Department of Electronic and Telecommunication Engineering

University of Moratuwa

EN 2090– Laboratory Practice II

Analog Function Generator

Group 16

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This is submitted as a partial fulfilment for the module

EN2090: Laboratory Practice II

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Abstract

This is the report for the Analog based function generator project. This project covers from the circuit designing and simulation to building. The device can generate Sin, square, triangle (symmetric), Sawtooth or Ramp and PWM with variable duty cycle. Waveform’s amplitude and frequency can be adjusted within 0- 10 V and 20Hz to 20kHz range as per required.

The report explores each waveform and its circuit design, problems faced and their solutions and final conclusions.

Content

1.Introduction

Generating various electrical waveform with variable amplitude in a range of frequencies is the purpose of the function generator. This is a device that can be implemented both in digital and analog in electronic sense. In early time analog based devices were widely used by utilizing IC's like AD9833. Then with introduction of direct digital synthesis chips digital based function generators became wide used.

In the world of programmed IC based function generators we took the approach of analog with usage of basic electronic components and selected Operational amplifier as the most complex electronic unit for waveform generation. The device can generate Sin, square, triangle (symmetric), Sawtooth or Ramp and PWM with variable duty cycle. Waveform's amplitude and frequency can be adjusted within 0- 10 V and 20Hz to 20kHz range. The end wave forms can support current to 50 Ohm resistor. The wave forms have a central frequency adjusting unit to make sure there won't be a need for the user to adjust each waveforms frequency individually (but for each waveform same setting have different frequency). The modifications are made through potentiometers and switches. The selection of circuit and components are prioritized by noise free undistorted wave forms.

The detailed description of the project is given below.

2. Design

2.1 Design Specifications

The Analog Function generator comes with following specifications in generating the required waveforms.

1. The function generator can generate five waveforms, square waves, triangular waves, sawtooth waves, PWM signals and sine waves.

2. The frequency of each waveform can be adjusted in the range 20Hz to 20 kHz.

3. Amplitudes of each waveform ranges from 0V - 10V, peak to peak in square waves and PWM waves, and 0V – 20V in other waveforms.

4. The pulse width of PWM waves is variable from 1% to 99%.

5. The function generator can supply a load of 50Ω without significant distortions.

2.2 Waveform Generation

According to the required specifications, our design can generate 5 waveforms in the frequency range 20 – 20,000Hz. The design primarily uses Op-Amps for the waveform generation.

The centre of the whole design is the Relaxation Oscillator, also known as **astable multivibrator**.

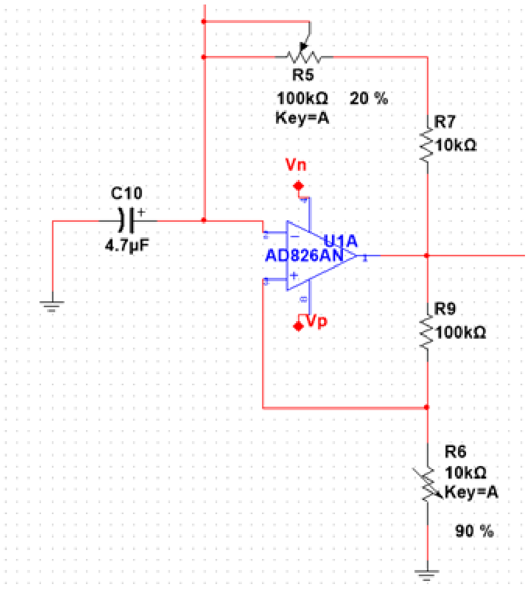


Figure 2.1 Relaxation Oscillator

This is basically a Schmitt Trigger based comparator which compares two voltages against a threshold voltage. The threshold voltage can be calculated as follows.

The op-amps used in our design is powered by ±12V. Hence the threshold is given as,

$$V_{TH} = \pm 12 * \frac{R6}{R6+R9}\ V$$

For R6 a trimmer potentiometer is used. Therefore, our threshold value is variable.

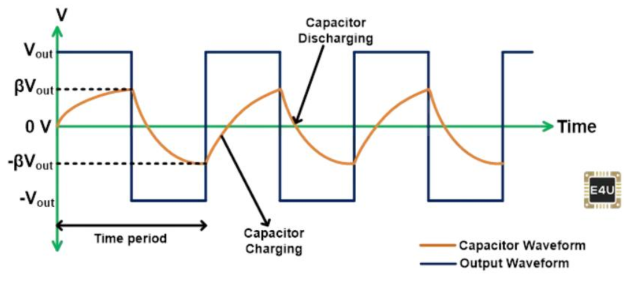


Figure 2.2 Op-Amp relaxation Oscillator Waveforms

Above waveforms represent the output voltage and capacitor voltage of the oscillator.

At the start assume that capacitor is fully discharged, hence voltage at the negative terminal of the Op-Amp is zero. Voltage at the positive terminal is equal to, βV_{out} where,

$$\beta = \frac{R6}{R6+R9}$$

Here $V_+ > V_-$; therefore, the output will rail to positive supply voltage. That is +12V. So, the capacitor will start charging at this stage.

When capacitor charges beyond βV_{out} , it will result in $V_- > V_+$. Hence the output will rail to negative supply voltage. Now the capacitor will start discharging. Therefore, this charging and discharging cycle of the capacitor result in a periodic square wave at the output of the oscillator.

Frequency of this output waveform depends on the time constant of the RC circuit. Hence, we change the value of the capacitor and the R5 resistor, to change the frequency of the output waveform. More on this will be explained in the section under Variation of Frequency

2.2.1 Square wave generation

The output of the relaxation oscillator is already a square waveform. But its amplitude is a little high at this stage, so we pass the waveform through an inverting amplifier to attenuate the square waveform to a low voltage.

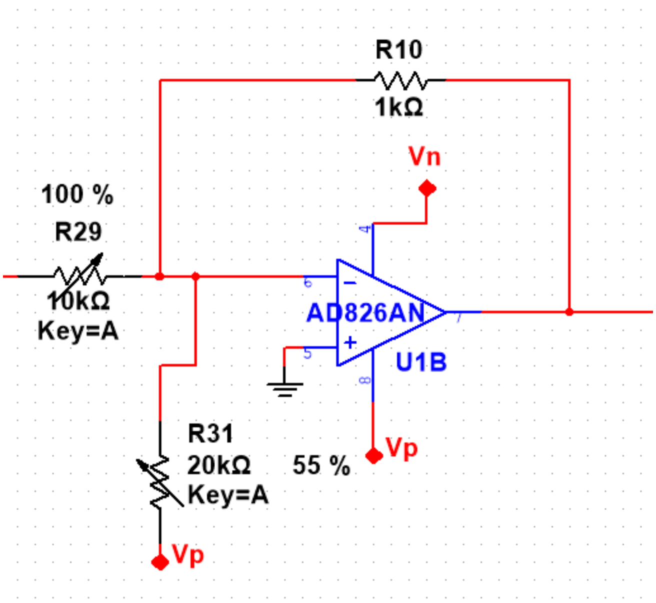


Figure 2.3 Inverting summing amplifier of the square waveform

The gain of an inverting amplifier is equal to $-\frac{R10}{R29}$ according to the above diagram. A trimmer is used as R29 for further calibration when the PCB is made.

The above circuit is indeed a Summing Inverter, which outputs the sum of input voltages. This is used as one design requirement of square wave is to make the wave positive only.

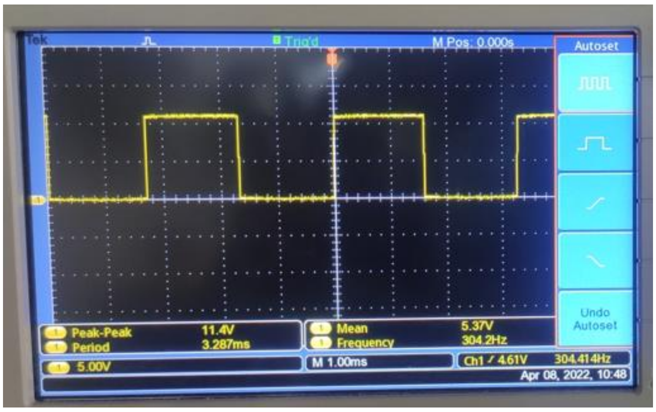


Figure 2.4 Square wave output

2.2.2 Triangular wave generation

Usually if a triangular waveform is to be generated, the square wave should be fed to an integrator which integrates the square wave to generate a triangular waveform. Using an integrator means a capacitor should be connected and once we want to change the frequency of the waveforms, the value of the capacitor should also be changed to obtain a waveform with useful amplitude. One benefit of the relaxation oscillator is that it can produce an approximate triangular wave along with the square wave. The voltage of the capacitor connected to the relaxation oscillator rise according to the following function. $V_c(t) = 12 * \left(1 - e^{\frac{-t}{RC}}\right)$

So, the capacitor voltage follows an exponential waveform. If we make "t" to be small and take the first order Taylor approximation of the above equation, we get an equivalent ramp function.

$$\begin{aligned} g_1(x) &= f(0) + f^{(1)}(0)x \\ &= e^0 + e^0 x \\ &= 1 + x \end{aligned}$$

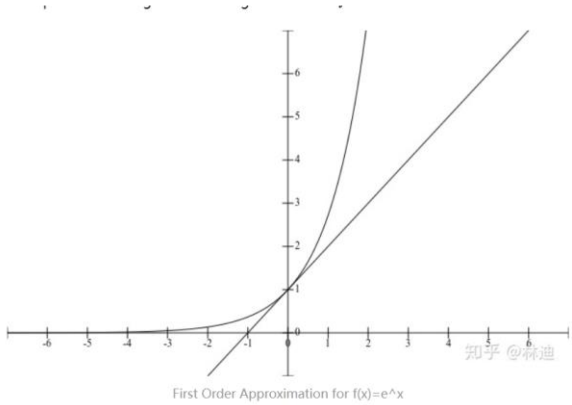


Figure 2.5 First Order approximation of e^x

$$e^{\frac{-t}{RC}} = 1 + \left(\frac{-1}{RC}\right)t$$

Hence, $V_c(t)$ can be approximated as,

$$V_c(t) = 12 * \left(\left[\frac{1}{RC}\right]t\right)$$

To implement this concept in the analog design, we make the V_{thres} much less than the supply voltage (by around a factor of 10) A non-inverting amplifier picks up this waveform. The reason for specifically using a non-inverting amplifier is that they have extremely high input impedance. As the charge of a capacitor is small, if any significant current is drawn from that point, it will affect the operation of the relaxation oscillator.

