Department of Electronic & Telecommunication Engineering

University of Moratuwa

EN2091 - Laboratory Practice and Projects

Analog Lab Project Report

Analog Function generator

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Analog Function Generator

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Abstract

An analog function generator capable of generating triangular waves, saw-tooth waves, sine waves, and square waves with an adjustable duty cycle, was designed and developed. The generator was built with precision and accuracy in mind, and its performance was characterized through a series of experiments. The results showed that the generator was able to produce high-quality waveforms with low distortion and a frequency range 20Hz- 20kHz, making it suitable for use in a wide range of applications, such as signal generation for testing and debugging, and as a source for analog circuits. The adjustable duty cycle feature of the square wave output provides added flexibility for applications that require control over the waveform shape. It supports 1% to 99% duty cycle adjustments. Overall, the analog function generator is a valuable tool for anyone working with analog signals and circuits.

1 Introduction

Function generators are an essential laboratory instrument, often employed in a wide variety of applications, such as designing and testing electronic circuits, producing sound and signal waveforms, and creating dynamic visual displays. A standard function generator provides a range of output waveforms, including sine, triangular, saw-tooth, and square waves with adjustable frequency, amplitude, and duty cycle.

The early design of function generators utilized a simple analog circuit made of operational amplifiers, resistors, and capacitors. These analog function generators worked by producing a waveform using a feedback loop, which is then filtered to generate the desired waveform.

Modern function generators are now designed using highly advanced direct digital synthesis (DDS) chips such as AD9833, MAX2611/MAX2621, and AD9951. DDS chips operate on a digital platform and employ a phase accumulator, phase-to-amplitude converter, and digital-to-analog converter to produce highly accurate and precise waveforms.

This report focuses on the development of analog function generators and their underlying procedure using operational amplifiers, resistors, and capacitors.

2 Requirements

The requirements for the function generator that was designed are as follows:

- Should generate sine, square, triangle and saw-tooth waveforms
- Amplitude variation from 0V to 10V
- Frequency variation from 20Hz to 20kHz
- Variable duty cycle for square wave from 1% to 99%
- Should be able to drive a 50 Ω minimum load

3 Design & Calculations

This section provides an overview of the fundamental principles and calculations underlying the generation of each type of wave. It describes the main concepts associated with wave phenomena and explains how to calculate important parameters such as frequency and amplitude.

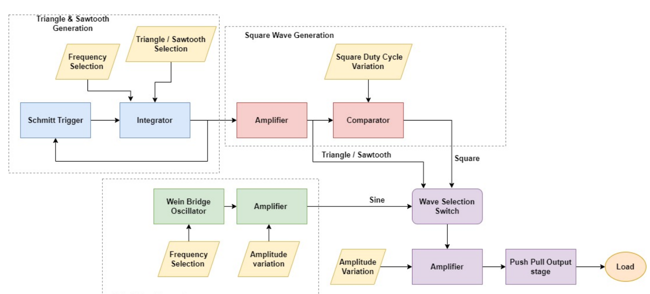

Figure 1: *Block diagram of the complete circuit*

3.1 Triangular Wave Generation

Triangular waves are produced by utilizing a Schmitt trigger cascaded with an integrator, followed by feeding the output signal back to the Schmitt trigger, which acts as a comparator.

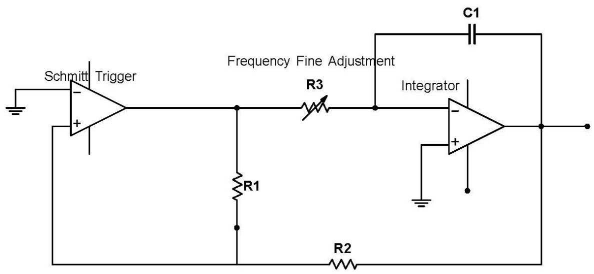

Figure 2: *Designing of triangular circuit*

Assuming that the output of the Schmitt trigger is at a $+V_{sat}$, the integrator integrates this signal until the output voltage crosses a certain threshold level, causing the output of the Schmitt to trigger to switch to a $-V_{sat}$. The integrator then continues to integrate this $-V_{sat}$ in a finite duration. By repeating this process, the circuit generates a triangular waveform.

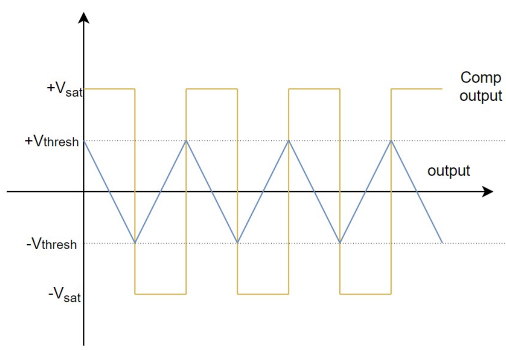

Figure 3: *Method of triangular circuit*

$$
\begin{aligned}
V_{+} &= \frac{R_2}{R_1+R_2} \cdot V_{sat} + \frac{R_1}{R_1+R_2} \cdot V_x \\
V_{+} &= 0 \quad (\textit{at the transition}) \\
V_{out1} &= -\frac{R_2}{R_1} \cdot V_{sat} \quad (i.e. - V_{thresh}) \\
V_{out2} &= \frac{R_2}{R_1} \cdot V_{sat} \quad (i.e. + V_{thresh}) \\
V_{pp} &= 2 \cdot \frac{R_2}{R_1} \cdot V_{sat} \qquad (1) \\
V_{pp} &= -\frac{1}{R_3 C_1} \cdot \int_0^{\frac{T}{2}} V_{in}(t)\, dt \\
\Rightarrow f &= \frac{R_1}{4 R_3 R_2 C_1} \qquad (2)
\end{aligned}
$$

Amplitude is given by (1) and the frequency is given by (2).

3.2 Saw-tooth Wave Generation

Saw-tooth waves are generated through the same method as triangular waves, but with the non-inverting input of the integrator connected to a voltage close to V_{sat} instead of ground. This was achieved using a potential divider.

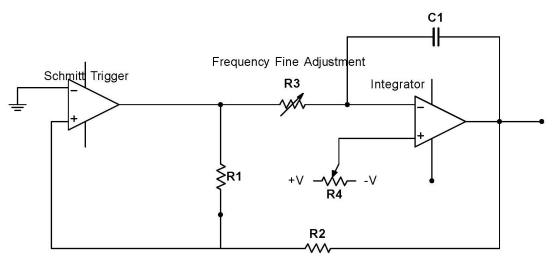

Figure 4: *Designing of Saw-tooth circuit*

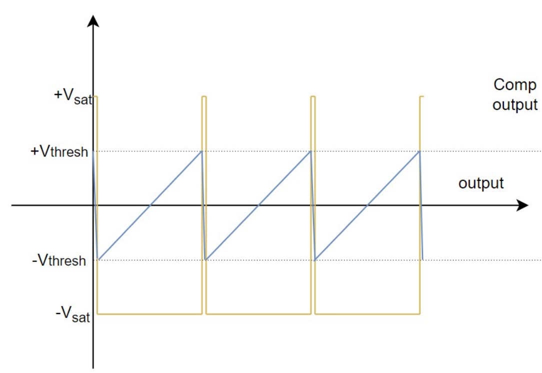

Figure 5: *Method of Saw-tooth circuit*

$$V_{pp} = 2 \cdot \frac{R_2}{R_1} \cdot V_{sat} \tag{3}$$

$$V_{out1} = -\frac{(V_{sat} - V)t}{R_3 C_1} \quad (i.e. -V_{thresh})$$

$$V_{out2} = \frac{(V_{sat} + V)t}{R_3 C_1} \quad (i.e. +V_{thresh})$$

$$t_1 = 2 \cdot \frac{R_2 R_3 C_1}{R_1 (1 + \frac{V}{V_{sat}})}$$

$$t_2 = 2 \cdot \frac{R_2 R_3 C_1}{R_1 (1 - \frac{V}{V_{sat}})}$$

$$T = t_1 + t_2$$

$$\Rightarrow f = \frac{R_1}{4 R_3 R_2 C_1} \cdot (1 - \frac{V^2}{V_{sat}^2}) \tag{4}$$

Amplitude is given by (3) and the frequency is given by (4).

