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Shuttle Box Design

(User Controllable PWM and Current Generator)

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The main objective of this study was to design a shuttle box for inhibition testing on rodents, such that as a mouse enters the box, it should experience a different intensity of current shocks for a different period of time, both being controllable by the user. The shuttle box needs to be designed with the conductive floor so that as the mouse enters the box it feels the electric shocks as generated by current sources and controlled by switching circuit.

In this project, AC and DC current sources are designed to provide a constant current to the mouse whereas, national instrument USB 6008 DAQ is implemented with Labview to create PWM signal for the switching of the current and controlling of current intensity. Similarly, the front panel in LabVIEW is designed in such a way that it serves as a user interface so that user can easily control the duty cycle of the pulse, pulse duration and total run time of the whole system.

The shuttle box was tested with different values of resistors as well as with human hand to ensure the effectiveness of the current source and the operation of PWM signal in LabVIEW. The simulated and measured results were supporting each other to a great extent. Throughout the operation, the actual intensity of current as experienced by the mouse and its duration was monitored in LabVIEW front panel that ensured the safety of mouse and the effectiveness of the experiment.

Keywords	Oscillator, PWM, Duty cycle, Labview, AC, DC, Current source

Contents

1 Introduction

Modern technology and science are soaring beyond imagination, creating new devices and introducing inconceivable solutions for different complications. Research in medical science blended with technology on different areas of animal behaviors have greater influence in today's world and mankind. Research in animal behavior has been a dedicated link between organism, environment and between nervous system.

Acknowledging striking similarities between mice and the human genome, behavior testing, using mice as a subject of the test using electric shock as an aversive stimulus is currently being used for the evaluation of different traits such as sensory-motor functions, social interactions, anxiety-like and depressive-like behaviors, substance dependence and different forms of cognitive functions. Furthermore, electric shocks as stimulus is highly admired because of its incredible ease in quantification; can be manipulated to have discrete or gradual onset and offset; and (intensity typically used in research) does not cause physical damage to the subject. Thus, the main idea of this thesis project is to design similar electric shock testing shuttle box for inhibition testing on mice.

The most crucial objective of this study was to design and develop a shuttle box with controllable PWM generator and current sources which can be readily used in the laboratory for testing mice, using control electric current as shock stimulus. Labview dominated designing of software part. National Instruments USB-6008 data acquisitions device (DAQ) was implemented with it to generate PWM signals to control pulses as generated by current sources. Thus, this mechanism enables the user to set current from the range of 0 to 0.5 mA to any desired time period.

2 Electric Properties of Living Tissues

Study of tissues interaction with the electromagnetic energy has significant effects on the field of impedance pneumography and electrical impedance tomography. Analysis of impedance factor on red blood cell suspensions up to 10 MHz and finding of the reciprocals relationship between impedance factor and frequency concluded that a poorly conducting membrane of relatively low resistivity surrounded the cells and the impeditive character of biological tissue eases the current to be spread through tissues in a frequency dependent manner.

Fig. 1 shows the electrical double layers formed at the surface of the skin. Dielectric and electrical conduction properties of biological materials are the fundamental parameters that influence the EM radiation. Most biological materials have permeability close to that of free space. Whereas, the magnetic field effect is limited to the nuclear magnetic moments or interaction between unpaired electrons. These effects are highly limited and have an insignificant effect on bulk electrical properties. [1]

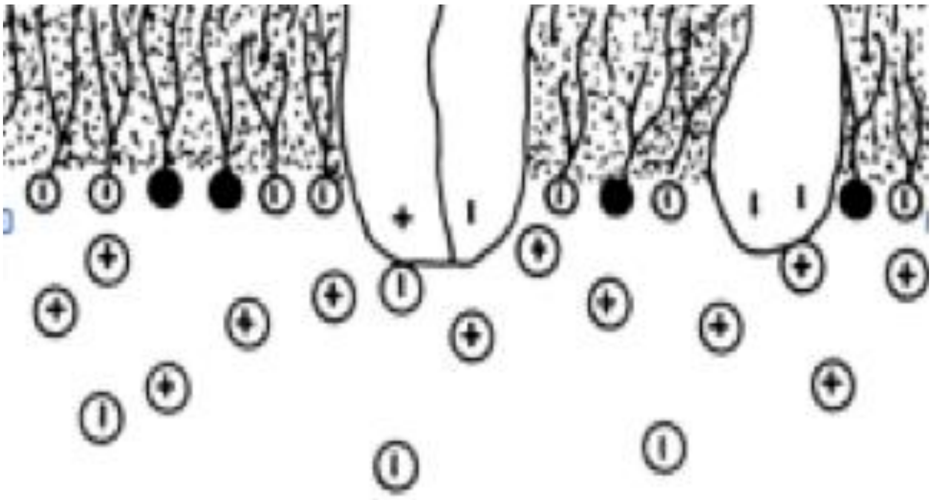


Figure 1. The electrical Double layer formed at the surface of the membrane. [1]

2.1 Dielectric Theory

Electrical properties of any materials that are held between parallel electrodes of area A with a considerable distance of D are characterized by their electrical conductance G and capacitance C, as given by following relations,

$$G = \sigma A/d \qquad (1)$$

$$C = A\mathcal{E}\mathcal{E}_0/d \qquad (2)$$

These equations are equally valid in impedance measurement in biological subjects where conductivity σ for any biological materials are given by the mobility of hydrated ion, whereas permittivity $\mathcal{E}$ are associated with electrical double layers occurring at membrane surfaces or with polar molecules.

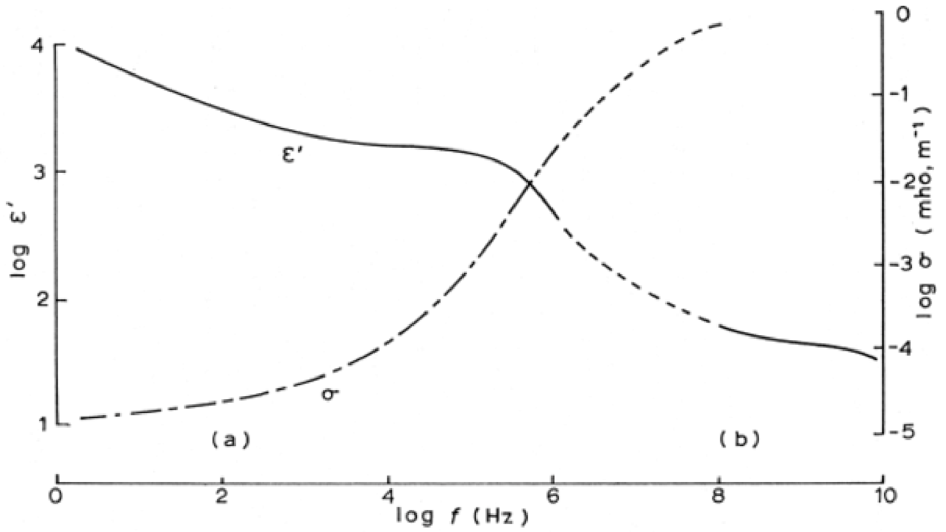


Figure 2. Frequency variation of the relative permittivity and conductivity of skin at 37℃. [1]

As illustrated in fig. 2, the increase of conductivity and decrease of the relative permittivity of skin with the frequency of applied current gives clear idea that relative capacitance decreases with frequency and conductance of skin increases with frequency, which is valid for all biological subjects.

3 Bioimpedance Representation

Measuring of bioimpedance is a complex method, which requires measurement of intracellular and extracellular resistance and capacitance of cell membranes. In all biological materials, cell membrane conducting electrical current exhibits capacitive behavior. Body fluids are rich in ionic materials that is why they are a good conductor, while fat cells are non-conductive in nature and bones are considered as non-conductor. Therefore resistive measurement is only focused on soft tissue hydration [3]. A simple electrical model can be represented as below in fig. 3.

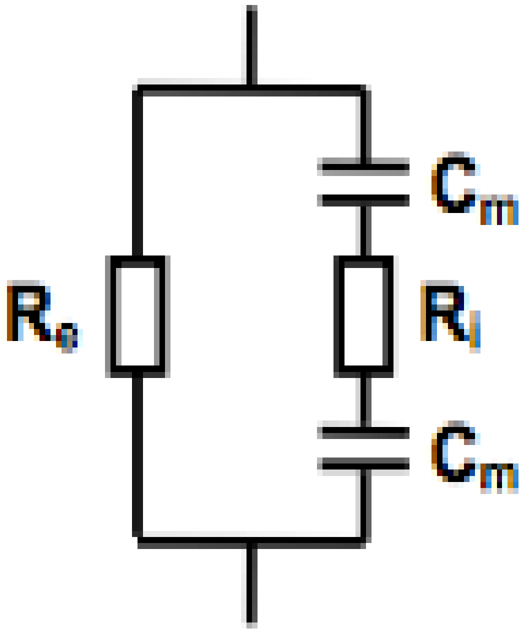


Figure 3. An electrical representation of a typical cell inside living organism. [2]

Where

C_m is the Capacitance of cell membrane (dielectric),R_e is the extracellular resistance and R_i is the intracellular resistance. [2]

As the model represents, living tissue is a combination of resistive and capacitive properties, which make them more effective to AC current, as frequency has a direct effect on the relative reactance and phase shift of the whole system.

Generally, there are two basic ways of measuring bioimpedance using current source by a contact method, i.e. electrodes used in measuring process are in direct contact with the measuring tissue.

3.1 Two-electrode Method

In this technique, two electrodes are used to measure tissue impedance as shown in fig. 4 (a), which introduces unavoidable interfacial impedance (Z_c), this is further added to the real impedance of the tissue Z_x as shown in fig. 4 (b). Thus, the total impedance (Z_{total}) measured in this method is the sum of real tissue impedance and parasitic impedance of electrode [2]. Mathematically it can be expressed as in equation 3.

$$Z_{total} = \frac{V}{I} = 2Z_c + Z_x \qquad (3)$$

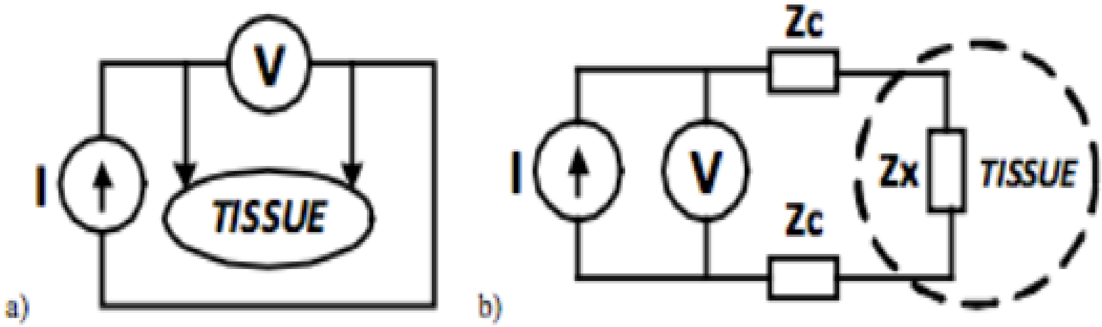


Figure 4. Two-electrode bio impedance measurement techniques (a), electrical representation of equivalent circuit of 4.a (b). [2]

3.2 Four-electrode Method

In this method four electrodes are used, two for supplying measuring current and two for measuring the voltage drop across the tissue, as produced by so-called excitation current. In doing so, the interfacial impedances (Z_c), are formed in both the pair of electrodes and are in series with the high input impedance of measuring device, therefore, it reduces the effect of unwanted parasitic impedance on tissue impedance Z_x. A mathematical expression is shown in equation 4.

$$Z_x = V/I \qquad (4)$$

Where V is the voltage across subject tissue and I the current applied to tissue as shown in fig. 5 (b).

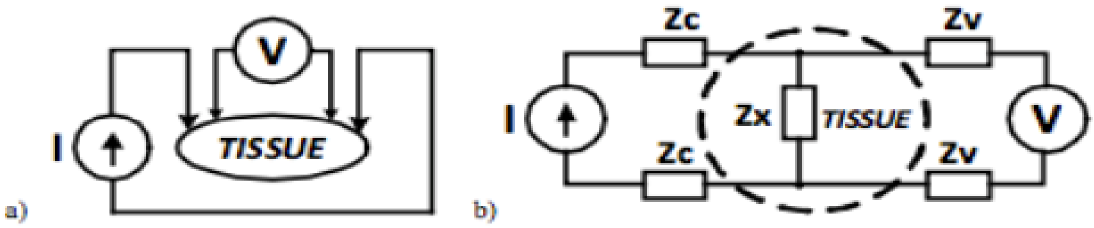


Figure 5. Four-electrode bio impedance measurement techniques (a), and the equivalent electrical circuit of a. (b). [2]

Therefore, tissue impedance is highly influenced by the frequency of electrical current because of the presence of capacitive component and is applicable for all biological materials. Since this study is much concerned in rodents, their body impedance factors are also the same as discussed above.