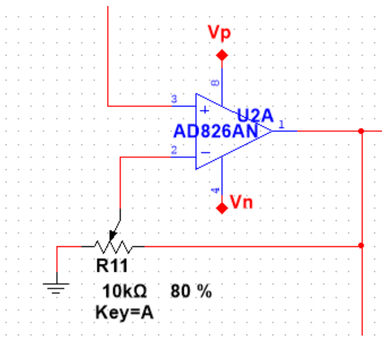


Figure 2.6 Non-inverting amplifier of triangular waveform generator

Therefore, output of this non-inverting amplifier can be used to obtain the triangular waveform without ruining the operation of the relaxation oscillator.

2.2.3 Sine wave generation

The triangular wave output is fed into an integrator which integrates the triangular waveform to produce a series of parabolas. The resulting waveform is an approximate sine wave. This can also be justified as the second order Taylor expansion of the desired sine wave.

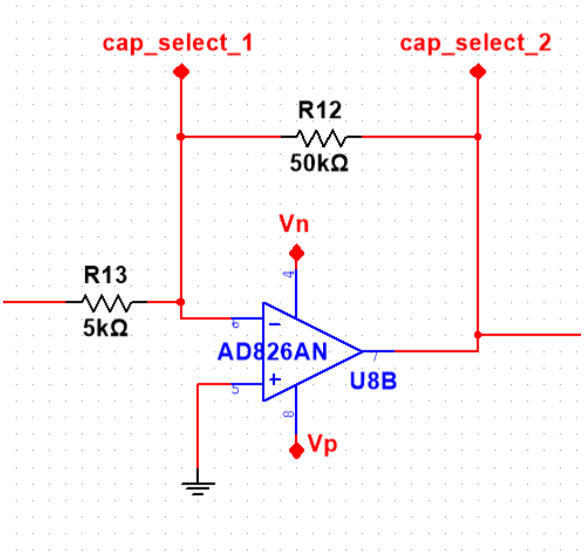


Figure 2.7 Integrating Amplifier

The integrating amplifier gain can be expressed as,

$$G = -\frac{1}{2\pi R C f}$$

One issue we had to deal with integrators is, when the frequency of the triangular waveform is changed, we must change the capacitance of the integrator also to get a useful output voltage, as the gain is inversely proportional to the frequency of the source waveform. The solution for this is to use a two-deck rotary switch which allows to change the capacitor value of this integrator while changing the capacitor value of the relaxation oscillator. (This will be explained more under *Variation of frequency* section). The R12 resistor reduces the **drift** caused by undesired integration of tiny offset voltages.

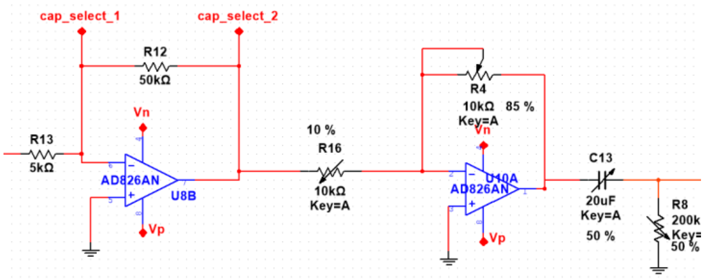


Figure 2.8 Sine wave generator

The waveform from the integrating amplifier is fed into an inverting amplifier. This is used for calibrating the amplitudes of the sine wave after the PCB has been designed.

A high pass filter of f_{3dB} = 0.1 Hz is used after the amplifier which removes any remaining offsets after the integration process.

2.2.4 Sawtooth wave generation

There are several ways a sawtooth can be generated. The most general way is to generate a PWM waveform with 99% duty cycle and then integrate it. Once again, the issue with integrators arises. Once the frequency of the PWM signal is changed, the capacitor value of the integrator should also be changed for a usable signal amplitude. Hence an alternative method is used to generate the sawtooth waveforms that doesn't use any integrators,

If a triangular and square waveform of the same frequency and phase, are taken and invert the triangle only when the square wave is high, a sawtooth waveform of twice the frequency of original waves can be generated.

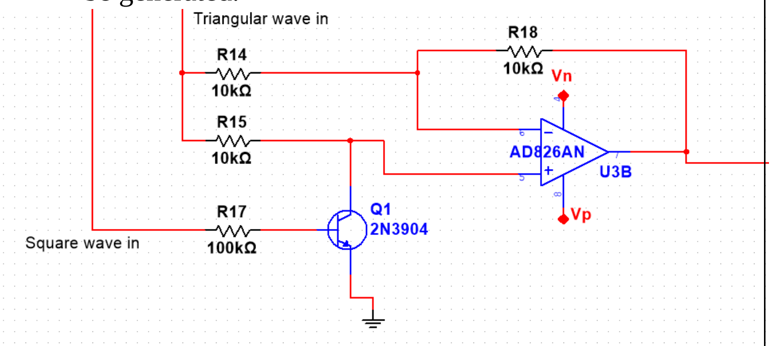


Figure 2.9 Sawtooth wave generator

At the positive cycle of the square wave the transistor will be conducting and act as a on switch. Then the non-inverting terminal of the Op-Amp is grounded, and it acts as an inverter with a gain of -1.

In negative half cycle of square wave, the transistor is off, and the triangular input will be applied to both inverting and non-inverting terminals of the Op-Amp.

Therefore, the Op-Amp will behave as a non-inverting follower with unity gain.

Figure 2.9 Generation of sawtooth waves

2.2.5 PWM wave generation

Pulse width modulated waveform is similar to square wave but has a variable duty cycle.
Due to the inherent nature of the Op-Amp as the comparator, we can use a symmetric waveform and compare it with a threshold voltage to create a PWM wave.

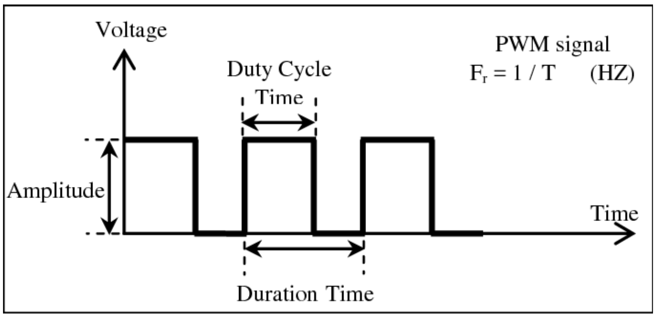


Figure 2.10 PWM waves

Here we are taking the triangular waveform as the input signal for PWM signal generation due to the case that the triangular wave is also a function in requirement. Selection of triangular waveform compared to sin wave is due to triangle waves linear movement in any time that leads to much more desired and predictable output and to have a very higher range of duty cycle using triangle wave is the best choice. By using a previously processed waveform the frequency selection stage can be negated for this unit (can be modified by modifying the triangular waveform).

The below image shows the design of the circuit.

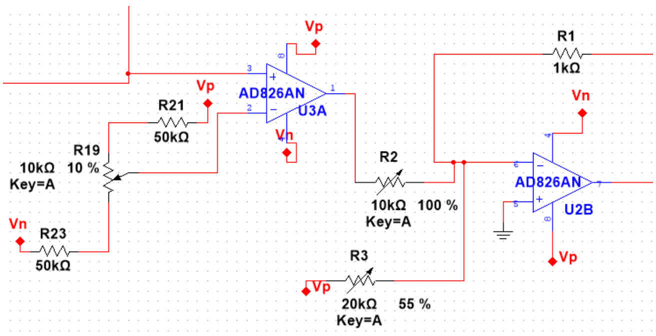


Figure 2.11 Generation of PWM waves

This unit of wave generation consists of 2 basic circuits. As said earlier the circuit takes a symmetric triangular wave and it's given to the positive input to the U3A Op-Amp. This stage is just a comparator but rather than having a fixed threshold voltage in the negative input we are using a potentiometer with a connection to Vp the +12V and Vn the -12V: by adjusting the potentiometer the threshold voltage can go from high positive voltage to very low negative voltage doing so we can use the whole wide range of triangle wave doing so allowing a higher range of duty cycle. But the resultant wave has an undesired feature of being symmetric to zero voltage.

The second stage of this unit is the Op-Amp based adder circuit and it takes the previous signal as its one negative input. The second negative input will be taken from +12V connected to a variable resistor; by adjusting its value we can add a DC offset to the symmetric PWM waveform and in the end, waveform can be adjusted to be in a completely positive range.