3.3 Square Wave Generation

A square wave is obtained by comparing the triangle wave with a constant voltage level using a comparator. The duty cycle variation was achieved by varying this voltage level between $-V_{sat}$ and $+V_{sat}$. Before the comparator, the triangle wave is amplified by a factor of R_1/R_2 in order to get a finer variation of the duty cycle.

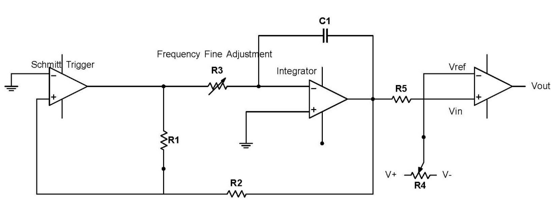

Figure 6: *Designing of square wave circuit*

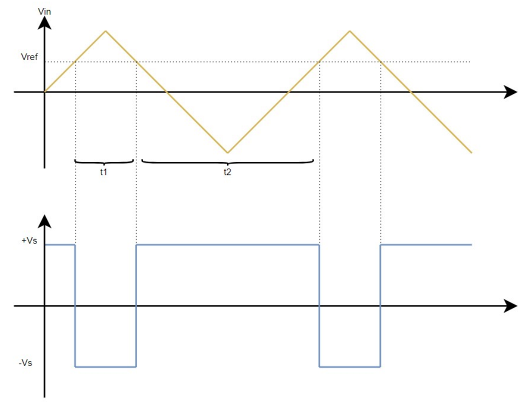

Figure 7: *Method of square wave circuit*

$$t_1 = 2 \cdot \frac{R_3 C_1 (V_s - V_{ref})}{V_s}$$

$$t_2 = 2 \cdot \frac{R_3 C_1 (V_s + V_{ref})}{V_s}$$

$$duty\ cycle = t_2 / t_1$$

$$duty\ cycle = \frac{V_s + V_{ref}}{V_s - V_{ref}}$$

$$T = t_1 + t_2$$

$$\Rightarrow f = \frac{1}{4 R_3 C_1} \tag{5}$$

3.4 Sine Wave Generation

Initially, the sine wave was generated using a Wien Bridge Oscillator circuit.

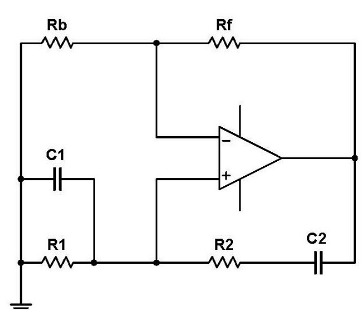

Figure 8: *Wien Bridge Oscillator*

When $R_1 = R_2$ and $C_1 = C_2$, frequency is given by $f = \frac{1}{2\pi RC}$ and the condition of stable oscillation $R_b = R_f$

However, to vary the frequency in this circuit, R_1 and R_2 must be adjusted to the same value to satisfy the conditions of stable oscillation. This procedure is not user-friendly. Using a dual gang potentiometer to control both R_1 and R_2 failed since the resistance values of the two potentiometers were not reliably equal. Therefore, a modified version of the Wien Bridge oscillator was used which can adjust the frequency using only one resistor.

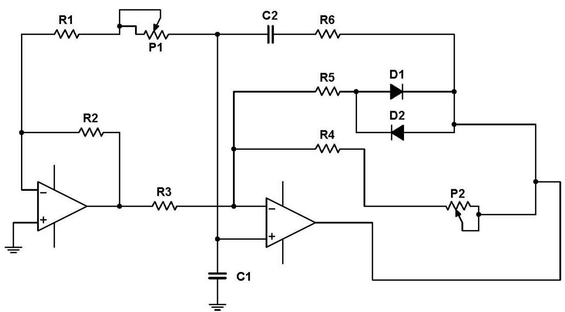

Figure 9: *Design of sine wave circuit*

$$f = \frac{1}{2\pi C\sqrt{R(R_1+P_1)}} \tag{6}$$

$$here\ R = R_2 = R_3 = R_4 = R_6;$$

$$C = C_1 = C_2$$

$$\frac{R_4}{R_3}\left(1+\frac{R_2}{R_1+P_1}\right) = \frac{R_6}{R_1+P_1}+\frac{C_1}{C_2} \tag{7}$$

The frequency of oscillation is given by (6) and the condition for stable oscillation is given by (7). The frequency can be varied by changing P_1 without affecting the stability condition.

The D1 and D2 diodes are used to stabilize the amplitude of the oscillation. When the output amplitude is low, the diodes will be reverse biased and the oscillation will start to saturate, increasing the amplitude. Then with the higher output amplitude, the diodes will be forward biased and the oscillation will start to attenuate.

The purpose of the P2 variable resistor is to adjust the stability condition accounting for practical inequalities in the resistors and capacitors. Due to these inequalities, sometimes the signal attenuated when the frequency was changed. Therefore the generated sine wave was sent through a non-inverting amplifier with adjustable gain to increase the amplitude before connecting to the common amplifier.

3.5 Frequency Variation

For each waveform, the frequency is variable by changing a resistor and capacitor. Four different capacitors were used to cover the required frequency range of 20Hz - 20kHz and a potentiometer was used to finely adjust the frequency in the range selected by the capacitor. A 3P4T rotary switch was used to change capacitors for all waveforms simultaneously.

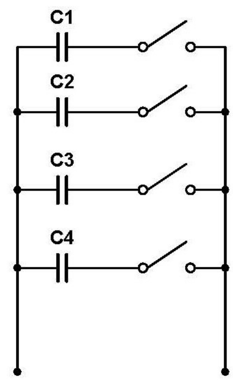

Figure 10: *Frequency selection*

3.6 Common Amplifier

All the wave outputs are connected through a four-way switch to a common inverting amplifier which will allow amplitude variation between 0-10 V. The wave amplitudes are adjusted to the same level before sending through this amplifier to maintain consistency. The inverting amplifier was chosen to allow decreasing the amplitude down to 0 V. The inversion does not affect the sine, square, and triangle waves as they are symmetric, and the saw-tooth wave circuit is designed to give the desired output after the inversion.