Fig. 6 shows an overview of impedance change in the healthy brain of rats in different frequencies. This shows a sharp reduction of impedance up to 25 % as frequency increases from 0-250 Hz and the reduction continues in a non-linear manner with higher frequencies. [4]

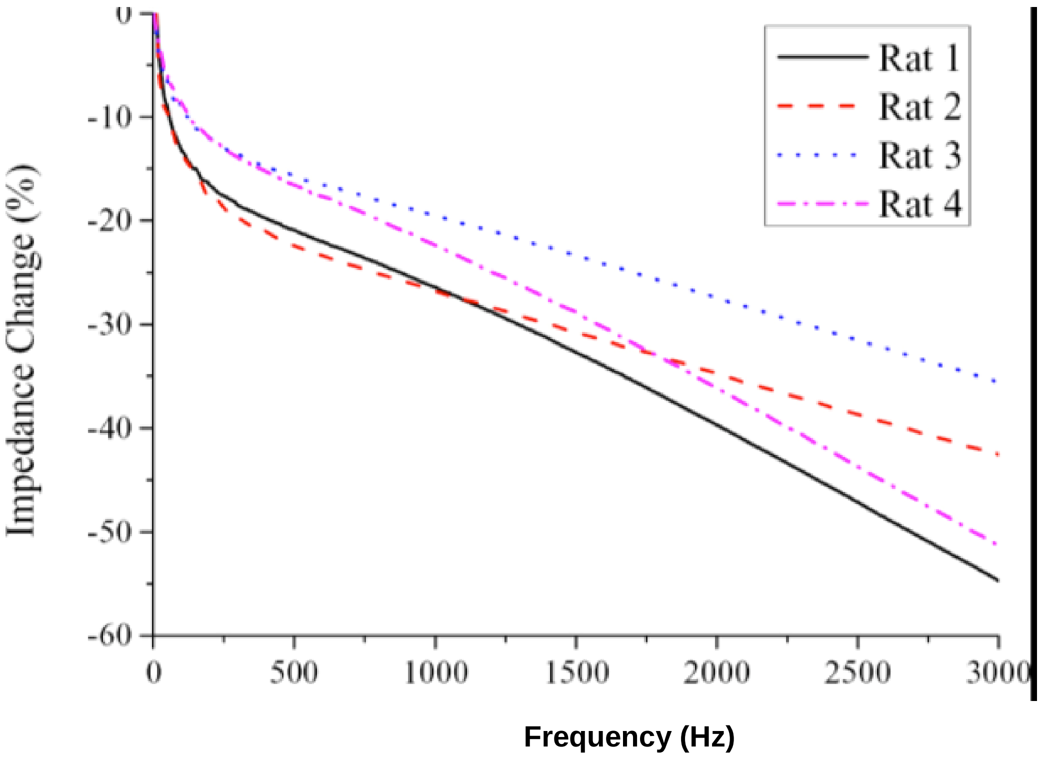


Figure 6. Change in impedance vs. frequency in a healthy rat's brain. [4]

In this project, rodents are used as bioimpedance for the whole system. Using DC voltage and current had no effect because the impedance factor of the skin of mice to DC current was too high for conduction resulting the circuit to be open circuit all the time. Therefore AC current source was implemented so that the frequency of current source makes a substantial decrease in subject's impedance and results in conduction for the very small amplitude of the current through it.

4 Shuttle Box Operation

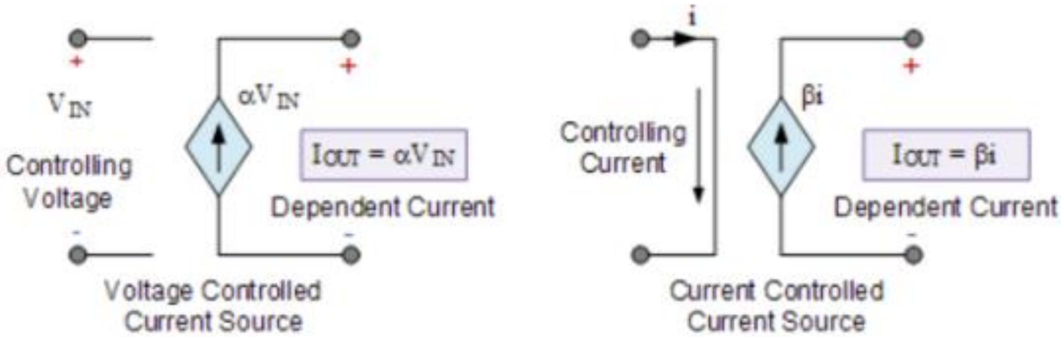
The shuttle box as a device operates in such a way that it gives shocks to the mouse in a controlled way. The most crucial objective of this system is to have a user-friendly software interface that enables the user to alter parameters like period, duty cycle, a number of iterations of shock cycle and amount of current (shock intensity) to the mice during avoidance testing. Thus the system consists of three major parts PWM switch as designed in LabVIEW programming environment, current source (AC and DC) and grid of consecutive power and ground lines where mouse is placed so that when it moves over grid the power and ground lines get connected via mouse and current flows through the subject (mouse).

Therefore when the PWM, also acting as DC switch is set to ON state, the current generated by the current sources AC and DC is allowed to flow through mouse via the grid. On the other hand, when it is set in OFF state, current stops to flow and mouse feels no current at all. The PWM switching system has features of setting time for each cycle along with the duty cycle furthermore user has the ability to pre-set operating conditions for up to twelve loops before execution.

5 Constant Current Generator Fundamentals

A constant current generator (source) is the dual of the voltage source. It is described as an electric element that delivers or absorbs constant current regardless of the voltage across its terminal. In other words, the current driven across current source remains steady, even if the value of resistance fluctuates during the time of operation. Any real current device is very close to ideal current source but can never be equal to a mathematical model of the ideal source, since the ideal current source has infinite output impedance, which requires having infinite voltage supply.

There are various applications of current-source in electronics compared to voltage-source. The most significant use of current sources is in transistor circuits inside complex IC's. Similarly, most logic functions and even signal processing such as audio amplifiers are based on the constant current source. On the other hand, constant current sources are also used in battery charging and LED lighting. LED circuits with the dimming use constant current source, since LED brightness is a function of current, (disproportional to the current) and voltage varies with temperature. [5] If the current through any source is independent of another variable in the circuit then it is considered as independent current source while the source that delivers constant current depending on some voltage is called voltage controlled current source whereas those circuits, which give constant current depending on some reference current, are called current controlled current source as shown in fig. 7.



(a) (b)

Figure 7. Voltage controlled current source (a), current controlled current source (b). [6]

6 Types of Current Sources

Constant current sources can be further analyzed on the basic components implemented for the generation of current namely passive and active current sources.

6.1 Passive Current Source

A simple non-ideal passive current source consists of the voltage source in series with a resistor, the current generated from such circuits are basically delivered to load which has zero drop of voltage (charged capacitor, uncharged inductor, short circuits or virtual ground circuits). If this current is delivered to load of non-zero voltage drop then the resulting current value is the ratio of the voltage drop across the resistor to its resistance. Passive current sources are of low efficiency due to power loss across the resistor and are limited to a very small range of current and load resistance. For example, a 2.5 V voltage source in series with 2.35 kΩ resistor can deliver a constant current of 1 mA $\pm$5 %, to narrow range of load resistance of 25 to 250 Ω. [7]

6.2 Active Current Source

In contrary to this, active current sources are generated using active electronic components (transistors, op-amp) and are more versatile having numerous applications in electronics circuits. Transistor circuits with common emitter configuration powered by constant current or voltage and common source (common cathode) driven by constant voltage are very common current source types because these devices have a very high output impedance. The output of simple current mirror circuit using transistors (BJT, MOS) is also very widely used the current source in an integrated circuit. [7]

Furthermore, the type of applied input voltage (AC or DC) on voltage control current source systems determines the output nature of the active current source. If the input voltage is AC then the voltage control current source generates constant AC current, i.e. alternating current with constant frequency and constant (root mean square) RMS amplitude, whereas use of DC source in the input of voltage control current source yields DC current of constant magnitude.

7 DC Current Sources

In this study, both the types of active current sources are implemented using transistors and operational amplifiers. Most basic and versatile types of DC current source are explained as below,

7.1 Constant Current Diode

Basic JFET transistor, whose gate and source electrodes are shorted, generates constant saturated current over a large voltage range acting as a constant current source. When the voltage applied exceeds the pinch-off voltage JFET operates in the saturation region where it generates constant current until the voltage reaches breakdown region. As shown in Fig. 8, the constant current is generated from pinch-off voltage to breakdown voltage range. [8]

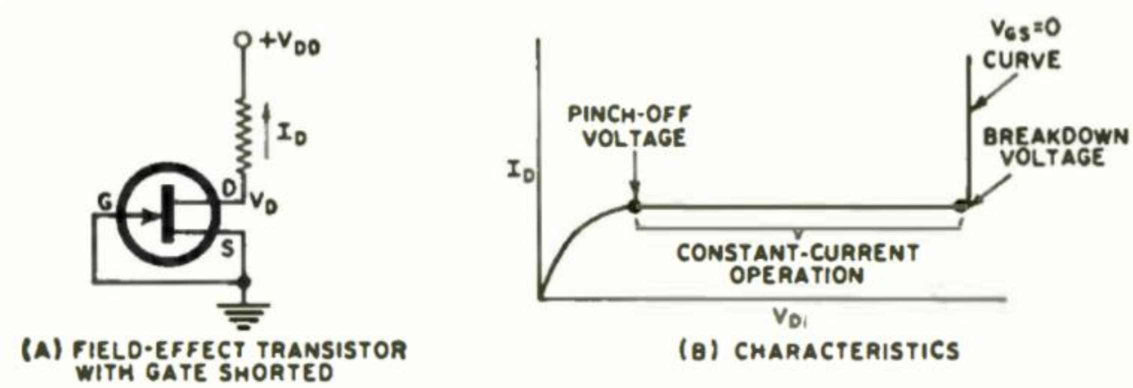


Figure 8. JFET operating with gate and source shorted. [8]

7.2 Zener Diode Current Source

The use of Zener diode with a transistor as shown in Fig. 9 generates a constant current acting as a source for floating load connected to the collector of transistor Q1. Basically all the Zener diode, when reversed biased delivers constant voltage for a wide range of current until it reaches its breakdown region. In Fig. 9 resistor R1 supplies Zener current and base current for Q1 (A common emitter NPN BJT transistor), such that when Q1 operates with sufficient current in the base it adjusts the collector current by keeping voltage drop across R2 constant and almost equal to the Zener voltage (DZ1).

Here the voltage drop in R2 connected to the emitter of Q1 is given by $(V_{z-}V_{be})$, where, V_z is the Zener diode operating voltage and V_{be} is pn junction diode voltage typically equal to 0.68 V (Silicon doped semiconductor). Since both voltage values are constant, a constant voltage appears across R2 generating constant current for a given constant value of R2. As in BJT transistor, the collector current (I_c) is assumed to be equal to emitter current (I_e), provided h_{fe} is sufficiently large, thus the collector current (I_c) remains constant regardless the value of output load resistance, provided there is enough supply voltage (V_{SS}) to drive the current through the load device in the collector. Hence the circuit operates as a constant current generator. [7]

The mathematical relation can be expressed as,

$$I_{R2} = (I_e = I_c) = (V_{R2} / R_{R2}) \quad (5)$$

Where, I_{R2} is the current flowing through resistor R2, I_e is the emitter current, I_c is the collector current, V_{R2} is the voltage across resistor R2.

$$V_{R2} = (V_z - V_{be}) \quad (6)$$

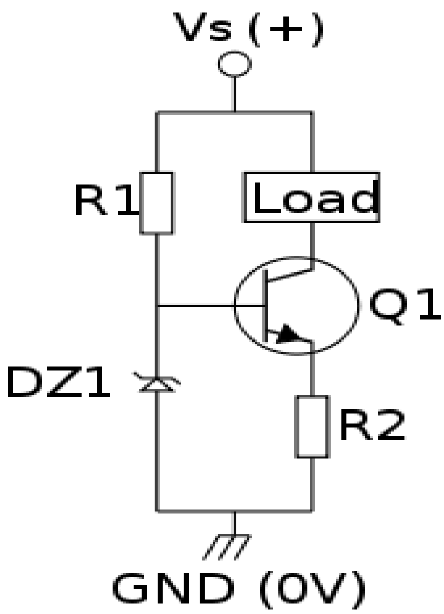


Figure 9. BJT NPN transistor Zener diode active current source. [7]

One of the major flaws of this kind of BJT transistor active current source is the temperature dependence, causing base-emitter junction voltage to fluctuate with temperature approximately -2 mV/℃ (degree Celsius). This ultimately causes variation in V_{ce} (collector-emitter voltage) roughly δVbe= δVce∗-0-0001.Thus, it affects the efficiency of the current source. One of the simple ways to remove this effect is to choose relatively high emitter resistor so that tens of millivolts of change in emitter voltage will only make a small change in overall emitter voltage.

Using a diode compensation method as shown in Fig. 10 where a diode (D), fabricated from same semiconductor material as in transistor cab be implemented so that any change in a voltage drop due to temperature on the diode (V_D) can track V_{be} as a result temperature dependency of the constant current source can be minimized.