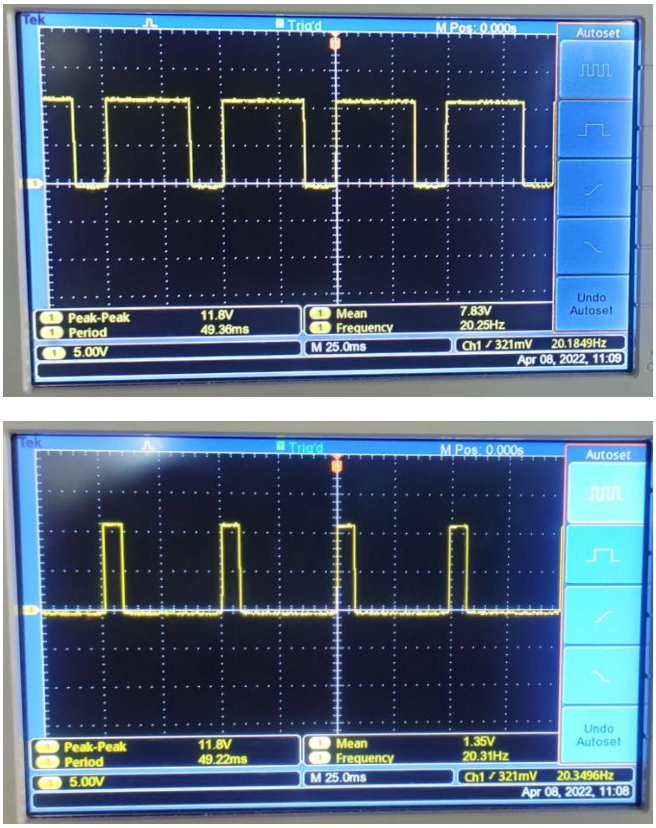


Figure 2.12 PWM waves results

2.3 Output Circuit

The output circuit of our design enables the adjustment of signal amplitude and driving small impedances without any significant distortions.

First an inverting amplifier is used for the adjustment of the signal amplitude. The output circuit is connected to the signals via three switches, which enables the user to directly increase the amplitude by factors of 1, 10 and 20.

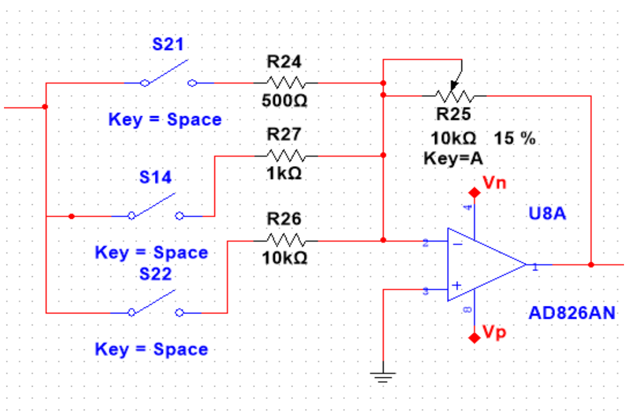


Figure 2.13 variation of amplitude

R25 potentiometer is the main amplitude adjustment knob. Selecting one of S21, S14 and S22 switches will give the signal the relevant coarse gain and then amplitude can be adjusted finely using R25. The output of this inverting amplifier can be used as a "High impedance output" which can only output a small current without any distortion.

Hence to drive a small impedance without any significant distortion, a transistor push-pull amplifier is connected to the output of above circuit.

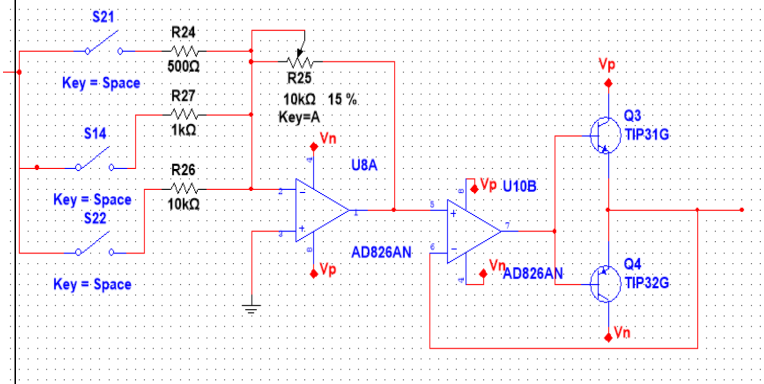
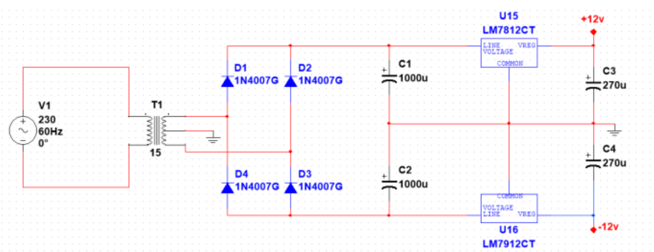


Figure 2.14 Output circuit

A Push pull amplifier is cable of driving current through a load in either direction. Here two power transistors, complementary to each other are used. In this design an Op-Amp drives the two transistors. The inverting terminal of the Op-Amp is connected to the power output stage as negative feedback. This creates a voltage follower circuit at the output. But as we are using a power stage, here we can deliver much more current than a single Op-Amp could provide. The Op-Amp will always try to make the voltage at the inverting terminal equal to the voltage at the non-inverting terminal, so the cross-over distortion is eliminated.

2.4 Power Circuit

The Op-Amps in the design requires positive and negative dual power supply. Hence the requirement of the power circuit is to take 230V AC as input and produce DC ±12V output voltage. For this, a transformer which steps down voltage from 230V to 15V is used. This stepped down voltage is rectified and L7812 and L7912 voltage regulators were used to regulate the voltage to +12V and -12V.



2.5 Variation of Frequency

One design requirement of the project is the variation of frequency of all the waveforms in the range 20 – 20,000 Hz. As the design is based on the relaxation oscillator, changing the frequency of oscillation will change the frequency of all the waveforms.

The frequency of the relaxation oscillator is roughly equal to,

$$f = \frac{(R6+R9)}{4*R6*C*(R5+R7)}$$

Therefore, decreasing the capacitance will result in increase of the frequency. Our design uses a capacitor bank which consists of 5 capacitors as a coarse frequency change and a potentiometer (R5) for fine frequency adjustment.

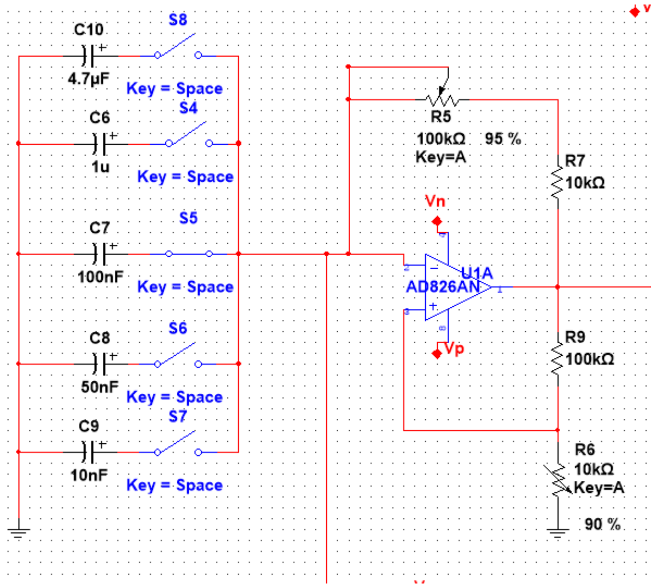


Figure 2.15 Relaxation Oscillator with capacitor bank

The coarse frequency adjustment will vary the frequency in ranges. Then the fine frequency adjustment knob will vary the frequency in the selected range with low resolution. Following table shows the size of capacitor in each frequency setting and the range for each waveform.

Frequency level	Capacitor Value
1	4.7uF
2	1uf
3	100nF
4	47nF
5	10nF

Capacitor values aren't selected in a linear way. The reason for this is, we wanted to make sure that highest possible frequency in one frequency level should be higher than the minimum frequency of the next frequency level.

As other waveforms are based on the relaxation oscillator, changing the oscillation frequency will result in variation of frequency of other waveforms. One issue arises here is the integrator of the sine wave. As gain of an integrator is inversely proportional to the frequency of the waveform, the capacitor connected to the integrator should also be changed accordingly. Say we increase frequency by a factor of 10, then we must decrease the size of capacitance of the integrator by a factor of 10.

Frequency level	Sine Integrator capacitor value
1	1uF
2	200nF
3	69nF
4	30nF
5	4.7nF

For this reason, we are using a two-deck rotary switch, which makes two connections along the capacitor bank and capacitors of the sine integrator.

Figure 2.16 Two deck rotary switch

2.6 Component Selection

The most crucial part of component selection is the selection of correct Op-Amp. As we are required a maximum frequency of 20,000Hz for the waveforms, slew rate of Op-Amps is one important factor to be considered. The relatively accessible and most common LM741 Op-Amps with 0.5V/µs slew rate cannot be used for this purpose. LM741 will take around 20 µs to rise to 10V at 20,000Hz of frequency. For an example the half period time of a square wave at 20kHz is 25 µs. So, the wave is straight distorted at 20kHz. Therefore, an Op-Amp which is much faster than LM741 is required. Our selection was the TL084 Op-Amp with 13V/µs slew rate which should produce pretty good result even at much higher frequencies. They also have JFET inputs with much higher input impedance, which will draw minimum current from the source connected.

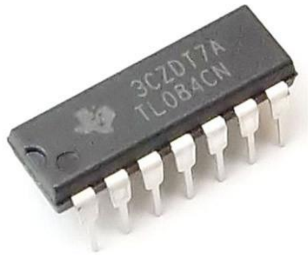


Figure 2.17 TL084 Op-Amp

But in our final design AD826 Op-Amps were used mainly because TL084s were not available in the market and the quality of the ones available is not up to the required level. AD826 is much faster Op-Amp with 350 V/µs slew rate which is much higher than what is required.

Also, the Op-Amp has 50MHz of unity gain bandwidth, which should satisfy all the amplifiers used in our design.

At the push pull stage amplifier, it should be able to drive a small resistor without significant distortions to the waveforms. The transistors should be selected to satisfy the power and current requirements. The maximum power for an amplitude of 10V should be $\frac{10^2}{50}$ = 2W and the maximum current should be 200mA. TIP32C and TIP31C selected are power transistors which satisfy the above requirements. These transistors can supply up to 40W of power and can give a maximum collector current of 3A.

