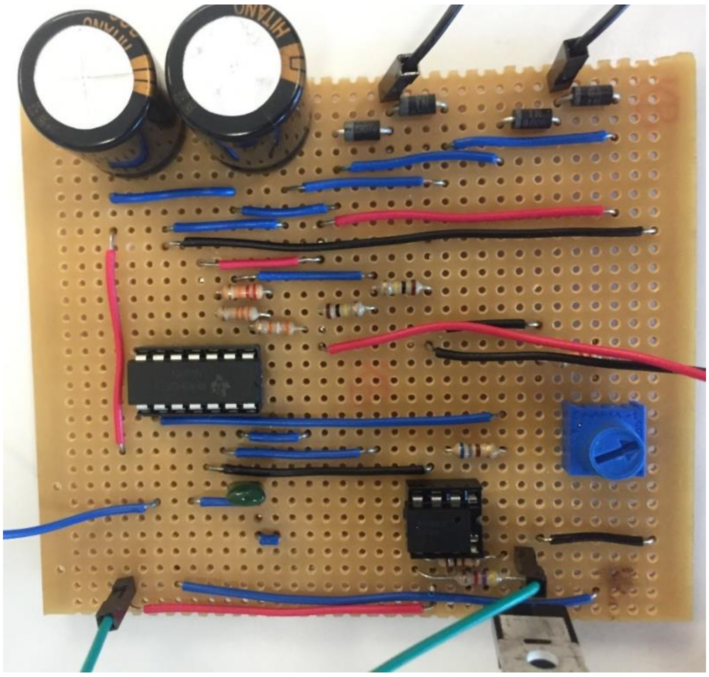
3312ENG Electrical Design Project

Final Project



DC Motor Speed Controller

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1. Introduction

DC Motor speed controllers are an integral part in many larger circuits which need to control the speed of a motor, with industrial and domestic applications such as controlling the speed of RC cars or controlling the speed of a hydraulic pump. To provide this speed control, a PWM generator is used. This can be achieved by comparing the output of a triangle wave generator with a DC reference voltage using a comparator circuit. The duty cycle of the PWM signal can be controlled to be between 0% and 100% by changing the reference voltage level between the minimum and maximum level of the triangle wave generator.

In this report, a DC voltage is supplied to an op-amp based circuit. consisting of the comparator and integrator to create a triangle wave. This triangle wave is then compared with a reference voltage to create a PWM signal. This PWM signal is provided to a driver circuit to drive a DC motor. The PWM generator circuit is supplied $9V_{DC}$. The motor driver circuit is electrically isolated from this and is supplied $9V_{DC}$ which uses a $240V_{AC} – 9V_{DC}$ power converter circuit.

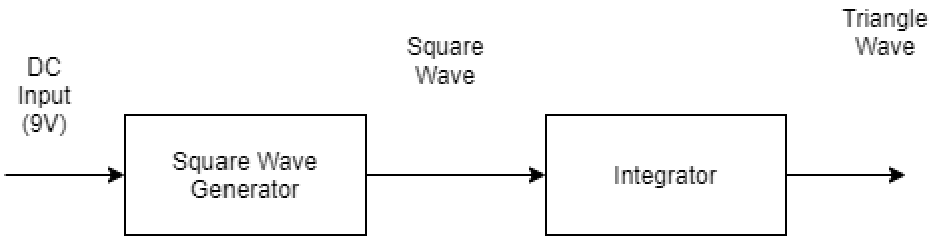

Figure 1.1 Block diagram of a triangle wave generator

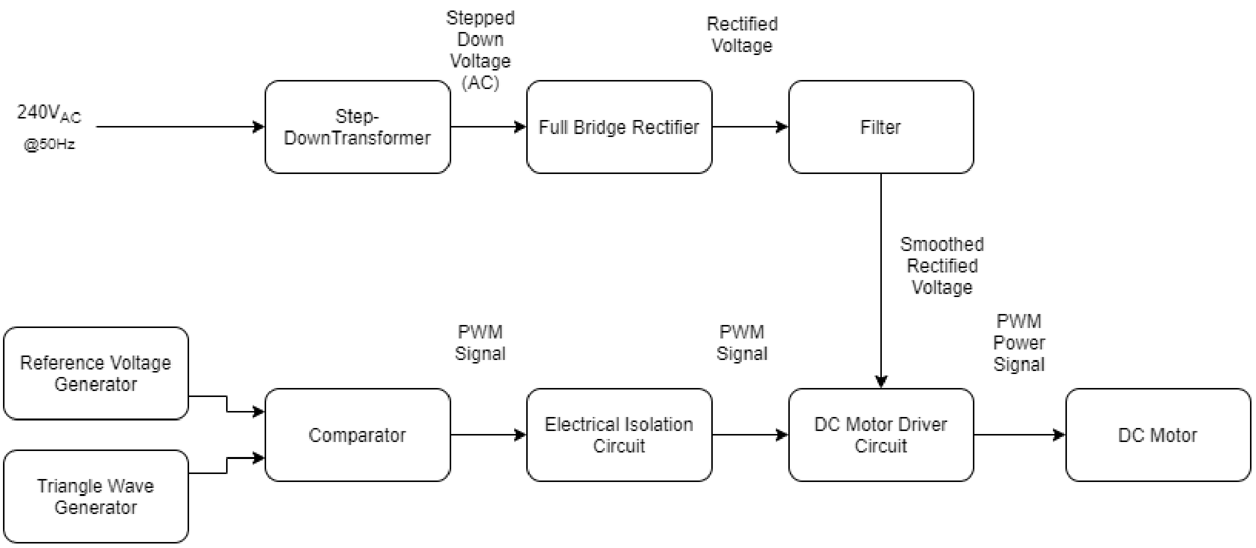

Figure 1.2 Block diagram of a DC Motor Speed Controller

Below are a collection of useful formula used for designing the power converter circuit (assuming a full-wave rectifier is used). The transformer turns ratio can be calculated by using equation 1. The average DC output voltage without a filter can be found using equation 2. The ripple voltage without a filter can be found using equation 3. Equation 4 can be used to find the maximum ripple voltage with a smoothing capacitor used as a filter.

$$n = \frac{N1}{N2} = \frac{Vp}{Vs} \qquad \text{Eq.1}$$

$$Vdc = Vavg = \frac{2Vm}{\pi} \qquad \text{Eq.2}$$

$$Vr(rms) = 0.3078Vm \qquad \text{Eq.3}$$

$$Vrmax = \frac{Vm}{2fRC} \qquad \text{Eq.4}$$

Where Vp is primary voltage, Vs is secondary voltage, N1 is primary windings, N2 is secondary windings, Vm is peak voltage, Vavg is average voltage, Vr is ripple voltage, f is frequency, R is load resistance, and C is filter capacitance. These equations are derived from the 3312ENG lecture notes (lecture 2)[1].

The following equations are used when designing the triangle generator circuit. Voltage divider output can be calculated by using equation 1. The peak to peak output voltage can be found using equation 2. Output frequency can be found using equation 3.

$$V_{out} = \frac{Ra}{Ra + Rb} * Vin \qquad \text{Eq.5}$$

$$V_{out(pp)} = 2\frac{R_2}{R_3}V_{cc} \qquad \text{Eq.6}$$

$$f_{out} = \frac{R_3}{4R_1R_2C} \qquad \text{Eq.7}$$

Where R2, R3 are the threshold resistors in the comparator circuit, and R1, C are the respective resistance and capacitance values of the RC network in the integrator circuit. These equations are derived from the 3312ENG lecture notes (lecture 5)[2].

