Design and Analysis of a New Immersion-type Liquid Conductivity Probe using Non-contact Electrodes

THESIS

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CERTIFICATE

This is to certify that the project titled **Design and Analysis of a New Immersion-type Liquid Conductivity Probe using Non-contact Electrodes** submitted by **Vadapalli Siddharth Narayan** to the Indian Institute of Technology Madras, Chennai for the award of the degrees of Bachelor of Technology and Master of Technology in Electrical Engineering is a record of bonafide work carried out by him under my guidance. 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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ABSTRACT

Current methods of measuring liquid conductivity (especially conductivity of seawater) consist of a pair of electrodes dipped into the liquid along with a measurement unit to estimate the conductivity of the liquid. This method has the drawback that the electrodes exposed to the liquid corrode over time thereby causing the measurement unit to estimate the conductivity of the liquid and the contamination over the electrodes. This results in faulty measurement and necessitates the invention of a new method to overcome this flaw. In this paper, we propose a method to measure the conductivity of liquids (with emphasis on seawater) using non-contact electrodes to a high degree of precision. Conductivity of the liquid can be measured once its resistance is known. Thus, we make use of Ohm's law to first measure the liquid's resistance from which its conductivity can be computed. The proposed unit has specially designed non-contact electrodes, and an interfacing circuit that consists of an instrumentation amplifier and a current-to-voltage converter. From Ohm's law, we can compute the resistance of the liquid, by measuring the voltage across as well as the current flowing through the column of liquid. The voltage across the column of liquid is measured using an instrumentation amplifier. The current through the liquid is measured using a current-to-voltage converter, whose output voltage serves as a proxy for the current. To test the performance of the circuit, simulations were performed in LTSpice. The resistance of the liquid was varied from 40 to 60 Ohms which is assumed to be the standard range for seawater resistance. The outputs of the voltages from the instrumentation amplifier and the current-to-voltage converter were measured and made use of in two different approaches to estimate the resistance of the column of seawater. The first approach involves making use of peak values of the voltages of the instrumentation amplifier and the current-to-voltage converter. It was observed that this approach wasn't good enough to achieve the desired precision of an error of ±0.0001 Ohm in the estimate of the resistance of the liquid. Thus, a more reliable measure of the outputs of the instrumentation amplifier and the current to voltage converter was necessary. The second approach involves using the RMS values of the voltages of the instrumentation amplifier and the current-to-voltage converter. Since the RMS values are relatively quite stable, the RMS values of the output voltages were measured for different values of the resistance of the liquid. It was then observed that the precision of the estimate was within the desired error range. The circuit was observed to be accurately estimating the resistance of the liquid up to the 4th decimal place with an error from the 5th decimal place. Additionally, to test

the robustness of the circuit to noise, noise sources were added appropriately throughout the circuit to simulate thermal noise in resistors, and also the ideal operational amplifiers were replaced with their noisy counterparts by appropriate modeling. The voltage source was also modelled to represent noise in voltage generation.The results of the circuit in the presence of noise were also found to be precise up to the 4th decimal place with an error of less than ±0.0001 Ohm, indicating that the circuit was noise-tolerant as well. An ADC shall be used to measure the outputs of the instrumentation amplifier and current-to-voltage converter. The precision of the ADC affects the precision of the estimate of the resistance of the liquid.

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Chapter-1

Introduction

Sensors play an important role in our lives. Almost all experiments that are performed make use of sensors to obtain information about some physical quantity that is used to formulate and test theories in science. The quality of a sensor is determined by how accurate, precise and robust the sensor is. Now that we know the basic requirements of a good sensor, we shall focus on the sensors used for measuring conductivity of liquids in general, with an emphasis on seawater. First, we shall see why it is important to measure conductivity of liquids. Consider seawater for example. Knowledge of the conductivity of seawater at any place in the sea gives us an insight of the quality of water at that place. This is essential to detect any toxic substances in water which might harm the animals living in that region. Conductivity measurements in freshwater lakes, rivers and ponds are a rapid and convenient way to detect pollution events or other changes in the system. Additionally, conductivity of seawater also determines its salinity. Salinity is a measure of the amount of salts dissolved in water. Since conductivity of water is directly influenced by the salts present in water, conductivity is an indirect measure for salinity. Salinity of water affects its temperature and density, thereby affecting the circulation of ocean currents. These ocean currents are an indicator of how heat is transported across the oceans of the world, thereby affecting the world's climate. Thus, the consequences of measuring the conductivity of seawater at various places can ultimately be helpful in predicting the ocean currents and the climate as well. In industries such as aquaculture, where aquatic life is grown and maintained in large pools of water, it is important to monitor the salinity of water continuously. Thus, we can observe that the sensor for measuring conductivity of water must be accurate, precise, robust and also quick. Keeping these requirements in mind, we propose a circuit that is capable of measuring quickly and accurately the conductivity of liquids using contactless probes.

1.1 Background and Literature Survey

Conductance of a material is defined as the ratio of the current flowing through the material and the voltage across it. Its unit is Siemens (S) . Conductivity is defined as LxG/A, where G is the conductance of the material in S, L is the length of the material in meters across which the voltage is applied and A is the cross-sectional area of the material in square meters. Thus, the SI unit of conductivity is S/m. This definition shall be used to compute the conductivity of the material from its conductance. Additionally, conductance is defined as the inverse of the resistance of the material. Resistance is defined from Ohm's Law as R = V/I where V is the voltage applied across the material when I is the current flowing through the material. Thus, knowing R is equivalent to knowing G and thus knowing the conductivity of the material. Throughout this paper, we shall focus on measuring R rather than conductivity since there is a direct relationship between the two. With this knowledge we need to design a circuit to measure the conductivity of liquids. We follow the same idea that is used to measure the conductivity of liquids, namely, making use of Ohm's Law to compute the resistance followed by computing the conductivity. The prevalent approach is to apply a voltage across a column of the liquid and measure the current flowing through it using probes. While measuring the conductivity of solids has been easy to deal with, measuring the conductivity of liquids, especially seawater, poses a challenge. This is because of the phenomenon of corrosion. The probes that are immersed in the column of liquid to create a potential difference across the liquid tend to corrode over time, leading to an inaccurate estimate of the resistance. Without corrosion, the estimated resistance would be the voltage V - applied across the liquid, divided by I - the current flowing through the liquid. However, due to corrosion, there is a layer of deposit on the probes. This implies that the current which was originally flowing only through the liquid, now also has to flow through the deposit. Thus the resistance measured is not just the resistance of the liquid but the resistance of the liquid plus twice the resistance of the layer of deposit on a probe (since there are two probes). Since it is neither practical nor economical to replace the probes frequently to counter corrosion, we need a new method to measure the resistance of the liquid accurately while avoiding the problems associated with corrosion entirely. This paper proposes a method to avoid this problem, thereby making the process of measuring conductivity of liquids economically feasible and practical. We have referred to the work done in the paper titled: *Conductivity Measurement Using Non-Contact Potential Electrodes and a Guard Ring* [1]. We have improved upon the results in the mentioned paper by resorting to a direct measurement method rather than the feedback dependent method mentioned in the paper. We shall make use of some of the figures from that paper in this thesis, wherever necessary.

1.2 Objective

We aim to design and test a circuit that can measure conductivity of liquids in a contactless manner to avoid corrosion and corrosion related measurement issues. The conductance measured should be accurate to ± 0.0001 S. The circuit should be tested under various temperatures and thermal noise conditions. The circuit should be capable of detecting a change in the capacitance of the probes, indicating that the probes need to be replaced when necessary. Primarily, the circuit should be accurate in the range of 40 to 60 Ohm of liquid resistance, since this circuit is designed to measure the resistance/conductivity of seawater whose nominal resistance range is 40 to 60 Ohm. NOTE: All the work including design of circuit and testing it has been done through simulation using LTSpice [2]. The circuit is yet to be implemented on a physical breadboard for further testing.

1.3 Structure of the Thesis

We shall start by going through the design of the proposed circuit followed by a detailed explanation of the same. Two approaches have been used to measure the voltage and current through the fluid which shall be explained in detail one after the other with the results presented for both approaches. The second approach was found to be more accurate than the first. Thus, we shall focus on testing the robustness of the second approach to noise and temperature variation. Next, we shall determine the ADC resolution needed to achieve the desired accuracy of ± 0.0001 S. Finally, we shall propose a method to detect a change in probe capacitances, to develop an automated method that indicates when the probes need to be changed.

Note: ***The number of significant decimal values in the measurements has not yet been determined. Thus, we let it remain as it is from the computation upto the maximum precision that LTSpice [2] can compute. We haven't trimmed to the desired significant figures in the decimal places yet. It shall be done in the section for determining ADC resolution.***

Chapter - 2

Device Implementation, Testing and Results

In this chapter, we shall begin by explaining the proposed circuit design, followed by the results in simulation for the circuit. We shall cover two different approaches that were made use of to estimate the resistance/conductivity. The problem of estimating conductivity of the liquid shall be treated as being equivalent to the problem of estimating resistance of the liquid for the sake of simplicity. As mentioned earlier, knowing the resistance, the conductivity can be computed directly with no error involved in the transformation.