2.7 Schematic and PCB design

After testing the circuits on a breadboard successfully, we moved to the PCB designing stage. PCB designing was done using the Altium software. We designed the PCBs as two separate circuits. One circuit for the power supply and the main PCB which contains all the other circuits. The power supply PCB was designed as a single layer PCB while the main PCB was designed as a double layer PCB. PCBs were manufactured by a local manufacturer. So, we had to make some adjustments so that the designs match the manufacturer's capabilities. Since the vias of locally manufactures PCBs are not connected through holes, we had to make that connection by soldering. We have used many vias to get almost all the soldering points to the bottom layer so that soldering becomes easy. A routing width of 0.7mm is used for normal routing and a 1.2mm width is applied for power nets.

As the initial step of soldering, vias were soldered from the top layer and bottom layer to establish the connection between the top and bottom layers. Then resistors were soldered. 8 pin IC bases were used to mount the Op-Amps to the PCB. Potentiometers and the rotary switch are used to change the frequency, amplitude, dc offset, and PWM duty cycle. Two 7-pin JST connecters were used to make the connections of the rotary switch. A couple of headers were used to establish the connections of switches to switch between waves.

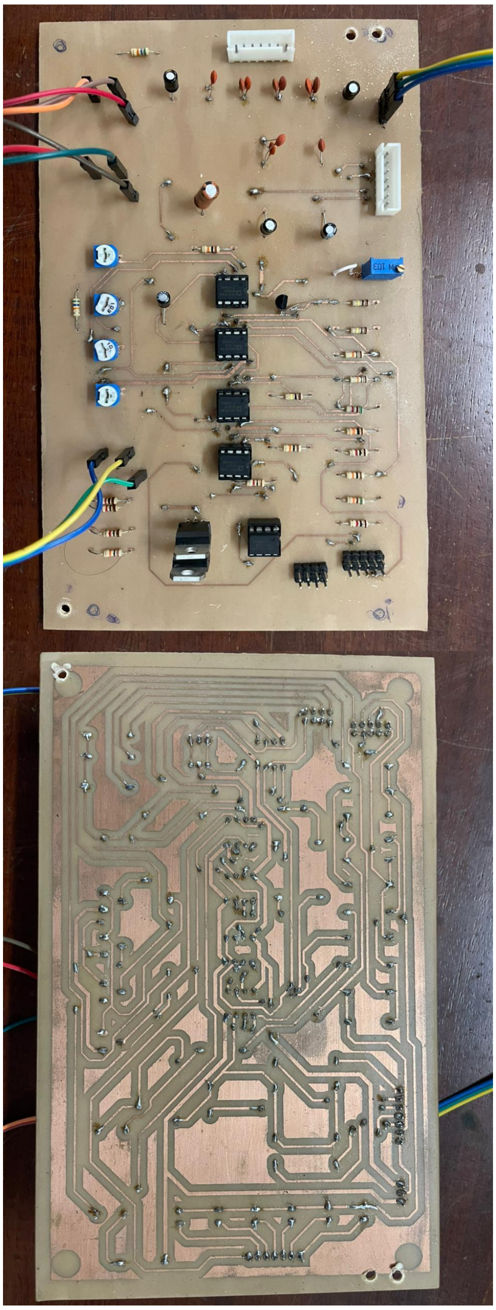


Figure 2.18 PCB

2.8 Enclosure Design

The enclosure was made to resemble an actual function generator. It was made to accommodate power circuit PCB and main PCB. SPDT switches are used to select the waveforms. Two banana connectors are used to take the signal out.

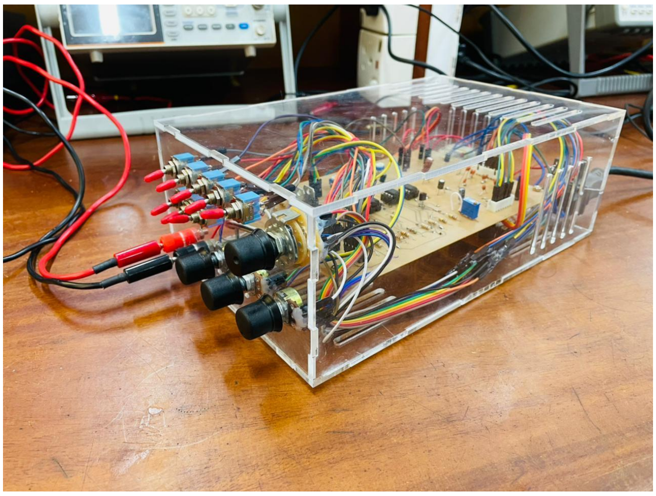


Figure 2.19 Final Product

3. Results and Discussion

First the design was simulated and debugged using a simulator on a computer. We used NI Multisim software to simulate the functioning of the function generator.

Next the design was implemented on a breadboard, and it was tuned to get the expected waveforms. As we used trimmer resistors for tuning purposes, it was much easier for us to alter and get the required output.

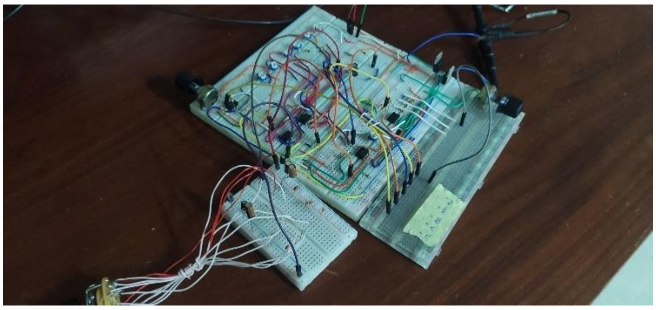


Figure 3.1 Breadboard implementation

Then the final PCB was made and soldered then tested to get the required waveforms.

The function generator is able to achieve the given requirements. All the required waveforms are generated, and their frequencies can be varied in the range 20 – 20,000Hz. Their amplitudes can be varied and a resistor around 56Ω could be driven without significant distortions to the waveforms.

3.1 Frequency range

For all the waveforms frequency can be varied in the range 20 to 20,000Hz without much significant distortions to the waveforms.

1. Square waves: 20 – 45kHz.
   Shows distortions after 30kHz.

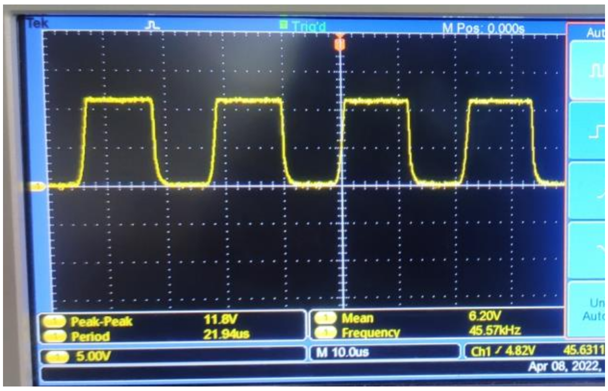


Figure 3.2 square wave at 45kHz

2. Triangular waves: 20 – 42kHz.
   Almost perfect till 20kHz. But shows a reduction in positive amplitude at higher frequencies.

Figure 3.3 Triangular wave

3. PWM waves: 20 – 20kHz.
   Much higher distortions after 20kHz. Duty cycle reduces significantly at higher frequencies.

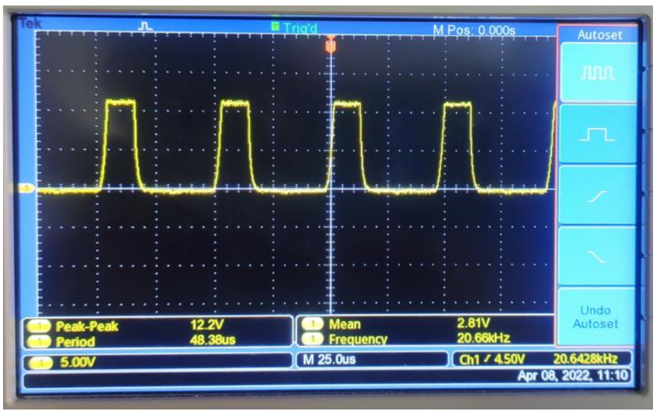


Figure 3.4 PWM wave

4. Sawtooth waveforms: 20 – 20kHz
   Frequency is twice that of the square wave. Much higher distortions at higher frequencies. Amplitude of alternating cycles reduces.

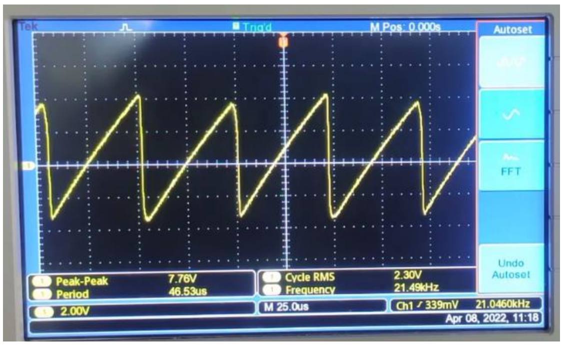


Figure 3.5 Sawtooth

5. Sine wave: 20 – 20kHz
   Resembles series of parabolas more than a sine wave at lower frequencies.

Figure 3.6 Sine wave

3.2 Amplitude

Amplitude can be varied in the range 0 – 10V without significant distortions in all waves other than sine waves. Sine waves can generate around 8V of maximum amplitude.

3.3 Discussion

Almost all the waveforms are generated without much distortion around the required frequency range.

- At higher frequencies the rise time of the square is visible, which shouldn't be the case with much faster Op-Amp like AD826. The summing inverter used to shift the square wave to the positive side introduces much noise at higher frequencies and causes distortions in the square wave.
- Triangular waves are almost perfect around the given frequency range. As our design uses the capacitor voltage to approximate a triangular

waveform, at higher frequencies, the triangular wave distorts to a curved waveform.

- Sawtooth waveforms are the most distorted at higher frequencies. When the transistor is off, it was supposed to cut-off the connection to the Op-Amp non-inverting terminal. But the transistor still conducts some current so that the amplitude of the waveform at that moment reduces slightly. This is the reason that we can see reductions in amplitude at alternating cycles of the sawtooth waveform.

