

DESIGN OF A LOCK-IN AMPLIFIER MICRO-OHMMETER USING PROTEUS VSM

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Abstract

This paper presents the design of a lock-in amplifier micro-ohmmeter using Proteus VSM. To achieve a seamless complex design, it is usually better and easier to break the design task into stages and this paper used that approach in Proteus to achieve the task of designing the micro-ohmmeter. The paper introduced the concept of a micro-ohmmeter and its constituent segments. Each segment was analyzed at component level with appropriate mathematical equations. The result and implementation of each analysis was verified through simulation in Proteus. The paper makes a comparison between the theoretical operation of the circuit and the operational result obtained via the simulation. The comparison confirms that the design of the circuit using Proteus was successful due to the fact that the simulation results matched that of theory.

Keywords: Micro-ohmmeter, Proteus, simulation, circuit design

1. Introduction

The increase in the demand for very accurate measuring instruments is motivating the design of highly sensitive instruments like the micro-ohmmeter with the ability to measure very small resistances in the presence of large noise. The more highly accurate measuring instruments there are, the more highly precise electronic components and devices can be designed and produced, thus enhancing reliability of such components. In sophisticated and advanced applications of electronics, integrity of signals and installation cannot be taken for granted once they have been ascertained. The integrity of component parts of such installations can be reliably measured using devices like the micro-ohmmeter.

The purpose of this paper is to design and test a lock-in amplifier based micro-ohmmeter, which has the capability of measuring very small resistances without the application of large currents. To achieve this, the device is specified to measure a maximum resistance of $0.22\Omega \pm 20\%$ with a supply voltage of 6V. The excitation oscillator is specified to output a frequency of $275\text{Hz} \pm 10\%$ and an unloaded output signal of $E_{TH} = 200\text{mV}$ (Bateson, 2011).

1.1 Overview of Instrument

The lock-in amplifier based micro-ohmmeter is made of four stages, starting from the source to the output:

- The source stage is made of an excitation oscillator, a quadrature divider and an attenuator.
- The instrumentation amplifier stage which has a buffered amplifier, a phase reversing switch, and a differential amplifier.
- The filter stage which has a Sallen-key equal value Butterworth lowpass filter to remove noise in the form of mains pick-up.

- The output stage which has a Voltage Controlled Oscillator (VCO), whose oscillation is muted by a transistor in the off-state. This is achieved using a muting detector circuit. (Bateson, 2011).

The block diagram of the interconnectivity between the different stages is shown in Figure 1.

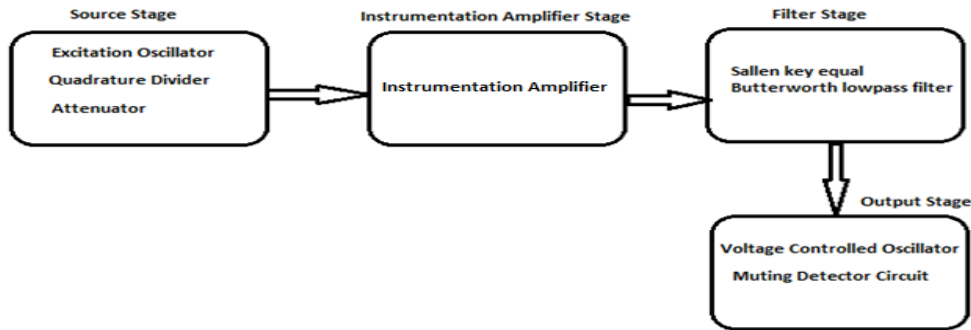


Figure 1: Block diagram showing interconnecting stages of the micro-ohmmeter

2. Sub-Circuits Design and Analysis

In this section, the detailed design and analysis of each of the four stages of the micro-ohmmeter is carried out.

2.1 Source Stage

This stage is made of a 555 timer, 4013 frequency divider, and an attenuator. The specifications for this section are:

$V_{in} = 6V$, $V_{out} = 200mV \pm 5\%$, Input frequency (f_{in}) = 1.1kHz, Output frequency (f_{out}) = 275Hz.