2. Circuit Design

2.1 Generic Circuit Design

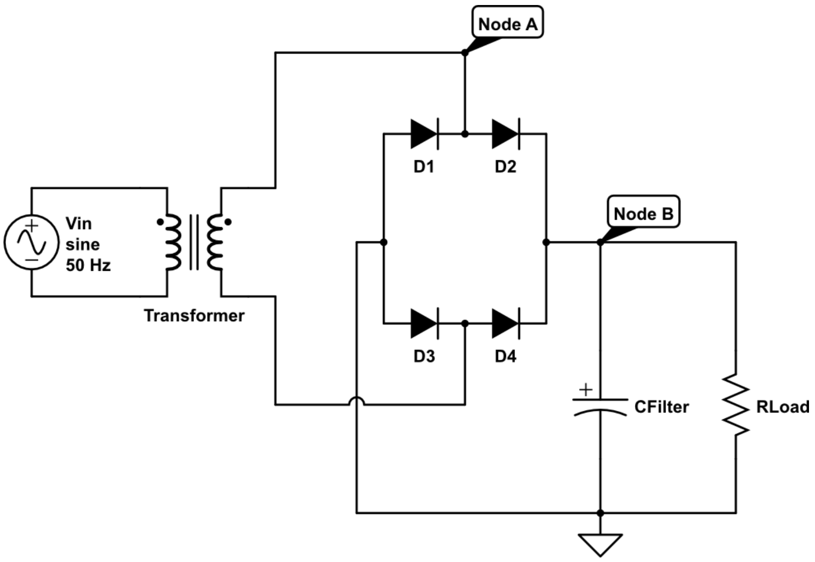

Figure 2.1 Circuit Diagram of full wave rectified AC / DC power supply with smoothing capacitor.

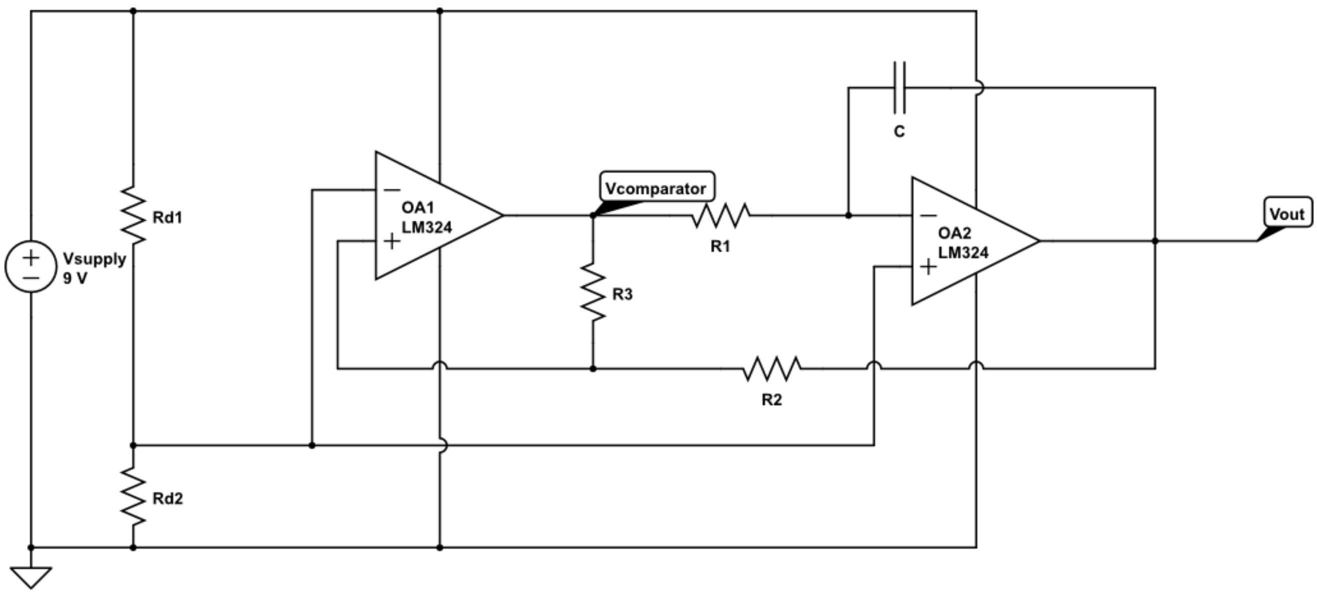

Figure 2.2 Circuit Diagram of a triangle wave generator.

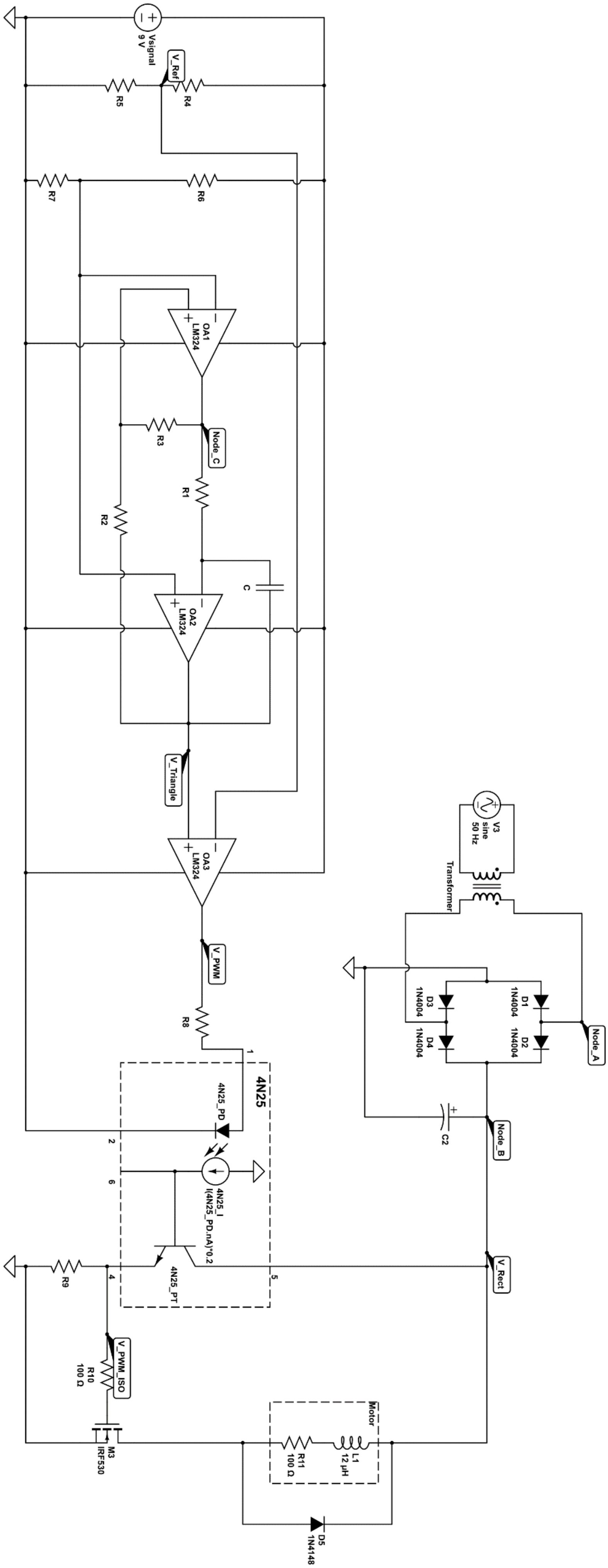

Figure 2.3 Circuit Diagram of a DC Motor Speed Controller.

Figure 2.1 shows the power supply described in figure 1.1 as a circuit diagram. Here, equating figure 2.1 to 1.2, 'Vin' is mains power, 'Transformer' is the step-down transformer, 'D1-4' form a full bridge voltage rectifier, 'Cfilter' is a smoothing capacitor which acts as a filter, and 'RLoad' is the load. The stepped down voltage is measured at 'Node A' and the rectified voltage is measured at 'Node B'.