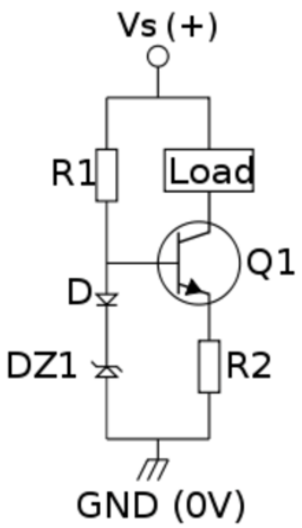


Figure 10. Transistor current source with diode compensation. (7)

However, a better model of the active current source with good temperature stability is shown in Fig. 11, where two BJT transistors T2 (NPN) and T1 (PNP) are used in such a way that change in voltage drop V_{be} in T1 is compensated by the second transistor T2. Furthermore, R3 is a pull-up resistor for T1 as a base current for T2 can sink current rather than sourcing it. [9]

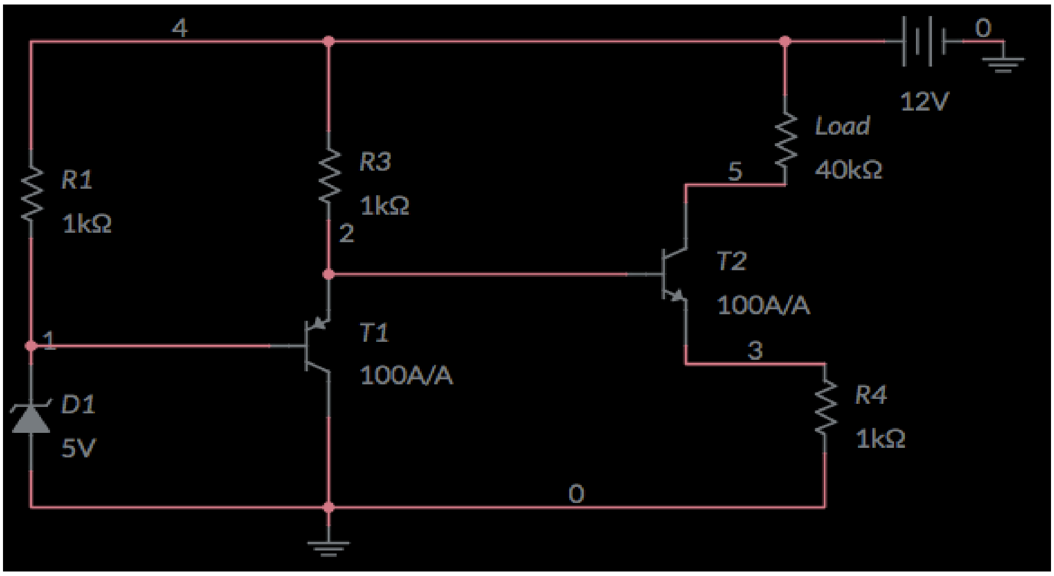


Figure 11. BJT current source with temperature compensation

7.3 Current Mirror as Constant Current Source

In the integrated circuits IC, current mirror as a constant source are mostly implemented for biasing purposes rather than using resistors and capacitors. Current mirror circuit consists of identical transistors, it can be either MOSFET or BJT. A current mirror implemented using two-matched BJT transistors Q1 and Q2 with their base and emitter connected together is shown in In Fig. 13. In this circuit, collector and base are short-circuited so that the transistors act as a single p-n junction diodes operating in the forward-active region. Then the current I_{OUT} of transistor Q2 is controlled by V_{be2}, which is identical to V_{be1}.

$$V_{BE2} = V_T \ln I_{C2}/I_{s2} = V_{BE1} = V_T \ln I_{C1}/I_{s1} \tag{7}$$

$$V_{BE2} = V_T \ln I_{C2}/I_{s2} = V_{BE1} = V_T \ln I_{C1}/I_{s1} \tag{8}$$

Here V_T = kT/q, where V_T is the thermal voltage and $I_{s1}$and I_{s2} are the saturation current of transistors Q1 and Q2 respectively.

$$I_{C2} = \frac{I_{S2}}{I_{S1}} I_{C1} \tag{9}$$

As both the transistors used are identical meaning I_{s1}=I_{s2}, therefore equation (9) implies collector current of Q2 is the mirror of Q1. From KCL, at the collector of Q1,

$$I_{IN} = I_{C1} + \frac{I_{C1}}{\beta_F} + \frac{I_{C2}}{\beta_F} \tag{10}$$

$$I_{OUt} = I_{C2} = I_{C1} = \frac{I_{C1}}{1 + \frac{2}{\beta_F}} \tag{11}$$

Assuming gain of transistor (β_F) is fairly large enough and base current is negligible compared to emitter and collector current,

$$I_{OUT} = I_{C1} \approx I_{IN} \qquad (12)$$

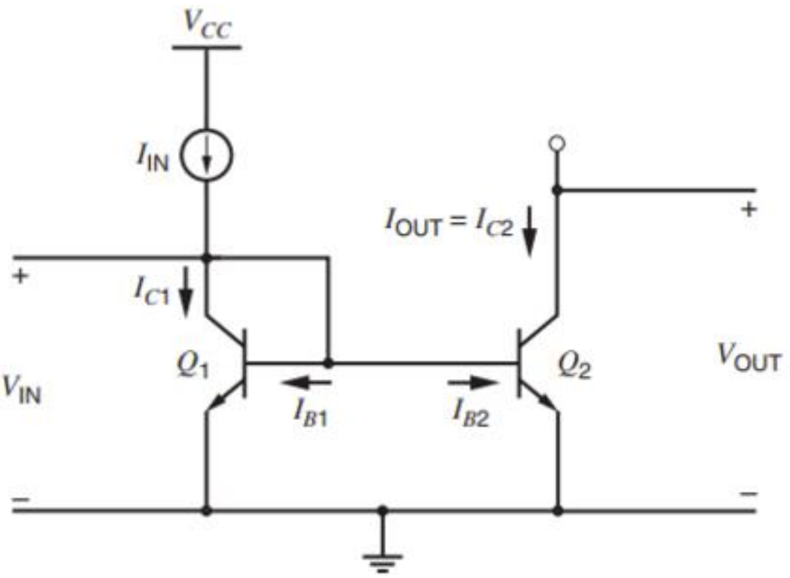


Figure 12. BJT current mirror current source. [10]

7.4 Operational Amplifier Current Source

A simple transistor current source like Zener diode current source can be improved by inserting the base-emitter junction of the transistor in the feedback loop of the op-amp to make it more thermally stable voltage control current source. A basic implementation of this type is shown in fig. 13. The circuit, in general, is a buffered non-inverting amplifier circuit driven by the constant input voltage (V_{supply}). The op-amp operates in such a way that it keeps both the input terminals in equipotential and increases its output voltage to compensate the V_{BE} drop. As a result, the voltage across R2 is always constant; it is exactly the Zener voltage and the current flowing through constant resistor R2 is constant as well as shown in equation 13. [7]

$$I_{R_2} = (V_{D1})/R_2 \qquad (13)$$

Basically, the op-amp implemented in negative feedback configuration adjusts the transistor base voltage so that I_{R_2} remains constant even with a varying value of the load.

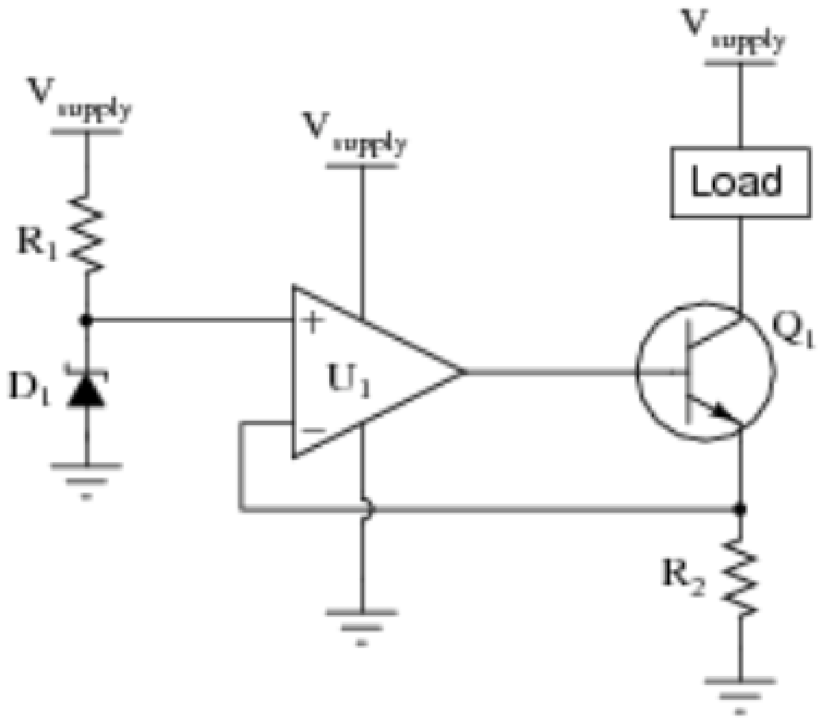


Figure 13. Op-amp current source. [15]

In this study, op-amp current source is implemented using BJT NPN 2N2222 transistor and monolithical operational amplifier MC33072P. Multisim simulation of actual circuit is shown in Fig. 14, where the base-emitter junction of transistor Q2 is configured in a negative feedback loop of the op-amp so that output voltage of the amplifier is used to compensate V_{be} drop. In another word, the circuit employs negative feedback and utilizes the very high gain of the op-amp to adjust its output (transistor base drive voltage) to bring its inverting input voltage equal to the non-inverting input voltage. This is more explicitly shown in the Fig. 14, where the voltage at the non-inverting terminal is shown by probe 4 (PR4) with the corresponding value of 3.261 V and voltage at inverting input is shown by probe 7 (PR7) which is also 3.261 V.

A Zener diode of reverse breakdown voltage 3.3 V is used as a fixed voltage input in the non-inverting input of the op-amp. Since both the inverting and non-inverting terminals of op-amp are in same voltage level throughout the operation, it maintains a constant voltage across emitter-base junction of transistor Q2. Therefore, changing the value of potentiometer connected between the base and the emitter of Q2 yields adjustable current to flow in emitter terminal. Nevertheless, the same current flows in the collector terminal of the transistor where Load (mouse) and current sensing resistor of 100 Ω is placed.

Mathematically,

$$V_{EE} = 3.3\ \mathrm{V} \tag{14}$$

In this study, a potentiometer of 100 kΩ is used. The required current limit is from 0 mA to 0.5 mA. This can be achieved by adjusting the resistor value of potentiometer as shown in equation 15.

$$I_{load} = V_{EE}/R_{pot} = 3.3\ \mathrm{V}/R_{pot} \tag{15}$$

For current in collector terminal to be 0 A, a resistor value of potentiometer (R_{pot}) needs to very high close to infinity, using resistance value of 100 kΩ across 3.3 V yields 3.3 microampere, which is almost negligible. Hence the maximum value of potentiometer is tuned so as to get very low current value almost close to 0 A for the project. Whilst decreasing the corresponding value of potentiometer increases current to flow through sensing resistor and load via collector terminal. Due to the upmost limit of 0.5 mA for this thesis project, the resistor can be tuned down to the optimal value of 5.2 kΩ. Further decrease in resistor value yields a higher value of current to flow in emitter-collector terminals of the 2N2222 transistor.

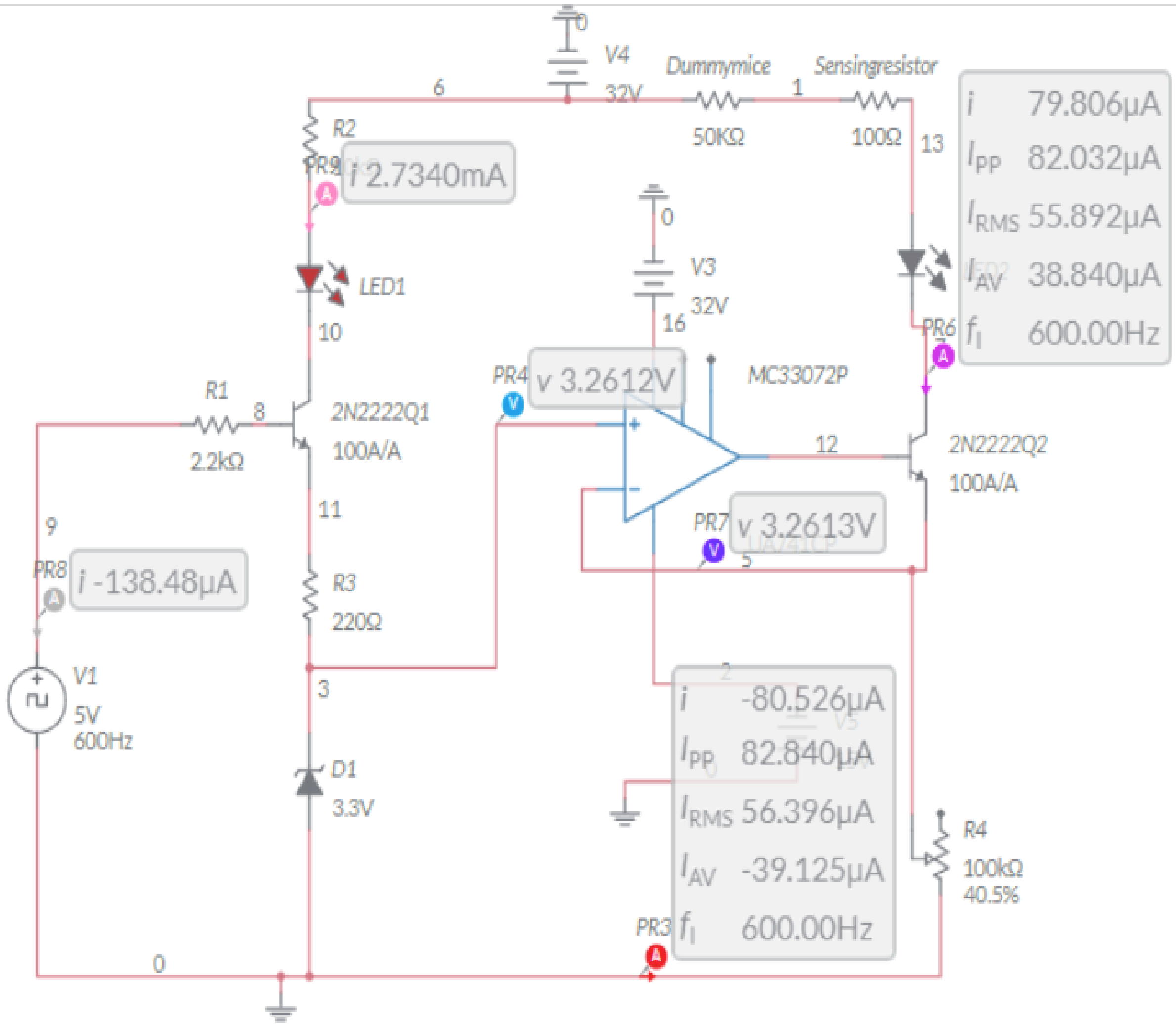


Figure 14. Multisim simulation of DC current source using an op-amp

As shown in Fig. 14 potentiometer is implemented in the emitter region, with the load placed in the collector of transistor Q2, which is further, connected to power supply of 32 V. The same power supply is used for op-amp MC33072P, implemented in a closed loop configuration.