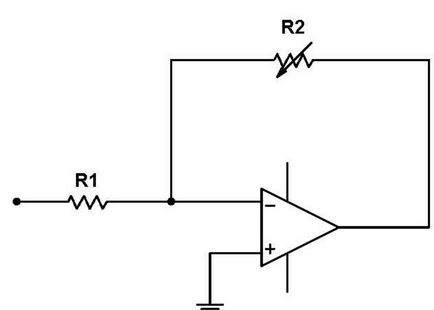

Figure 11: *Common amplifier*

Gain is given by $\frac{R_2}{R_1}$

3.7 Push-Pull Output with Voltage Buffer

The amplifier output is sent to a buffer that has a push-pull output stage to increase the current drive. A complementary NPN and PNP transistor pair is used for this.

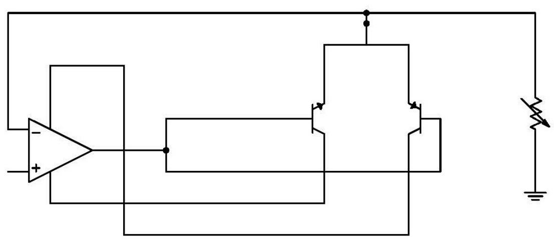

Figure 12: *Designing of Buffer and the Push-Pull amplifier*

The op-amp buffer removes the crossover distortion of the push-pull amplifier. In a normal push-pull output, when the instantaneous amplitude is small, both transistors will be off which causes distortion. However, in this circuit, there will be no negative feedback in that situation which makes the op-amp output saturate. Therefore, one of the transistors will turn on and no distortion occurs. The buffer also ensures a unity gain.

4 Component Selection

AD826AN op-amps were used to generate square, triangle, and saw-tooth waves and for the common amplifier and buffer. It has 20V/μs measured slew rate and a 10MHz bandwidth, which is sufficient to generate frequencies from 20Hz-20kHz. A high slew rate is required to minimize distortion of the square and saw-tooth waves at higher frequencies.

NE5532 op-amps with a measured slew rate of 3V/μs were used for the sine wave generation since the slew rate is sufficient for the maximum rate of change of voltage in the sine wave.

BD139 (NPN) and BD140 (PNP) transistors were used for the push-pull output as they are complementary symmetric transistors. The circuit should support a maximum current of 10 V/50 Ω = 200 mA. These transistors are rated for a safe maximum collector current of 1.5 A.

Non-polarized capacitors are used in the circuit as polarized capacitors may degrade over time when it is used with the wrong polarity.

5 Simulation & Testing

The process of designing and developing electronic circuits can be challenging and time-consuming. In order to ensure that the final product meets the desired specifications, it is important to simulate and test the circuit before manufacturing the printed circuit board (PCB).

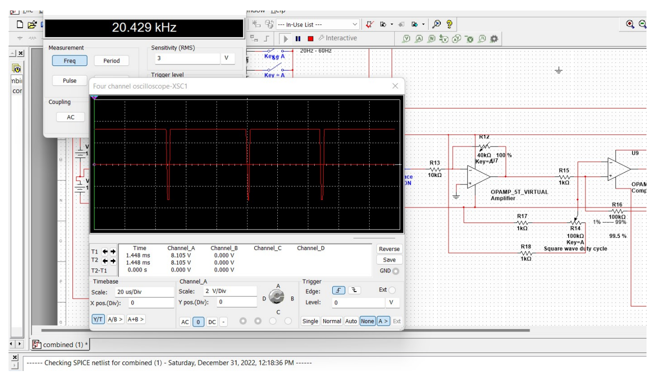

Figure 13: *Simulation of the circuit using (NI) Multisim*

The National Instruments (NI) Multisim software was used to simulate the circuit design and validate its functionality. Once the circuit was simulated and optimized for performance, it was then implemented on a breadboard and the waveforms were analyzed using an oscilloscope. This provides a visual representation of the signals produced by the circuit, allowing us to identify any discrepancies between the simulated and actual results.

6 PCB Design

Once the circuit on the breadboard was satisfactorily tested, it was then designed for a printed circuit board (PCB) utilizing the Altium Designer software. Subsequently, we carried out the PCB printing process through JLCPCB.