2.1 Device Design

We require a circuit that can estimate the resistance of a liquid. Taking a look at the existing methods, we see that they involve making use of a set of probes that are immersed in the liquid, applying a potential difference across the liquid. This causes a current to flow through the liquid which can be measured. Thus, knowing both the voltage across the liquid and the current through it, the resistance is estimated as the ratio of the voltage to the current. Now, keeping in mind the problem of corrosion, we know that the probes that apply voltage to the liquid cannot be relied on to determine the voltage across the liquid. Thus, in our method, we propose using another set of probes that are not immersed in the liquid but can inductively measure the voltage across any section of the column of liquid. To make things clear, we shall name the probes to make it easier to refer to them. We shall use P1 to denote the set of probes that are immersed in the liquid to apply the potential difference and P2 to denote the set of probes that are insulated from the liquid and use an inductive method to measure the voltage drop across any section of the liquid. The probe set P1 consists of the electrodes $T_{\mathbf{E}}$ (Excitation Electrode) and $T_{\mathbf{R}}$ (Return Electrode), while the probe set P2 consists of the electrodes $T_{\mathbf{1}}$ and $T_{\mathbf{2}}$. $T_{\mathbf{G}}$ (Ground Electrode) is the electrode connected to ground via the resistor $R_{\mathbf{Ground}}$. Additionally, let T denote the tube which encases the probes P2 within it while allowing the liquid to flow through it. The tube T can be visualized as a pair of concentric hollow cylinders. The probes P2 are present in between the outer and inner cylinders while the liquid flows through the inner cylinder of the tube. In this manner, the probes (P2) that measure the voltage drop are not subject to corrosion the way the probes (P1) that are immersed in the liquid are subject to corrosion. The current that flows through the liquid within the tube T is denoted by Ix. The voltage drop generated by the probes P1 is denoted by Vs while the voltage drop across the section containing the probes P2 is denoted by Vx. In figure 2.1, we refer to a figure from the paper [1], to better illustrate the construction of the device.

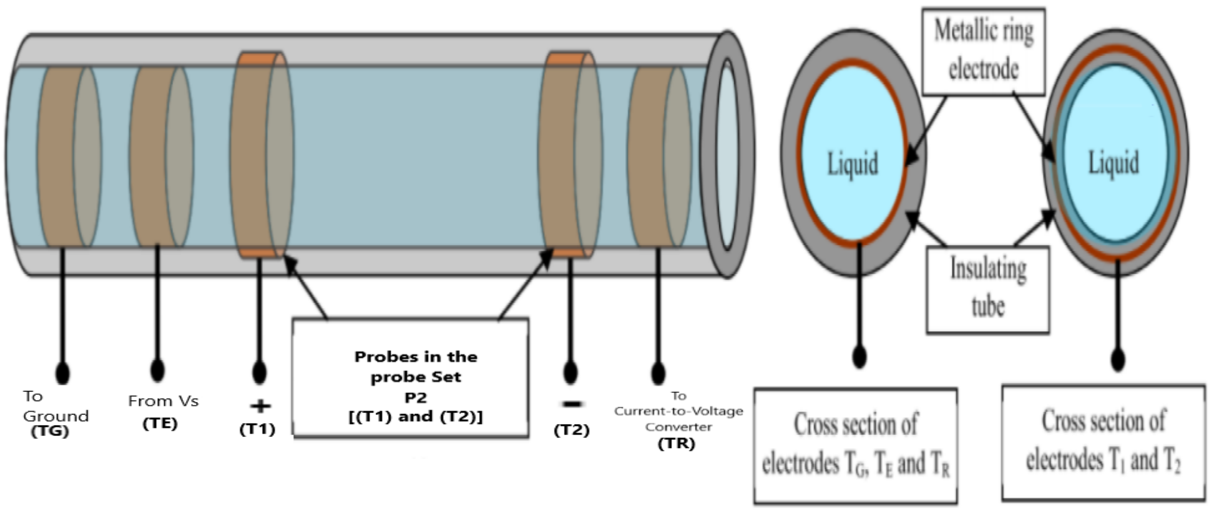

Fig. 2.1 Probe Design Illustration

Ref: *Conductivity Measurement Using Non-Contact Potential Electrodes and a Guard Ring [1]*

As illustrated in Fig. 2.1, the electrodes T1 and T2 in probe set P2 are insulated from the liquid. The electrode T_R is connected to the current-to-voltage (I-V) converter to serve as a proxy for the current Ix through the liquid.

Estimating the resistance of the liquid is the process of measuring Vx and Ix accurately and taking their ratio and scaling it up appropriately. The assumption we make is that the resistance of the liquid is proportional to Vx/Ix and thus, scaling it appropriately would give a good estimate of the resistance. This scaling constant is fixed for all future measurements and needs to be calibrated only once, making use of a standard solution of the liquid whose resistance at other temperatures or at other places needs to be estimated.

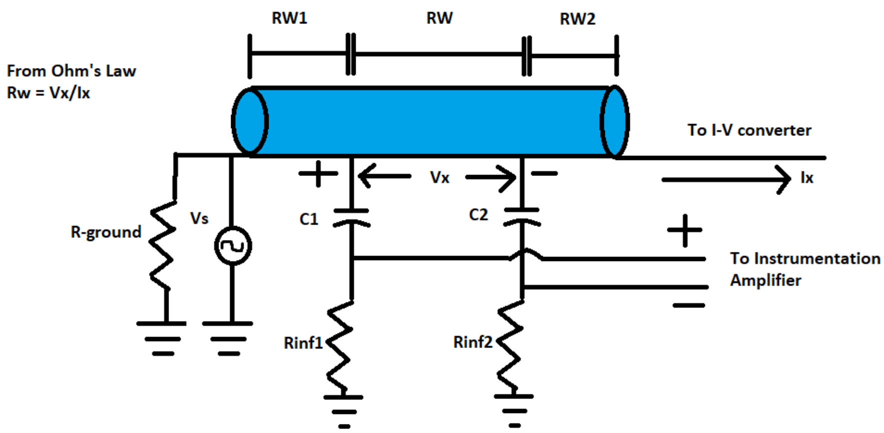

Fig. 2.2 Device Design Illustration

We shall now focus on the illustration in Fig. 2.2 to describe the device in detail for a better understanding. The region shaded in blue in the above image is the tube T containing the liquid in which the tube is immersed. The probes P2 are present within the tube and are insulated from the liquid. The symbol Vx is used to denote the potential drop across the probes P2 within the tube T. The wires of the probes are brought out of the tube and are modelled using a capacitor in series with a resistor. The insulation between the liquid and electrode T1 is responsible for a capacitance C1 and between the liquid and electrode terminal T2 is responsible for a capacitance C2. The wire connected to the electrodes T1 and T2 have resistances Rinf1 and Rinf2 respectively. Therefore, the wires corresponding to the probes P2 are shown as the capacitance C1 with the resistance Rinf1 connected to it and the capacitance C2 with the resistance Rinf2 connected to it. The names Rinf1 and Rinf2 are used to indicate that these resistances are very high (of the order of MΩ). As shown in the illustration, there are two wires connected in between [C1 and Rinf1] and [C2 and Rinf2]. These wires are connected to an instrumentation amplifier to amplify the potential difference Vx across the probes P2. The section across which the probes P2 are connected has the potential drop Vx and its resistance is referred to as Rw. The symbols Rw1 and Rw2 denote the resistance of the liquid on either side of the probes. The probes P2 are connected such that the length of the sections corresponding to Rw1 and Rw2 are exactly half the length of the section corresponding to Rw (which is the same as the length of the section corresponding to the probes P2) This ensures that Rw1=Rw2=Rw/2. The probes P1 which are immersed on either end of the tube T are shown by the voltage source Vs in the diagram on the left side and the wire going to the I-V (Current to Voltage) converter on the right side of the illustration. Since the tube T is immersed in the liquid, the liquid is outside the tube T as well, though it is not shown in blue, to avoid confusion. Since the liquid is present outside the tube as well, the current due to the voltage Vs flows not only through the tube as Ix but also outside the tube (very close to the tube) and is modelled as the current through the resistor R-ground. The current in the probes P1 is Ix which is sent to an I-V converter. The output voltage of the I-V converter acts as a proxy of the current Ix through the liquid.

We shall model the illustration shown in Fig. 2.2 in the form of a circuit as shown in Fig. 2.3 .