4.References

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6) https://en.wikipedia.org/wiki/Push%E2%80%93pull_output

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8) https://circuitdigest.com/electronic-circuits/12v-dual-power-supply-circuit

5.Contributions

1) Treshan (190443T) – Main simulation design, enclosure design

2) Uvin (190432J) - Main PCB design, Soldering, Final product assembly

3) Pankajan (190428D) - Power supply unit simulation, PCB and soldering, Initial Solidworks design

4) Bimsara (190446F) – Initial simulation design, breadboard implementation

6. Appendices

6.1 Schematic Designs

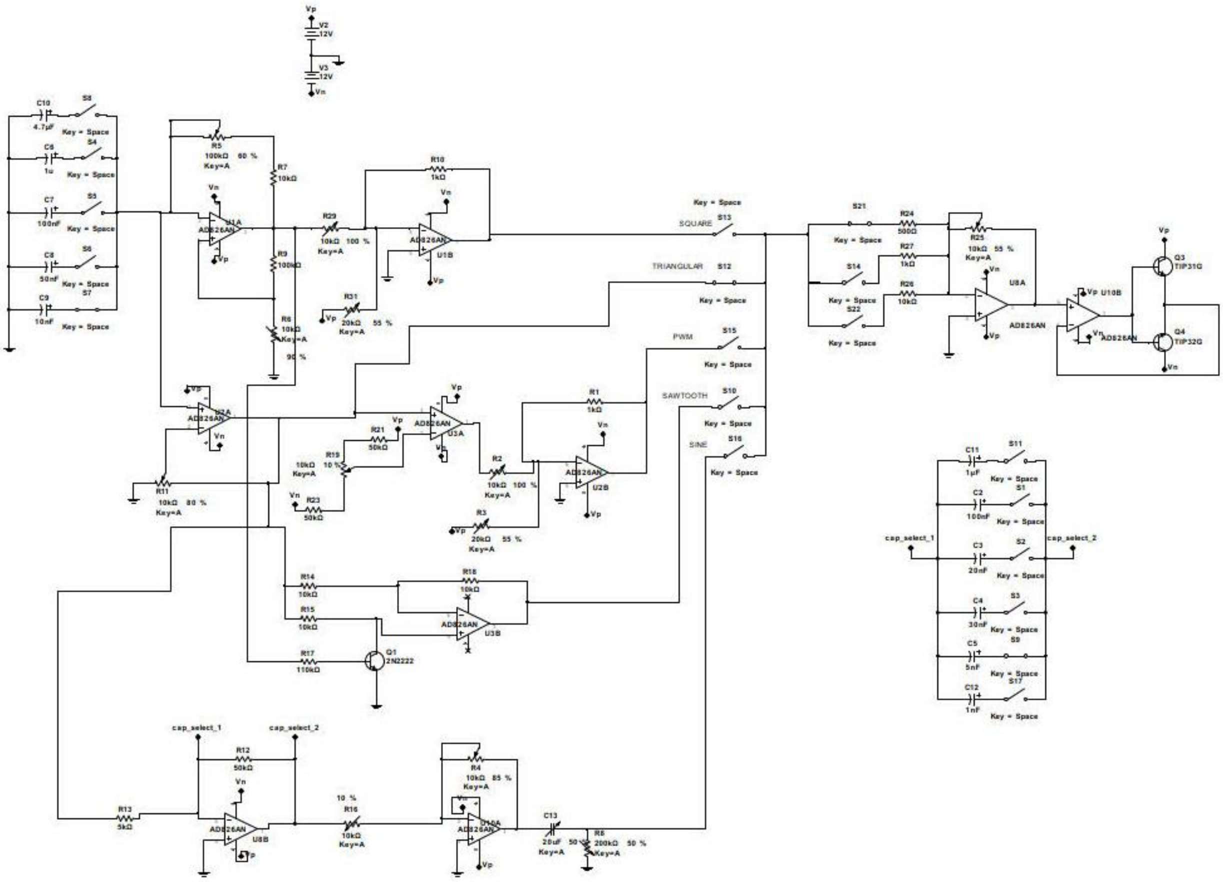


Figure 6.1 Main circuit

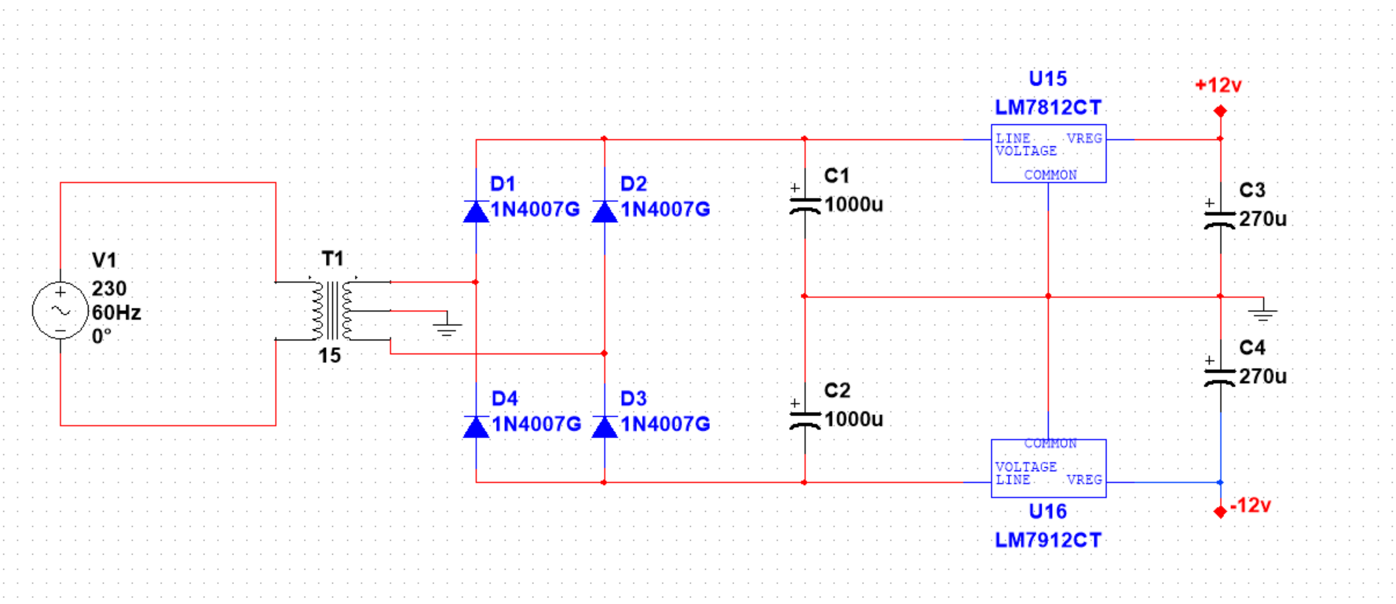


Figure 6.2 Power Supply Circuit

6.2 PCB layout Designs

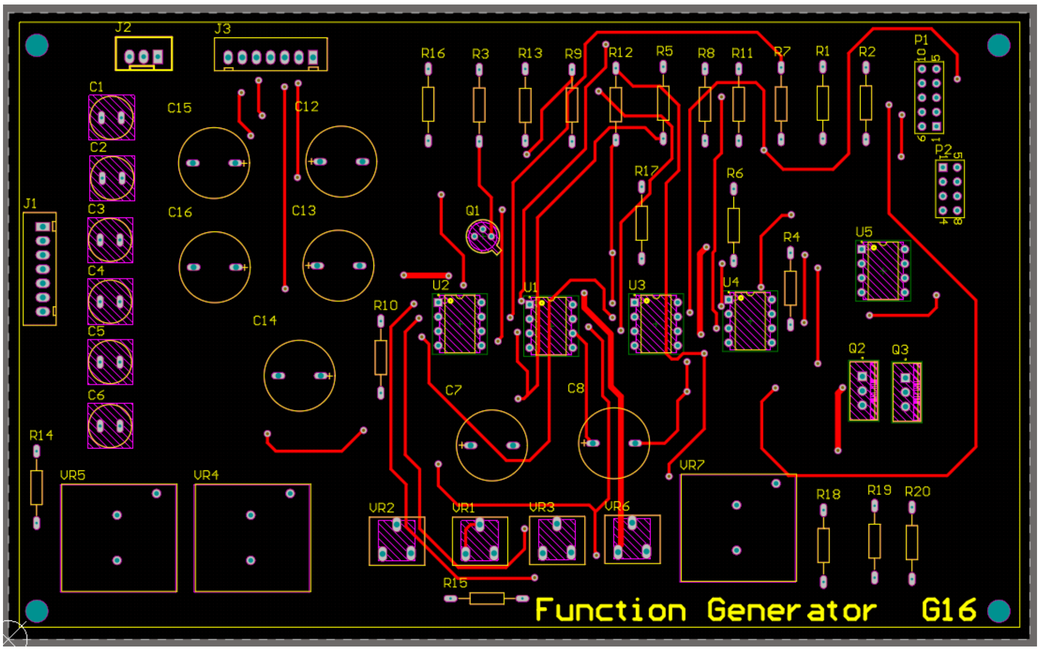


Figure 6.3 Top Layer

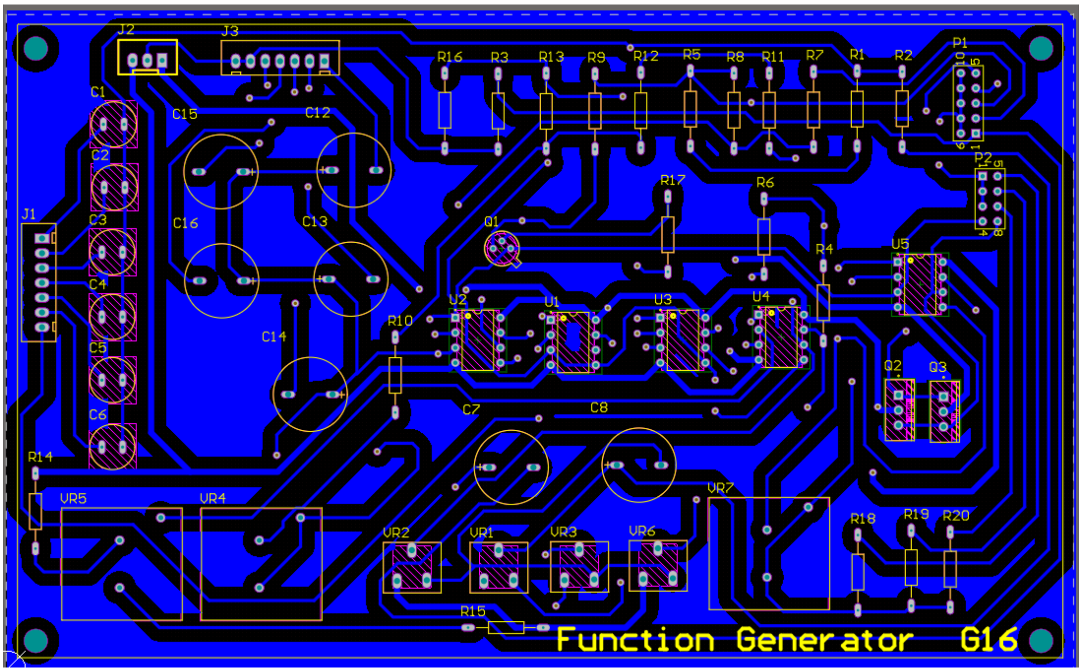
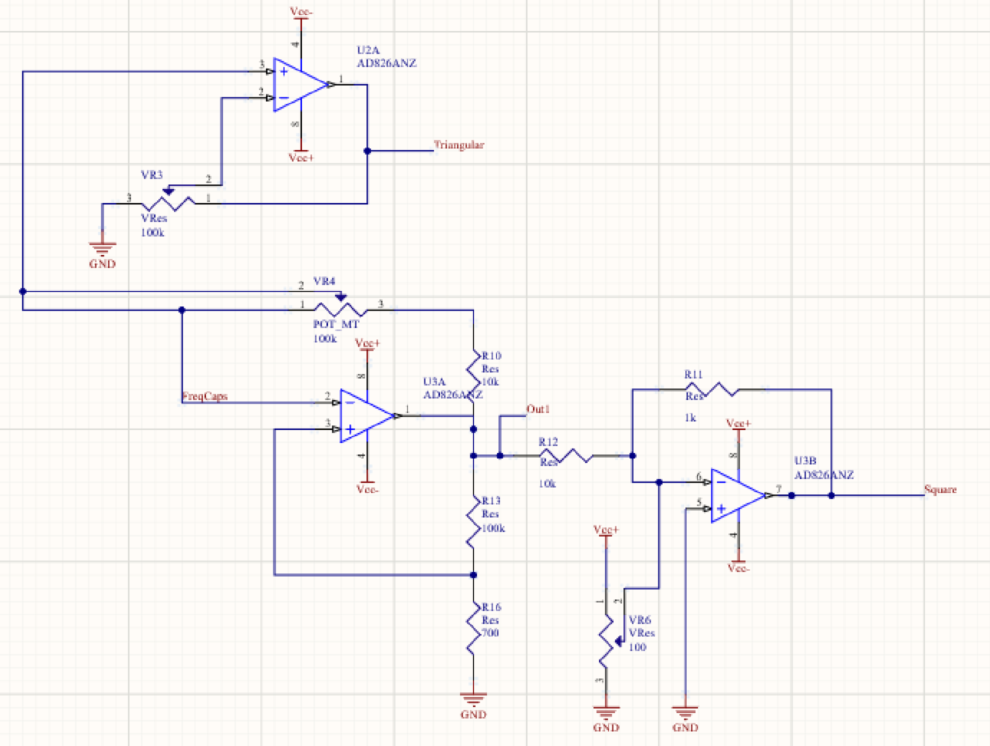
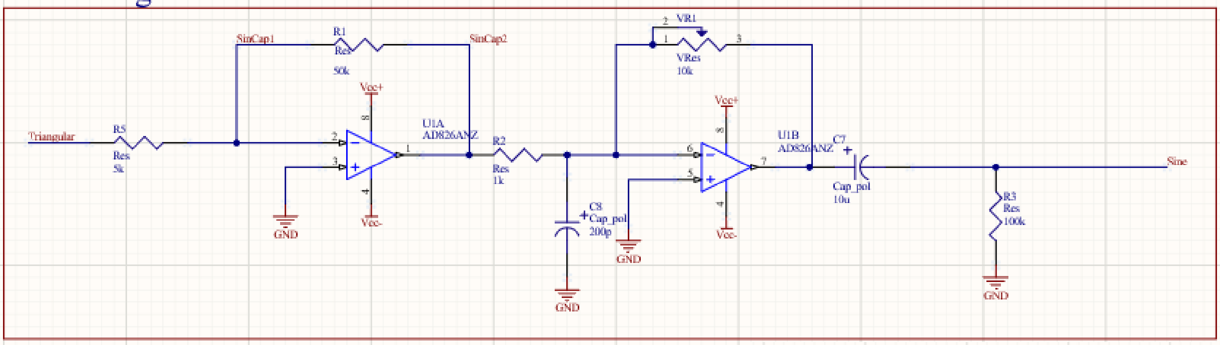