2.2 The 555 Timer

The 555 timer (Horowitz and Winfield, 1989) is connected as an oscillator in a stable mode in this stage. Figure 2 shows this connection:

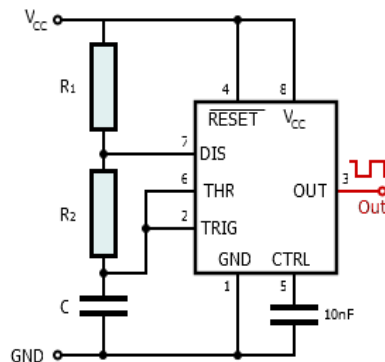


Figure 2: The 555 timer in a stable mode

The capacitor C (Horowitz and Winfield, 1989) is discharged when power is applied, causing a triggering of the 555 timer, and the output goes HIGH. The capacitor begins to charge towards V_{cc} through $R_1 + R_2$. When it reaches $2/3 V_{cc}$ or V_s as shown in Figure 3, the THRESHOLD input becomes triggered, causing the output to go LOW. The capacitor C is then discharged towards ground through R_2 . The operation is now cyclic and the voltage of C goes between $1/3 V_{cc}$ and $2/3 V_{cc}$, with a period of

$$T = 0.693(R_1 + 2R_2) C \tag{1}$$

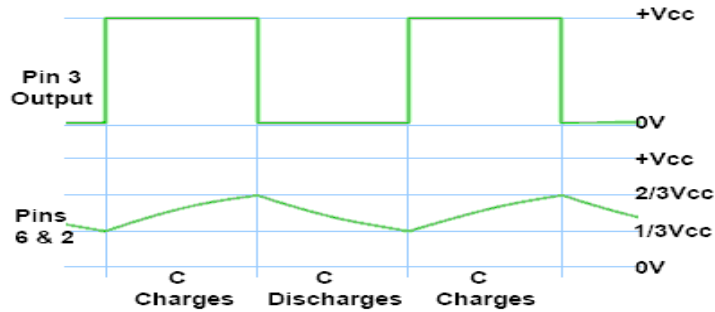


Figure 3: Charging and discharging of capacitor C

2.3 Quadrature Divider (4013 Frequency Divider)

The 4013 frequency divider used in this stage is in pairs, and both of them are triggered by the 555 timer. Figure 4 shows the 4013 divider and its output waveform. The function of the 4013 divider is to divide frequency of the signal at its clock input.

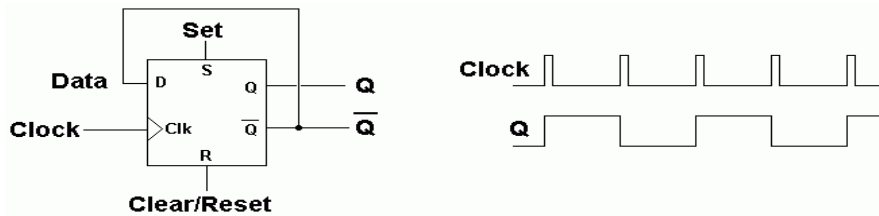


Figure 4: The 4013 frequency divider and output waveform

From the waveform of the frequency divider, by “feeding back” the output from Q' to the input terminal D, the output pulses at Q have a frequency $f/2$ that of the input clock frequency (Horowitz and Winfield, 1989).

2.4 Attenuator

This is a resistive divider network used for precise control of amplitude. In this stage, the amplitude being controlled is that of the signal from the quadrature divider. The attenuator is shown in Figure 5.

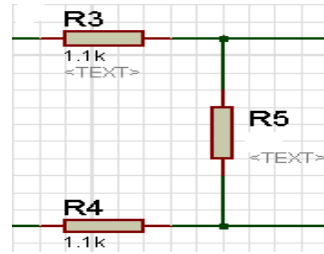


Figure 5: Attenuator

The period T is given in Equation (1) as:

$$T = \frac{1}{f} = 0.693(R_2 + 2R_1) C \quad (1)$$

Where: f is the frequency = 1.1 kHz, from the given specification.