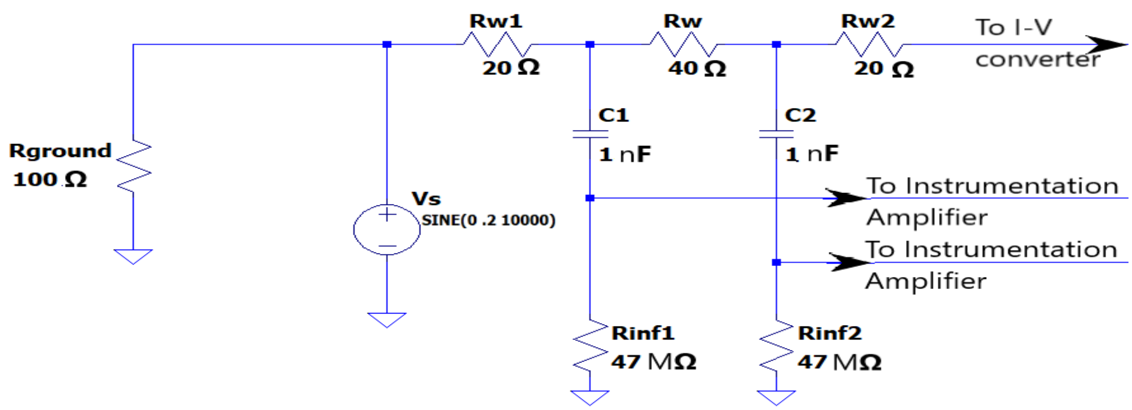

Fig. 2.3 Schematic of device design

In Fig. 2.3, we have represented the earlier illustration in the form of a circuit with values assigned to the resistors, voltage sources and capacitors. The peak value of the voltage source Vs is a relatively small value of 200 milliVolts and not a high value like 5 Volts or so, to ensure that the current Ix that flows through the liquid and enters the operational amplifier which is a part of the I-V converter, is lower than the output current of the operational amplifier. C1 and C2 are taken to be 1nF as that is the typical range of the probe capacitances. Rinf1 and Rinf2 are chosen such that at the frequency of 10 kHz, the impedance of Rinf1 and Rinf2 is much larger than that of capacitors C1 and C2. With this figure in mind, we shall proceed further to discuss the two approaches used to measure the current Ix and the voltage Vx.

We used an op-amp for the I-V converter and LT6370 for the instrumentation amplifier.

2.2 Peak Detection Method

In this approach, the outputs of the instrumentation amplifier and I-V converter are individually passed through peak detector circuits to get the peak voltage values. Once the peak voltages are obtained, Rw is estimated by scaling the ratio of these peak values. The circuit with the peak detectors at the outputs of the instrumentation amplifier and the I-V converter is shown in Fig 2.4

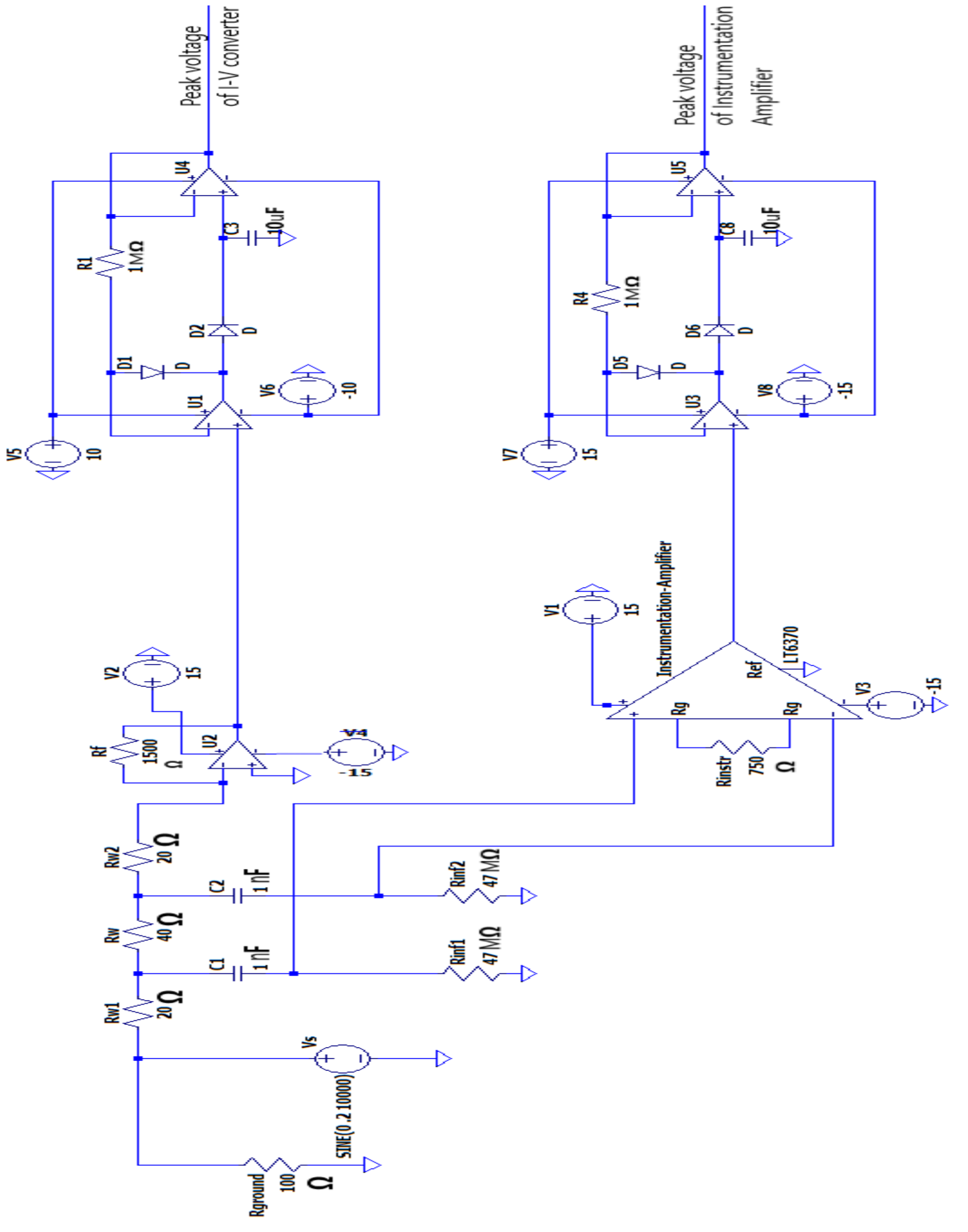

Fig 2.4 Peak Detection Circuit Schematic

The outputs of the peak detectors are made use of to estimate the resistance Rw (which serves as the resistance of the liquid). In the table below, we vary Rw from 40 Ohm to 60 Ohm while adjusting Rw1 and Rw2 such that Rw1=Rw2=Rw/2. The choice of Rw from 40 to 60 Ohm is due to the reason that the dimensions of the tube are 20 cm in length and having a radius of 1.5 - 2 cm, and the value of seawater's conductivity ranges from 46-72 mS/cm.The ratio of the peak voltages i.e. output of peak detector connected to the instrumentation amplifier (Vina to denote amplified Vx which is the output of the instrumentation amplifier) and output of the peak detector connected to the I-V converter (referred to as Vc from now on) is noted down in the column titled Ratio of peak voltages. Making use of the ratio of the peak voltages, we estimate Rw by scaling the ratio of peak voltages appropriately.

Table 2.1 Peak Detection Method Estimates for Rw

True value of Rw	Values of Rw1=Rw2	Ratio of peak voltages	Estimated Rw	Scaled Rw	Error (True Value - Estimated Value)	Percentage Error (Error/True Value*100)
40	20	1.2	37.11340206	40.00008247	-0.00008247422681	-0.000206185567
41	20.5	1.23	38.04123711	41.00008454	-0.00008453608248	-0.000206185567
42	21	1.26	38.96907216	42.0000866	-0.00008659793814	-0.000206185567
43	21.5	1.29	39.89690722	43.00008866	-0.00008865979381	-0.000206185567
44	22	1.32	40.82474227	44.00009072	-0.00009072164948	-0.000206185567
45	22.5	1.35	41.75257732	45.00009278	-0.00009278350515	-0.000206185567
46	23	1.38	42.68041237	46.00009485	-0.00009484536082	-0.000206185567
47	23.5	1.41	43.60824742	47.00009691	-0.00009690721649	-0.000206185567
48	24	1.44	44.53608247	48.00009897	-0.00009896907216	-0.000206185567
49	24.5	1.47	45.46391753	49.00010103	-0.0001010309278	-0.000206185567
50	25	1.5	46.39175258	50.00010309	-0.0001030927835	-0.000206185567
51	25.5	1.53	47.31958763	51.00010515	-0.0001051546392	-0.000206185567
52	26	1.56	48.24742268	52.00010722	-0.0001072164948	-0.000206185567
53	26.5	1.59	49.17525773	53.00010928	-0.0001092783505	-0.000206185567
54	27	1.62	50.10309278	54.00011134	-0.0001113402062	-0.000206185567
55	27.5	1.65	51.03092784	55.0001134	-0.0001134020619	-0.000206185567
56	28	1.68	51.95876289	56.00011546	-0.0001154639175	-0.000206185567
57	28.5	1.71	52.88659794	57.00011753	-0.0001175257732	-0.000206185567
58	29	1.74	53.81443299	58.00011959	-0.0001195876289	-0.000206185567
59	29.5	1.77	54.74226804	59.00012165	-0.0001216494845	-0.000206185567
60	30	1.8	55.67010309	60.00012371	-0.0001237113402	-0.000206185567

From table 2.1, we can observe that the scaled Rw is quite precise for estimating the resistance Rw upto 3 decimal places. However, it was found that this method is not reliable since it cannot distinguish a resistance of 40 Ohm from a resistance of 40.0001 Ohm. This was observed to be due to the instability of the peak detector output. Additionally, the simulation software was observed to vary the peak detector outputs for multiple iterations with the same value of Rw. On further analysis it was observed that changing values of probe capacitance had a major impact on the accuracy of the peak detector circuit based approach. The probe capacitances are denoted by C1 and C2 in the Fig 2.2 described earlier.

