E344 Assignment 1

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Report submitted in partial fulfilment of the requirements of the module Design (E) 344 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

September 25, 2022

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Nomenclature

Variables and functions

Acronyms and abbreviations

AC	Alternating Current
DC	Direct Current
Op-Amp	Operational Amplifier
BW	Bandwidth
R	Resistor
W	Watt
PS	Power Supply
PWM	Pulse Width Modulation
dB	Decibel
DAC	Digital to Analog Converter

Chapter 1

Literature survey

The purpose of this document is to present the reader with the basic principles low side current sensing. In order to do this, the most commonly used operational amplifiers are examined as well as the basics of current sensing. By observing the purpose and specifications of different configurations. The correct filter and operational amplifier configuration can be chosen in order to implement a low side current sensor.

1.1. Operational amplifiers

Operational amplifiers: limitations and considerations

Practical operational amplifiers have certain limitations when compared to ideal operational amplifiers. For example a differential amplifier amplifies the difference between the two input terminals. Therefor ideally if the two input terminals were the same then the output should be zero. In practice though this does not happen. There will be noise at the terminals which will make the inputs unequal and even if they were equal the operational amplifier would still have an output. When designing the correct configuration, the slew rate, bandwidth, input current and common mode rejection need to be considered. When observing the circuits frequency response, we design it to obtain the correct frequency response over a specific bandwidth. All practical operational amplifiers have a finite BW, this point where the gain begins to roll-over as the frequency increases is called the '3dB point'. It is shown in figure 1.1.

Operational amplifier configurations

Using different configurations of resistors and capacitors, many different types of operational amplifiers can be made. Some of the different types include inverting amplifiers, non-inverting amplifier, voltage follower, comparator, differential, summing and integrators. Operational amplifiers can have four different types of gain. Voltage gain, voltage in is amplified making voltage out larger in magnitude. Current gain, the current is amplified. Transconductance, voltage is made into current and finally trans resistance where current in and voltage out.