Figure 2.2 shows the triangle wave generator described in figure 1.1 as a circuit diagram. Here, equating figure 2.1 to 1.1, 'V_{supply}' is the DC power supply, 'QA1, R2, R3' make up the square wave generator and 'QA2, R1, C' form the integrator. 'V_{out}' is the triangle wave and 'Vcomparator' is the square wave. Rd1 and Rd2 form a voltage divider. This voltage divider is used in parallel with a single power supply to supply to replace the need for two separate power supplies for the op amps. This means that $V_{cc} = 9/2 = 4.5V$.

Figure 2.3 shows the circuit in its entirety as described in figure 1.2 as a circuit diagram. Here, equating figure 2.3 to 1.2:

- V_triangle is the output of the triangle wave generator
- V_Ref is the output of the reference voltage generator (and R3 is a potentiometer controlling V_Ref)
- QA3 is the comparator which produces the PWM signal V_PWM
- '4N25' is an optocoupler which acts as an electrical isolation circuit
- M3 is used as the motor driver circuit and acts as a switch that closes when it receives current from 4N25.
- 'Motor' is the DC motor

2.2 Component Selection

2.2.1 Power Converter Components:

**Note the below component names refer to those in figure 2.1.*

The diodes (D1-4) chosen for this circuit are #1N4004 since this type of diode is widely available. These diodes have a forward voltage of 0.6V. RLoad will have a complex value since in the final design it will be a motor with both a resistance and inductance. For the purpose of its design however, Rload will be assumed to be purely resistive at 560Ω.

It is known that RLoad must receive a maximum of 9V, therefore Node B must have a peak voltage of 9V. Since current must pass through either D2 then D3, or D4 then D1 to pass through Node B from/to Node A, the peak voltage of Node A must be 0.6V * 2 = 1.2V higher than Node B.

$$A_{\text{Voltage p}} = 1.2V + 9V = 10.2V.$$

$$A_{\text{Voltage rms}} = A_{\text{Voltage p}} / \text{sqrt}(2) = 7.2V.$$

From this step-down voltage, the transformer turns ratio can be calculated from Eq.1:

$$n = \frac{N1}{N2} = \frac{Vp}{Vs} = \frac{240V}{7.2V} = 33.33$$

Looking at Eq. 4, the ripple voltage with a smoothing capacitor depends on its capacitance. It was decided that the maximum ripple voltage should be no more than 0.5V.

$$Vrmax = \frac{Vm}{2fRC} < 0.5V$$

$$\frac{9V}{2 * 50Hz * 560\Omega * C} < 0.5V$$

$$C > \frac{9V}{2*50Hz*560\Omega*0.5V} > 321\mu F.$$

A 440µF bank of 2 parallel 220µF electrolytic capacitors was used as electrolytic capacitors are relatively inexpensive and widely available. From this, the maximum ripple voltage with a smoothing capacitor can be calculated:

$$Vrmax = \frac{Vm}{2fRC} = \frac{9V}{2 * 50Hz * 560\Omega * 660x10^{-6}F} = 0.37V$$

For comparison, if no smoothing capacitor was used, the ripple voltage would increase, this can be calculated from equation 3 as:

$$Vr(rms) = 0.3078Vm = 0.3078 * 9V = 2.77V\ (rms).$$

2.2.2 Triangle Wave Generator Components

**Note the below component names refer to those in figure 2.2.*

Rd1 and Rd2 form a voltage divider which is used to evenly split Vsupply into two parts in order to supply the op-amps. To find the ratio of these two resistors, Eq.5 can be used:

$$\frac{9}{2} = \frac{Rd2}{Rd1 + Rd2} * 9$$

$$\frac{Rd1 + Rd}{2} = Rd2$$

$$Rd1 = Rd2$$

In order to reduce resistive losses, the values Rd1 and Rd2 should be high:

$$Rd1 = Rd2 = 100k$$

It was decided that the triangle wave should range from 1.5V to 7.5V in order to allow some margins for R_Ref. The output voltage (peak to peak) Vout(pp) should therefore be (7.5V-1.5V) = 6V.

Let Vout(pp) = 7.5V (arbitrary value that meets requirements)

The ratio of R2 and R3 can be determined using Eq.6:

$$6V = 2\frac{R_2}{R_3}4.5V$$

$$R3 = 1.5\text{R2}$$

Let R2 = 22kΩ and R3 = 33kΩ

(standard resistor values that match required ratio)

Next, an arbitrary value of C can be chosen:

Let C = 4.7nF (standard capacitor value)

Finally, a frequency of f_{out} = 2000Hz was chosen such that it is high enough to ensure smooth motor operation (a low frequency would result in perceivable motor vibrations due to the low frequency PWM being supplied to it). R1 can be found using Eq.7:

$$f_{out} = \frac{R_3}{4R_1R_2C}$$

$$R1 = \frac{R_3}{4f_{out}R_2C} = \frac{33000}{4*2000*22000*4.7*10^{-9}} = 39.9k\Omega \approx 39\text{k}\Omega$$

(Closest standard resistor value)

The frequency as a result of R1 can then be calculated using Eq.7:

$$f_{out} = \frac{R_3}{4R_1R_2C} = \frac{33000}{4*39000*39000*4.7*10^{-9}} = 2045.8Hz.$$

2.2.3 Other Components

**Note the below component names refer to those in figure 2.3.*

The value of the resistor R8 coming out of the comparator QA3 and going into the optocoupler 4n25 should be low enough to allow the LED within the optocoupler to receive enough forward current but also high enough to avoid drawing too much current from QA3. From their respective datasheets[3][4], the maximum current that QA3 can output is 40mA while the forward current of the LED in 4n25 is between 10~60mA. The forward voltage of the LED is 1.3V and the output voltage of QA3 V_PWM is saturation voltage (9V).

$$R = \frac{V}{I} = \frac{V_{PWM} - V_f}{I_f} = \frac{9-1.3}{0.01} = 770\Omega \approx 680\Omega\ (standard\ value)$$

R9 and R10 were chosen empirically during simulation. The purpose of these resistors is to improve the transient response of the motor driver circuit:

Let R9 = 10k Ω;

Let R10 = 100 Ω;

R4 and R5 form a voltage divider which output the reference voltage V_Ref. This voltage needs to have a minimum of just under 1.5V (the minimum value of V_Triangle). The potentiometer is R4 and ranges from 0 Ω – 100k Ω.

$$1.5 = 9 * \frac{R5}{100000 + R5}$$

$$R5 = \frac{150000}{7.5} = 20\text{k}\Omega \approx 18k\Omega\ \text{(standard value)}$$