Case 1: C1=C2

Table 2.2 Error due to change in capacitances with C1=C2

C1=C2	Rw1=Rw2	Rw	Ratio of peak voltages	Estimated Rw	Error(True Value - Estimated Value)	Percentage Error	
2.00E-10	25	50	1.39	46.33333333	3.666666667	7.333333333	BAD
1.00E-10	25	50	1.29	43	7	14	ESTIMATE
2.00E-09	25	50	1.5	50	0	0	
1.00E-09	25	50	1.49	49.66666667	0.3333333333	0.6666666667	
2.00E-08	25	50	1.51	50.33333333	-0.3333333333	-0.6666666667	GOOD
1.00E-08	25	50	1.51	50.33333333	-0.3333333333	-0.6666666667	ESTIMATE
2.00E-07	25	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-07	25	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
2.00E-06	25	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-06	25	50	1.52	50.66666667	-0.6666666667	-1.333333333	

For C1 and C2 both below 1 nF, the error in estimated Rw is quite large, meaning that the linearity assumed between the true value of Rw and the ratio of peak voltages of instrumentation amplifier and I-V converter is no longer valid. Thus, we have to ensure that C1 and C2 are strictly above 1 nF for this approach to be accurate.

Case 2: C1≠C2

Table 2.3 Error due to change in capacitances with C1≠C2

C1	C2	Rw = 2*Rw1=2*Rw2	Ratio of peak Voltages	Estimated Rw	Error(True Value - Estimated Value)	Percentage Error	
1.00E-09	1.00E-09	50	1.49	49.66666667	0.3333333333	0.6666666667	
1.00E-09	5.00E-09	50	1.48	49.33333333	0.6666666667	1.333333333	
1.00E-09	1.00E-08	50	1.48	49.33333333	0.6666666667	1.333333333	
1.00E-08	1.00E-08	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-08	5.00E-08	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-08	1.00E-07	50	1.51	50.33333333	-0.3333333333	-0.6666666667	GOOD
1.00E-07	1.00E-07	50	1.51	50.33333333	-0.3333333333	-0.6666666667	ESTIMATE
1.00E-07	5.00E-07	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-07	1.00E-06	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-06	1.00E-06	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-06	5.00E-06	50	1.51	50.33333333	-0.3333333333	-0.6666666667	
1.00E-06	1.00E-05	50	1.51	50.33333333	-0.3333333333	-0.6666666667	

When C1 is not equal to C2 and both are above 1 nF each, the estimated Rw is close to true value as long as C2 is within 10 times the value of C1. Thus, slight difference in the values of C1 and C2 from each other is tolerable as long as both are above 1 nF each. From the results, we understand that there is a need to detect whenever the probe capacitances fall below 1 nF. Thus, we propose a method to do the same later on in this thesis in **Section - 2.6** .

Due to the aforementioned issues with the Peak Detection Method, we came up with a more robust method to estimate Rw, namely the RMS Computation Method.

2.3 RMS Computation Method

In the Peak Detection Method, the drawback was the lack of stability with the peak detector outputs. Since the outputs of the peak detectors serve as an estimate for the voltage Vx and the proxy voltage Vc for the current Ix, any error in measuring Vx and Vc would lead to large error in estimating the resistance Rw. Thus, we require a more stable and accurate measure of Vina(amplified Vx which is the output of the instrumentation amplifier) and Vc. This led to the idea of measuring the RMS (Root Mean Square) values of the voltages Vina and Vc. Instead of the peak detector circuits at the outputs of the I-V converter and instrumentation amplifier, we now have RMS computing circuits. In the simulation, since there was an in-built tool to measure the RMS values of voltages in the circuit, we made use of the tool instead of connecting a new RMS circuit to the outputs of the I-V converter and the instrumentation amplifier.

The LTSpice[2] schematic for the circuit is shown in Fig 2.5 on the following page .

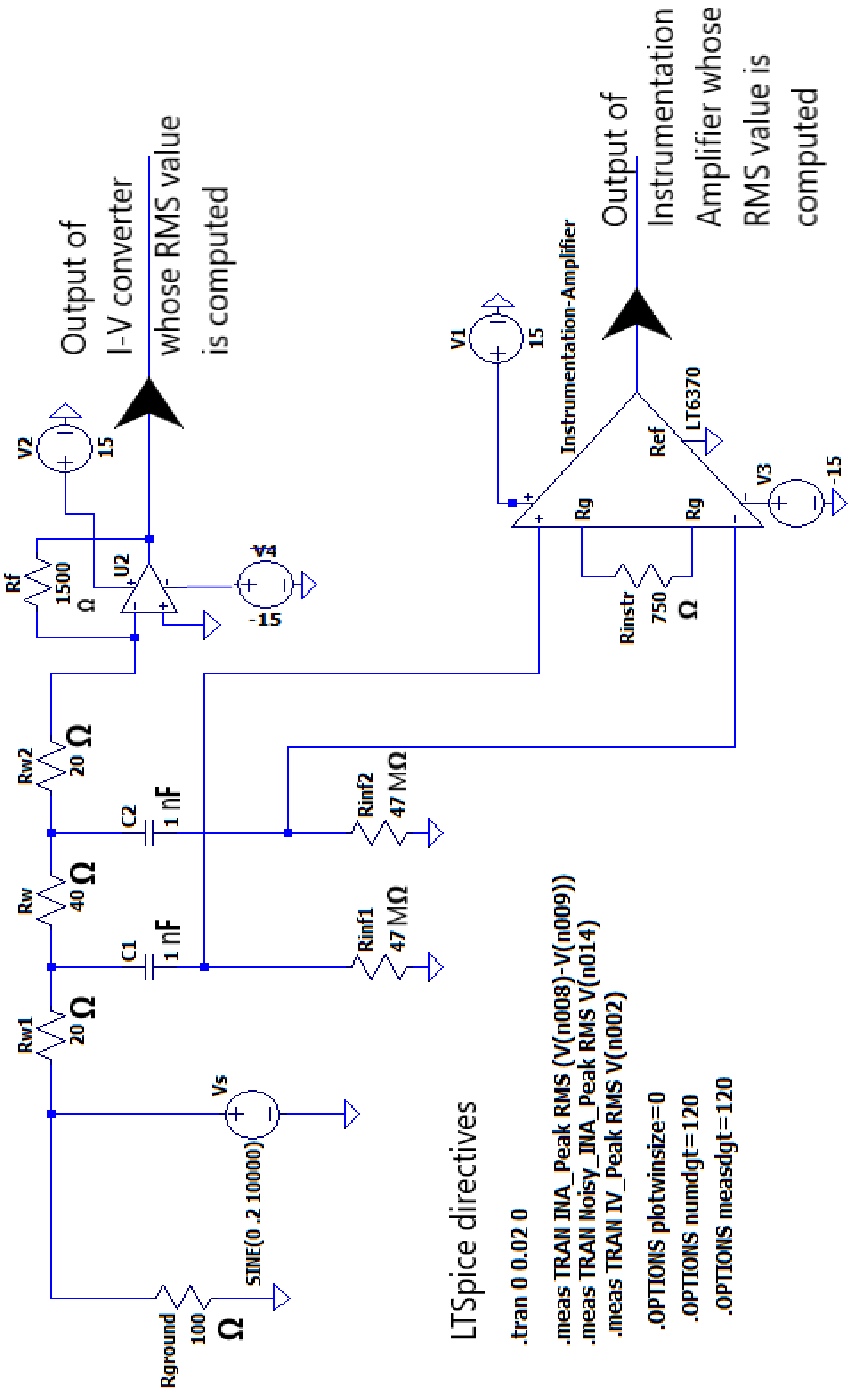

Fig 2.5 RMS Computation Method Schematic

The circuit shown in Fig 2.5 was simulated and the RMS values of the voltages Vina and Vc were noted down. The results are shown in table 2.4.