Therefore, $T = \frac{1}{1100} = 0.000909$. Substituting for T in equation (1),

$0.000909 = 0.693(R_2 + 2 * 1000) * 10e - 9$. Setting R_1 at $1k\Omega$

$$R_2 = 129.168k\Omega \approx 130k\Omega$$

By the rule of voltage divider (Horowitz and Winfield, 1989):

Setting R3, and R4 to $1.1k\Omega$, $V_{out} = 200mV$ from specification, and $V_{in} = 6V$ from specification.

$$V_{out} = V_{in} * \frac{R5}{R3+R4+R5} \quad (2)$$

$$0.2 = 6 * \frac{R5}{2200 + R5} \Rightarrow R5 = 75.86\Omega$$

From the foregoing calculations, the design of the source stage is shown in Figure 6.

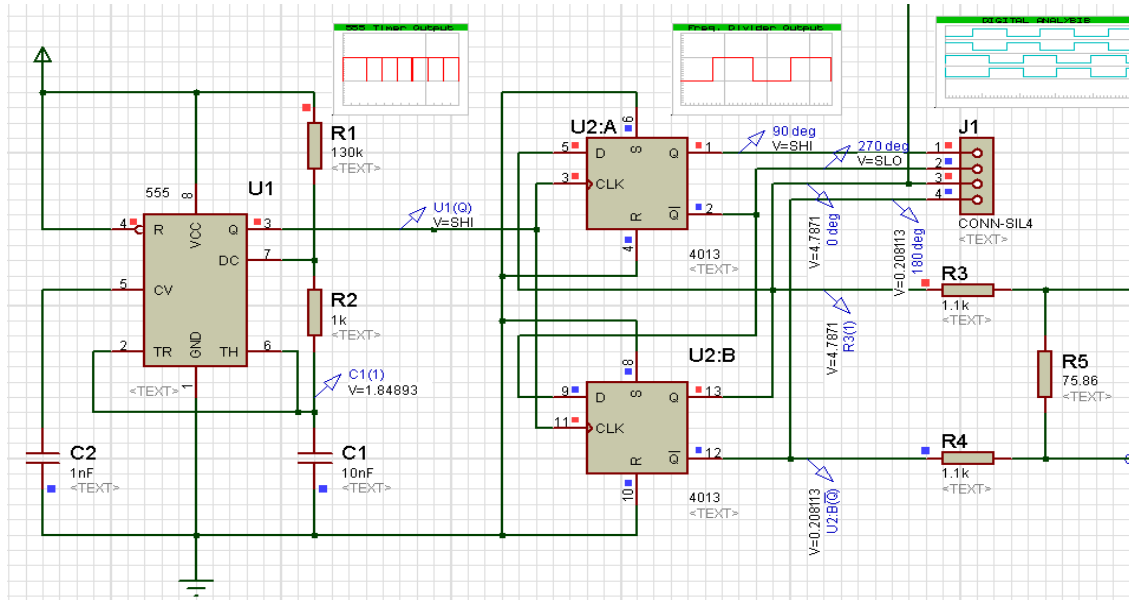


Figure 6: Design of the source stage for the micro-ohmmeter

When a $1\text{m}\Omega$ resistor is connected across R5, the effective resistance becomes $1\text{m}\Omega$. By voltage divider in equation (2), the output becomes $2.72\mu\text{V}$. When a 0.22Ω resistor is connected across R5, the effective resistance becomes 0.219Ω , and by equation (2), the output voltage is calculated as $597\mu\text{V}$.

However, due to the inherent forward voltage drop ((Horowitz and Winfield, 1989) from the 4013 frequency divider, the recalculated value of R5 becomes:

$$0.2 = 4.8 * \frac{R5}{2200 + R5}$$

Therefore, $R5 = 95.65\Omega$, and the nearest value of R5 is 91Ω .

$$\text{This implies } V_{out} = \frac{0.219}{2200+0.219} = 477\mu\text{V}$$

2.5 Instrumentation Amplifier Stage

Instrumentation amplifiers have high gain differential input with high input impedance and they have a single-ended output. The input stage is a configuration of op-amps that provides high differential output representing a signal with substantial reduction in the comparative common-mode signal, and is used to drive a conventional differential circuit (Horowitz and Winfield, 1989). Figure 7 shows the buffered stage of the instrumentation amplifier.

