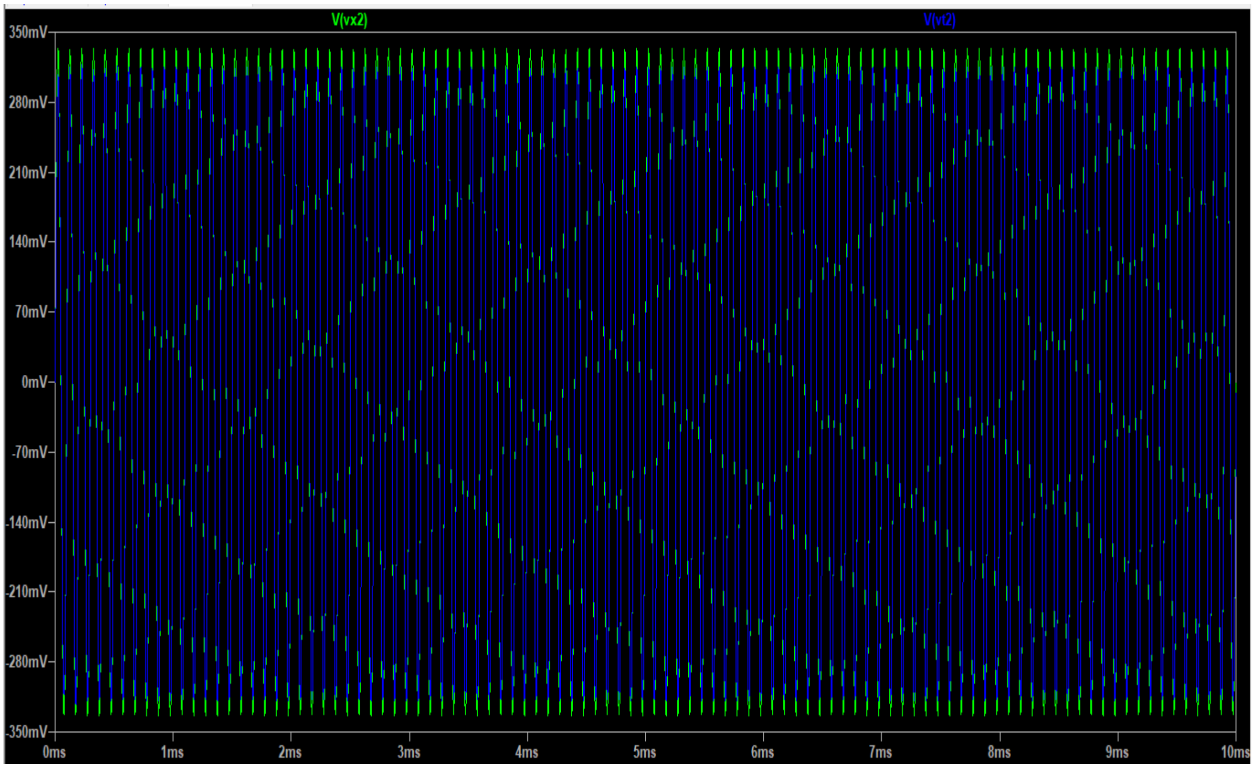


Fig17B: The above graph plots the voltages across second capacitive terminal with time

iii) On X-axis is plotted the output of Phase Detector Circuit as in the schematic implemented in the method “B”