Table 2.4 Noiseless estimate of Rw by RMS computation method

Rw	Rw1=Rw2	RMS(Vc1-Vc2)	RMS(Vi-v)	RMS(Vc1-Vc2)/RMS(Vi-v)	Estimate for Rw	Estimated Rw upto 4 decimals	Error
40	20	0.0706948931535000	2.6510537134100000	0.0266667147466305	40.0000000000000000	40	0.00
40.0001	20.00005	0.0706948932219000	2.6510470883500000	0.0266667814134905	40.0001000001097000	40.0001	0.00
45	22.5	0.0706978300647000	2.3565899496600000	0.0300000558327511	45.0000026141829000	45	0.00
45.0001	22.50005	0.0706978301120000	2.3565847143800000	0.0300001224995640	45.0001026142220000	45.0001	0.00
50	25	0.0706999555389000	2.1209945955400000	0.0333333973068894	50.0000058103914000	50	0.00
50.0001	25.00005	0.0706999555744000	2.1209903546200000	0.0333334639737514	50.0001058105041000	50.0001	0.00
55	27.5	0.0707015461194000	1.9282201723200000	0.0366667391692792	55.0000095889761000	55	0.00
55.0001	27.50005	0.0707015461454000	1.9282166671800000	0.0366668058360892	55.0001095890107000	55.0001	0.00
60	30	0.0707027699635000	1.7675656512200000	0.0400000814197198	60.0000139496359000	60	0.00
60.0001	30.00005	0.0707027699859000	1.7675627058400000	0.0400001480865709	60.0001139497323000	60.0001	0.00

From table 2.4, we can observe that the value of Rw is varied from 40 Ohm to 60.0001 Ohm, selectively, choosing two values such that they differ by 0.0001 Ohm in resistance. This is to check if the circuit can distinguish between the slightly different values of Rw. Vc1 is the input voltage to the positive terminal of the instrumentation amplifier (INA) while Vc2 is the input voltage to the negative terminal of the INA. Rw1 and Rw2 are maintained at Rw/2 for all values of Rw. RMS(Vc1-Vc2) is simply the RMS value of Vx (Vx = Vc1-Vc2). Vi-v is an alternative notation for the voltage Vc which is the output voltage of the I-V converter. We take the ratio of RMS(Vx) and RMS(Vc) and estimate Rw by scaling this ratio appropriately. From the table, we can observe that the estimated Rw is accurate to 4 decimal places.

This shows that with the RMS computation method, we can differentiate between Rw of 40 Ohm and Rw of 40.0001 Ohm. As of now, we haven't yet considered the impact of the instrumentation amplifier. We measured the RMS value of Vx instead of Vina. This was done to ensure no noise in the circuit due to the instrumentation amplifier to check if the RMS method is better than the peak detection method. Since the results show that the RMS method is quite accurate, we now proceed to include the instrumentation amplifier as well in the noise model and for temperature analysis.

NOTE: We have chosen the RMS computation method over the peak detection method and will stick to it for the rest of the thesis. All results after this point will be for the RMS computation method alone.

2.4 Testing Robustness of the RMS computation method

To test the robustness of this method with varying temperature, the circuit was simulated with the temperature varying from 25° C to 125° C in steps of 20° C. The measurements were noted down and used to estimate Rw. The results are tabulated below.

Table 2.5 Temperature varying estimate for Rw in RMS computation method

					TEMPERATURE ANALYSIS			
Rw	Rw1=Rw2	Temperature	RMS(Vc1-Vc2)	RMS(Vi-v)	RMS(Vc1-Vc2)/RMS(Vi-v)	Estimate for Rw	Estimated Rw upto 4 decimals	Error
40	20	25	0.070694884952500	2.651053480080000	0.02666671400018930	40.000000000152100	40.0000	0.0000
40	20	45	0.070694885334500	2.651053494410000	0.02666671400013880	40.000000000076300	40.0000	0.0000
40	20	65	0.070694885661800	2.651053506680000	0.02666671400017630	40.000000000132500	40.0000	0.0000
40	20	85	0.070694885921000	2.651053516400000	0.02666671400017610	40.000000000132300	40.0000	0.0000
40	20	105	0.070694886121200	2.651053523910000	0.02666671400015080	40.000000000094400	40.0000	0.0000
40	20	125	0.070694886233300	2.651053528120000	0.02666671400008790	40.000000000000000	40.0000	0.0000
40.0001	20.00005	25	0.070694885020500	2.651046855010000	0.02666678066700310	40.000100000195200	40.0001	0.0000
40.0001	20.00005	45	0.070694885402900	2.651046869350000	0.02666678066700250	40.000100000194300	40.0001	0.0000
40.0001	20.00005	65	0.070694885730200	2.651046881630000	0.02666678066693910	40.000100000099200	40.0001	0.0000
40.0001	20.00005	85	0.070694885994600	2.651046891540000	0.02666678066698890	40.000100000174000	40.0001	0.0000
40.0001	20.00005	105	0.070694886191600	2.651046898930000	0.02666678066696350	40.000100000135800	40.0001	0.0000
40.0001	20.00005	125	0.070694886299700	2.651046902990000	0.02666678066690040	40.000100000041300	40.0001	0.0000
50	25	25	0.0706999494036000	2.120994470970000	0.03333339637197010	50.000005807780000	50.0000	0.0000
50	25	45	0.0706999497266000	2.120994480660000	0.03333339637196980	50.000005807779500	50.0000	0.0000
50	25	65	0.0706999499872000	2.120994488480000	0.03333339637193810	50.000005807732000	50.0000	0.0000
50	25	85	0.0706999501811000	2.120994494300000	0.03333339637189080	50.000005807661000	50.0000	0.0000
50	25	105	0.0706999502990000	2.120994497830000	0.03333339637200070	50.000005807825900	50.0000	0.0000
50	25	125	0.0706999503057000	2.120994498040000	0.03333339637185930	50.000005807613700	50.0000	0.0000
50.0001	25.00005	25	0.070699949443100	2.120990230170000	0.03333346303883410	50.000105807898500	50.0001	0.0000
50.0001	25.00005	45	0.070699949762100	2.120990239740000	0.03333346303883360	50.000105807897700	50.0001	0.0000
50.0001	25.00005	65	0.070699950024400	2.120990247610000	0.03333346303881740	50.000105807873400	50.0001	0.0000
50.0001	25.00005	85	0.070699950219000	2.120990253450000	0.03333346303878560	50.000105807825700	50.0001	0.0000
50.0001	25.00005	105	0.070699950336000	2.120990256960000	0.03333346303878540	50.000105807825400	50.0001	0.0000
50.0001	25.00005	125	0.070699950345000	2.120990257230000	0.03333346303878530	50.000105807825300	50.0001	0.0000
60	30	25	0.070702765055300	1.767565578160000	0.04000008029625700	60.000013944163000	60.0000	0.0000
60	30	45	0.070702765309700	1.767565584520000	0.04000008029625680	60.000013944162600	60.0000	0.0000
60	30	65	0.070702765488200	1.767565588990000	0.04000008029608680	60.000013943907700	60.0000	0.0000
60	30	85	0.070702765598200	1.767565591740000	0.04000008029608670	60.000013943907500	60.0000	0.0000
60	30	105	0.070702765612600	1.767565592100000	0.04000008029608670	60.000013943907400	60.0000	0.0000
60	30	125	0.070702765511900	1.767565589580000	0.04000008029614340	60.000013943992500	60.0000	0.0000
60.0001	30.00005	25	0.070702765080200	1.7675626328500000	0.04000014696293930	60.000113944008900	60.0001	0.0000
60.0001	30.00005	45	0.070702765331600	1.7675626391300000	0.04000014696305200	60.000113944177900	60.0001	0.0000
60.0001	30.00005	65	0.070702765511600	1.7675626436300000	0.04000014696305160	60.000113944177300	60.0001	0.0000
60.0001	30.00005	85	0.070702765619300	1.7675626463200000	0.04000014696310800	60.000113944261800	60.0001	0.0000
60.0001	30.00005	105	0.070702765639100	1.7675626468200000	0.04000014696299480	60.000113944092000	60.0001	0.0000
60.0001	30.00005	125	0.070702765533400	1.7675626441800000	0.04000014696293840	60.000113944007500	60.0001	0.0000

From the results in table 2.5, we can conclude that our circuit using the RMS method is robust to temperature within our desired degree of precision. Thus, based on the simulation results the circuit can be considered to be robust to temperature changes.

Now, we shall test the robustness of the circuit to noise. Noise in resistors, operational amplifiers and voltage sources has been modelled based on standard noise analysis procedure stated in the Texas Instruments manual for modelling noise in op-amps [3] by making use of the datasheet for the op-amp IC LF347[4] and the voltage waveform generator AD5932 [5].

The schematic has been modified to model noise in the circuit. The schematic for the noisy circuit is shown in Fig. 2.6 .