Since the non-inverting input of amplifier $(V_{+}) = V_{Diode}$ and both inputs of op-amp are same, it can be concluded that inverting input of the amplifier is equal to diode voltage i.e (inverting input of amplifier) $V_{-} = V_{Diode}$. As shown in fig. 14, V_{-} (inverting input) is connected to R4 (potentiometer) and emitter of Q2, that is to say V_{Diode} appears across potentiometer. Thus, V_{Diode}, which is a constant value of 3.3 V, controls the magnitude of the current flowing through R4. Due to the negative feedback arrangement of the circuit, the op amp delivers whatever base current is required by the Q2 to maintain V_{Diode} at its emitter. The base current delivered by the op-amp comes from the supply voltage, V4 (32 V) as shown in fig. 14 not from V_{Diode} which sees the very high impedance of the non-inverting input (Z_{in} for either input of op-amp are typically high in the range of mega ohms). Therefore, V_{Diode} doesn't need much drive capability since its load, the (non-inverting input) V_+ of op-amp barely demands any significant current instead V_{supply} (V4), as shown in fig. 14, needs to have enough current drive capacity to maintain output current of the op-amp.

Furthermore, even if the supply voltage varies or the collector resistor value varies, the current flowing through the load remains constant provided V_{supply} and collector resistor don't go outside the circuit's operating limit and the circuit operates in valid Ohms law.

As shown in fig. 14, if V4 (V_{supply}) decreases then the negative feedback will cause the op amp's output to increase the Q2's base current so it can deliver more and lowers its V_{CE} to maintain the same voltage drop across potentiometer to keep current constant. At some point, the transistor is fully on (saturation mode) and its V_{CE} is a constant value of 0.3 V. A further decline in V_{supply} will result in a decrease in current value through R4 despite the negative feedback because there is no longer enough V_{supply} to keep current through load constant and the circuit no longer operates as intended.

In contrary to this, if V_{supply} increases, the op amp delivers less current to the base of transistor Q2. Consequently, transistors conduct less and increases the voltage drop across V_{CE}, this phenomenon maintains the voltage drop across R4 and current following through it to remain constant despite the increased supply voltage. But if the V_{supply} continues to increase significantly, the voltage drop across V_{CE} becomes large and at some point, it exceeds the transistor's V_{CE} rating or its power rating (I_{R4} may be constant but V_{CE} xI_{R4} continues to increase) and results in failure of the system. Therefore there is a limit of V_{supply} that can be used to power the system and 32 V is chosen to be inside the power rating of the transistor.

Similarly, there is also the limit of resistor that can be used in the collector region of Q2 (resistor value of dummy mouse). If the value of $R_{collector}$ increases, the op-amp drives more current to Q2, decreasing transistor's V_{CE}. This results in the increase of voltage drop across $R_{collector}$. Thus current across load (I_{Load}) remains constant. When the transistor runs in saturation mode, then further increase of $R_{collector}$ results in a decrease in I_{Load} because the circuit cannot continue to increase the voltage drop across collector resistor. Therefore, op-amp current source operates in a dynamic way to suppress changes $R_{collector}$ and V_{supply} but within the transistor's power limit. [16]

The simulation of DC current source with the DC switch which turns it on and off is shown in fig. 15. The graph with blue line represents the voltage drop across the potentiometer, which remains fairly constant to diode voltage whilst the red dotted line represents the DC current in microampere that flows through a potentiometer.

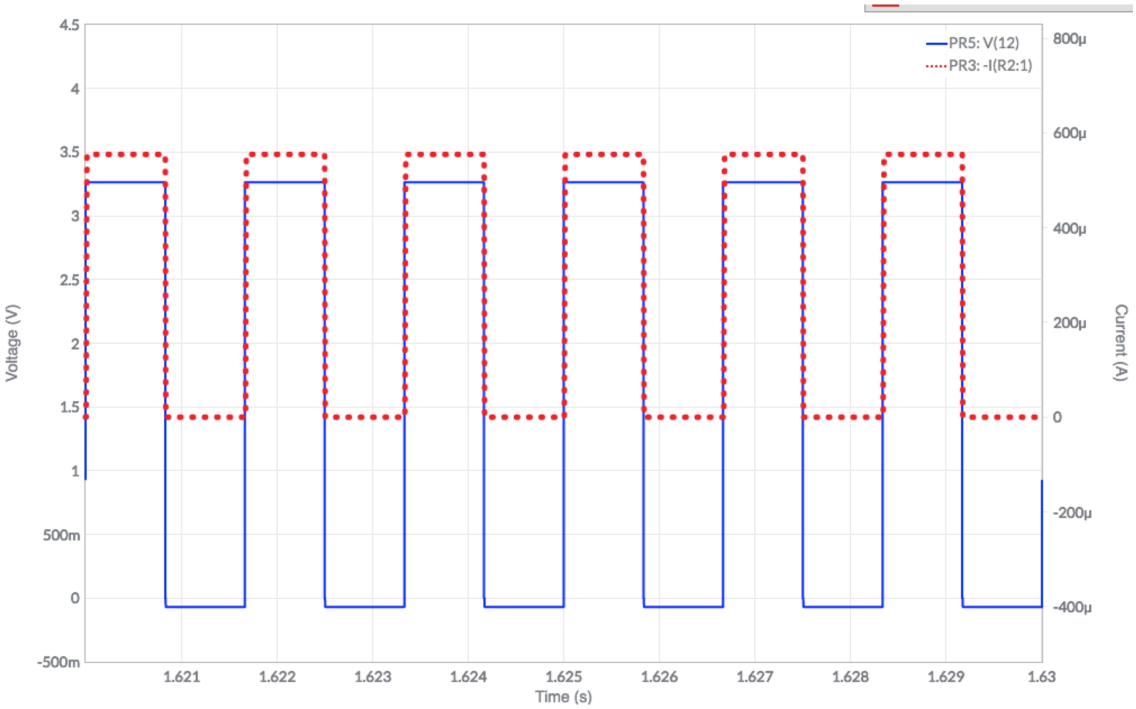


Figure 15. Multisim simulation of DC current source with the switching system

The actual DC current source generator used in this project is designed in PADS software and is printed in double layer copper board as shown in fig. 16. It has five connectors for wiring DAQ 6008, load (mouse), the source voltage of 32 V, potentiometer and sensing resistor respectively. Three LEDs are also used as the indicators so that the current flowing in the different branches can be monitored when the circuit is operating.

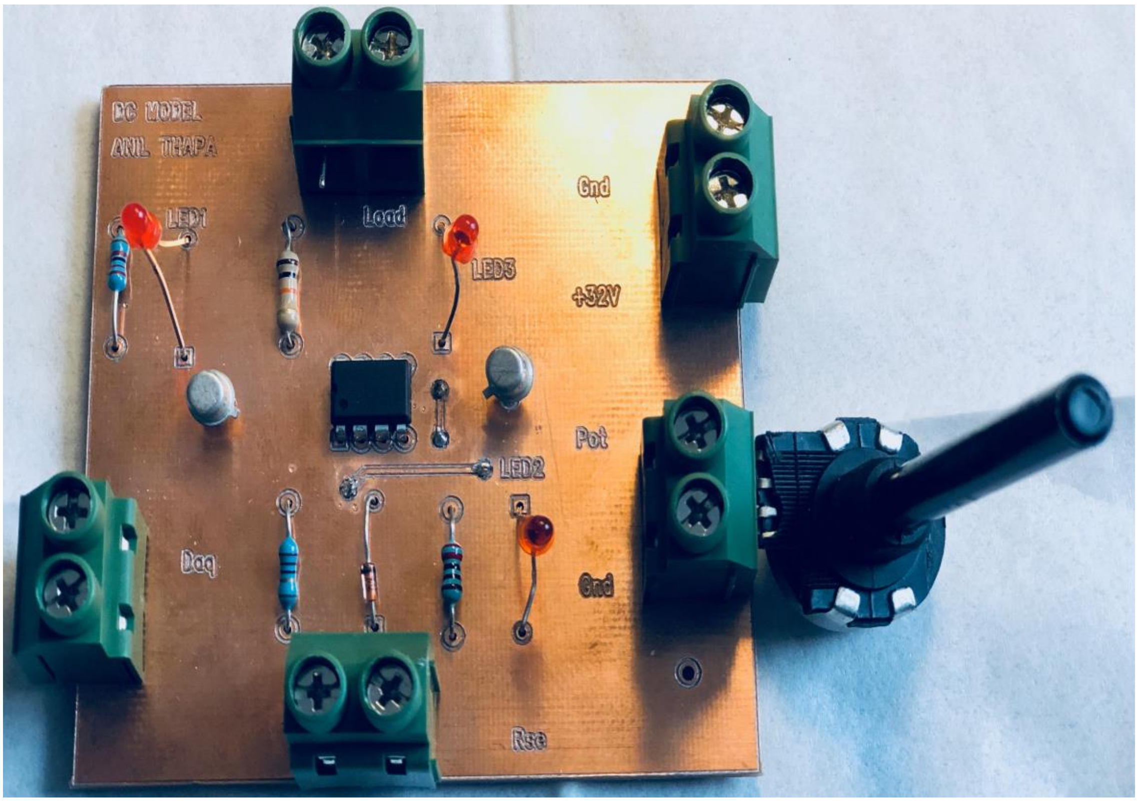


Figure 16. DC model current source printed in two side copper board

8 AC Current Source

AC current is an electric current that reverses its direction periodically, whereas DC current flows in only one direction. It is accompanied by AC voltage, which switches polarity from positive to negative and back again over a period of time. The oscillating nature of AC supply follows that of the mathematical form of sine wave commonly called a sinusoidal waveform. Therefore, it can be described as a function of time, as in equation 16. Since the instantaneous value of AC voltage and current are changing with time, root mean square "rms" value is used while working with AC.

$$v(t) = V_{peak} \times \sin(\omega t) \qquad (16)$$

Where, V_{peak} is the peak voltage of AC waveform, ω is the angular frequency and t is the instantaneous time.

The main reason for using AC current source in this study is due to the presence of capacitors in electrical model of living tissues i.e. to say, the mouse which acts as an impedance factor in this project is not purely resistive instead its skin of paws has combination of resistors and capacitors as shown in fig. 3.

Electrical impedance (Z) defined, as the measure of opposition that a circuit presents to a current when a voltage is applied is limited to normal resistance in DC circuit. However, in AC circuit, two additional impeding mechanism capacitance and inductance which are always present in any real-world components are taken into account.The impedance caused by these two effects is encapsulated as reactance and forms imaginary part of complex impedance (Z= R + jX) while resistance forms the real part. Nonetheless, it is only AC source that addresses the complex impedance (capacitive and inductive reactance).

Therefore capacitors present in the paws of mice which when connected to DC source act as open circuit whereas when switched to AC source behave like impedance factor. More precisely, the capacitive reactance can be expressed as the opposition by a capacitor or a capacitive circuit to the flow of current and is inversely proportional to the value of capacitor and frequency of applied voltage as expressed in equation 17.

$$X_c = \frac{1}{2\pi f C} \qquad (17)$$

Where f is the frequency and C is the capacitance.

And the current flowing in the capacitive circuit can be further expressed as

$$I = \frac{E}{X_c} \qquad (18)$$

Where,
E = Effective voltage across capacitive reactance and X_c is the capacitive reactance.

Hence the flow of current in capacitive reactance is directly proportional to the frequency of applied AC voltage. In this project, AC current of 108 Hz is implemented using constant AC current source. [17]

8.1 Oscillator Fundamentals

Signal generators are most crucial for different electronic systems, mostly used to provide clock pulses to control the sequential operations of the entire system, as well as to provide excitation pulses for various measuring devices and processing circuits, so as to convert numerous transducer outputs into useful electric signals. These signals can be either stable AC or DC of different amplitude and frequency. Furthermore, it can be sinusoidal, rectangular, triangular, square or pulse waveforms. Therefore any electronic circuits designed to generate such waveform are called oscillators. These circuits implement both active and passive components to generate output signals with constant magnitude and the desired value of frequency. It requires no external signal to initiate or maintain the energy conversion phenomenon as long as a DC power source is connected to the oscillator circuit.

Generally, an oscillator circuit is an amplifier circuit with positive feedback, which is capable of generating output signal without any input. As shown in fig. 17, an amplifier with an open loop gain of A is used in positive feedback network in phase with a signal to generate output waveform.

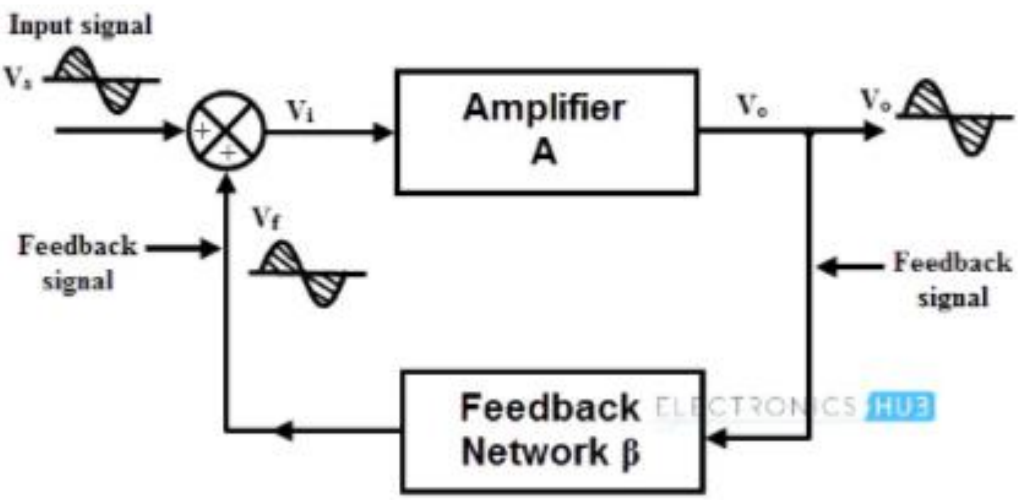


Figure 17. Block diagram of a simple oscillator circuit. [12]

For any oscillation to be sustained, Barkhusen criterion for oscillation should be strictly followed which focus on maintaining total loop gain to unity. As mentioned in fig. 17, the total loop gain of the amplifier circuit is the product of A and β. If A β is less than unity then A $\beta_{V_{IN}}$ is smaller than V_{IN} and gradually output voltage die out with time when the applied voltage is removed as shown in fig. 18. [13]

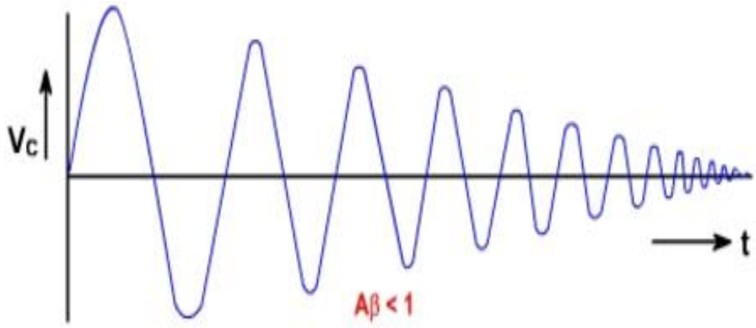


Figure 18. Oscillation produced with total loop gain less than unity. [13]

On the other hand, if the total gain after feedback A β >1, then signal amplitude increases with each loop, building up the output voltage and thus produced oscillation is not the perfect oscillation rather than oscillation with different amplified magnitude with hard-limiting caused by the fixed supply voltage. It also generates large distortions (bad THD), In fig. 19 a similar oscillation with total loop gain greater than unity is shown.