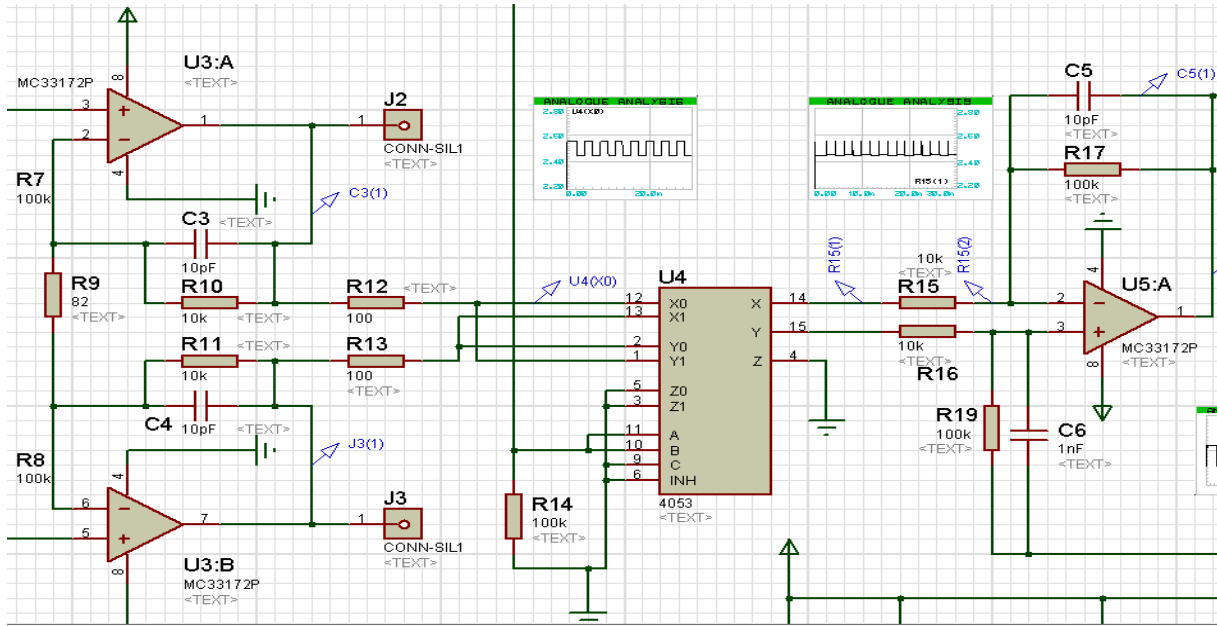


Figure 7: Instrumentation Amplifier

The relationship between the gain and the value of R9 from is given by:

$$V_{out} = \left(1 + \frac{2R_{10}}{R_9}\right) \frac{R_{17}}{R_{15}} (v_1 - v_2) \quad (3)$$

From equation (3), we can see that the gain is distributed. This gives the advantage of an overall increase in bandwidth. However, the disadvantage of such an action is that the gain will be at the expense of Common Mode Rejection Ratio (CMRR) (Stephen, 2001)

Given the peak voltage amplitude of 1.2V at the output of U5A, and by equation (3), R₉ is calculated thus:

$$2.4 = \left(1 + \frac{20000}{R_9}\right) * \frac{100000}{10000} * (0.000954)$$

Where v₁ = 477μV, and v₂ = -477μV.

There R₉ = 79.81Ω, and we choose the nearest value of 82Ω.

The 4053 phase reversing switch shown in Figure 7, has a single pole change-over switches, which are simultaneously operated pairs of transmission gates. Since their switch actions are simultaneously in opposite directions, they cancel most of the switch charge injection (Lee and Philip, 2003).

2.6 Filter Stage

This is the stage in which we remove unwanted noise (switching noise, noise from main pickup, thermal noise, and DC offset) coming from the instrumentation amplifier stage. It has the Sallen-key equal value filter, which is a low-pass filter. Figure 8 shows the Sallen-key equal value filter.