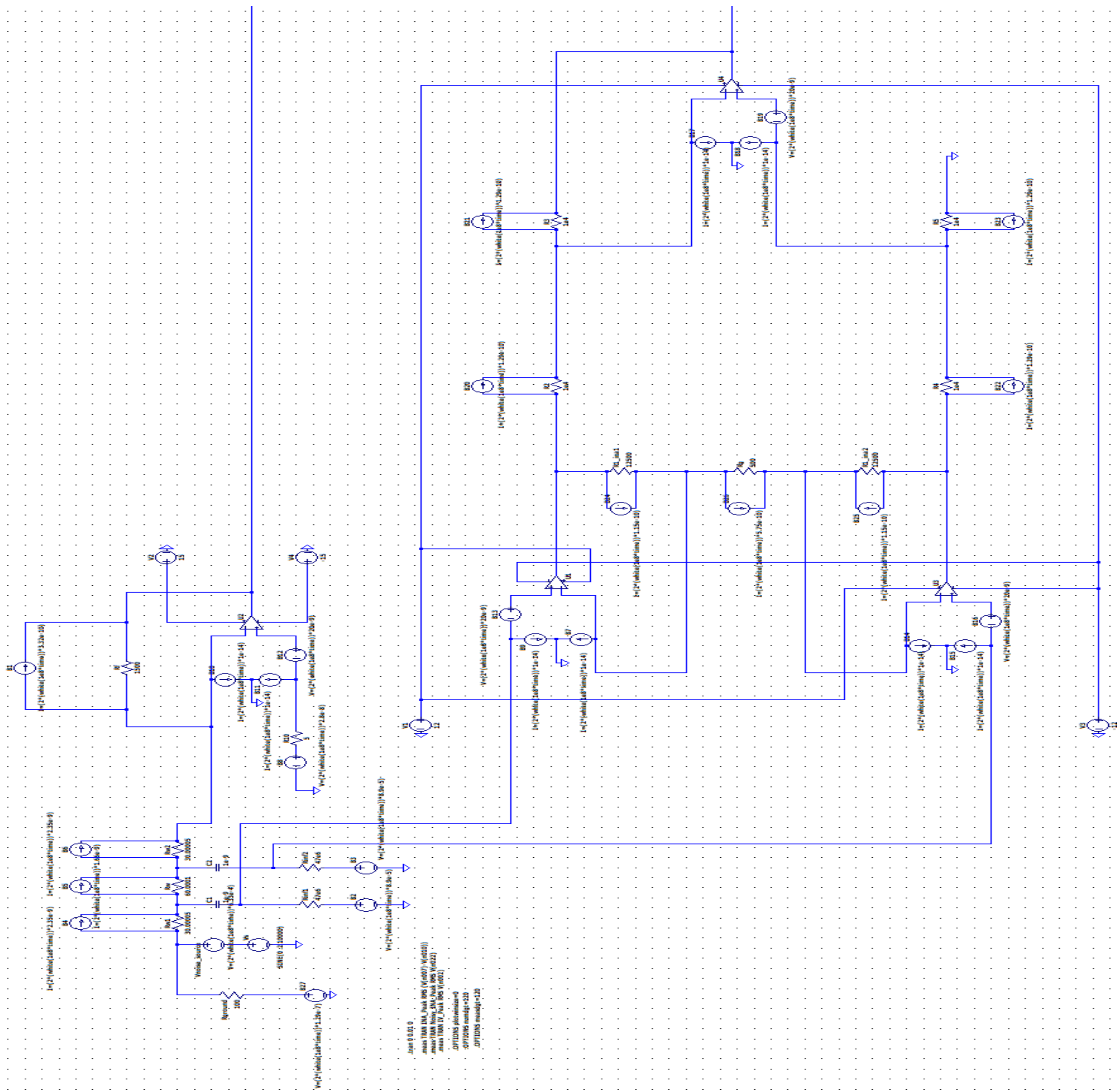

Fig. 2.6 Noise model for RMS computation method schematic

Since the circuit is too large to be visible clearly in a single figure, it is shown in a series of two figures (Fig. 2.7 and Fig. 2.8) on the following pages. Fig. 2.6 can be used as a guide to connect the individual figures of the circuit in Fig. 2.7 and Fig. 2.8 . Fig. 2.7 is that of the bottom left of the Fig. 2.6 including the I-V converter, while Fig. 2.8 is that of the inputs to the instrumentation amplifier all the way till the output of the instrumentation amplifier.