Figure 6.4 Bottom Layer

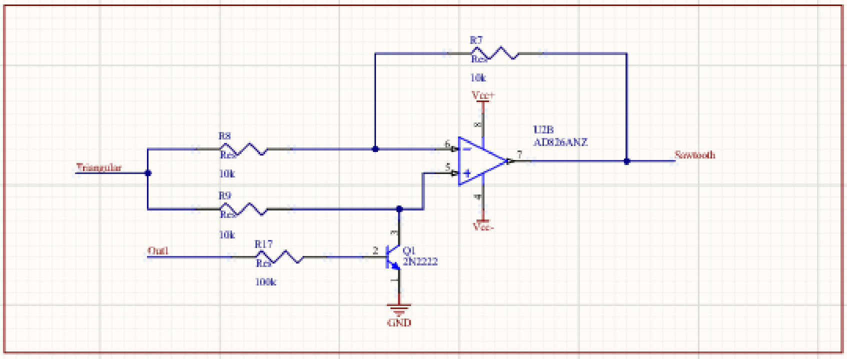
Trangular and Square Wave Generation



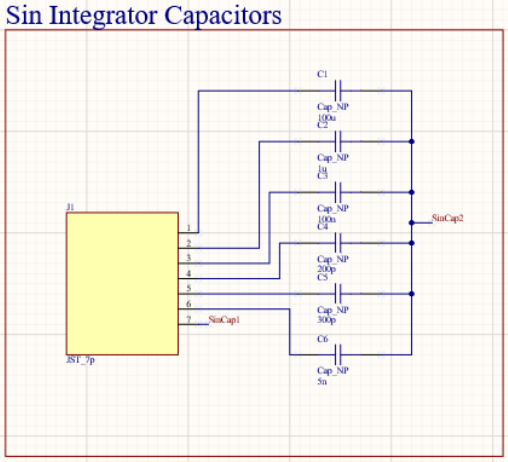
Sin wave generation



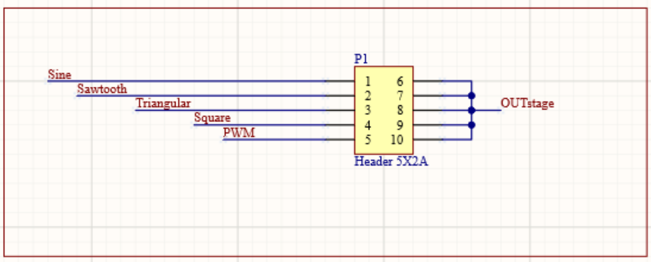
Sawtooth Wave Generation



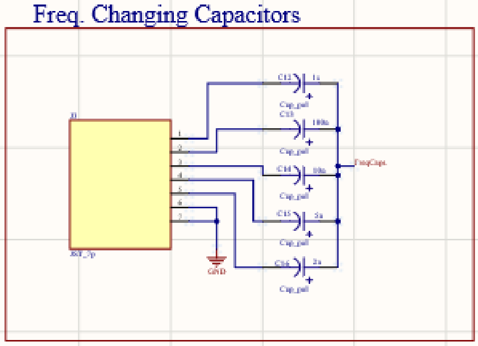
Sin Integrator Capacitors



Switches Connector



Freq. Changing Capacitors



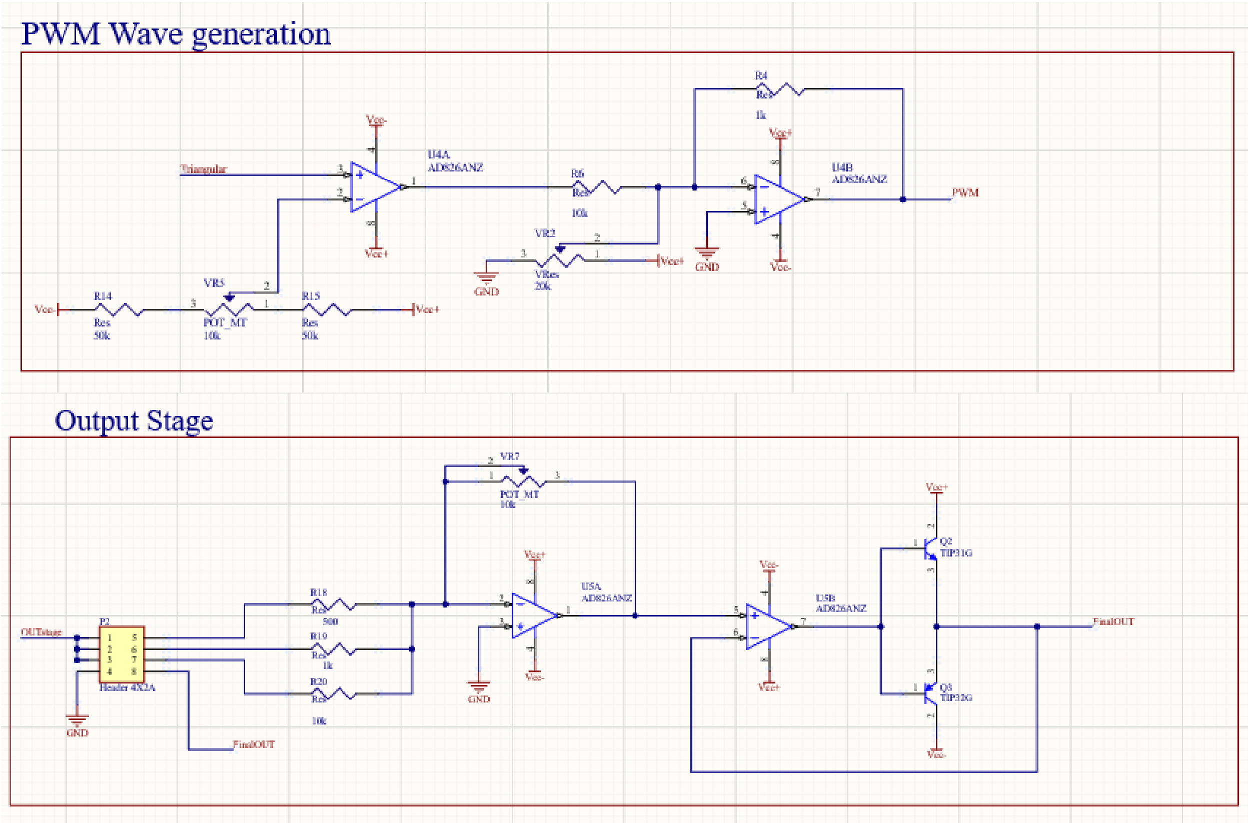


Figure 6.5 Schematic Designs

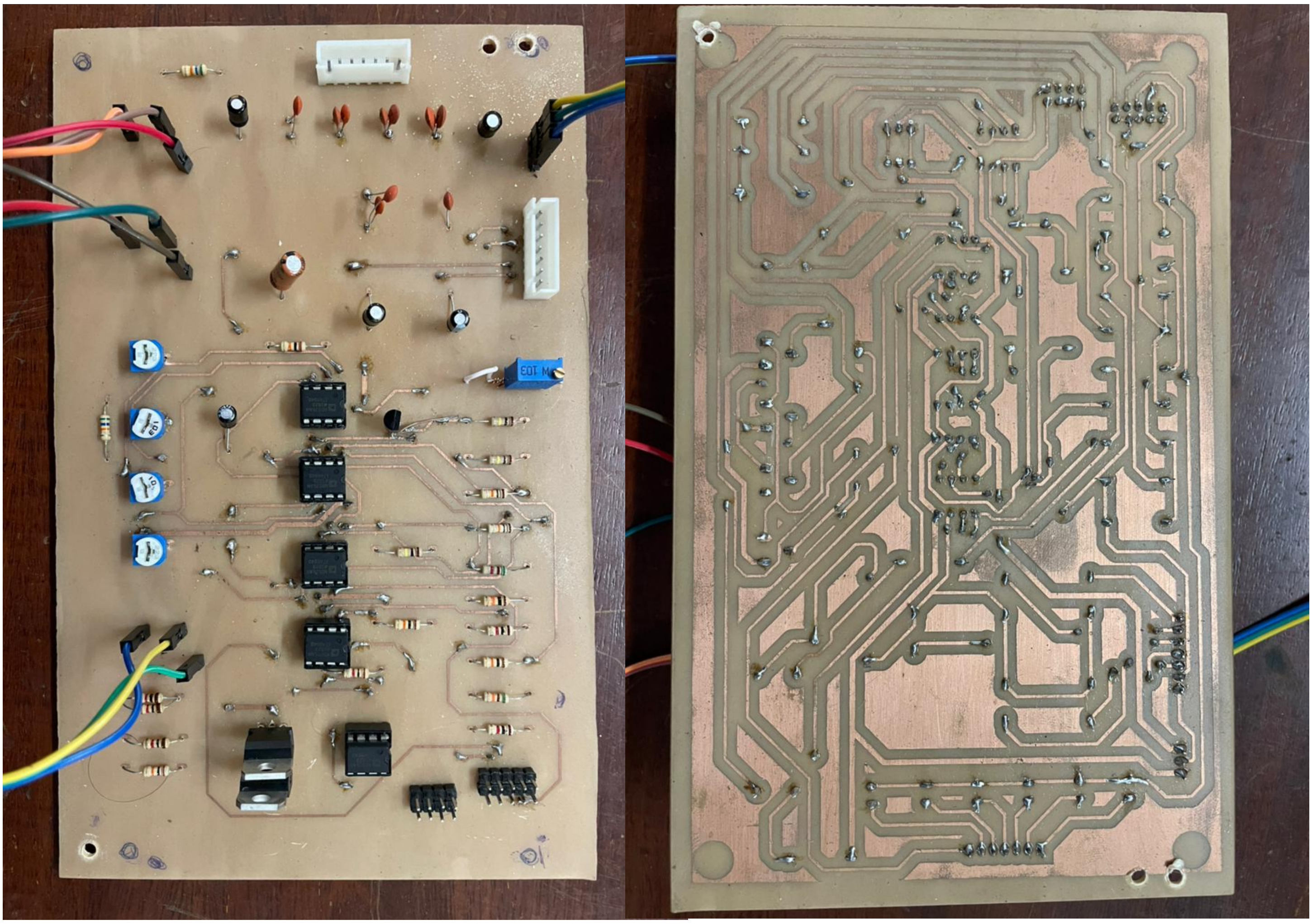


Figure 6.6 Soldered PCB

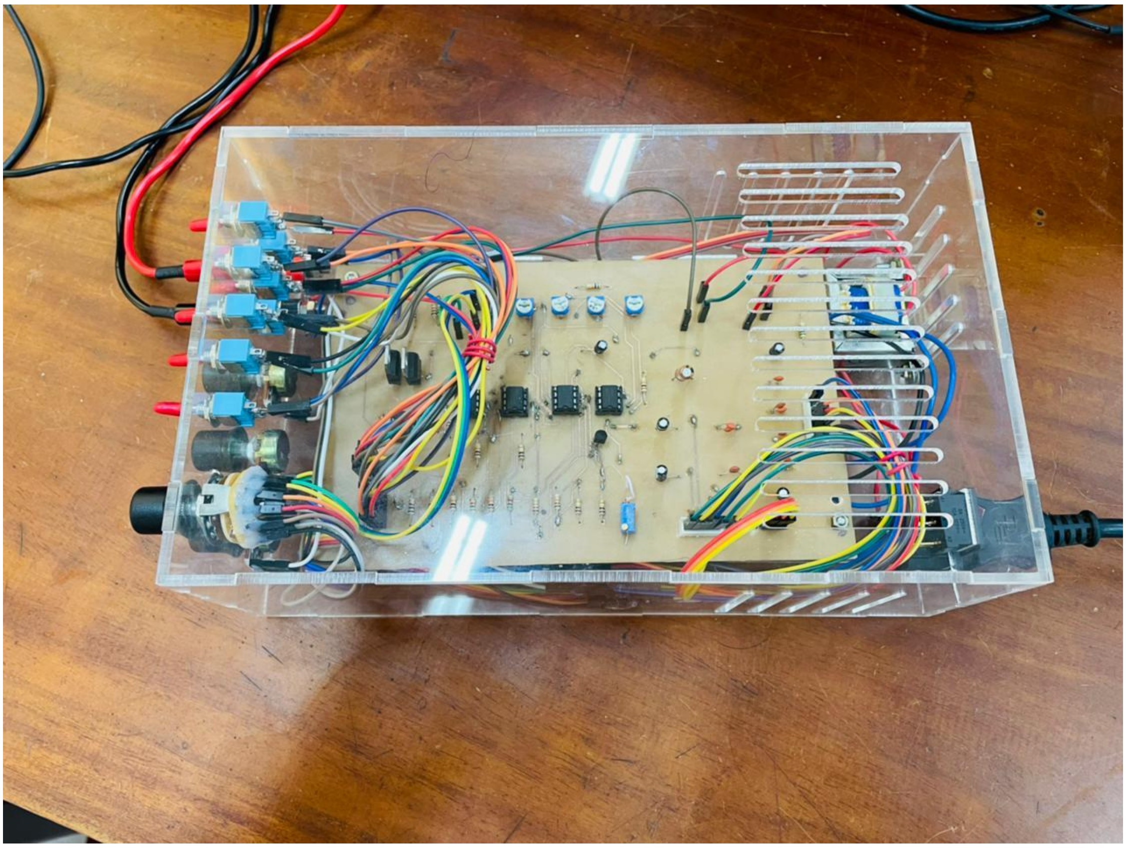


Figure 6.7 Enclosure top view

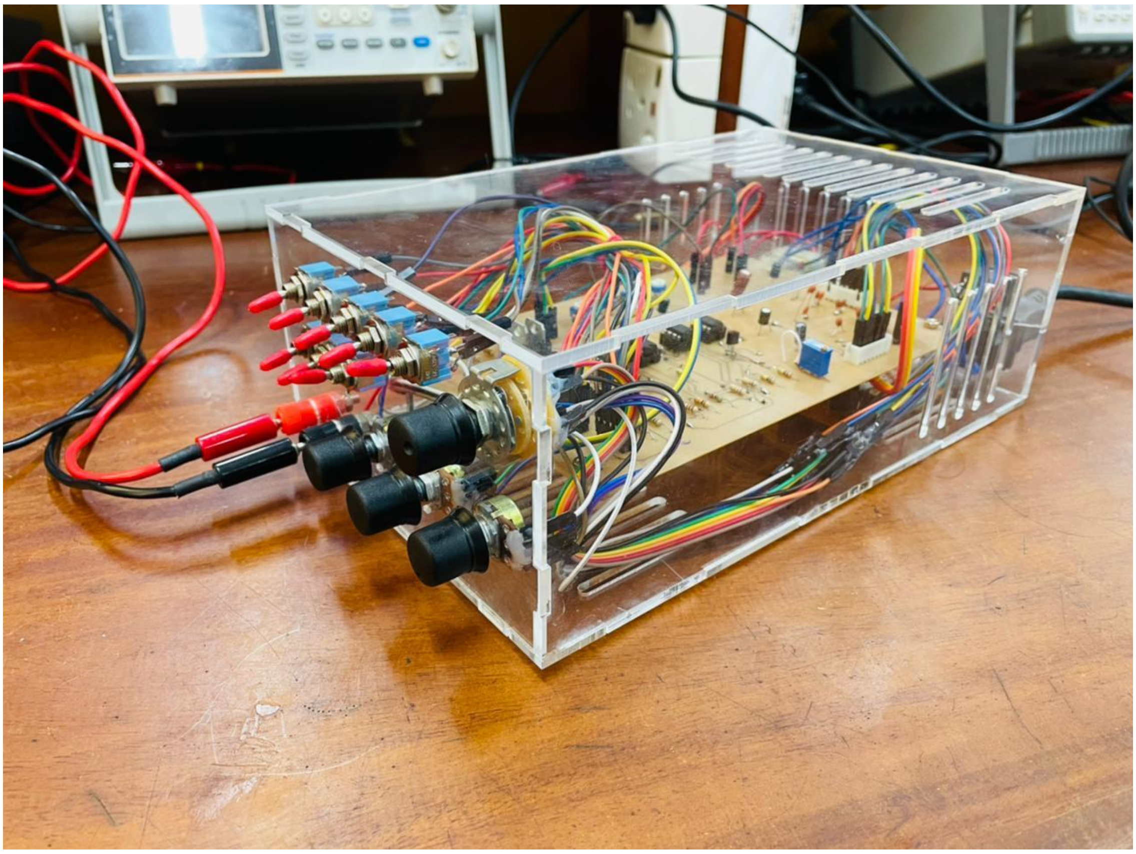


Figure 6.8 Enclosure side view

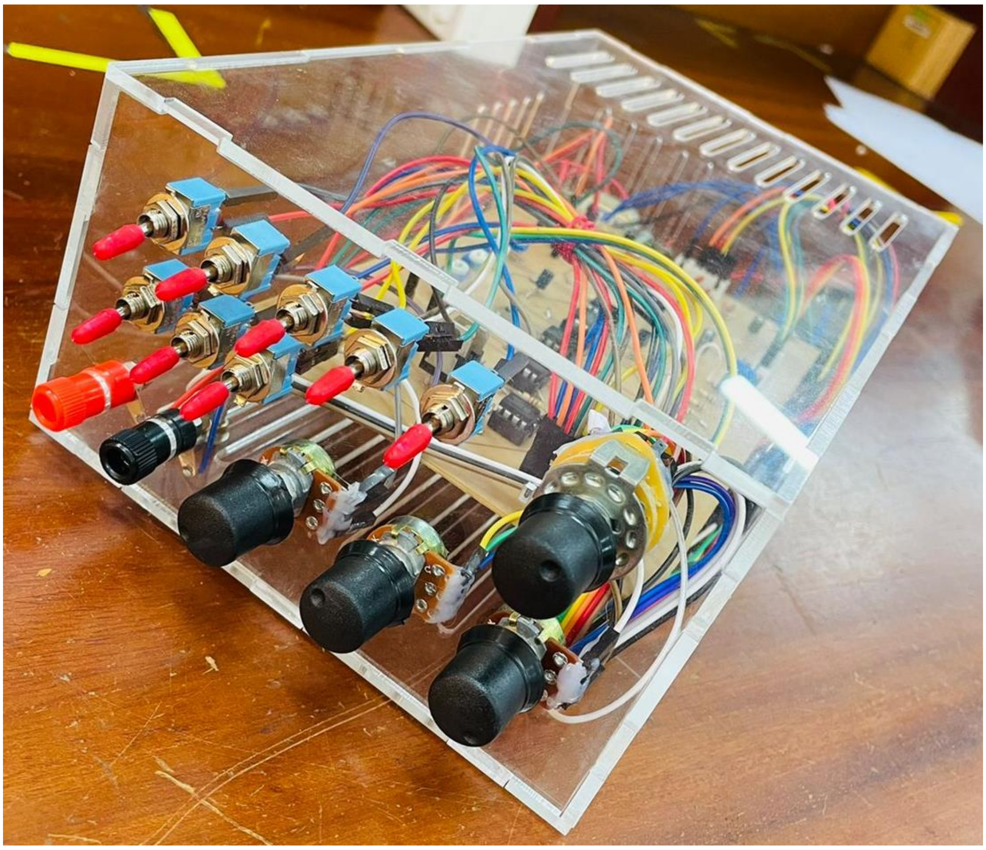


Figure 6.9 Enclosure front view

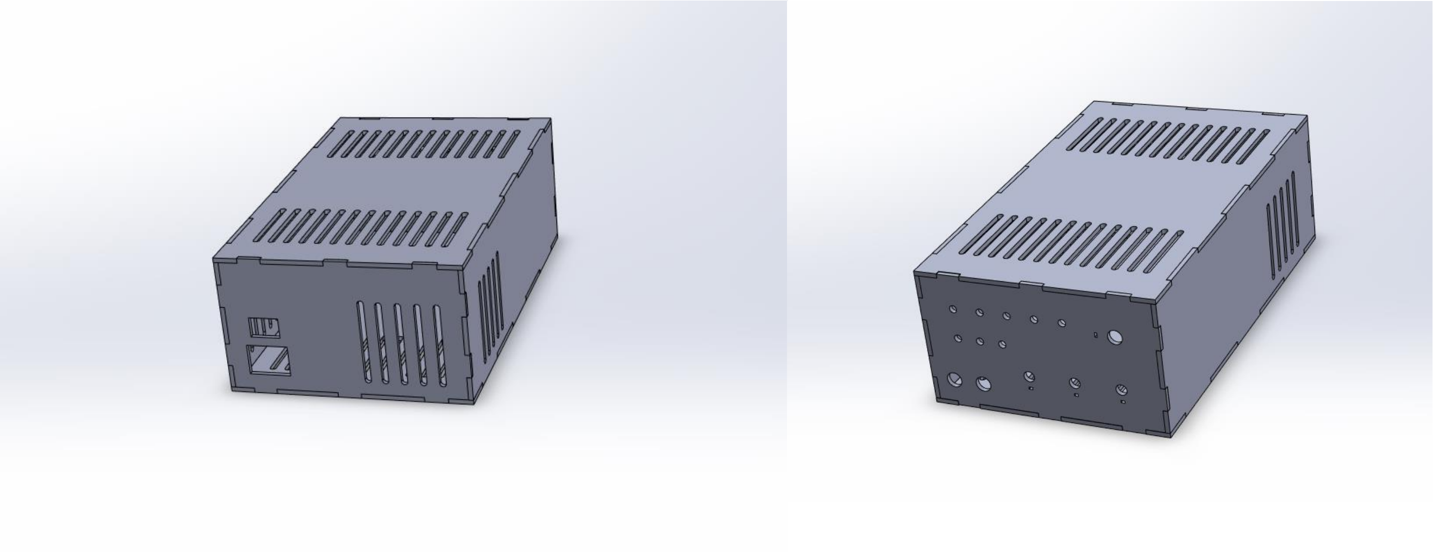


Figure 6.10 Enclosure Solidworks design

6.3 Datasheet

Frequency level Setting capacitors

Frequency settings	capacitors
1	4.7μF
2	1μF
3	100nF
4	47nF
5	10nF

Sin wave integrator capacitors

Frequency setting	Capacitors
1	1μF
2	200nF
3	69nF
4	30nF
5	4.7 nF

Note:

Above values must be selected for corresponding wave specifications to get desired valued output.