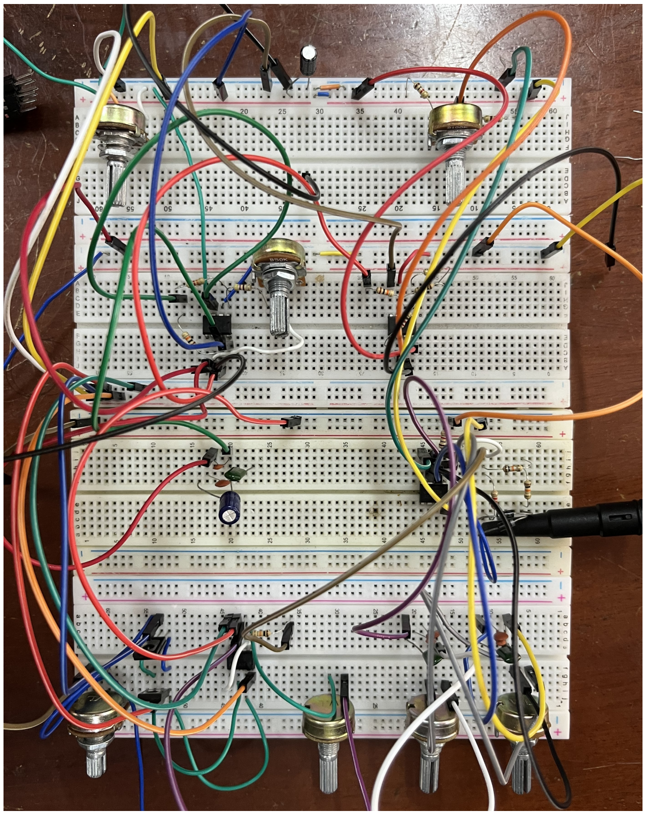

Figure 14: *Breadboard implementation of the whole circuit*

6.1 Schematic Design

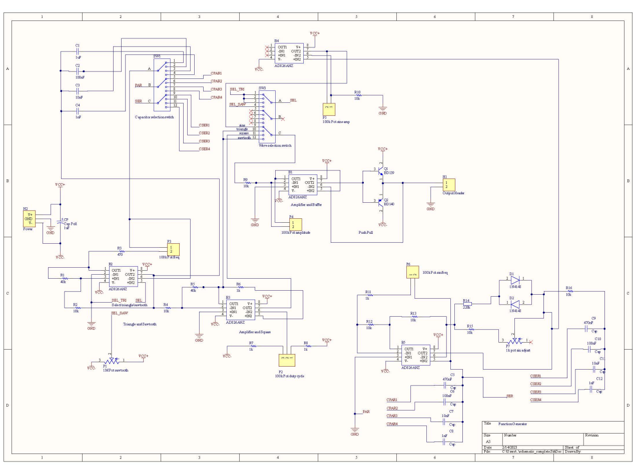

Figure 15: *Schematic of the circuit*

6.2 PCB Layout Design

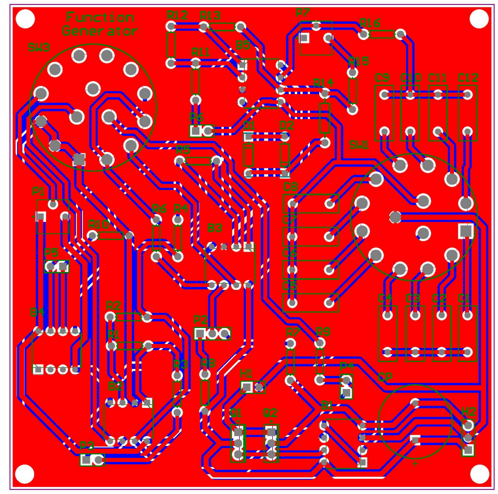

Figure 16: *2D view of PCB*

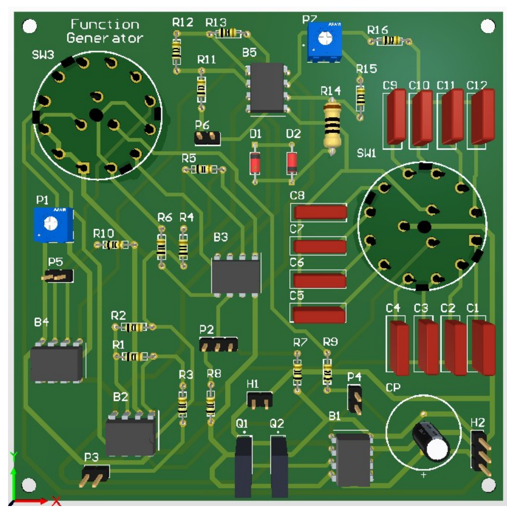

Figure 17: *3D view of PCB*

7 Power Supply

The circuit requires at least a dual 12 V DC power supply in order to output signals of up to 10 V amplitude. A 15V transformer with a bridge rectifier circuit and 7812/7912 voltage regulators were used as a power supply.

7.1 Power Supply Schematic Diagram

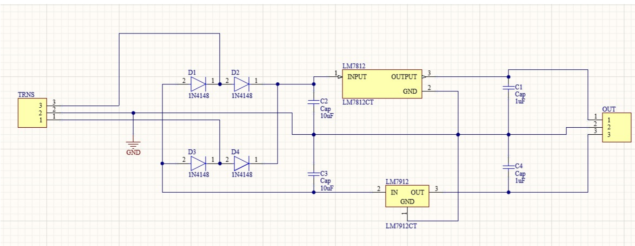

Figure 18: *Schematic of the power PCB*

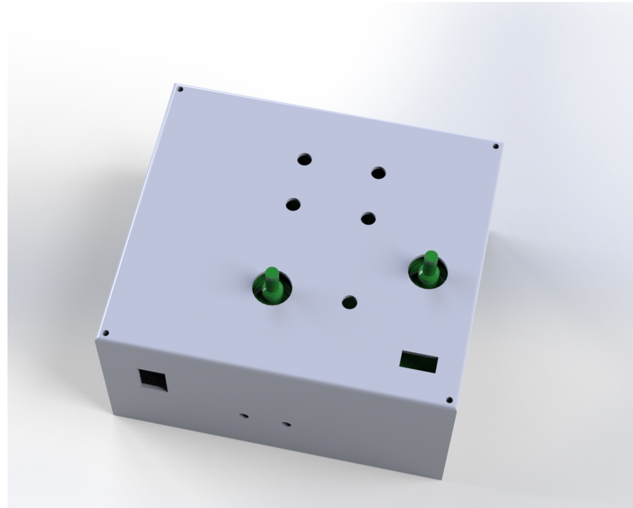

Figure 20: *3D view of the enclosure*

7.2 Power Supply PCB Layout

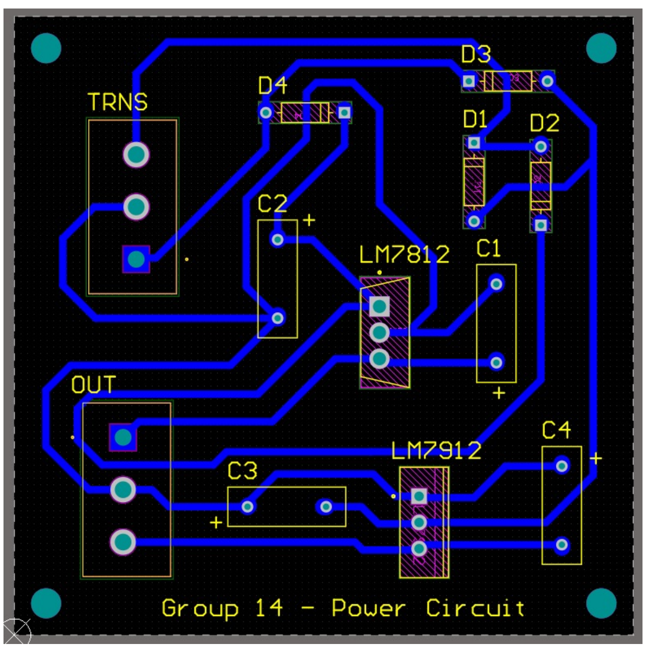

Figure 19: *Power PCB*

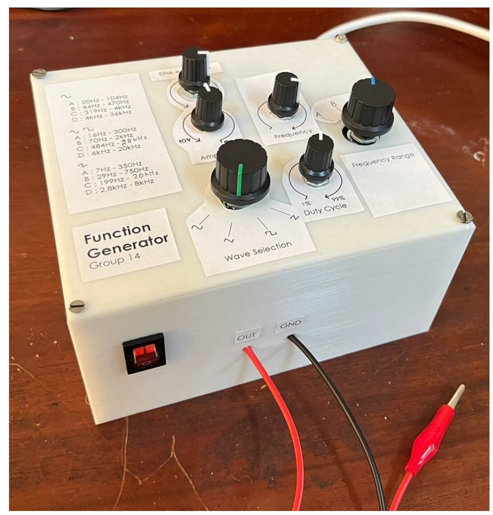

Figure 21: *Enclosure*

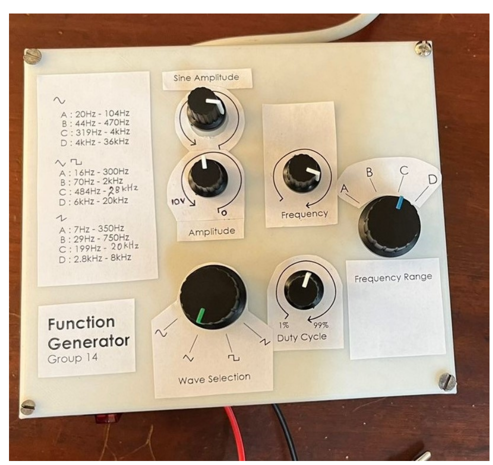

Figure 22: *User interface*

8 Enclosure Design

An enclosure for the function generator was designed using the SolidWorks software and it was manufactured by 3D printing.