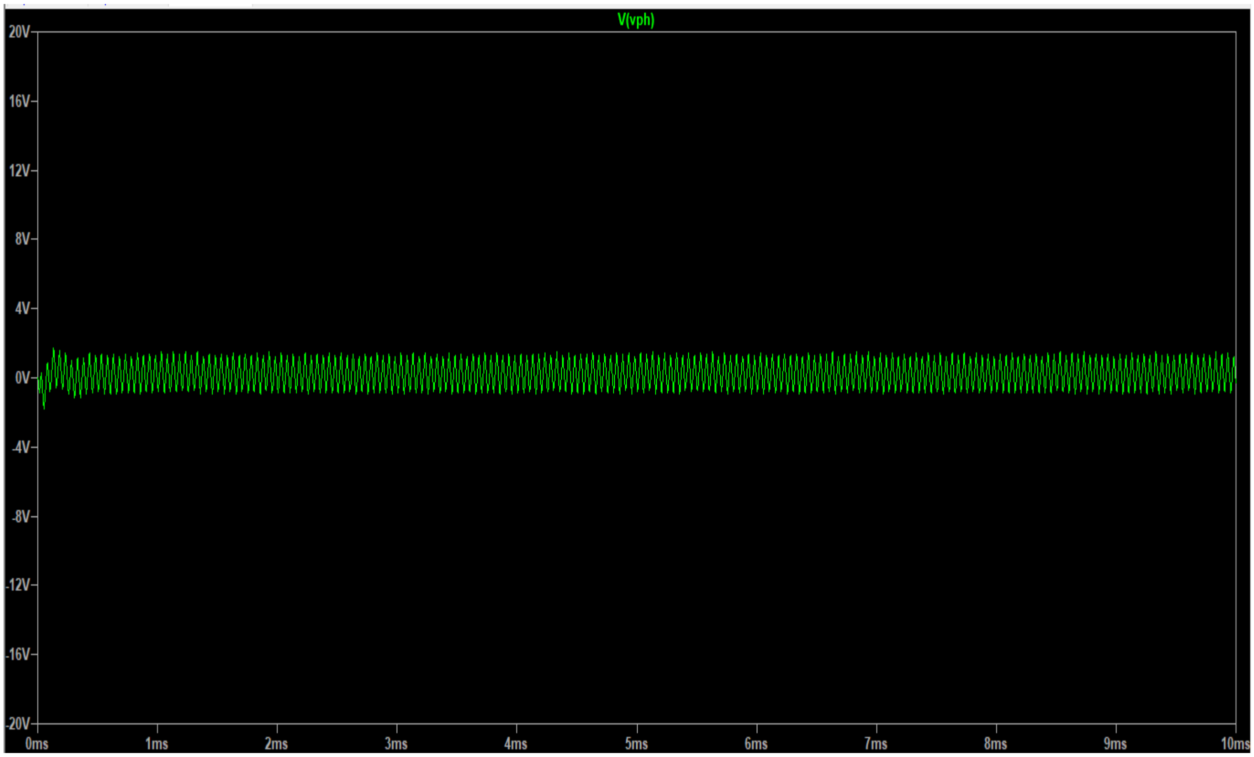


Fig17C: The above graph plots the voltage of phase detector circuit with time

4.4 CALCULATION OF VARIABLE RESISTORS IN METHODS “A” & “B”

$$v_{t1} = -v_1 \frac{R_5}{R_7}$$

$$v_{t2} = -v_1 \frac{R_5}{R_4}$$

$$v_1 = -v_s \frac{R_1}{R_x + R_{x1} + R_{x2}}$$

$$v_{t1} = v_s \frac{R_1}{R_x + R_{x1} + R_{x2}} \times \frac{R_5}{R_7}$$

$$v_{t2} = v_s \frac{R_1}{R_x + R_{x1} + R_{x2}} \times \frac{R_5}{R_4}$$

In method A,

Values of the above terminal voltages at their amplitudes (from the graphs)-
Vs=1V, Vt1=700mV=0.7V, Vt2=370mV=0.37V
As mentioned in the previous section, the values of Rx,Rx2,Rx1 are 50Ω.
So by substituting in the above equations, we get-

R_4 ***= 39.64 kΩ and*** R_7 ***= 21.95 kΩ.***

In method B,

Values of the above terminal voltages at their amplitudes (from the graphs)-
Vs=1V, Vt1=650mV=0.65V, Vt2=310mV=0.31V
As mentioned in the previous section, the values of Rx,Rx2,Rx1 are 50Ω.
So by substituting in the above equations, we get-

R_4 ***= 47.312 kΩ and*** R_7 ***= 22.546 kΩ.***

In *the previous* ***section 2.3.4***, when the method as in the paper was implemented, we got the values for R_4 and R_7 to be ***44KΩ*** and ***22KΩ*** respectively.

But by monitoring the phase detector output values as mentioned in the method described in the paper, i.e, at the juncture when they become 0 by digitally altering the resistor values in steps of 1KΩ, they turn out to be-

R_4 ***= 46KΩ and*** R_7 ***= 23KΩ.***

CHAPTER 5

CONCLUSION

5.1 INFERENCE

TABLE 2: TERMINAL VOLTAGES OF ELECTRODES MEASURED FROM THE RESULTS OBTAINED IN THE GRAPHS.

S.no	METHOD	Vt1	Vt2
1	Reference Paper	670 mV	335 mV
2	“A”	700 mV	370 mV
3	“B”	650 mV	310 mV

TABLE 3: VARIABLE RESISTANCES AS CALCULATED FROM THE EQUATIONS AND RESULTS OBTAINED IN THE GRAPHS.

S.no	METHOD	R_4	R_7
1	Reference Paper	***44KΩ***	***22KΩ***
2	“A”	***39.64 KΩ***	***21.95KΩ.***
3	“B”	***47.312 KΩ***	***22.546 KΩ***

My manually changing the resistor values digitally in steps with the help of Phase detectors output , we obtain the values of R_4 and R_7 as ***46 KΩ*** and ***23 KΩ..***

From the above tables, it is quite evident that the resistances more or less lie in the range encompassing the values we have obtained manually.

5.2 CONCLUSION

We have understood various process of conductivity measurement of liquids and studied their progression alongside their drawbacks. Firstly, we have studied an improved method to measure water conductivity which is immune to various external factors like polarization, contamination, current flow path, etc and implemented the schematic of self-balancing signal conditioning circuit as in the paper and obtained the vales of the voltages at the terminals of the electrodes and the measurement probe.

Later, to enhance the accuracy of the measurement, we came up with two methods which computes the values of the variable resistances such that they equate to the actual ones. To do so, few changes are made in the conditioning circuit for the output of the Phase Detectors to automatically update the resistor values. We simulate all the above prototypes in LT Spice to analyze how they function.

This way of effectively measuring the conductivity of water provides a better picture about its quality, reliability and utility in numerous industrial and chemical applications.

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