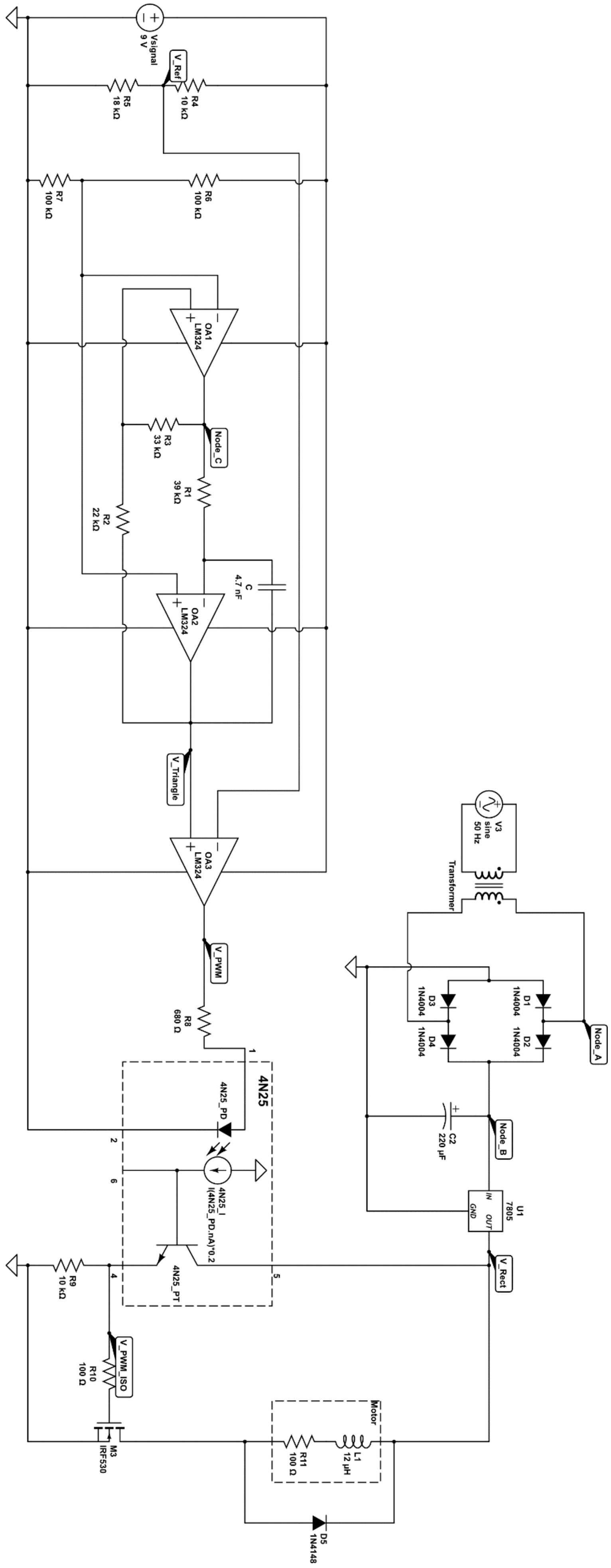

Figure 2.4 Circuit Diagram of DC Motor Speed Controller with component values.

3. Simulation Results and Analysis.

To test the simulation of the circuit, test points at the rectifier input/output, the triangle/square waves of the triangle generator, and the PWM output of the MOSFET drain in the motor driver circuit were chosen. These test points show that the outputs of all three main stages of the circuit are correct.

Simulations of the circuit shown in figure 2.1 show similar results to the calculated behaviour of the circuit. Figure 3.1 shows the simulated results of the circuit without the smoothing capacitor and figure 3.2 shows the results with a smoothing capacitor. As can be seen by comparing the two, ripple voltage is greatly reduced when a smoothing capacitor is used as a filter. The filtered waveform much more closely resembles a steady DC output. The maximum ripple voltage of the filtered circuit is 0.31V with an average voltage of 8.41V.

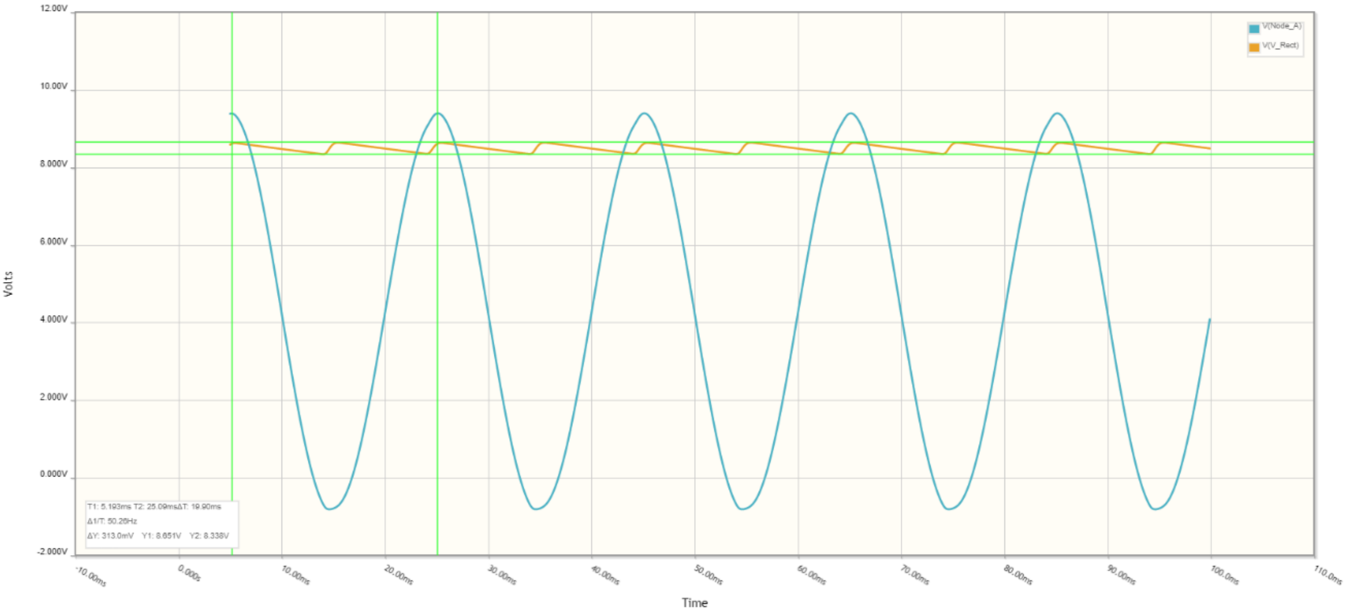

Figure 3.1 simulated results for power supply circuit with filter. Stepped down voltage = blue, load voltage = orange.

Simulations of the circuit shown in figure 2.2 show similar results to those calculated. The peak output voltage is 7.51V which is close to the expected 7.50V and the minimum output voltage is 1.31V which is close to the expected 1.5V. The simulated frequency of the output is 1.9kHz which is close to the expected 2kHz. The square wave waveform is as expected with its peak value being close to $2V_{cc} = 9V$ at 8.96V.

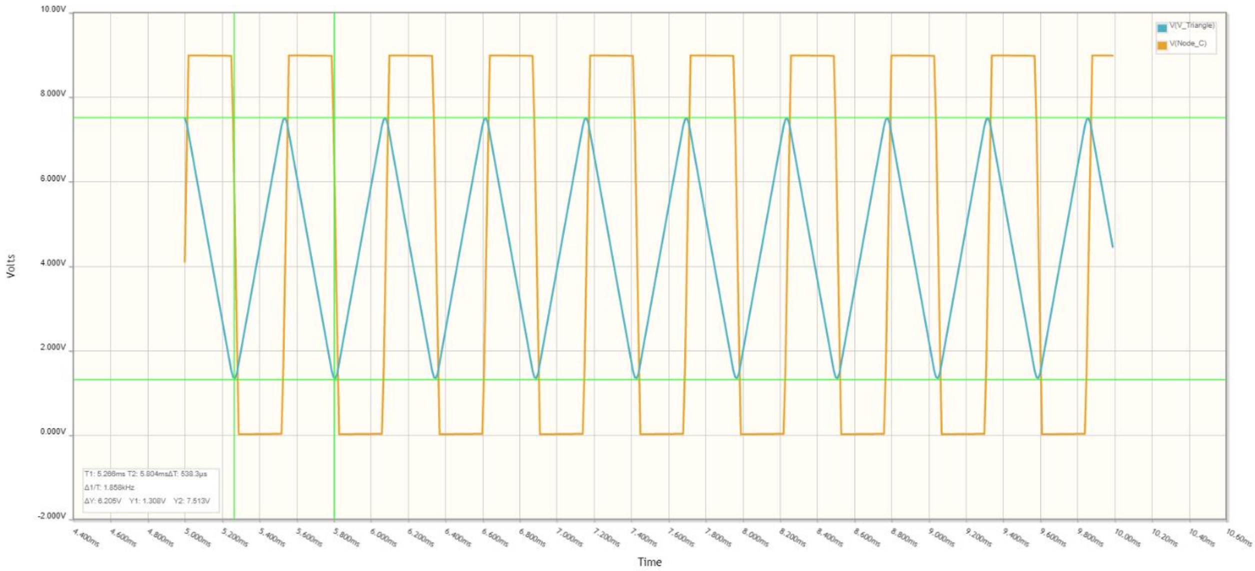

Figure 3.2 simulated results for Triangle Wave Generator. Triangle Wave = blue, Square Wave = orange.