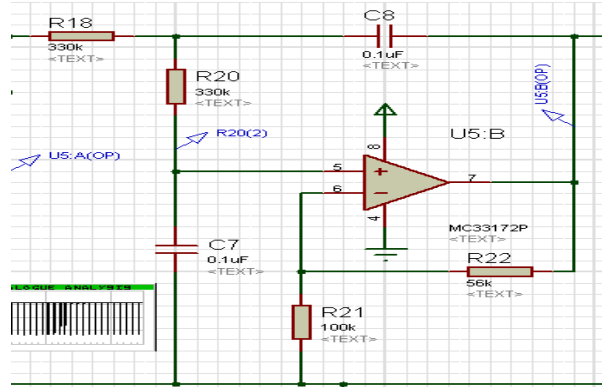


Figure 8: Sallen key equal value filter

From (Bateson, 2011), Equation (4) shows that:

$$R18 = R20 = \frac{1}{2\pi f_0 C_7} \quad (4)$$

where: f_0 is chosen to be 5Hz.

$$R18 = R20 = \frac{1}{2\pi * 5 * 0.1\mu F} = 318.309k\Omega$$

The nearest value for $R18 = R20 = 330\Omega$.

2.7 Output Stage

This stage is the output of the system. It consists of a Voltage Controlled Oscillator (VCO).

2.7.1 Voltage Controlled Oscillator

The Voltage Controlled Oscillator (VCO) is an oscillator circuit whose frequency can be controlled or varied by a DC input voltage. In this design, the VCO has an integrator whose output is fed to a Schmitt trigger. The design of the VCO is realized in Figure 9 below:

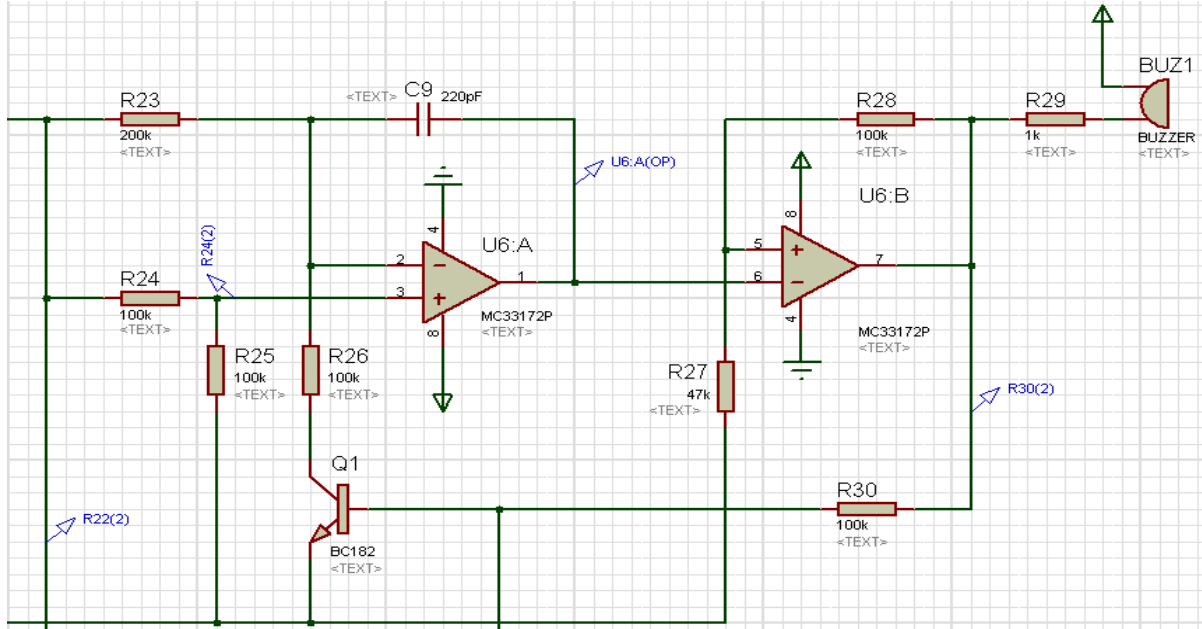


Figure 9: Voltage Controlled Oscillator

When the output of the Schmitt trigger U6:B is in the low state i.e. approximately 0V (Figure 10a), it causes Q₁ to be off (Figure 10b) and all the current supplied by R₂₃ flows into capacitor C₉, thereby causing a down ramp of the output of U6:A. When this output from U6:A reaches 0V, a snapping of the Schmitt trigger occurs, which causes the output of U6:B to jump to maximum voltage (Figure 11a). This turns Q₁ ON (Figure 11b), shorting R₂₆ to ground and sinking a current $\frac{V_{vco}}{2R_{26}}$, where V_{vco} is the input voltage to the VCO stage. But this current is twice that supplied by R₂₃; so the other half comes from C₉. Because Q₁ is ON and current flowing through C₉ is reversed, the output of U6:A is now ramped upward.

The frequency of the VCO is given as Equation (5):

$$f_o = \frac{V_{vco}}{8RC_{13}(V_{TH} - V_{TL})} \quad (5)$$

Where V_{TH} = upper threshold, V_{TL} = lower threshold, R = R₂₆ = 100kΩ.

Hence,

$$C_{13} = \frac{V_{vco}}{8Rf_o(V_{TH} - V_{TL})}$$

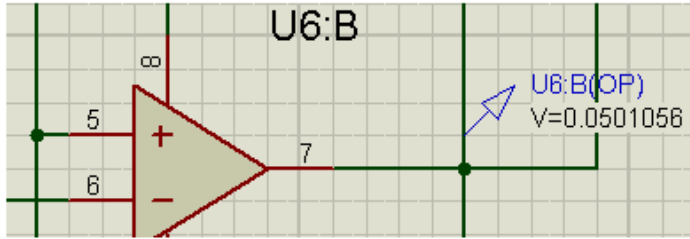


Figure 10a: U6:B in LOW state



Figure 10b: Q1 turned OFF with base ≈ 0

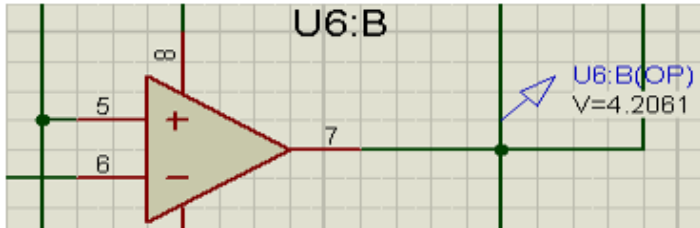


Figure 11a: U6:B in HIGH state



Figure 11b: Q1 turned ON

3. Simulation and Results

The simulation of the entire design (done with Proteus VSM) reveals the following results: the output of the 555 timer shown in Figure 12 reveals the relationship between output of the timer (pin 3) and the charge and discharge behavior of the capacitor (pin 6). The result obtained in Figure 12 confirms that the design produced the expected result as shown in Figure 3.

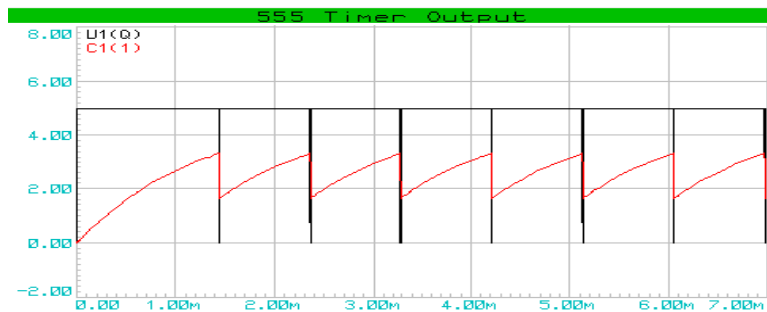


Figure 12: Output of pin 3 and 6 of the 555 timer

The simulation result of the 4013 frequency divider shown in Figure 13 shows the output is half that of the 555 timer Figure 12. The result obtained confirms that the design produced the expected output depicted in Figure 4.