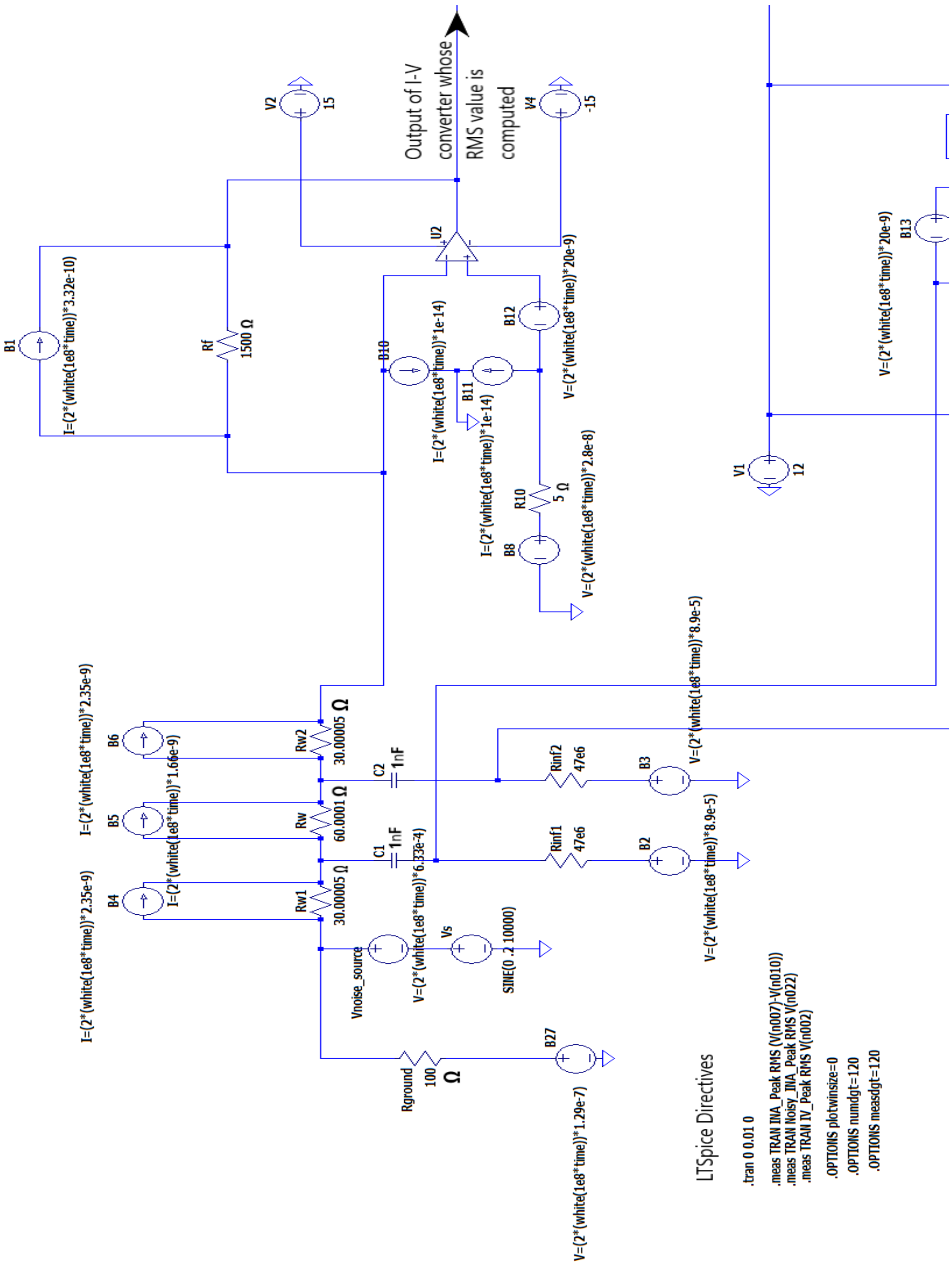

Fig 2.7 Noise model for RMS computation method schematic- Part 1

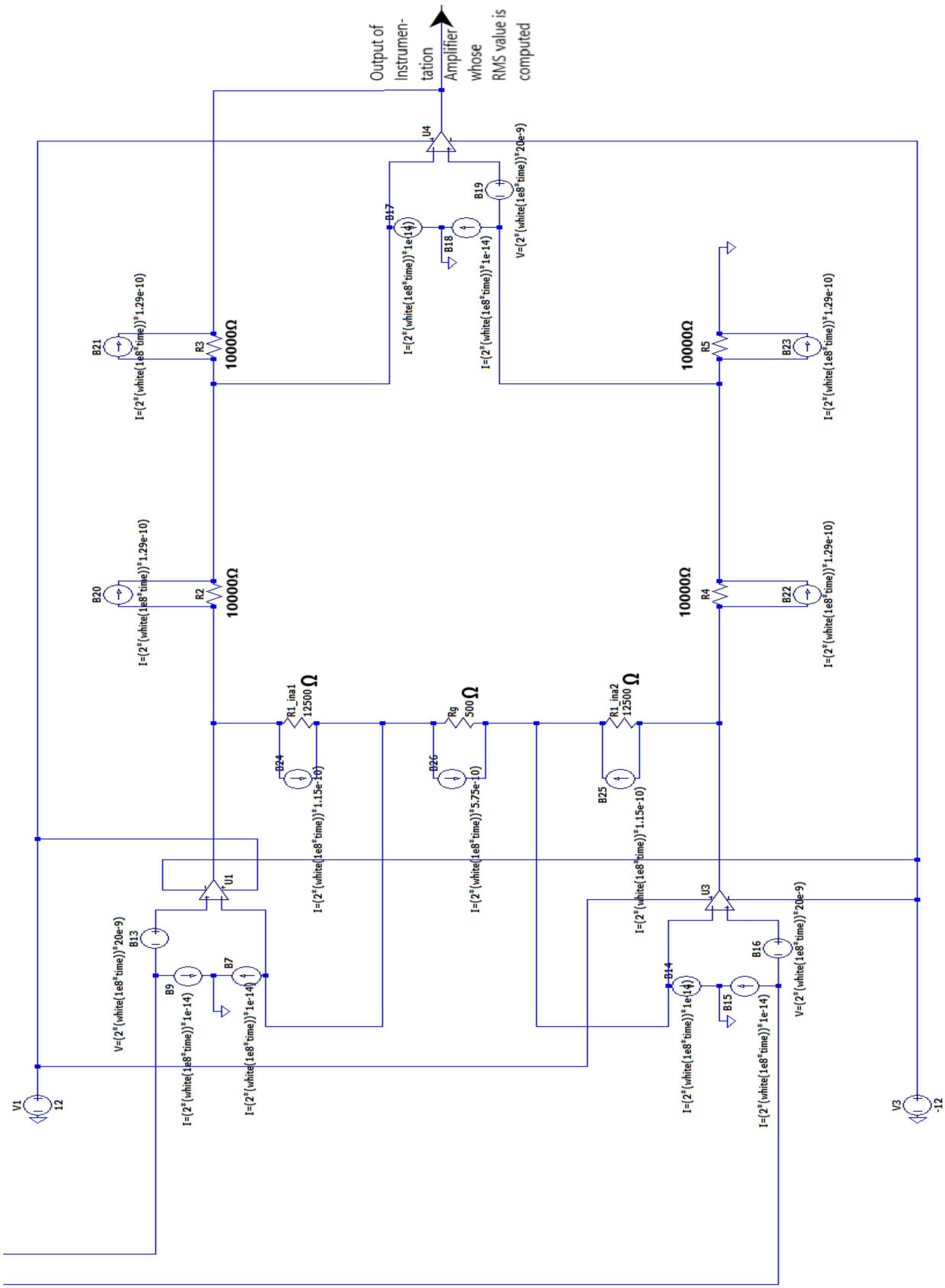

Fig 2.8 Noise model for RMS computation method schematic- Part 2

The instrumentation amplifier IC LT6370 has been replaced by its internal circuit to model the noise accurately. The measurements of the RMS values of the voltages at the output of the I-V converter, the difference in voltage at the inputs of the instrumentation amplifier and the output voltage of the instrumentation amplifier were noted.

The results are tabulated in table 2.6.

Table 2.6 Noisy RMS computation method estimates for Rw

Rw	Rw1=Rw2	RMS(Vc1-Vc2)	RMS(Vi-v)	RMS(Vina)	RMS(Vc1-Vc2)/RMS(Vi-v)	RMS(Vina)/RMS(Vi-v)	Ideal Estimate for Rw
40	20	0.0706954045021000	2.6510729603100000	3.6005545152600000	0.02666671402881090	1.3581499148325900	40.0000000830904000
40.0001	20.00005	0.0706954053296000	2.6510663640100000	3.6005545581600000	0.02666678069222920	1.3581533103206800	40.0001000780403000
45	22.5	0.0706983417622000	2.3566070652000000	3.6007041329000000	0.03000005508181740	1.5279187549216700	45.0000027925795000
45.0001	22.50005	0.0706983418719000	2.3566018311700000	3.6007041374300000	0.03000012175871040	1.5279221503627200	45.0001028077417000
50	25	0.0707004663955000	2.1210099735100000	3.6008123559300000	0.03333339648493010	1.6976876115160900	50.0000060272272000
50.0001	25.00005	0.0707004669259000	2.1210057464300000	3.6008123815100000	0.03333346316713210	1.6976910070002200	50.0001060503527000
55	27.5	0.0707020581761000	1.9282341827200000	3.6008934311200000	0.03666673830891560	1.8674564860376600	55.0000098931828000
55.0001	27.50005	0.0707020572673000	1.9282306516700000	3.6008933845200000	0.03666680498314160	1.8674598816284500	55.0001099043444000
60	30	0.0707032830583000	1.7675785143800000	3.6009558068400000	0.04000008060920570	2.0372253778515100	60.0000144735940000
60.0001	30.00005	0.0707032814441000	1.7675755300400000	3.6009557285500000	0.04000014723133220	2.0372287731707300	60.0001144066065000

Ideal Estimate for Rw	Ideal Estimate upto 4 decimals	Error in Ideal Estimate	Real Estimate for Rw	Real Estimate upto 4 decimals	Error in Real Estimate
40.0000000830904000	40.0000	0.0000	40.0000000050000	40.0000	0.0000
40.0001000780403000	40.0001	0.0000	40.0001000083372	40.0001	0.0000
45.0000027925795000	45.0000	0.0000	45.0000029724554	45.0000	0.0000
45.0001028077417000	45.0001	0.0000	45.0001029744071	45.0001	0.0000
50.0000060272272000	50.0000	0.0000	50.0000064260231	50.0000	0.0000
50.0001060503527000	50.0001	0.0000	50.0001064292435	50.0001	0.0000
55.0000098931828000	55.0000	0.0000	55.0000104075783	55.0000	0.0000
55.0001099043444000	55.0001	0.0000	55.0001104139398	55.0001	0.0000
60.0000144735940000	60.0000	0.0000	60.0000148984225	60.0000	0.0000
60.0001144066065000	60.0001	0.0000	60.0001148967862	60.0001	0.0000

Table 2.6 has been broken into two tables one below the other. The last column of the first table is the same as the first column of the second table below it. The tables are meant to be read as though they were stitched together continuously. The long table has been split into two to make the numbers in the table legible. As stated earlier, Vx is Vc1-Vc2 and Vi-v is the same as Vc. Vina is used to denote the output of the instrumentation amplifier. Here, we consider the effect of the instrumentation amplifier as well. Thus, we have two different ratios. The first ratio is that of RMS(Vx) and RMS(Vc) while the second ratio is that of RMS(Vina) and RMS(Vc). The first ratio is treated as the ideal ratio and scaled appropriately to get the ideal estimate for Rw while the second ratio is treated as the real ratio and scaled appropriately to get the real estimate for Rw.

To model noise in the components, we chose LF347[4] for op-amps and AD5932[5] for the voltage waveform generator. For modelling noise in the voltage source, the SNR value of a voltage waveform generating circuit was noted down to be around 53 dB. To add more noise, we considered the SNR to be 50 dB instead of 53 dB. For an SNR of 50 dB, with the voltage source Vs having a peak of 200 mV, the noise voltage peak comes out to around 0.633 mV. The noise is modeled using arbitrary voltage generators in LTSpice[2] with the distribution of noise being Gaussian White Noise.From the results, we can conclude that the effect of noise is minimal. The estimate is accurate to the 4th decimal place as desired, with the error lying in the 5th decimal place. Since the circuit has been tested to be robust, we now proceed to check how many decimal places of voltage outputs need to be measured using an ADC to ensure that Rw is measured to the desired precision.