As can be seen in figure 3.3, the voltage on the drain of the MOSFET M3 resembles a PWM signal as expected. The frequency of this signal is 1.8kHz and has a peak amplitude of 8.63V.

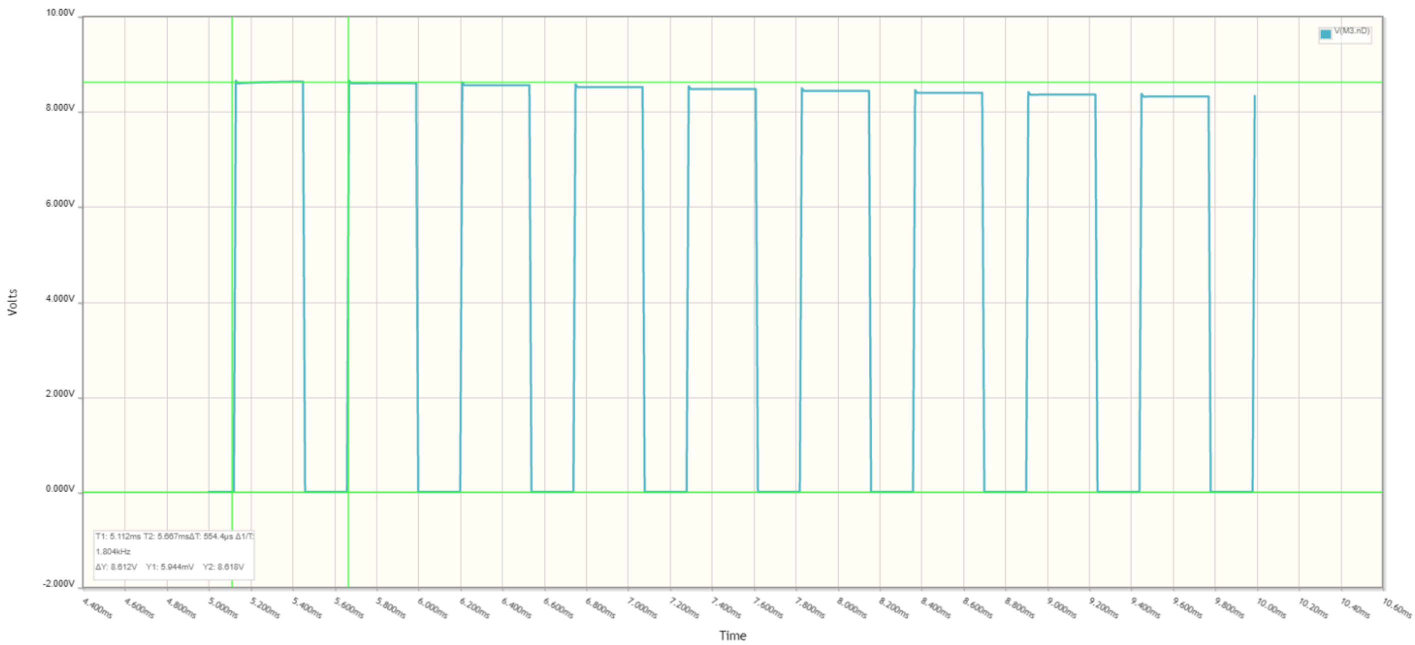

Figure 3.3 simulated results for DC Motor Driver Circuit MOSFET Drain Voltage (PWM @ 75% duty cycle).

4. Circuit Implementation

To implement the circuit, first a breadboard was used. The circuit was then implemented on a Veroboard. To supply the 9V DC for the signal, a bench power supply was used. Instead of using an ideal transformer with a turn ratio of n = 33.3, an AC/AC bench power supply was used with supplied a peak voltage of roughly 10.2V. A 9V DC motor was used as the load.

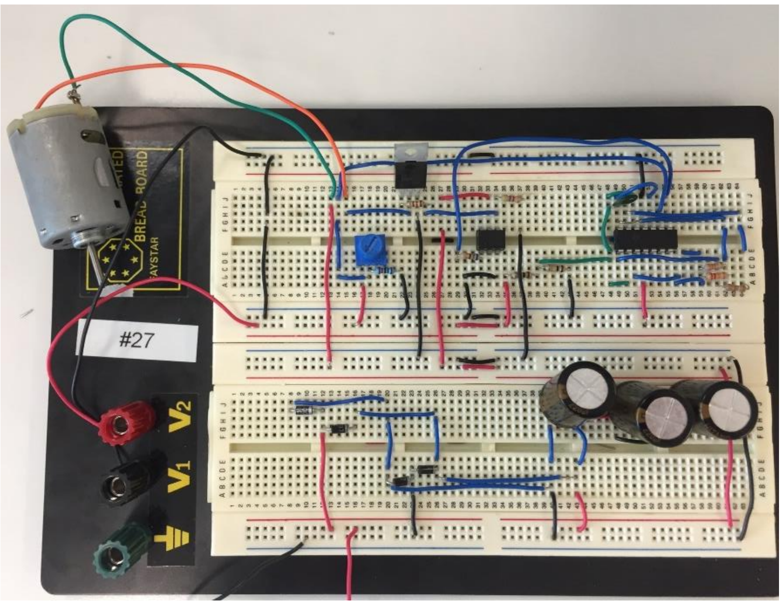

Figure 4.1 breadboard implementation of power supply circuit.

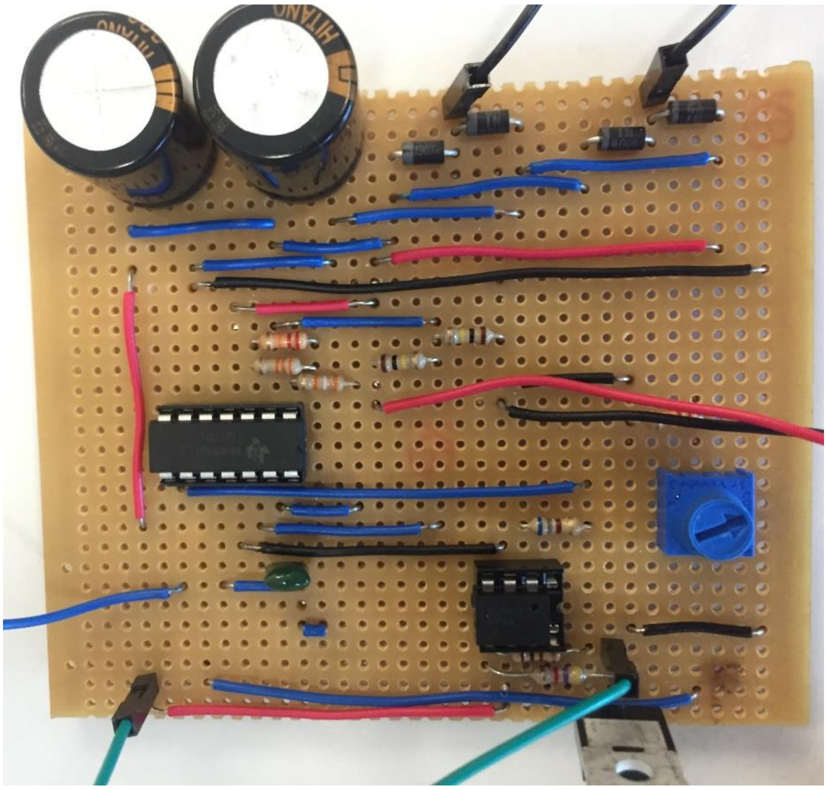

Figure 4.2 veroboard implementation of power supply circuit.