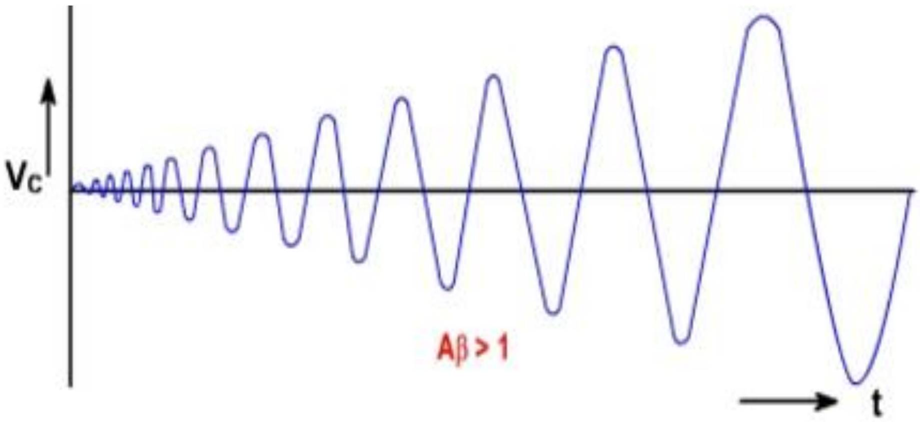


Figure 19. Oscillation produced with total loop gain greater than unity. [13]

Therefore for the sustained oscillation to be formed the total loop gain should be unity or slightly larger than one which later saturates to applied DC voltage limit, producing oscillation of constant amplitudes, slightly less than supply DC voltage at some fixed frequency.

Similarly, another important condition for oscillation is the phase shift after feedback network (phase shift of the feedback loop), which always needs to be an integral multiple of 2*π (360°). In amplifier network oscillation the input is always applied in inverting input which always gives 180° phase shift.

Through feedback network, a further 180° phase shift is created, resulting in a total of 360° phase at the input after feedback. This results in sustained positive feedback oscillation. There are different oscillators like phase shift oscillator, wien bridge oscillator, hartley oscillators, colpitts oscillator, crystal oscillator etc. used in a different system for stable oscillation.

8.2 Phase-Shift Oscillator

In this study a simple phase shift oscillation system, as modeled in Fig. 20 is implemented to produce 6 V peak to peak sine wave of 108 Hz using very common and versatile amplifier UA741CP, and cascading three stage of RC circuit in feedback network so as to produced 180° phase shift which further adds to 180° phase produced at inverting terminal of op amplifier resulting in total phase shift of 360° thereby giving us the required positive feedback.

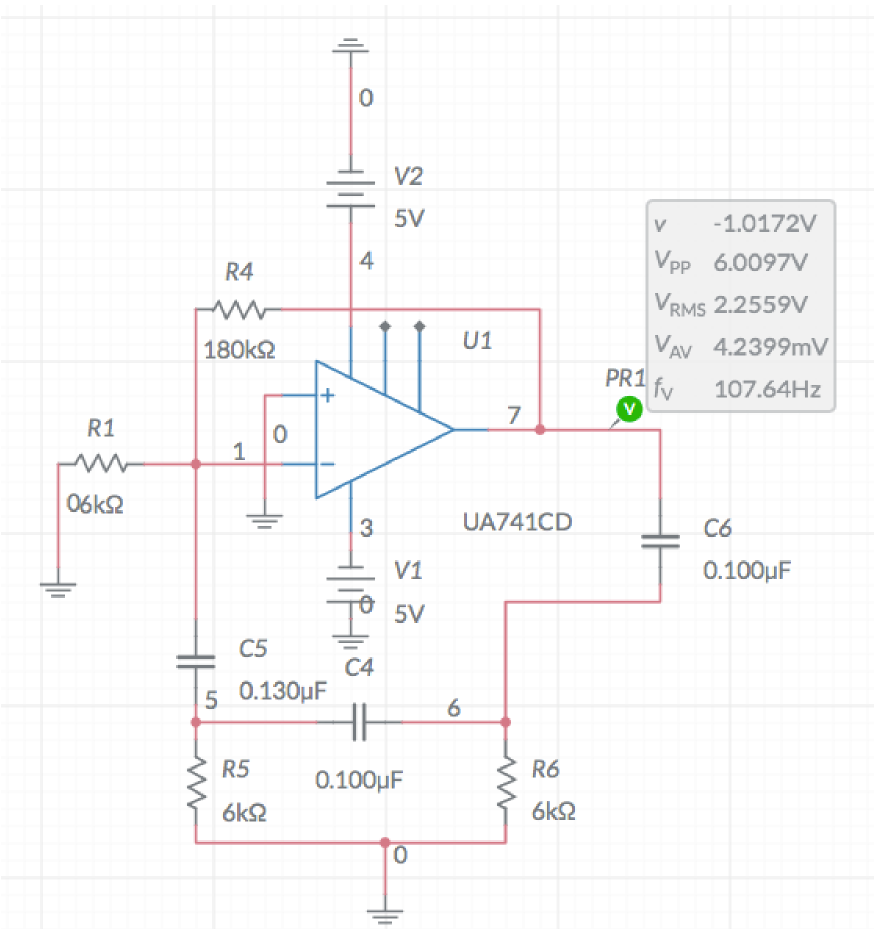


Figure 20. Phase shift oscillator using 3 stages of RC network.

A model of phase shift produced by RC series circuit is shown in fig. 20. Here a single pole RC network produces a phase shift of less than 90°. Though an ideal RC circuit produces 90° phase shift which is impossible to find in a real circuit. Therefore three stages of RC networks are applied to produce a phase shift of 180°. The oscillation thus produced is more stable than the two-stage RC network. The value of capacitors, resistors and chosen frequency of oscillation varies the actual phase shift, as shown in mathematical expressions 19 and 20. [14]

$$X_c = \frac{1}{2\pi fC}, Z = \sqrt{R^2 + (X_c)^2} \tag{19}$$

$$\text{Phase } (\varphi) = \tan^{-1}(X_c/R) \tag{20}$$

Where: X_c is the capacitive impedance and R is the resistance, f is the frequency of oscillation and Z represents the total impedance of RC series network. [14]

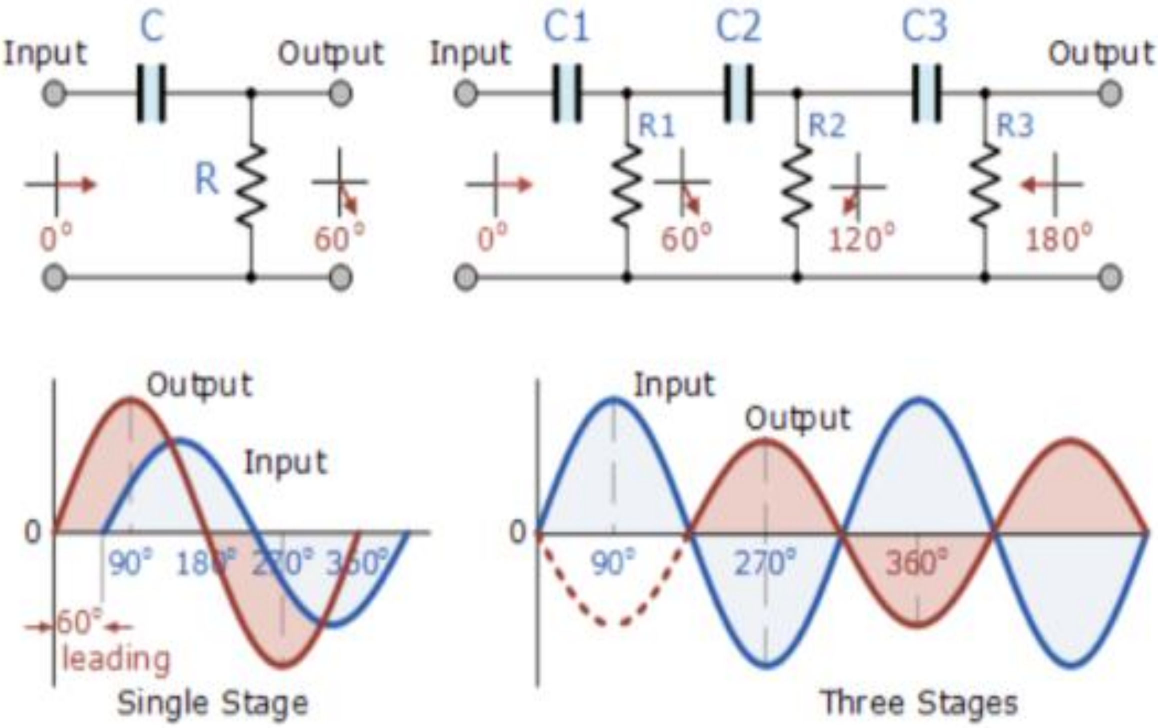


Figure 21. Phase shift change in RC network. [14]

The frequency of oscillation as produced by this oscillator is shown in equation 21.

$$f_r = \frac{1}{2\pi RC\sqrt{2N}} \tag{21}$$

Where, f_r is the frequency of oscillation, R, and C being the value of resistor and capacitor used in the network with N being the number of RC stage used in the oscillator.

In this project, the desired frequency of oscillation is 108 Hz. Thus using a resistor (R) of 6K and capacitor (C) of 0.1 uF in three stages of RC network yield corresponding oscillating sine wave of 108 Hz as shown in fig. 22.

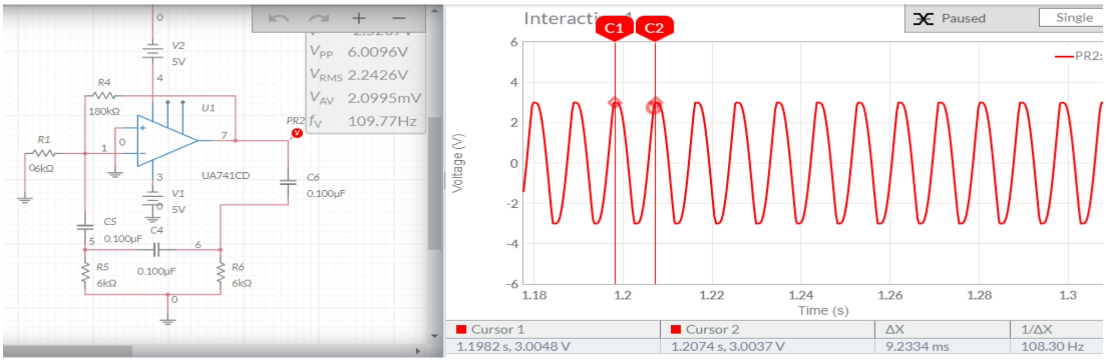


Figure 22. Oscillation produced by RC oscillator

Thus the oscillating wave produced from the oscillator is then fed into the active current source as input in order to construct constant AC current source of frequency 108 Hz.

8.3 Operational Amplifier Based Current Source

In this project, a single op-amp UA 741 with AC signal input at inverting input is implemented in negative feedback mode to form constant AC current source. The AC sine wave used as input for the op-amp is obtained as output from phase shift oscillator. In fig. 23, the circuit schematics of the oscillator is shown along with current source since oscillator severs as a crucial part of AC current source.

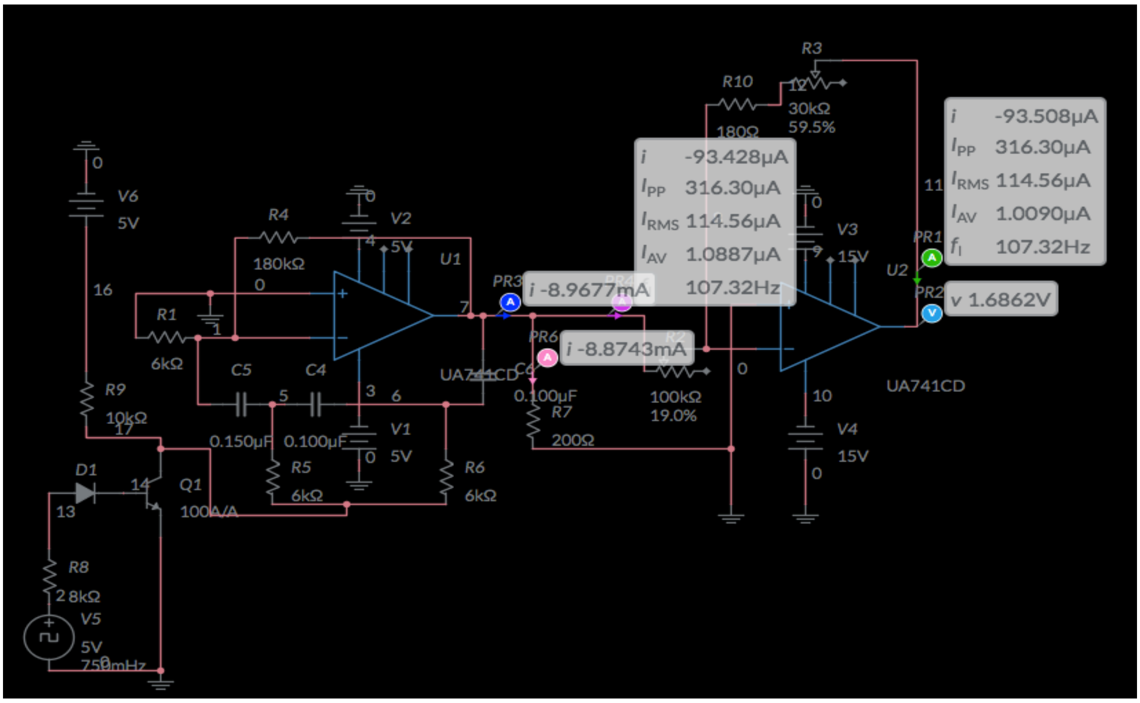


Figure 23. Simulation of op-amp based current source in multisim

In the circuit, AC sine wave of frequency 108 Hz is feed into inverting terminal. It is clear that the output taken into consideration in the negative feedback loop also follows the same frequency of input signal whilst, the magnitude of the output current is determined by the potentiometer as resembled by R2 of value 100 kΩ in the circuit. Basically, the operation of this circuit is based on this fundamental principle of operation of the op-amp.