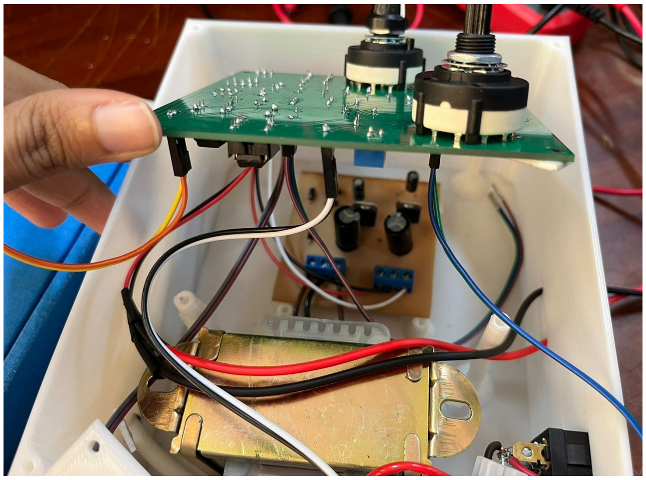

Figure 23: *Assembly of the enclosure*

9 Results

9.1 Square Wave

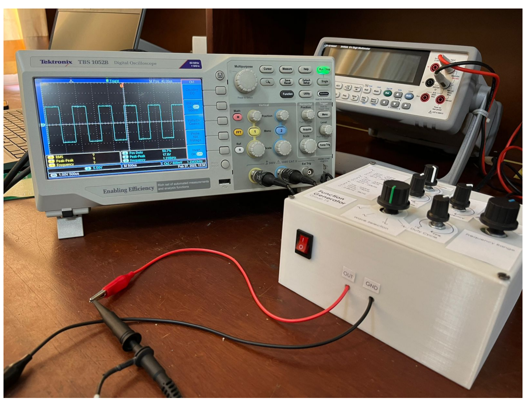

Figure 24: *Square Wave*

9.2 Triangular Wave

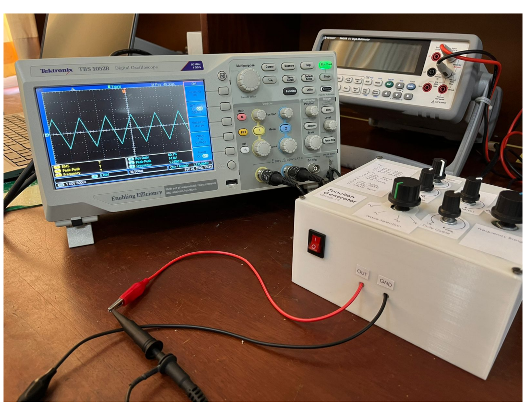

Figure 25: *Triangular Wave*

9.3 Saw-tooth Wave

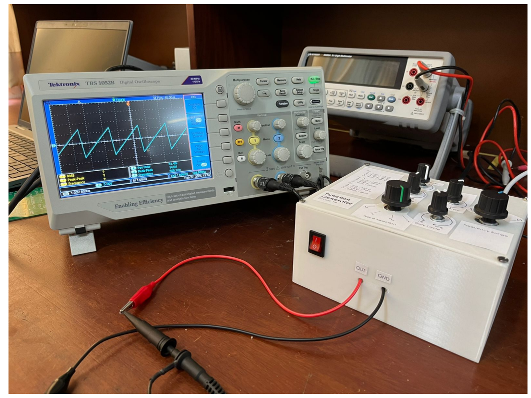

Figure 26: *Saw-tooth Wave*

9.4 Sine Wave

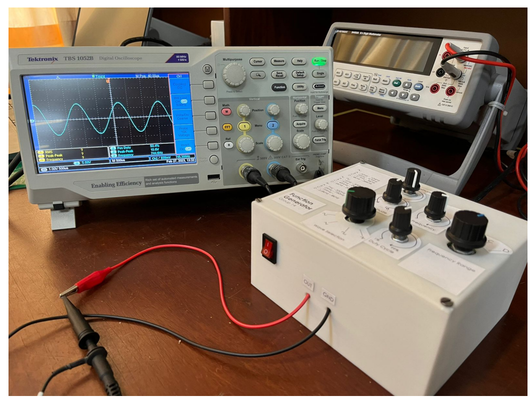

Figure 27: *Sine Wave*

9.5 Duty Cycle Adjustments

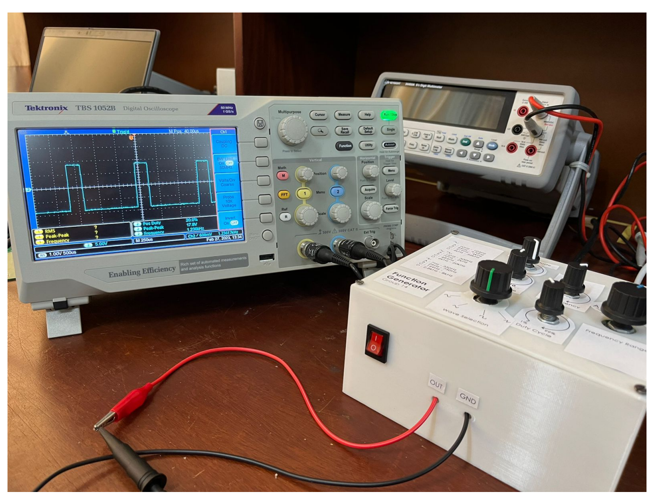

Figure 28: *Duty cycle adjustments*

9.6 Output Capabilities

Frequency Range

Sine Wave	20Hz - 36kHz
Square Wave	16Hz - 28kHz
Triangle Wave	16Hz - 28kHz
Saw-tooth	7Hz - 20kHz

Duty Cycle of Square Wave

16Hz - 375Hz	1% - 99%
375Hz - 1.5kHz	2% - 98%
1.5kHz - 2.5kHz	3% - 97%
2.5kHz - 28kHz	6% - 94%

Output Characteristics

Output amplitude	0V - 10V
Min. load impedance	50 Ω

According to the above results, the designed function generator meets the requirements to a satisfactory level.

10 Future Improvements

The duty cycle variation of the square wave was limited at higher frequencies due to the slew rate of the op-amp used. An op-amp with a higher slew rate could be used to remove this limitation.

In the sine wave generation circuit, the highest frequency range was greatly attenuated which introduced some noise to the waveform. This was because the same calibration potentiometer (P2) was used for all four capacitor pairs. The issue can be resolved by using separate calibration potentiometers for each capacitor pair. However, the circuit will become more complicated by this process.

The voltage regulators used in a power supply require 14 V input to produce a 12 V output, which is inefficient. A switch mode power supply could be used to provide power more efficiently.