5. Test Procedure

To test the implemented circuit either on a Veroboard or breadboard, the following tools are needed:

- Digital Storage Oscilloscope (DSO)
- Multimeter
- AC/AC Lab Bench Power Supply
- Regulated Lab Bench Power Supply ($9V_{DC}$)

1. According to the circuit diagram in figure 2.3, use the $9V_{DC}$ lab power supply as Vsignal and the 9V AC/AC Lab Bench Power Supply as the secondary winding of the transformer in the rectifier circuit. To begin with, set the potentiometer to its '0^{th}' position such that the motor is not spinning.
2. Using the DSO, measure the voltage across the terminals of one of the capacitors in the capacitor bank C_filter. This is the output of the rectifier and should be around 8-9V with minimal ripple.
3. Using the DSO, measure the voltage between the negative terminal of Vsignal and pin 14 on the op amp IC (OA2). This is V_triangle and should have a frequency of around 2kHz with a range of 1.5-7.5V.
4. Using the DSO, measure the voltage between the negative terminal of Vsignal and pin 10 on the op amp IC (OA2) when the potentiometer is at both of its extremal positions. This is V_Ref and should range from just under 1.5V up to 9V.
5. Using the DSO, measure the voltage between the negative terminal of Vsignal and pin 8 on the op amp IC (OA2), adjusting the potentiometer to get 0%, 25%, 50%, 75%, and 100% duty cycle on the PWM signal. This is V_PWM and should be 0V at 0% duty cycle, 9V at 100%, and range between 0-9V otherwise. The waveform should be a clean PWM signal.
6. Using the DSO with the negative probe attached to the negative terminal of one of the capacitors in the capacitor bank C_filter, measure the voltage at pin 4 on the optocoupler (4N25), adjusting the potentiometer to get 0%, 25%, 50%, 75%, and 100% duty cycle on the PWM signal. This is V_PWM_ISO and should be 0V at 0% duty cycle, 9V at 100%, and range between 0-9V otherwise. The waveform should be a relatively clean PWM signal.
7. Using the DSO measure the voltage across the DC motor, adjusting the potentiometer to get 0%, 25%, 50%, 75%, and 100% duty cycle on the PWM signal. This voltage should be 0V at 0% duty cycle, 9V at 100%, and range between 0-9V otherwise. The waveform should be a PWM however it will be affected by the impulse response of the DC motor.

6. Test Results

4.1 Implementation Results

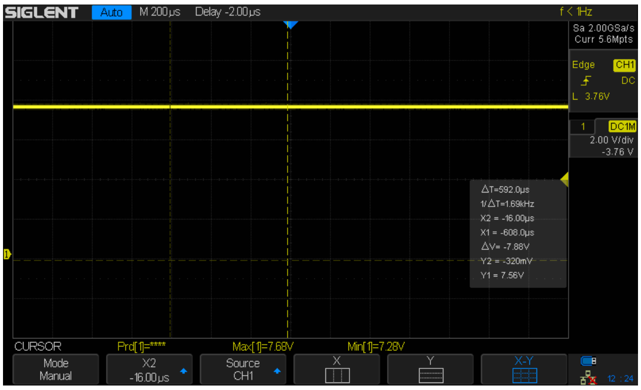

Figure 4.1 Implementation results for power converter (V_Rect)

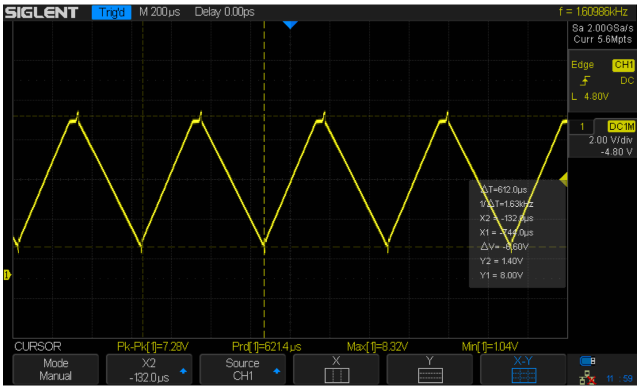

Figure 4.2 Implementation results for triangle wave generator (V_Triangle)

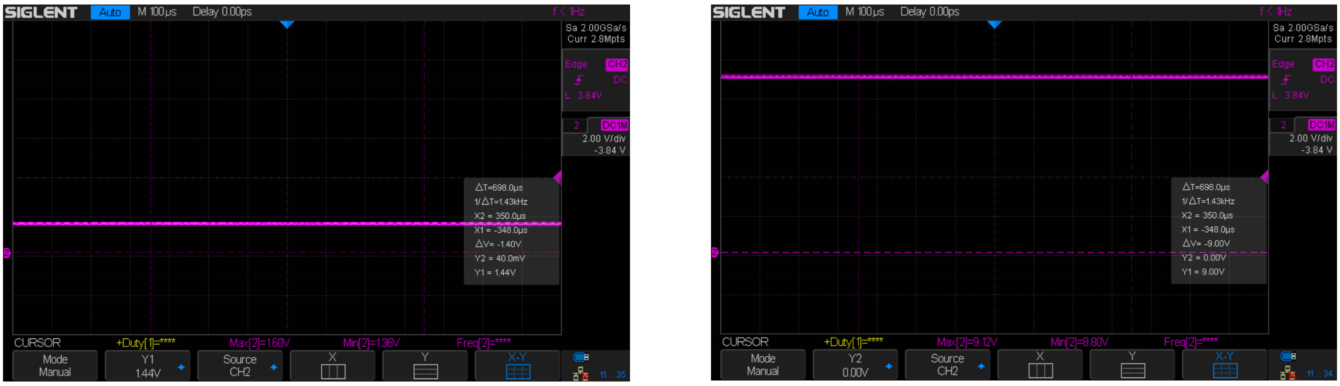

Figure 4.3 Implementation results for reference generator (V_Ref), minimum voltage on left, maximum voltage on right.