1. A current flow into the input terminal is zero because of the extremely high impedance at the input terminals.
2. In single input configuration, the voltage at the inverting and non-inverting terminals remains same.

By considering the first rule, no current is flowing into input terminal thus the feedback current is zero. Hence the current flowing through the potentiometer of 100 kΩ is forced to flow across the load (R3) and the test resistor of 180 Ω. That is why by adjustment value of potentiometer different current value can be assigned to flow across the load as indicated by R4 in the fig. 23.

From the second rule, the voltage at inverting and non-inverting terminals of UA 741 remains same and equal to 0 V. Since the non-inverting terminal is ground in the circuit the voltage at inverting terminal i.e. the voltage at the junction between load (R3) and a potentiometer (R2) is also forced to be zero. So they are in virtual ground mode.

Therefore, the current flowing through the load (R3) can be determined by the output voltage of amplifier and resistor value of the load. Mathematically it can be expressed as in equation 22.

$$\mathrm{I_{LOAD}} = \frac{\text{Output voltage}}{\mathrm{R_{LOAD}}} \qquad (22)$$

The maximum output voltage of op-amp is always less than or closely equal to the supply voltage of op-amp. As the supply of op-amps in this circuit is 15 V in either of supply terminals, the output voltage is nearly equal to 15 V.

Furthermore, the desired range of current across the load (R3) is 0 A to 0.5 mA. Therefore, the maximum value of load that can be implemented in this circuit for the desired current can be calculated using equation 23.

$$\mathrm{R_{LOAD}} = \frac{15}{0.5} = 30\ \mathrm{k\Omega} \qquad (23)$$

Hence the current generated on negative feedback region of op amplifier remains constant provided that, the resistor value of load doesn't exceed $30\ \mathrm{k\Omega}$ otherwise circuit doesn't comply with ohms law and it fails.

Furthermore, the current ($\mathrm{I_{RMS}}$) flowing from the output of the oscillator is large compared to required current to be feed into the system which is 0.5 mA as a maximum limit. It would have been even larger if op-amp used in oscillator would have been powered by same voltage supply as a current source (15 V) because the current from the output of the oscillator is the ratio of output voltage to resistor value connected in series to it. Therefore to yield smaller value of current at the output, the oscillator circuit is powered with of 5 V of either polarity as supply voltage and a smaller value of the resistor is connected to ground parallel to the larger resistor value (potentiometer) from the output of the oscillator.

As shown in fig. 23, resistor R7 of value (200 Ω) is implemented in shunt with potentiometer so that the output current from oscillator can be divided in such a fashion that a larger portion of it flows through R7 to the ground and small amount of it through potentiometer to the load because R7 has significantly small resistor value compared to potentiometer and current is inversely proportional to the resistance. Therefore the smaller current flowing through the potentiometer can be easily adjusted to a very smaller range of microampere by changing its wiper. As shown in fig. 24 when the wiper position is at 19 % of 100 kΩ potentiometers the output current of the oscillator is 8.9677 mA out of which 8.8747 mA is made to flow through ground via R7 and very small current of 316 µA flows through the load via a current source.

The actual AC current source circuit that is used in the study was designed in PADS and was printed in double layer copper board as shown in fig. 24

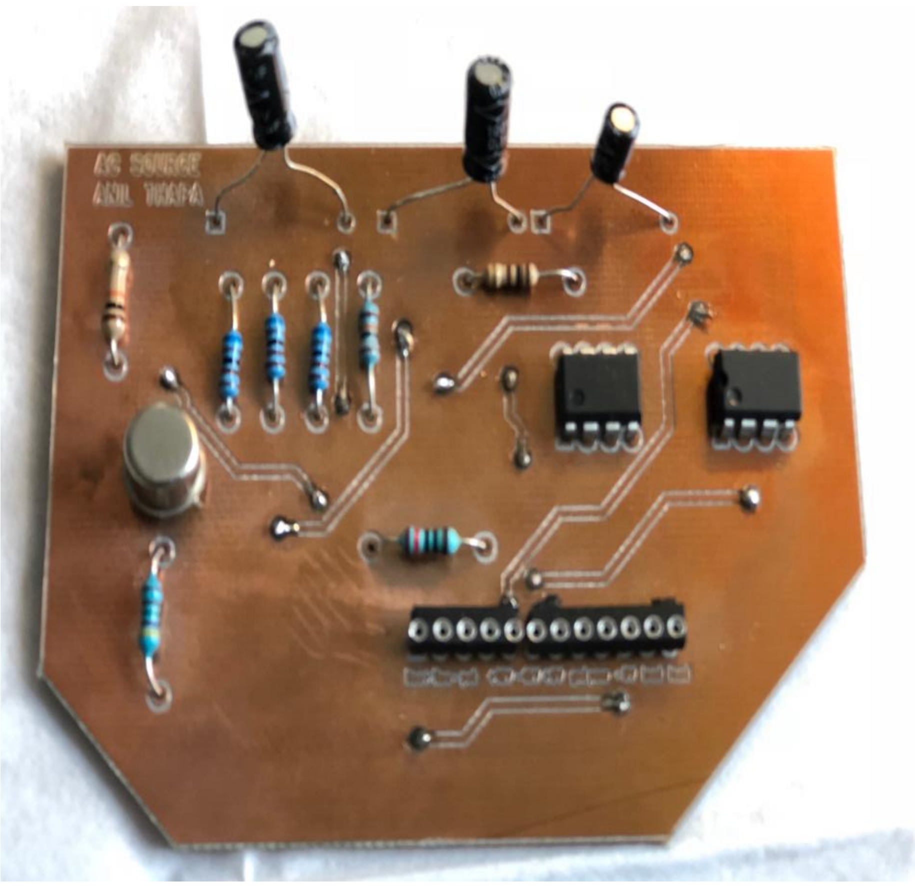


Figure 24. AC current source pcb designed in PADS

As shown in the schematic of simulation in fig. 23 and actual circuit in fig. 24, transistor switch is implemented before oscillator circuit so that it can be switched with PWM signal form LABVIEW software to control the AC current source. Hence when the DC switch is ON, the AC current as generated through the combination of an oscillator and a current source, flows through load otherwise it will be cut-off. It is shown in fig. 25.

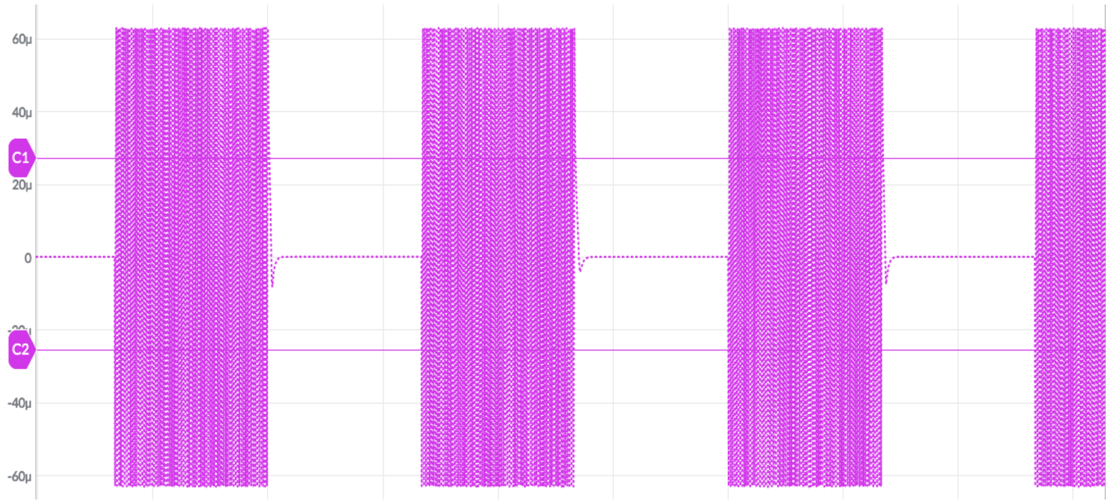


Figure 25. AC current implemented in DC switch

In fig. 25 each block encapsulates AC current inside it, fig. 26 shows this phenomenon more clearly.

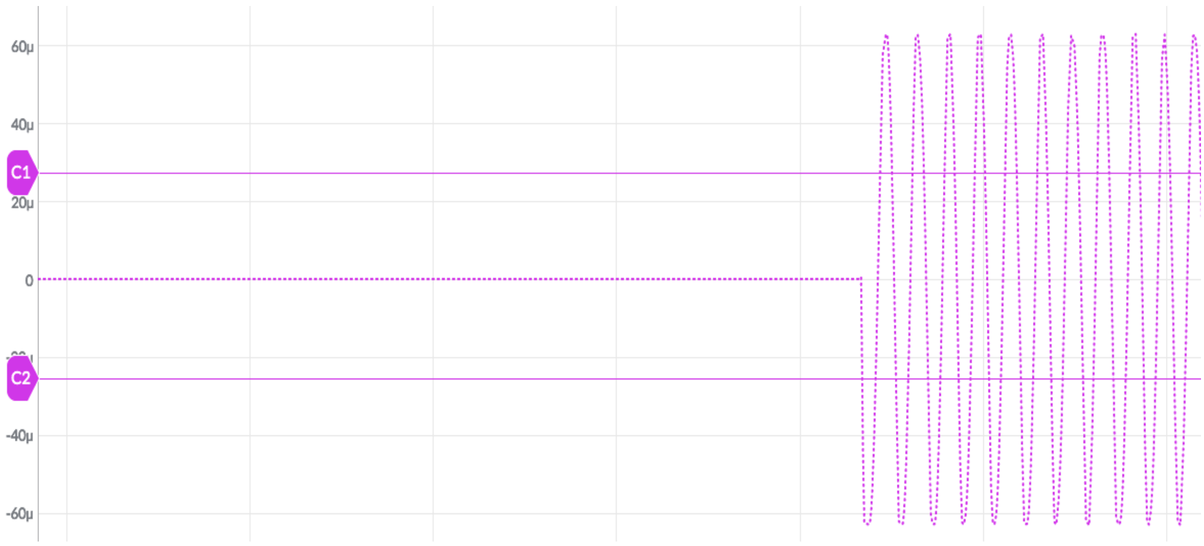


Figure 26. AC current waveform inside DC switch

9 Pulse Width Modulation

PWM (Pulse Width Modulation) is a way to describe a digital signal, it allows us to vary how much of the time the signal is high in an analog fashion. While a digital signal can be only high or low at any time, we can vary the proportion of time a given signal pulse is high compared to when it remains low over a consistent time interval. Duty cycle is fundamental concept associated with PMW technique. When a digital signal is high, it is termed at “On Time”, and when it is at low stage normally at 0 V it is called as “ Off Time”. Thus duty cycle, usually expressed in percentage is used to describe the percentage of time a signal is on over an interval or period of time. An identical signal with different duty cycle is shown in fig. 27.

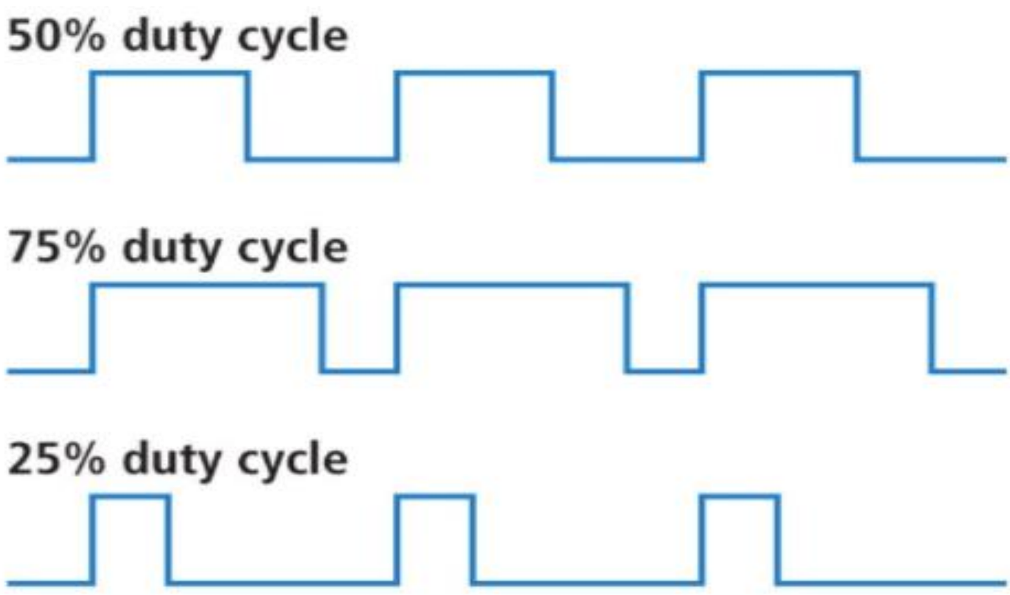


Figure 27. The different duty cycle of an identical signal

10 National Instruments USB 6008 Data Acquisition Device as PWM Hardware

Controlling of the electrical current pulse to the subject (mouse) was another crucial task of this thesis project. Initially, AC and DC pulse were created with the constant current generation and those pulses are meant to feed on the system so that it can be switched on and off at a desirable time. Furthermore, the duration of each pulse can be controlled and monitored with ease. Thus, this PWM was designed with labview software, which was later integrated with current sources to accomplish the final task i.e. to generate constant desirable current and ability to control the time and duty cycle of the pulse.