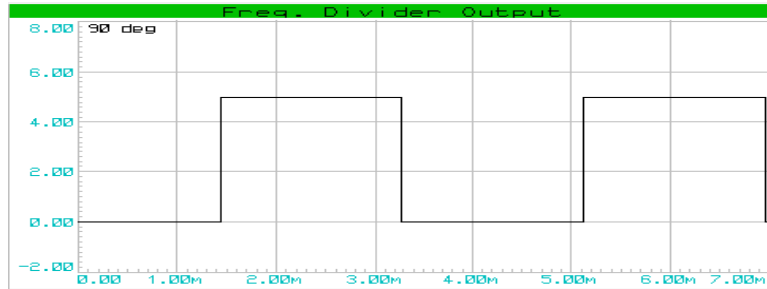


Figure 13: Output of 4013 frequency divider

The simulation of the output stage of the design is shown in Figure 14. The buzzer is used because the design is conceived to give an audible sound as it makes small measurements. Figure 15 shows the complete system design.

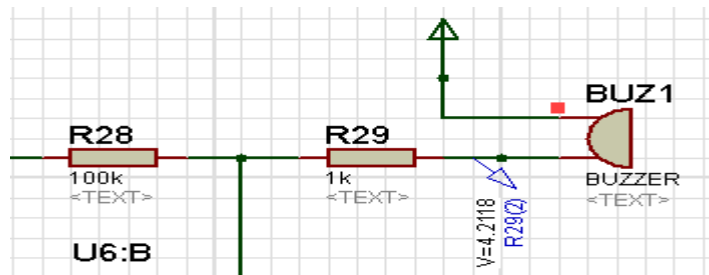


Figure 14: Buzzer output

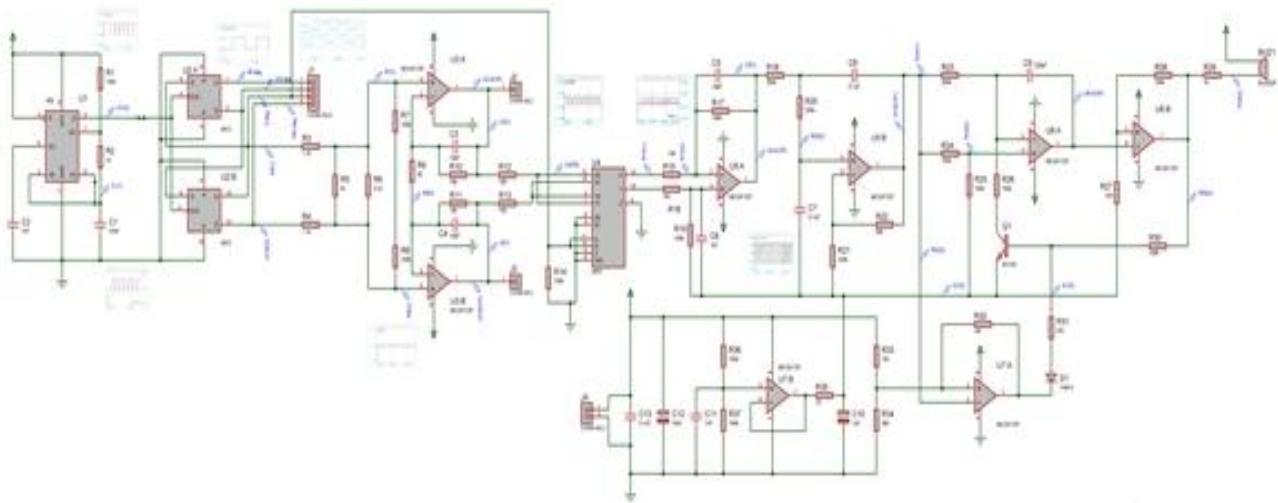


Figure 15: Complete System Design

4. Conclusion

In this design, the operating principle and simulation results of different segments of a micro-ohmmeter were presented. The function of each segment and the effect they have on the signal were discussed. Calculation of values for each component used in the design was performed and presented in each subsection that deals with the analysis of each component. It should be noted that the values obtained and used in design are ideal values; hence the output of the system will be ideal. In practice however, there will be a variation in the output of the design because the components selected and used will have slight tolerances. Using Proteus VSM, the design of the Lock-in Amplifier Micro-Ohmmeter was successfully carried out and the result obtained in the design matched the expected theoretical results.

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