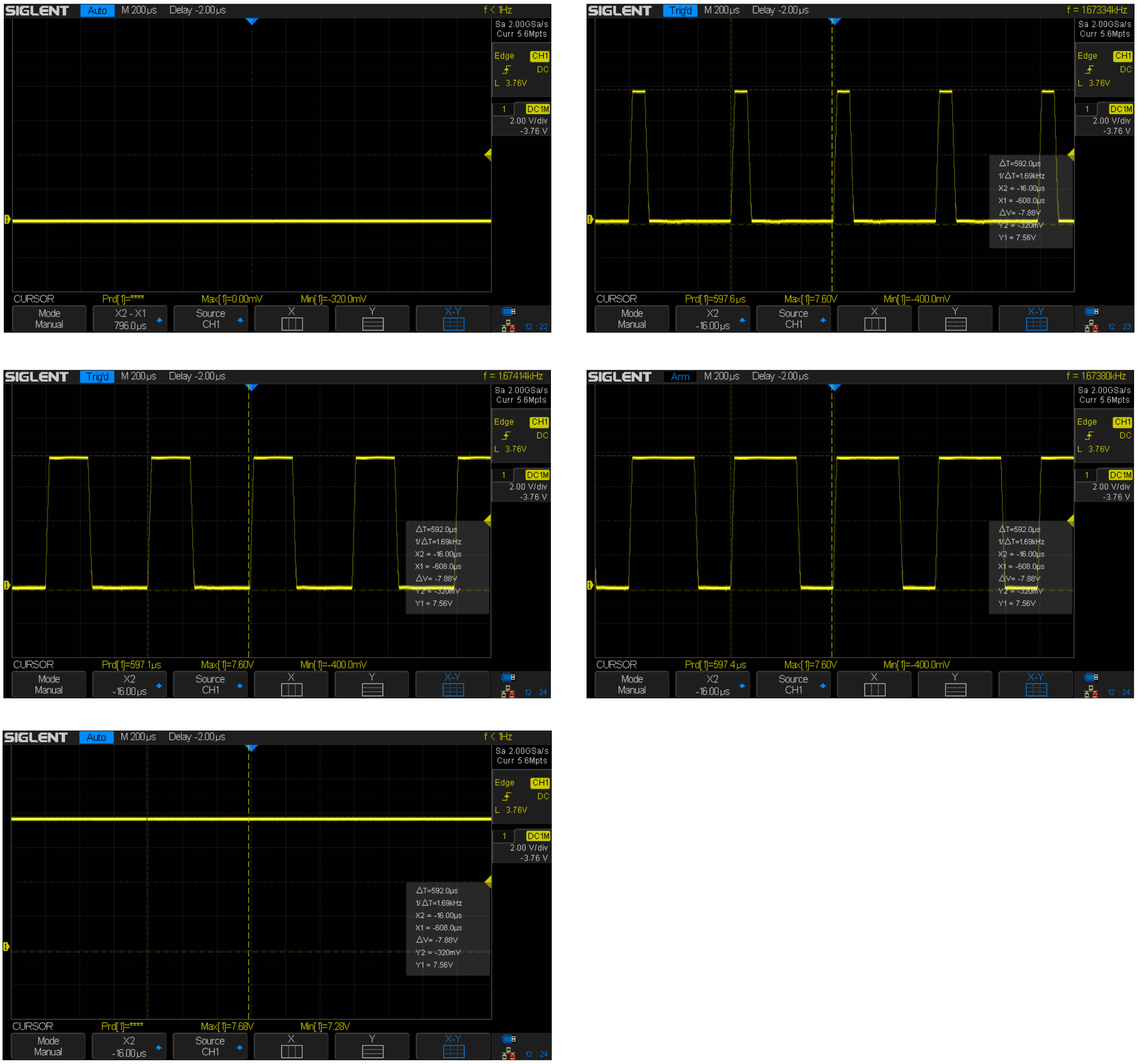

Figure 4.4 Implementation results for PWM generator (V_PWM) @0%, 25%, 50%, 75%, 100% duty cycle

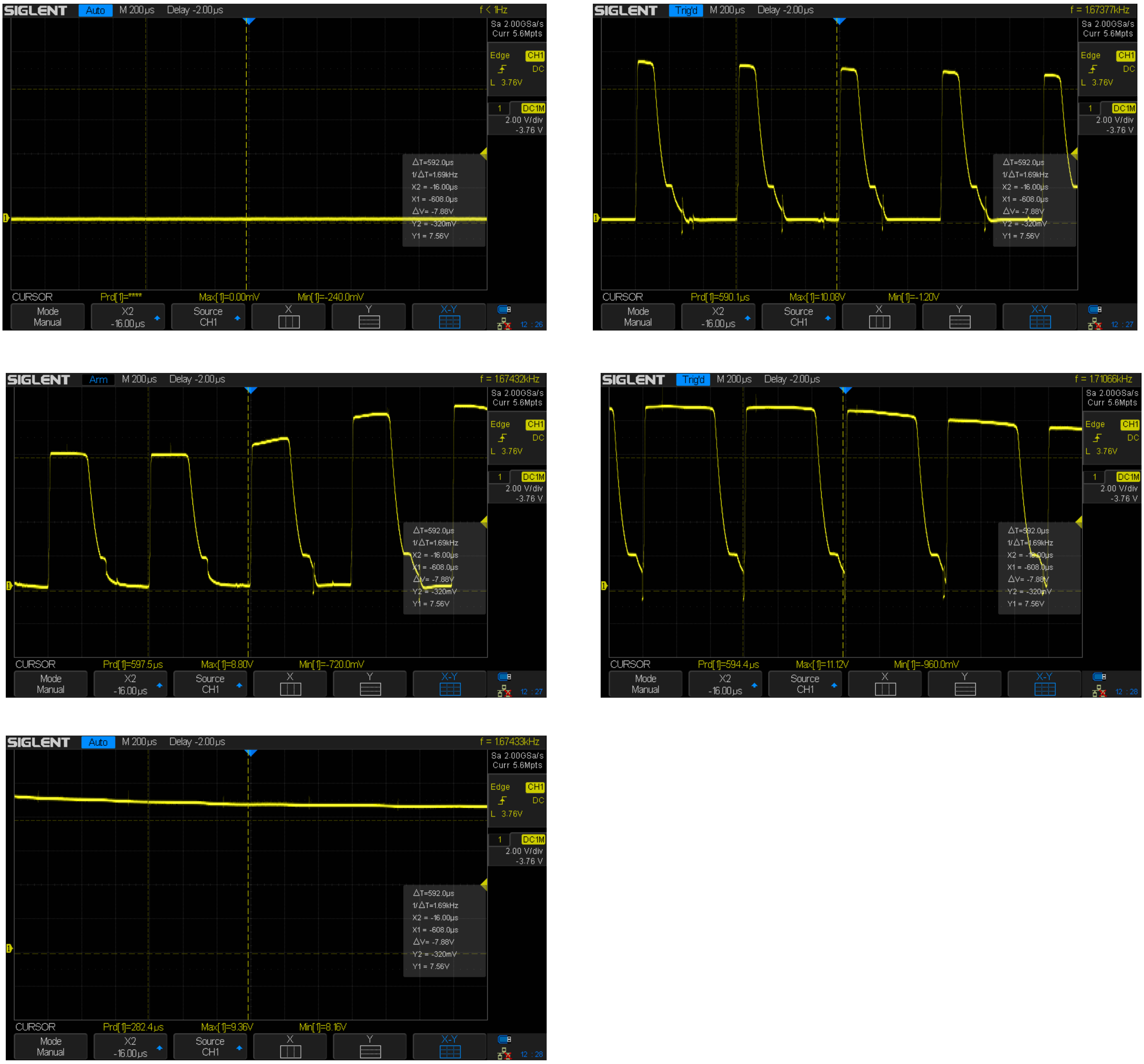

Figure 4.5 Implementation results for isolator (V_PWM_ISO) @0%, 25%, 50%, 75%, 100% PWM duty cycle