For PWM design, national instrument device USB 6008 is implemented. It features a USB connector for full speed USB interface together with eight single-ended analog input channels, two analog output channels, 12 DIO (digital input output) channels, and a 32-bit counter with a full-speed USB interface.

There are two ports for digital pins, all pins from either of the ports can be used as digital input or output pins. Similarly, (analog inputs) AI channel from 0-7 can be used for single-ended input voltage with reference to the ground, whereas for differential measurement, signal pair pins need to be used. For example, to measure differential analog input voltage in channel 0, AI0 and AI4 are the corresponding positive and negative pins further pin pairs for each channel are shown in fig. 28.

In this project, the differential voltage is measured across sensing resistor of 220 Ω from AI channel 1 to monitor the value of current flowing through the load and at the digital side, pin 1 of port 1 is used as the digital output. Nonetheless, there is flexibility to change the pin number by the user for either analog or digital section from the front panel of labview and configure hardware accordingly for using other pins. [17]

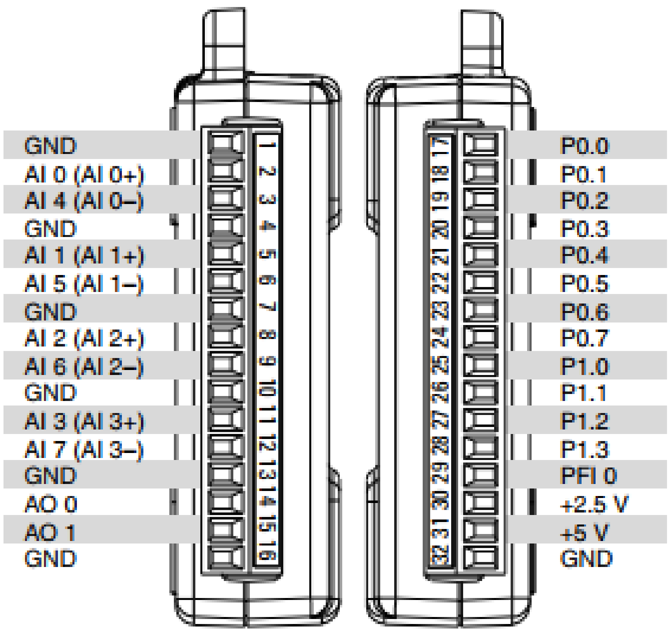


Figure 28. Pin configurations of NI USB 6008. [17]

10.1 Labview Front Panel

The PWM is implemented using Labview G program, as a DC switching system for both DC current and AC current of 108 Hz constant current source. This PWM switching system allows the user to change the on time and off time of digital waveform along with, the time period for one cycle and a total number of irritation of signal over one process of measurement. The system is designed to provide constant current 0 to 0.5 mA current over a period of time.

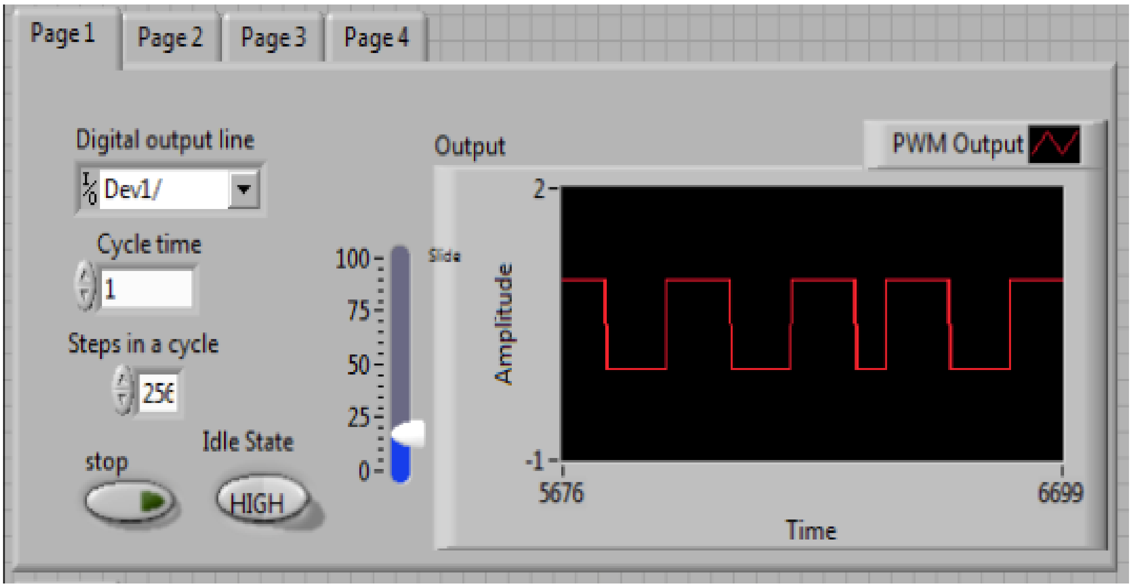


Figure 29. Front Panel showing user inputs

As shown in Fig. 29, the PWM module created by labview has digital numeric input shell to enter the desired time for one complete cycle of the wave to be produced under the name icon of “Cycle time”. In the same tab, a slider is present calibrated form o to 100 in a step 5, the user can change the duty cycle of the wave using the pointer in the slider, i.e. to determine the percentage of time the signal remains on or off for a given time interval.

The idle state push button allows the user to set default status of the duty cycle to be on or off. If it is set LOW, then the percentage set by slider is the percentage of time period going to be in low level or 0 V state for the period of time while setting in HIGH means the percentage set by slider is the percentage of time period going to be in high state or 5 V. The ability to set steps in one cycle for the precision of waveform can be controlled by “Steps in a cycle”, numeric input shell, it is set with default value of 256, but increasing the value enable user to see the waveform moving faster and decreasing the value makes the opposite effect on the speed of waveform generated.

STOP push button stops the execution of running waveform and switches to next cycle as set by the user. Similarly, a user input shell is present in shock cycle panel corresponding to each page to enable the user to set the number of iteration for a particular cycle of the signal pulse. All these phenomena can be simultaneously observed in output waveform chart in the right corner of each page where the amplitude of the pulse is shown in Y-axis over time in X-axis, as well as on the output panel named “current” on the middle right part of user interface window as shown in fig. 30.

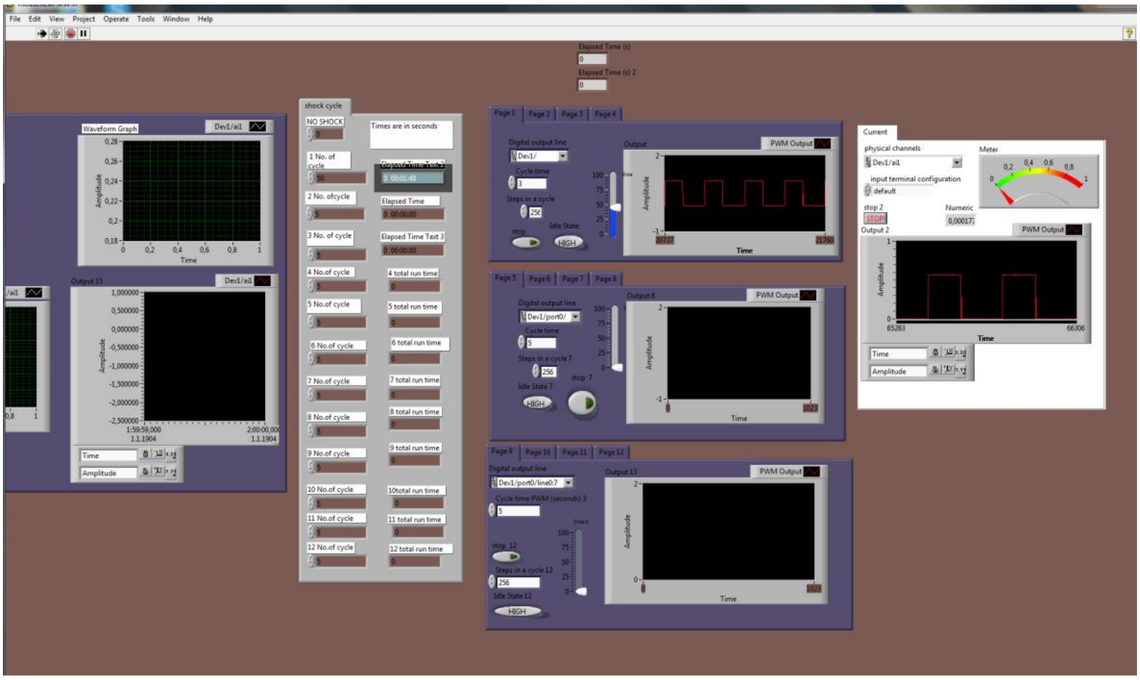


Figure 30. User interface window created in the front panel of Labview.

10.2 Labview Block Diagram

Labview is used for both generating PWM signal as well as to monitor the nature and value of current flowing through the load. As shown in fig. 31 first the pin for digital output is set using DAQmx create a channel to generate a digital signal, which is then passed to DAQmx start task for the transition of the task to the running state to begin the measurement or generation. Then the while loop is used to encapsulate the further codes so that user can stop the execution of loop by either using stop button inside the loop or complying with the condition as set by the elapsed timer.

Inside while loop, Slider control in the step of 100 is used to determine the duty cycle of the pulse, which is further implemented with numeric control (steps in a cycle) to determine the number of execution of for loop. Similarly, an array is initialized with constant 1 with a Boolean element which is further integrated with the output of slider and steps in a cycle. Inside For loop, cycle time as set by the user through numeric input is divided with steps in one single cycle to determine the one pulse duration which is implemented with mathematical multiplication function with a constant number of 1000 to determine iteration of for loop. After all these executions the software finally produces PWM signal at one of the digital pin of USB 6008.

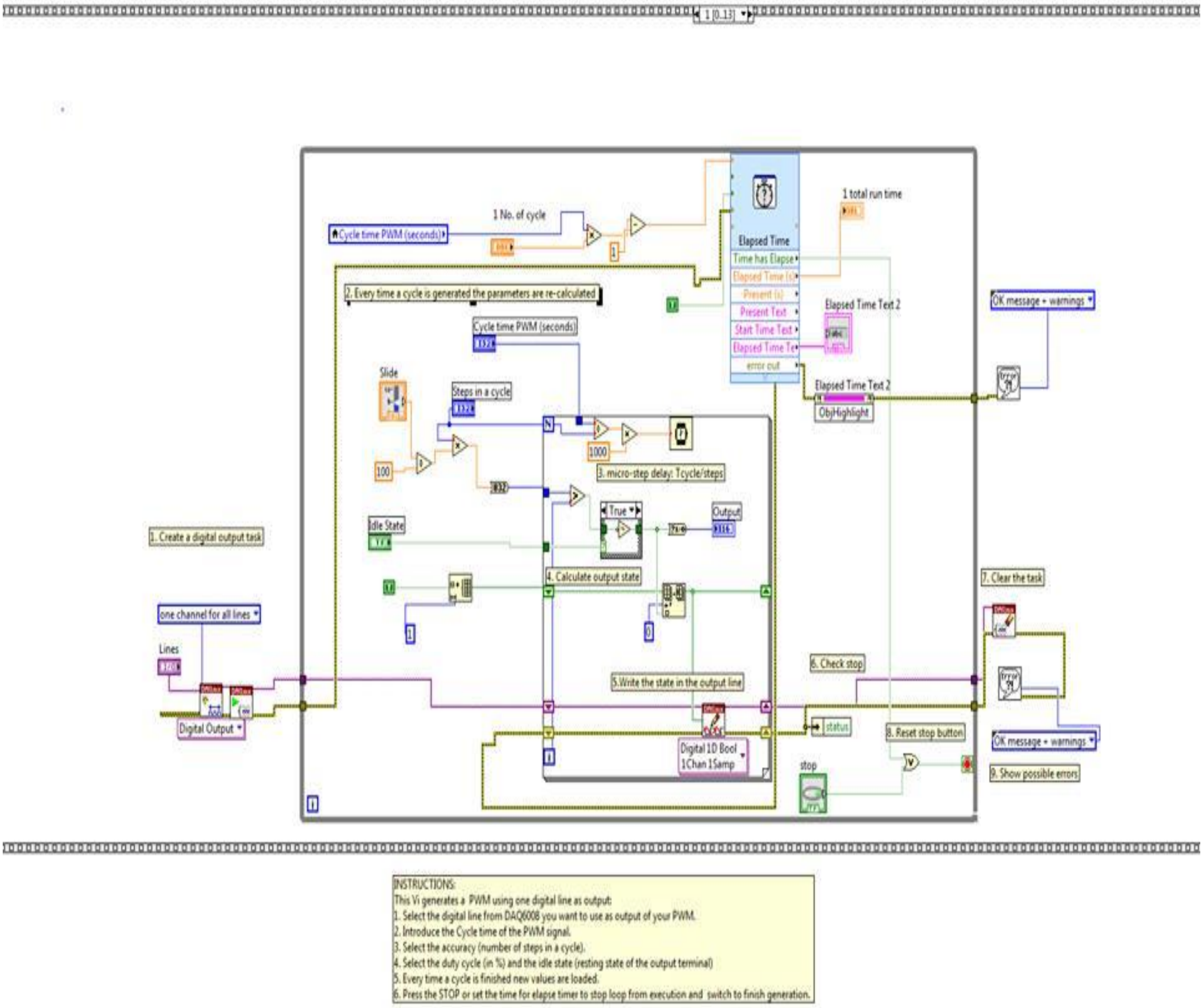


Figure 31. Labview block diagram for PWM

11 Grid

The grids where the mouse is supposed to walk consist of power and ground lines with a proper gap in between them. Two different models were designed for the grid purpose. First was designed in the copper plate as shown in fig. 32 with power and ground lines along with holes in between them so that if mouse urinates during the experiment, its urine can penetrate through the hole but these holes are smaller for the feces to sneak through it. However, feces of mice are solid and are non-conductive so there is no risk of the short circuit even when there are feces on grid floor during the experiment.