2.5 Determining ADC Resolution

Table 2.7 ADC Resolution

The table below illustrates that 6 decimal places of RMS value of Vina and Vi-v need to be measured to achieve desired precision up to 4th decimal of Rw

Rw	RMS(Vi-v)	RMS(Vina)	Rounding RMS(Vi-v)	Rounding RMS(Vina)	RMS(Vina)/RMS(Vi-v)	Estimate for Rw	Estimate(4 decimals)	Error in Estimate
40	2.651072960310	3.600554515260	2.651073	3.600555	1.358150077346040	40.0000100000000	40.0000	0.0000
40.0001	2.651066364010	3.600554558160	2.651067	3.600555	1.358153151165170	40.0001005296094	40.0001	0.0000
45	2.356607065200	3.600704132900	2.356608	3.600705	1.527918516783440	45.0000018186143	45.0000	0.0000
45.0001	2.356601831170	3.600704137430	2.356602	3.600705	1.527922406923190	45.0001163903625	45.0001	0.0000
50	2.121009973510	3.600812355930	2.121010	3.600813	1.697687893975040	50.0000212558089	50.0000	0.0000
50.0001	2.121005746430	3.600812381510	2.121006	3.600813	1.697691095640470	50.0001155507261	50.0001	0.0000
55	1.928234182720	3.600893431120	1.928235	3.600894	1.867455989544840	55.0000029468918	55.0000	0.0000
55.0001	1.928230651670	3.600893384520	1.928231	3.600894	1.867459863470710	55.0001170411118	55.0001	0.0000
60	1.767578514380	3.600955806840	1.767579	3.600956	2.037224927428990	60.0000094456765	60.0000	0.0000
60.0001	1.767575530040	3.600955728550	1.767576	3.600956	2.037228385087830	60.0001112800691	60.0001	0.0000

If we have only a 17 bit ADC, then we can measure up to 5 decimal places
Then, the corresponding error in that situation is shown in the table below:

Rw	RMS(Vi-v)	RMS(Vina)	Rounding RMS(Vi-v)	Rounding RMS(Vina)	RMS(Vina)/RMS(Vi-v)	Estimate for Rw	Estimate(4 decimals)	Error in Estimate
40	2.651072960310	3.600554515260	2.65108	3.60056	1.358148377265110	40.0000100000000	40.0000	0.0000
40.0001	2.651066364010	3.600554558160	2.65107	3.60056	1.358153500284790	40.0001608825116	40.0001	0.0000
45	2.356607065200	3.600704132900	2.35661	3.60071	1.527919341766350	45.0000824452756	45.0000	0.0000
45.0001	2.356601831170	3.600704137430	2.35661	3.60071	1.527919341766350	45.0000824452756	45.0000	0.0001
50	2.121009973510	3.600812355930	2.12101	3.60082	1.697691194289510	50.0001810444579	50.0001	-0.0001
50.0001	2.121005746430	3.600812381510	2.12101	3.60082	1.697691194289510	50.0001810444579	50.0001	0.0000
55	1.928234182720	3.600893431120	1.92824	3.60090	1.867454258805960	55.0000208204053	55.0000	0.0000
55.0001	1.928230651670	3.600893384520	1.92824	3.60090	1.867454258805960	55.0000208204053	55.0000	0.0001
60	1.767578514380	3.600955806840	1.76758	3.60096	2.037226037859670	60.0001172557749	60.0001	-0.0001
60.0001	1.767575530040	3.600955728550	1.76758	3.60096	2.037226037859670	60.0001172557749	60.0001	0.0000

Table 2.7 illustrates the values of RMS(Vina) and RMS(Vc) rounded up to either 5 or 6 decimal places, depending on whether the ADC used has 17 bit resolution or 20 bit resolution respectively. It has been found that measuring 6 decimal places of the voltages requires a 20 bit ADC and the precision in the estimate of Rw is up to the 5th decimal place which is beyond what is required. Measuring 5 decimal places of the voltages requires a 17 bit ADC and the precision in the estimate of Rw is up to the 4th decimal place which matches the desired precision. Based on the analysis so far, we believe that the circuit is robust to variation in temperature and noise. Additionally, due to non-contact probes, the effect of corrosion is eliminated.

2.6 Detecting change in probe set (P2) capacitances

The probes in probe set P2 which are used to measure the voltage Vx need to have their capacitances above a certain value for them to measure Vx accurately. Thus, if their capacitances fall below this threshold, the circuit should be able to detect this anomaly and inform the user to replace the probes. While it may appear that we have run into the issue of replacing probes again, similar to the problem that exists with corrosion, the change in the capacitances of probe P2 are not as frequent as in the case of corrosion. Thus, while the probes may still have to be replaced, they won't have to be replaced as frequently as they would have to be in the case of corrosion.

To detect the change in the capacitances C1 and C2 in the probe set P2, we varied C1 and C2 for 2 values of Rw (40 Ohm and 50 Ohm) and measured the voltages V1(voltage across Rinf1) and V2 (voltage across Rinf2). In the table below, C1 and C2 are in Farad while V1 and V2 are in milli volt and Rw,Rw1 and Rw2 are in Ohm.

Table 2.8 Detecting change in capacitance of probe set P2

True Value of Rw	Values of Rw1=Rw2	C1	C2	V1(mV)	V2(mV)
40	20	1.00E-08	1.00E-08	149.45	49.83
40	20	1.00E-09	1.00E-08	140.0107	49.6
40	20	1.00E-09	1.00E-09	139.13	46.47
40	20	1.00E-10	1.00E-09	41.18	46.111
40	20	1.00E-10	1.00E-10	42.03	14.03
50	25	1.00E-08	1.00E-08	149.66	49.89
50	25	1.00E-09	1.00E-08	139.64	49.61
50	25	1.00E-09	1.00E-09	139.5	46.59
50	25	1.00E-10	1.00E-09	41.34	46.04
50	25	1.00E-10	1.00E-10	41.94	14.03

From the data in table 2.8, we can observe that the standard values for V1 and V2 are in the range of 140-150 mV and 40-50 mV, indicated in green. However, at 100 Hz, we see that if C1 or C2 falls below 1 nF, there is a sudden fall in V1 or V2 respectively. This is because the impedance of capacitors with capacitance less than 1 nF is large in comparison to the Rinf1 and Rinf2 at 100 Hz. Due to this, the voltage across Rinf1 and Rinf2, denoted by V1 and V2 in the table fall drastically. This is a good method to detect change in C1 or C2 independently as can be seen from the table, where changing C1 alone to 0.1 nF keeping C2 at 1 nF causes only V1 to fall while leaving V2 at its standard value.

Since maintaining C1 and C2 above 1 nF might be difficult, we considered the possibility of increasing Rinf1 and Rinf2 from 4.7 MΩ to 47 MΩ each. With Rinf1 and Rinf2 being 47 MΩ, the threshold of C1 and C2 falls further down from 1 nF to 0.1 nF, implying that unless either of the probe capacitances falls below 0.1 nF, the circuit's accuracy is within the desired range and thus, the probes won't have to be replaced.

With this, we conclude the work done in the project and present the conclusion of the work in the following section.

2.7 Conclusion

Based on the results presented so far, we can conclude that the RMS computation method is robust to noise and temperature variation. The contactless method proposed in this paper avoids the problems associated with corrosion and is capable of accurately estimating the conductivity of a liquid (within the error of ± 0.0001 S/m). We have also estimated the ADC resolution required for the circuit's estimate to be accurate to 4 decimal places and 5 decimal places. Additionally, we proposed a method to detect change in capacitances of the probe set P2, to replace them when necessary. While the work done so far is simulation based, we believe that the results will be quite close to the scenario when the circuit is implemented on a physical breadboard or PCB since the noise analysis has been performed thoroughly during the simulation to model noise present in real circuits.

Chapter-3

Summary and Future Scope

3.1 Summary

In this paper, we started off by discussing the importance of accuracy, precision, robustness and quickness of sensors and sensing circuits in general. Then, we moved onto the specific area of work this paper deals with, namely, designing a circuit that can estimate the conductivity of liquids quickly and precisely in a non-contact manner. We stated the importance of conductivity measurements of seawater as an example to emphasise the importance of the work being done in this paper. The circuit was designed, keeping in mind the problems associated with corrosion of probes in the existing methods to measure conductivity of liquids. We presented two different approaches to estimate the conductivity of liquids with a special emphasis on seawater. The first method - peak detection method - was neither accurate enough within the desired range of precision nor robust. Thus, the second method - RMS computation method - was used to obtain an accurate, precise and robust estimate of the conductivity. We transformed the problem of measuring conductivity to the problem of measuring resistance since they are equivalent and one can be directly derived from the other. We determined the ADC resolution required for the accuracy within ± 0.0001 S or ± 0.0001 Ohm equivalently. Then, we proceeded to propose a method to automatically detect the change in probe capacitances of the probe set P2 to indicate potential error in measurement beforehand to the user. All the circuit modelling and simulations were performed on LTSpice[1]. The noise modelling in circuits was performed using the manual provided by Texas Instruments[3].

3.2 Future Scope

The work done so far was performed in a simulation environment. Thus, there is still work to be done in terms of implementing the circuit on a PCB and testing the accuracy of the measurements. One avenue for further improvement is in terms of finding a better way to measure Vx and Ix apart from the RMS computation method, in case there is a need for an accuracy better than ± 0.0001 S. However, we feel that other methods proposed would still rely on an ADC with a much higher resolution than the one determined for the RMS computation method, thereby making it infeasible. Another avenue for further improvement is in the design of better probes which have capacitances much higher than the standardly available 1 nF capacitance probes.

References

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