11 Contribution of Group Members

Name	Contributions
Clarance L.G.S	Enclosure, Simulation
Kariyawasam K.K.D.	PCB design, Simulation
Pasqual A.C.	Simulation, PCB design, Report writing
Vishwamith P.G.H.	Simulation, PCB design, Report writing

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A Appendix

A.1 Circuit Simulation of the System

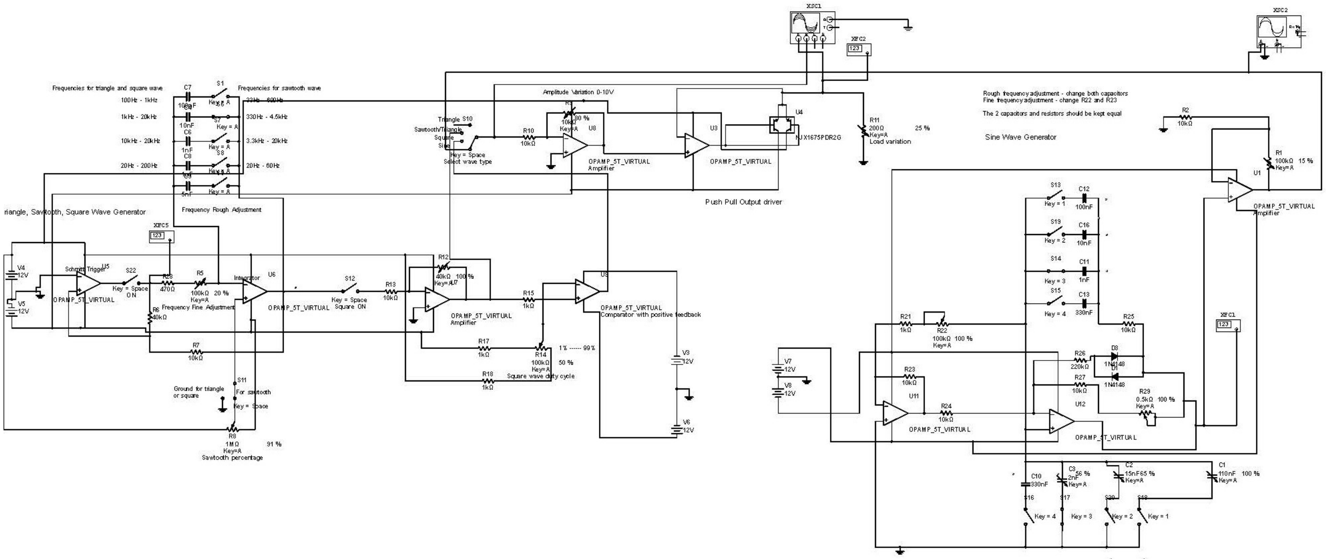

Figure 29: *Simulation diagram*

A.2 Schematic of the main PCB

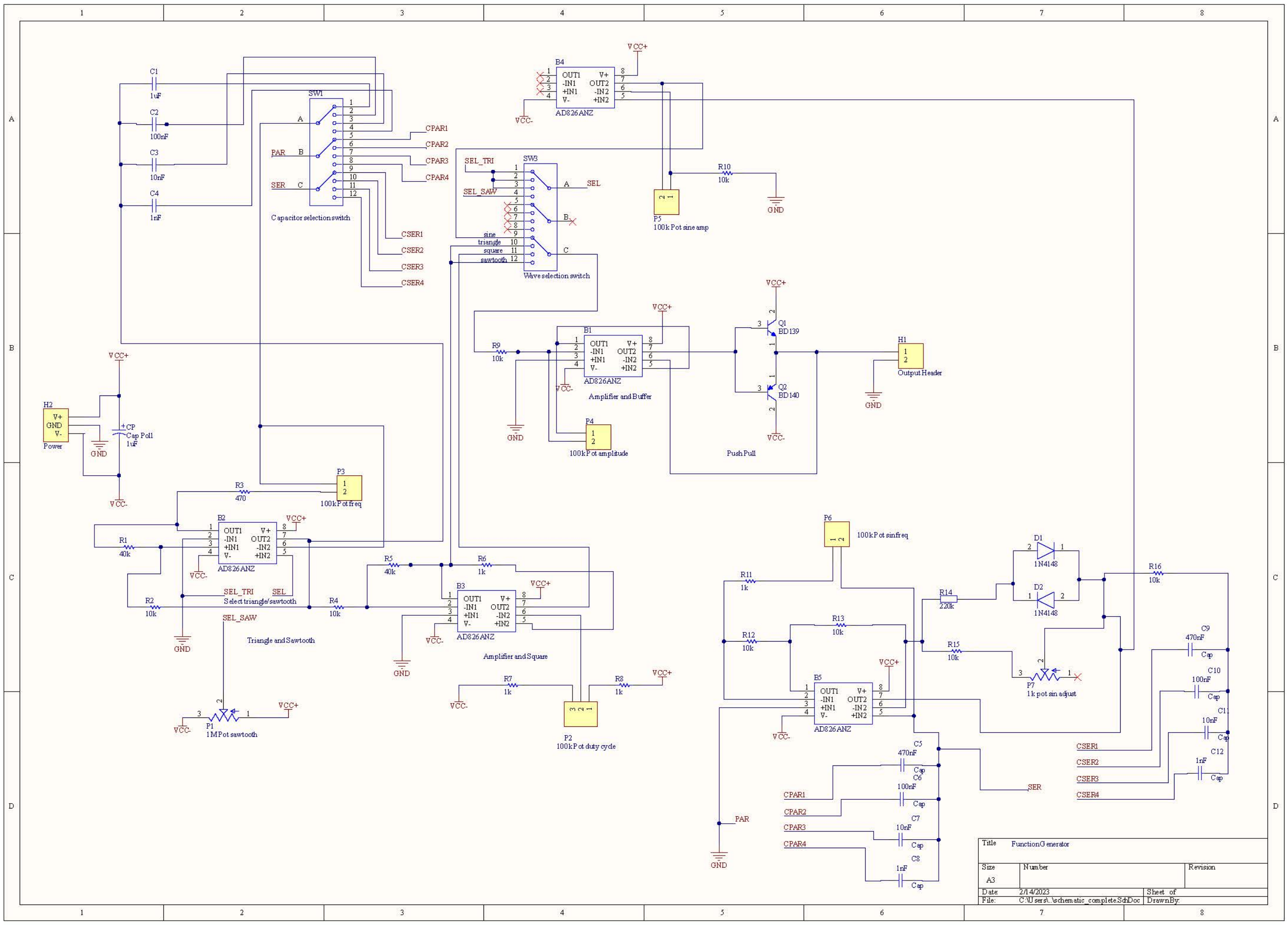

Figure 30: *Schematic of the PCB*

A.3 PCB - Top Layer

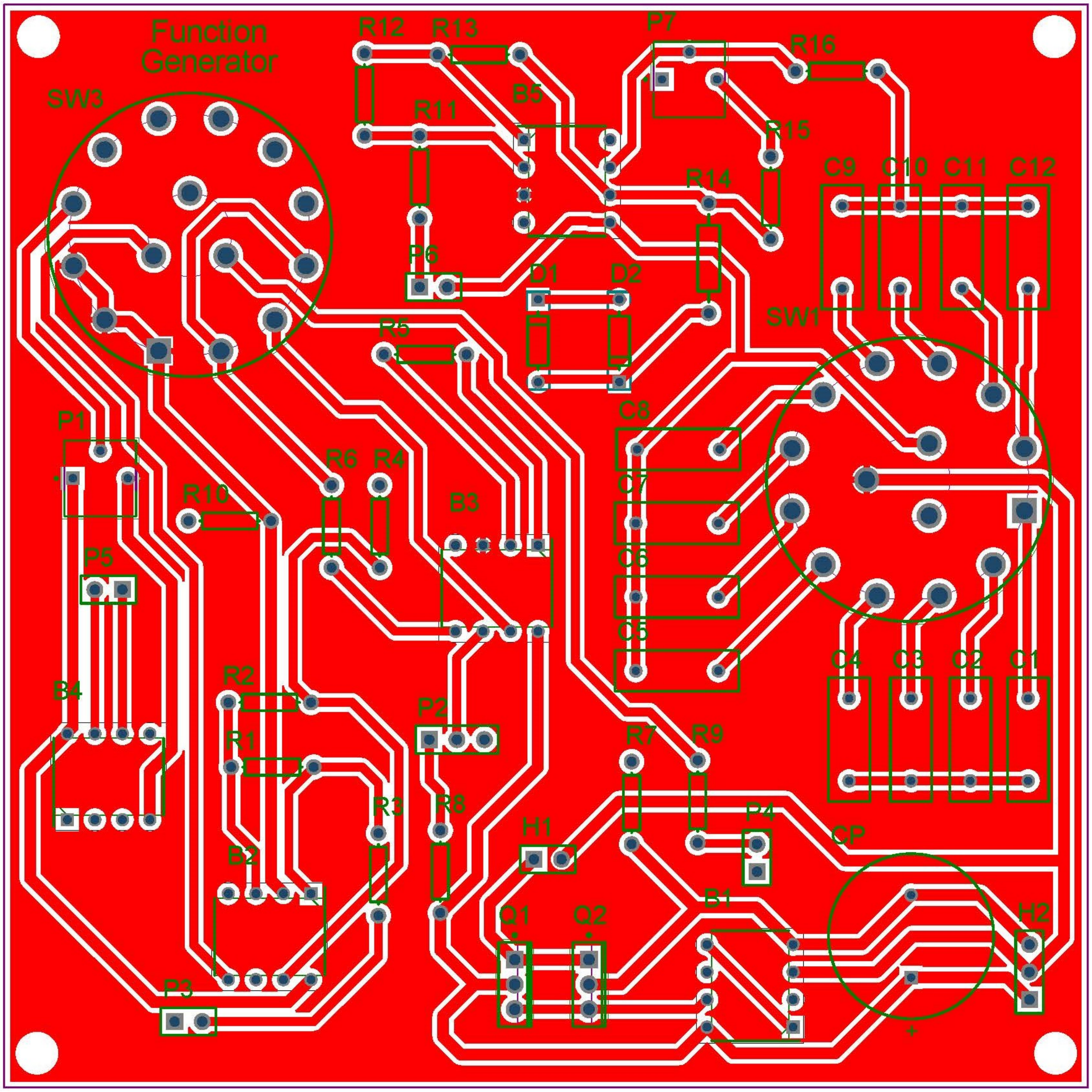

Figure 31: *Top layer of the PCB*