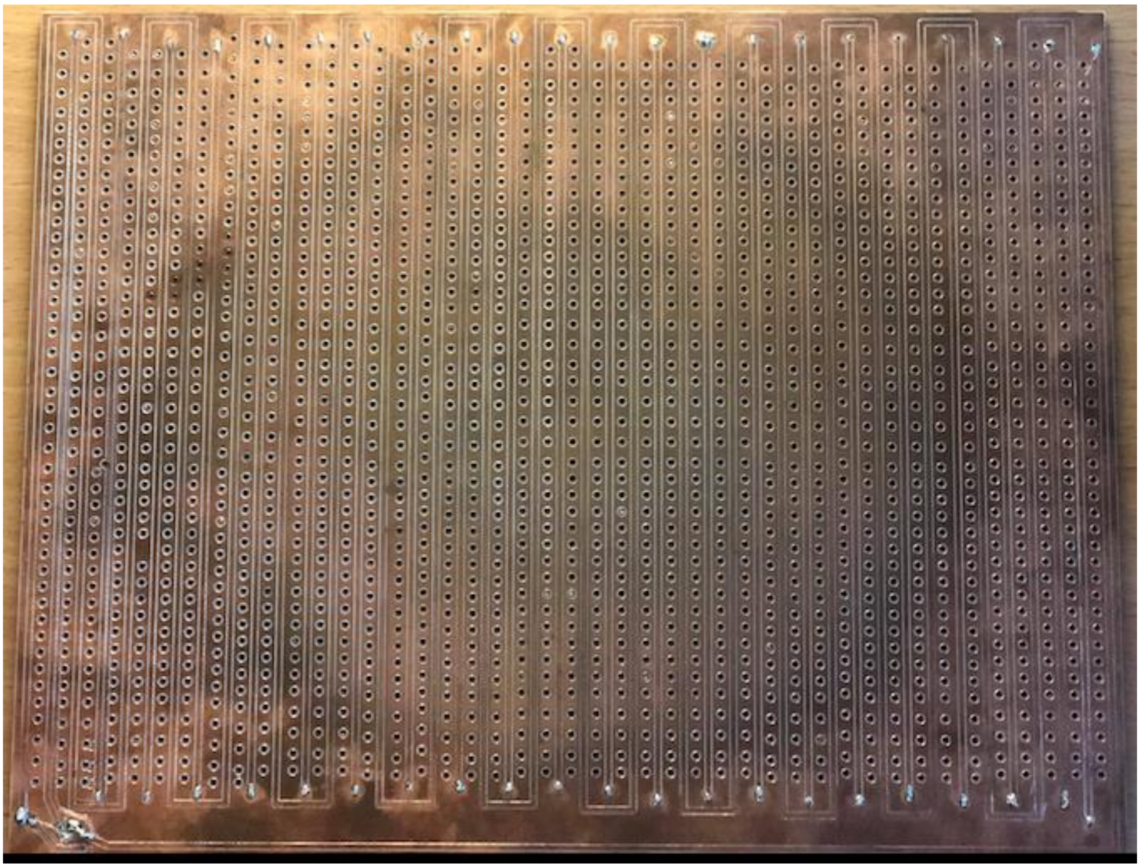


Figure 32. Grid design in RF4 PCB

The second model was designed with stainless steel bars as shown in fig. 33, these bars are connected through copper lines in PCB board so that each two consecutive steel rods act as ground and power lines respectively. Therefore when the mouse is made to walk over it and switch is ON, the mouse makes power and ground lines connected through its body acting as impedance factor. The lines are 0.7 cm far and hence are perfect for solid feces to sneak through the gap. Nonetheless, urine can easily drop down through the gaps of grids.

Figure 33. Grid designed with stainless steel bars

12 Results

After accomplishing the successful design of current sources, grid, and PWM software system. They were all put together and observed. Each current source was examined separately using labview and load of different resistor values. Fig. 34 shows the implementation of DC current source with PWM switching system. The graph on page 1 shows the signal as produced through DAQmx using LabVIEW with the time period of 3 seconds. The duty cycle is less than 50 percent. When it is run the corresponding graph of current 0.3 mA is seen on right side of screen following the same pattern as set before. The value of DC current flowing through the load can be also seen in numeric pallet along with the meter on right tab.

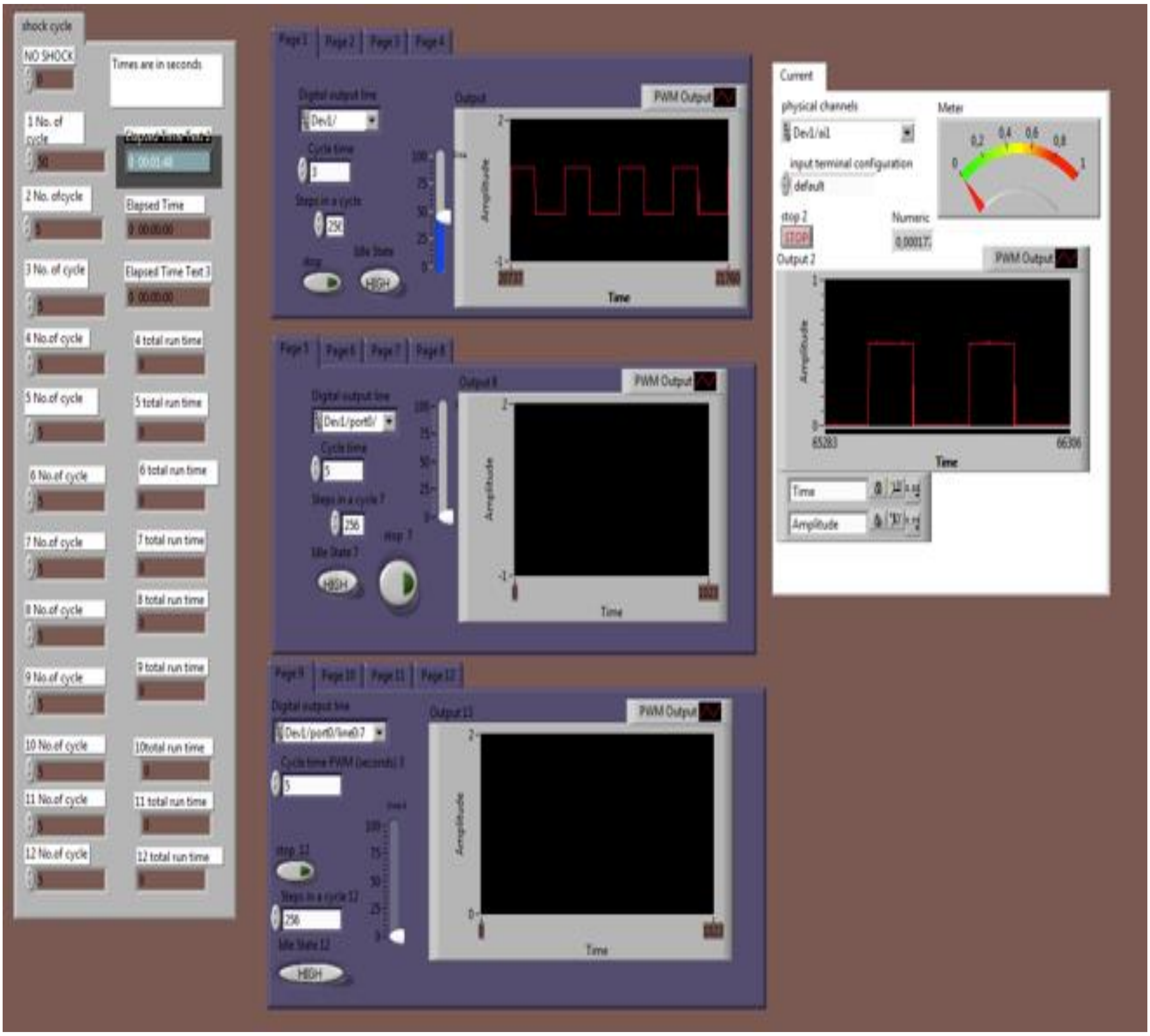


Figure 34. DC current source with PWM switching system

To analyze the credibility and maximum limit of resistance that the current source can handle, different values of resistors are placed as load and the corresponding value of current is observed by tuning potentiometer so that 0.5 mA current is set to flow through the load. Fig. 35 shows a graph of current flowing through the different value of resistors. The graph complies with the theoretical analysis. It is clear from the graph that current remains constant nearly up to 30 kΩ of resistance but beyond that, the current steadily falls which proves that current source is no more functioning as it should be.

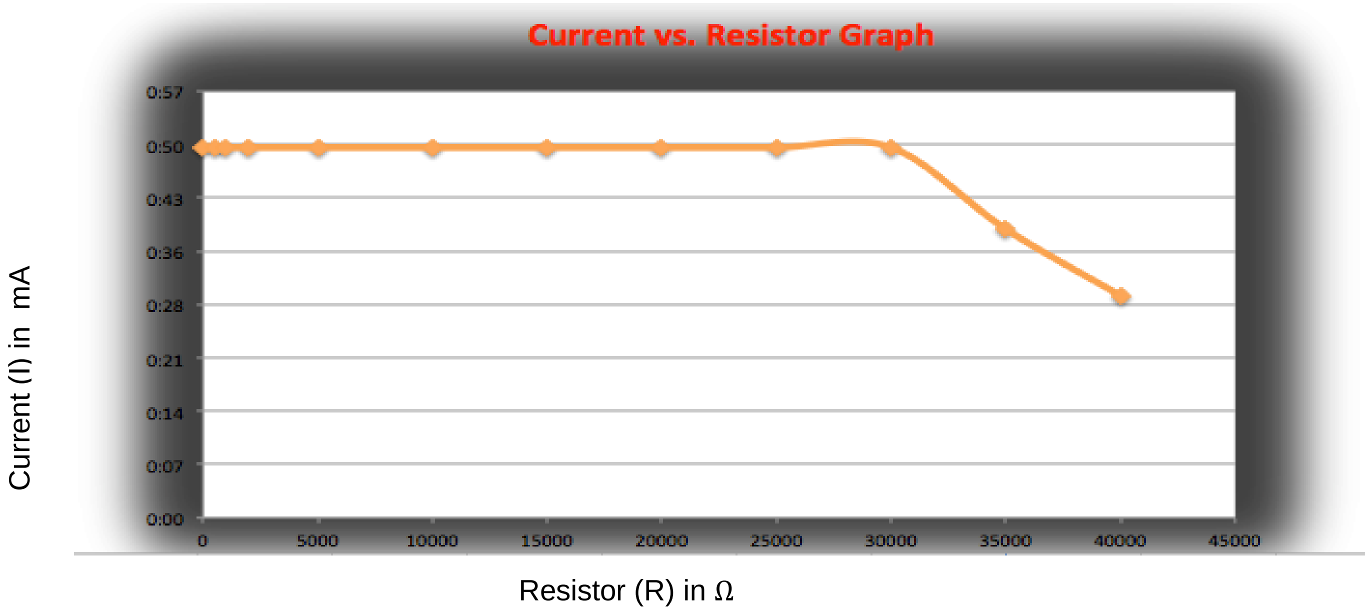


Figure 35. Graph showing current flowing through the different value of resistors

Similarly, in fig. 36 same phenomenon with AC current is implemented. The waveform on the right tab shows AC current pulses flowing through load and being perfectly chopped by the DC switch. The parameters for PMW is made same as DC model. The actual result complies with the simulation and the system works as expected with AC current pulse too.

Figure 36. AC current source with PMW switching system

13 Conclusion

This study focuses on the basic design of a shuttle box which can be used for the inhibition testing on the mouse. The major parts of the shuttle box were PWM switching system, current sources (both AC and DC) and the grid. National Instruments USB 6008 data acquisition device was implemented with LabVIEW to generate PWM signal from one of its digital output pin and to take an analog reading from one of its analog input channel. Similarly, the front panel of labview was designed to serve as a user interface to control different parameters like duty cycle, the time period for the output signal, number of iterations of pulse and pins for digital output and the analog input of USB 6008. The PWM signal was later implemented as a switch to control the ON time and OFF time of the current, generated from current sources.

For the generation of constant current sources, different electric circuits were analyzed and tested. Finally, op-amp current source was used as DC current source. It was designed to generate DC current form the range of 0 to 0.5 mA and the amount of current flowing through the source was controlled by the potentiometer. Whereas for AC current source at first oscillator was designed to generate a sine wave of 108 Hz then the oscillating wave was fed into a single-ended op-amp in a negative feedback configuration to design AC current source. It was also designed to generate rms current from a range of 0 to 0.5 mA. Schematics and layouts of both the circuits were designed in PADS software and later printed in FR4 PCB. The grid was made in two different models one using stainless steel bars acting as the power and ground lines and the another was designed in PCB with copper traces acting as power and ground lines.

Finally, all the parts were put together and the shuttle box was made. In the beginning, it was tested in computer simulation and later with variable resistors were used as dummy mouse. The system operates in such a way that the current is generated from a current source and flows to the mouse through the conductive grid surface where the mouse is placed as an impedance factor. The amount of current flowing into the mouse is controlled by changing wiper’s position of potentiometer whilist PWM signal from USB 6008 is used to control the duration of ON and OFF time of current, which is used to give shocks to the mouse.

Through the analysis of results, it can be concluded that the main targets of the project were achieved which were to design current sources that could deliver current from 0 to 0.5 mA (AC and DC) and to implement PWM signal to control the current value, duty cycle and period of those generated waveforms. The actual results comply with the simulated values to a great extent.

However, there are some limitations on load impedance value that can be used for testing due to the supply voltage. The power used for DC system was only 32 V and 15 V of either polarity was used to powers AC source. Further modification of these systems with higher power supply for current source makes this system more versatile.

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