Below the PWM and the Square have max amplitude 10V; such situation is due to the +12V positive power supply so cannot exceed its value.

Some of the waveform might have above 20kHz frequency yet after 20kHz they will distort severely. Increasing amplitude above 20V will to distortion too additionally after 21V they will have a cut-off level in the output.

Specifications for waveforms

1. Square wave

Frequency setting	Frequency range	Amplitude
1	20Hz – 89Hz	10V
2	38Hz – 395Hz	10V
3	361Hz-3.604kHz	10V
4	722Hz-6.89kHz	10V
5	5.355kHz-42.5kHz	10V

2. Triangular wave

Frequency setting	Frequency range	Amplitude
1	20Hz – 89Hz	10V
2	38Hz – 395Hz	10V
3	361Hz-3.6kHz	10V
4	722Hz-6.8kHz	10V
5	5.3kHz-42.5kHz	10V

3. PWM wave

1-99% pulse width

Frequency setting	Frequency range	Amplitude
1	20Hz – 89Hz	10V
2	38Hz – 395Hz	10V
3	361Hz-3.6kHz	10V
4	722Hz-6.8kHz	10V
5	5.3kHz-42.5kHz	10V

4. Sawtooth wave

Frequency setting	Frequency range	Amplitude
1	20Hz – 178Hz	10V
2	75Hz – 808Hz	10V
3	738Hz-7.278kHz	10V
4	1.45Hz-13.85kHz	10V
5	11kHz-20kHz	10V

5. Sine wave

Frequency setting	Frequency range	Amplitude
1	20Hz – 88.96Hz	10V
2	130Hz – 396Hz	10V
3	360Hz-3.6kHz	10V
4	1.5Hz-6.9kHz	9V
5	6.5kHz-43kHz	8V