A.4 PCB - Bottom Layer

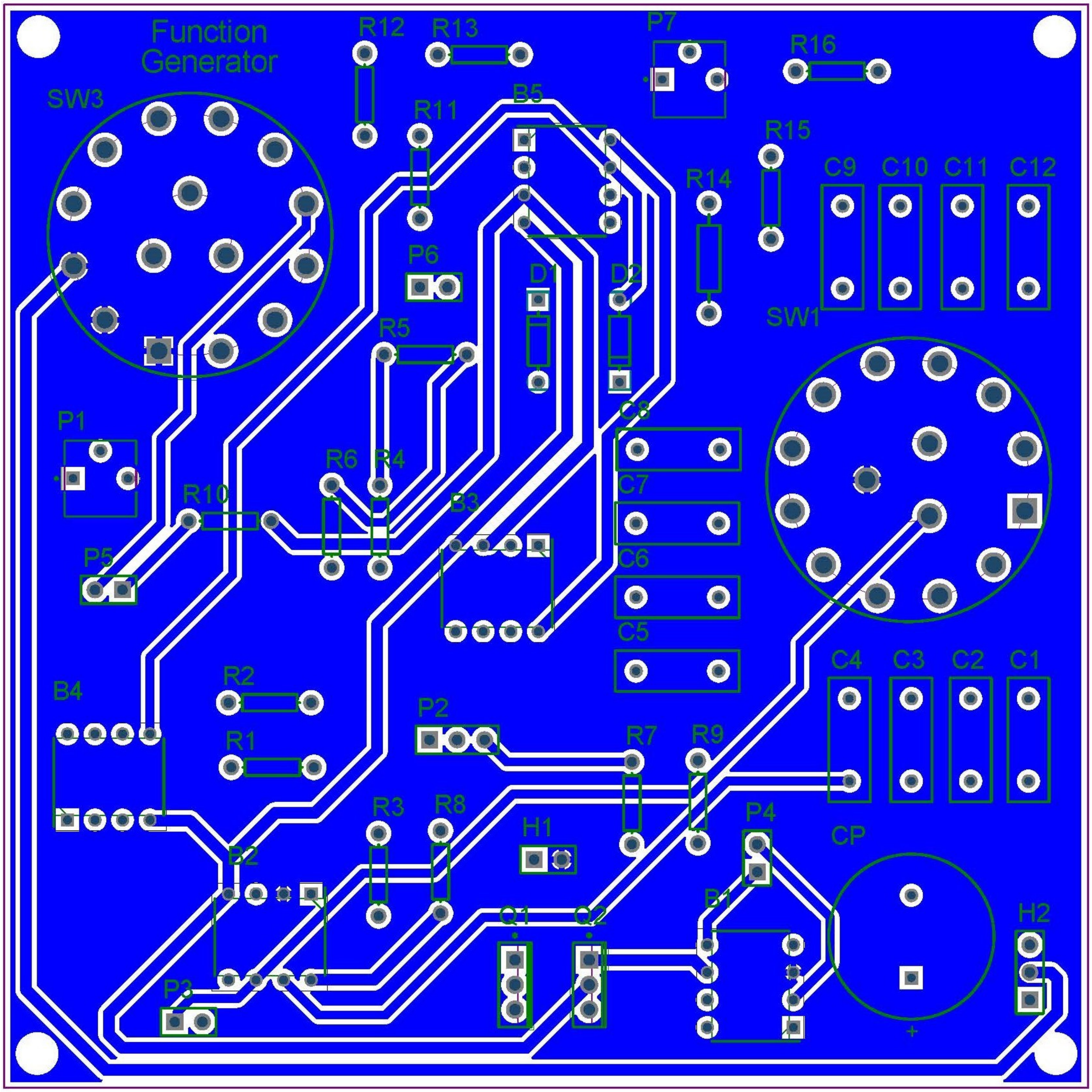

Figure 32: *Bottom layer of the PCB*

A.5 Schematic - Power PCB

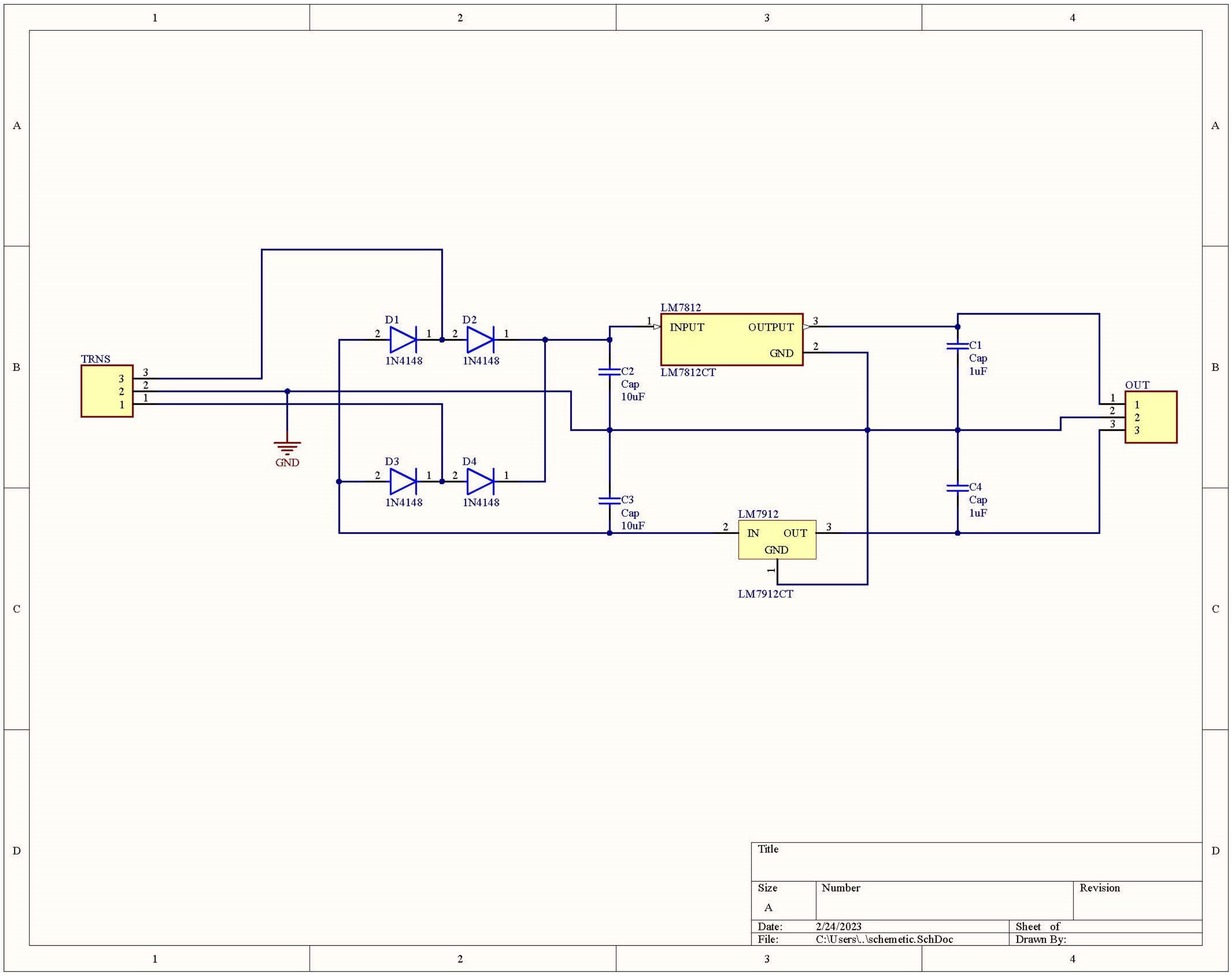

Figure 33: *Schematic of the power PCB*

A.6 Layout - Power PCB

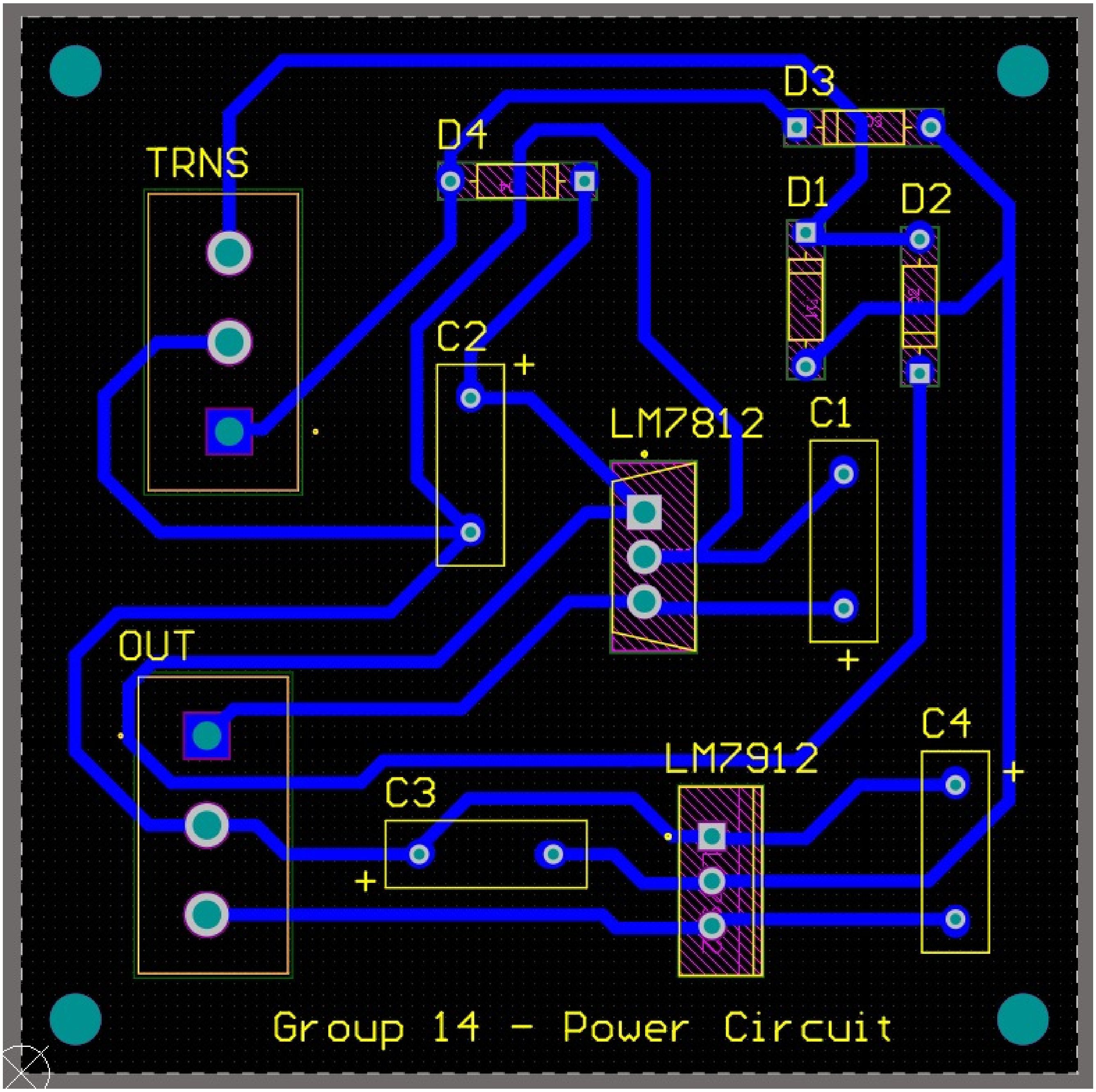

Figure 34: *Power PCB*