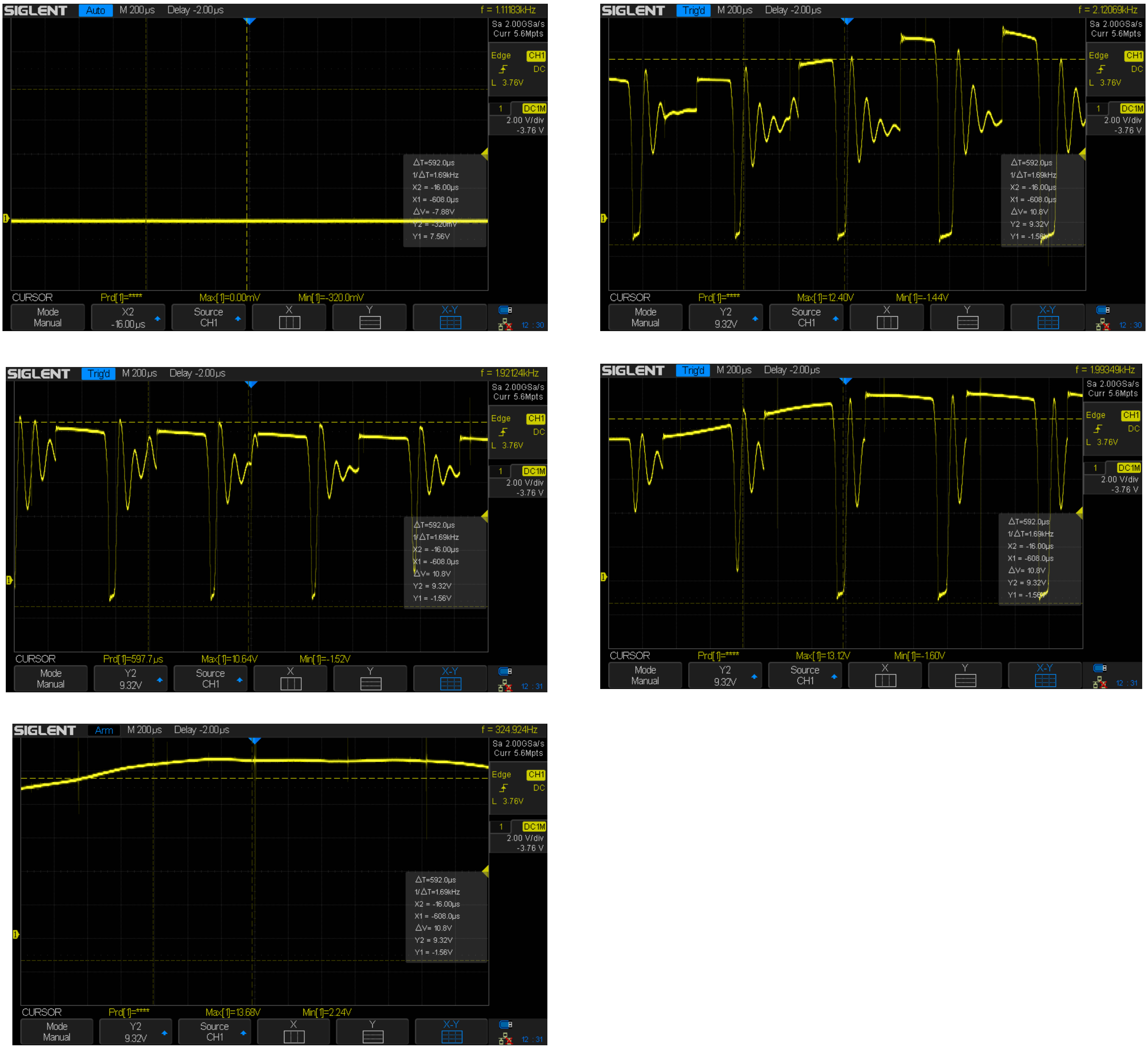

Figure 4.6 Implementation results for Motor Voltage @0%, 25%, 50%, 75%, 100% PWM duty cycle

4.2 Implementation Results Analysis

As can be seen in figure 4.1, the output of the rectifier circuit is slightly lower than expected at around 7.5V. This may be because the AC/AC power supply was either inaccurate or improperly set when this measurement was taken. The ripple of this output is also much smaller than expected in the simulations. This may be because either the DC motor was not similar to the 560Ω resistor that was used to model it during design and simulation, or this measurement was taken when the PWM waveform was at a 0% duty cycle, meaning the motor was drawing no power from the rectifier. This low ripple means the rectifier circuit has better than expected results.

As can be seen in figure 4.2, the triangle wave peak voltage and shape are similar to the simulated results. The range of the triangle wave was 1.4V to 8V as opposed to the expected 1.5V to 7.5V. These discrepancies are likely due to a higher OP amp swing voltage than expected as well as component tolerances. The frequency of the triangle wave was measured at 1.63kHz as opposed to the expected 2kHz. This discrepancy can be explained by the component variance in the resistance values of R1-R3 and capacitance value C due to their tolerances. Overall, the output of the triangle wave generator was suitable for its purpose in the larger circuit.

As can be seen in figure 4.3, the reference voltage has a range of 1.44V to 9V which is very close to the expected range of the reference voltage generator circuit. As expected, changing the position of the potentiometer across its range results in the motor speed changing from 0% to 100%.

As can be seen in figure 4.4, the PWM signal can be obtained with 0%-100% duty cycles. The amplitude of the signal was 7.5V as opposed to the expected 9V. This drop in output voltage of the op amp may be due to the optocoupler drawing too much current. This voltage drop does not affect the overall performance of the circuit however. Figure 4.5 shows the isolated PWM signal is not as clean as that in figure 4.4. This is likely due to 'noise' from the motor or parasitic capacitances/inductances affecting the high frequency signal across the pins of the transistor in the optocoupler. The switching speed of the optocoupler may also be causing this signal distortion. This distortion does not greatly affect the overall performance of the circuit however.

Figure 4.6 shows the voltage across the motor as a noisy PWM signal ranging from 0V to around 9V. This noise is expected due to the impulse response of the motor. The effect of this was to 'smooth' out the PWM signal, causing the motor to reach 100% speed before the PWM duty cycle was at 100%.

7. Bill of Materials

Component	Description	Manufacturer	Supplier	Quantity	Total Cost ($AUD)
LM324	Quad OP amp IC	Texas Instruments	Jaycar Electronics	1	2.35
4N25	Optocouper IC	Vishay Semiconductors	Jaycar Electronics	1	1.75
1N4001	Diode	ON Semiconductors	Jaycar Electronics	5	1.96
-	4.7nF 100VDC Polyester Capacitor	-	Jaycar Electronics	1	0.30
-	10k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	2	0.68
-	18k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68
-	100k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	2	0.68
-	100 Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68
-	680 Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68
-	39k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68
-	33k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68

-	22k Ohm 1 Watt Carbon Film Resistors	-	Jaycar Electronics	1	0.68
RT464x	100Kohm Spectrol 25 Turn Trimpot	-	Jaycar Electronics	1	2.95
IRF1405	MOSFET N-Channel 55V 169A TO-220	International Rectifier	Jaycar Electronics	1	5.95
				Grand Total	**20.7**

8. References

[1] Fuwen Yang (2021). Lecture 2: Rectifiers and Power Supply. Retrieved from: https://bblearn.griffith.edu.au/bbcswebdav/pid-5793337-dt-content-rid-117220187_1/xid-117220187_1

[2] Fuwen Yang (2021). Lecture 5: Triangle Wave Generator and PWM. Retrieved from: https://bblearn.griffith.edu.au/bbcswebdav/pid-5793340-dt-content-rid-117500746_1/xid-117500746_1

[3] Optocoupler, Phototransistor Output, with Base Connection Datasheet, Vishay Semiconductors, Retrieved from: https://bblearn.griffith.edu.au/bbcswebdav/pid-5793345-dt-content-rid-116210922_1/xid-116210922_1

[4] LMx24-N, LM2902-N Low-Power, Quad-Operational Amplifiers Datasheet, Texas Instruments, Retrieved from: https://bblearn.griffith.edu.au/bbcswebdav/pid-5793345-dt-content-rid-116210919_1/xid-116210919_1