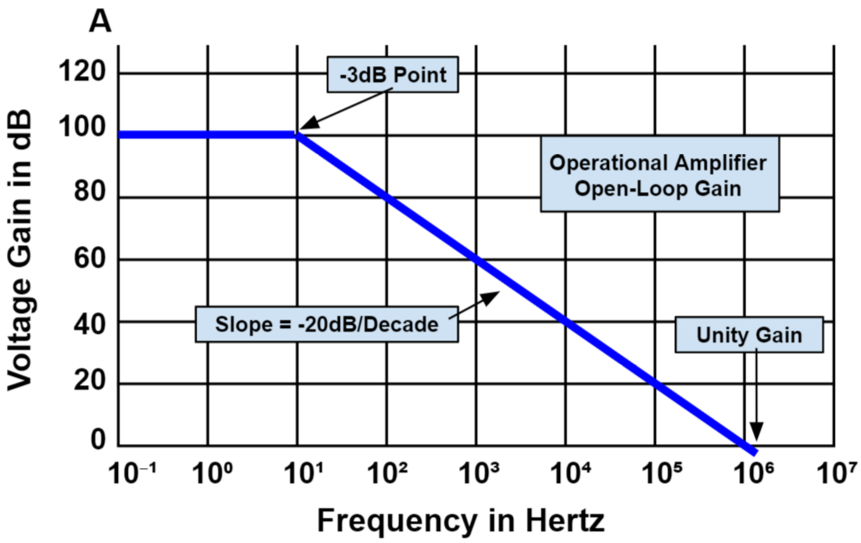

Figure 1.1: Frequency Response and Bandwidth

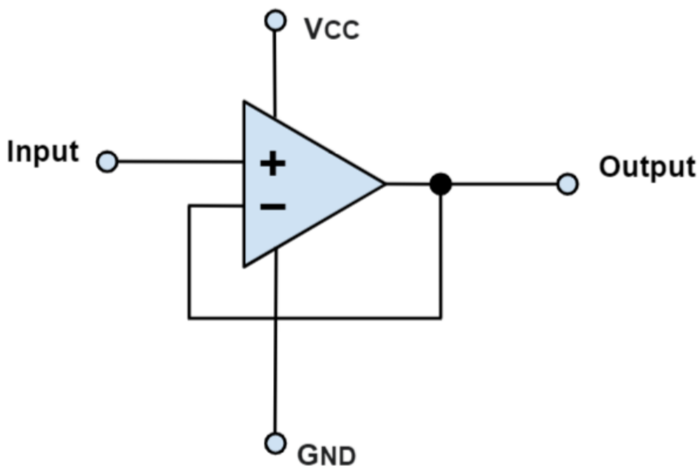

Figure 1.2: Voltage Follower

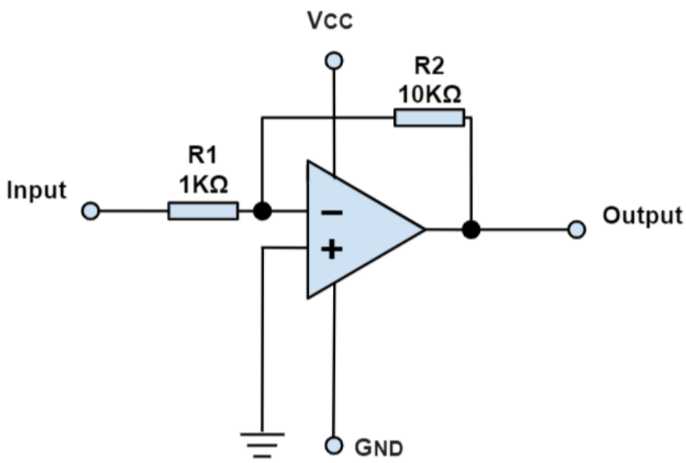

Figure 1.3: Inverting Amplifier

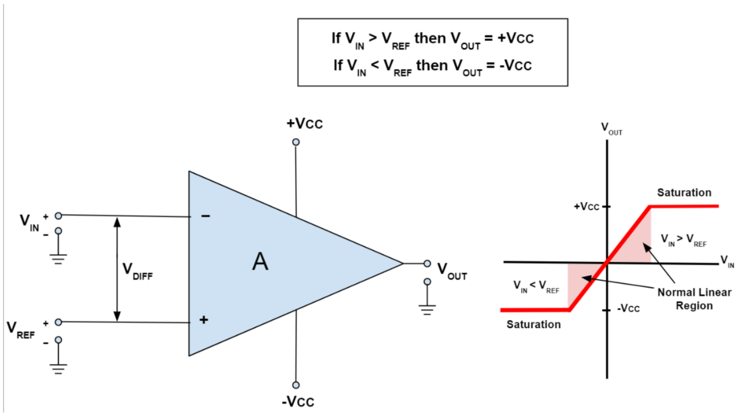

Figure 1.4: Voltage Comparator

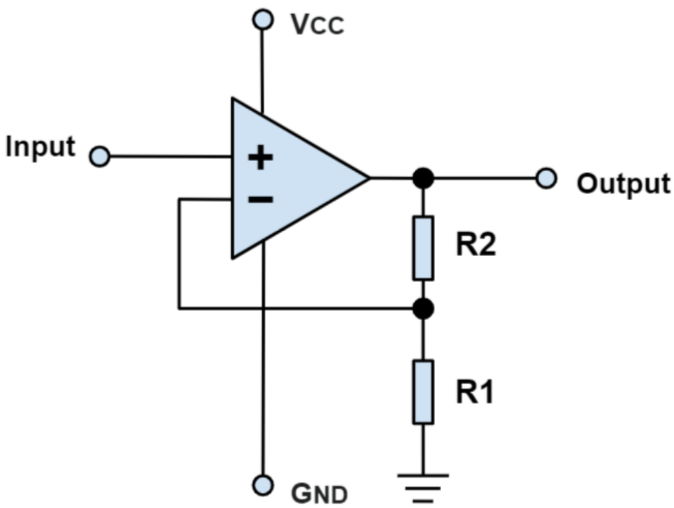

Figure 1.5: Non-Inverting Amplifier

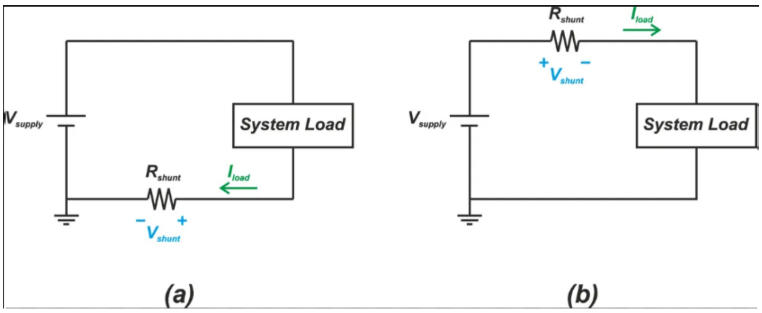

Figure 1.6: Lowside vs Highside

	Rogowski coil	Current Transformer	AMR	GMR	Hall effect	Fluxgate	Shunt
Current type	AC	AC	AC and DC	AC and DC	AC and DC	AC and DC	AC and DC
Current range	Medium	High	Medium	Medium	Medium	High	Low
Accuracy	Low	Medium	Medium	Medium	Medium	High	High
Temperature drift	High	Medium	Medium	Medium	Medium	Low	Low
Inherent isolation	Yes	Yes	Yes	Yes	Yes	Yes	No

Figure 1.7: Different Current Sensors

1.2. Current sensing

Low Side and High Side Current Sensing

Low side current sensing happens when the sensing resistor is placed below the load. The voltage seen at the current sensing circuit is near ground and therefor uses less power and is safer. This does however make the system ground and supply ground different. The configuration can be shown in Figure 1.6. A high side current sensor configuration is achieved by placing the sensing resistor between the power supply and load. The system then only has one ground however the sensing circuit is more susceptible to fluctuations over the load.

AC Current Sensing and DC Current Sensing

Certain current sensors and methods of measuring current can only measure AC or DC currents. Different methods are shown in figure 1.7. This needs to be considered when designing for the collision detection.

Power requirements

It is important to not use too much power when designing the current sensor. By using a low-side current sensor. The dissipated power in the shunt resistor will be less. By using less power, the DC motor will be able to perform better and the vehicle will last longer.

1.3. Converting PWM to Analog

What is PWM

Pulse width modulation is a way to control analog devices using with a digital output. PWM can be used by the MCU to control a variable speed motor. PWM simulates an analogue signal by applying power in pulses. Typically the base frequency is fixed This is done by changing its duty cycle. Figure 1.8 shows an example of different PWM signals with varying duty cycles. As the duty cycle increase so will the average value and as it decreases so will the average value. PWM can be converted to an analogue signal using a simple RC low-pass filter or a Sallen-Key filter. The duty cylce determines the magnitude of the filters output. Figure 1.9 shows the spectrum and desired bandwidth of the pulses. A simple RC or active filter can be used to get the desired bandwidth.

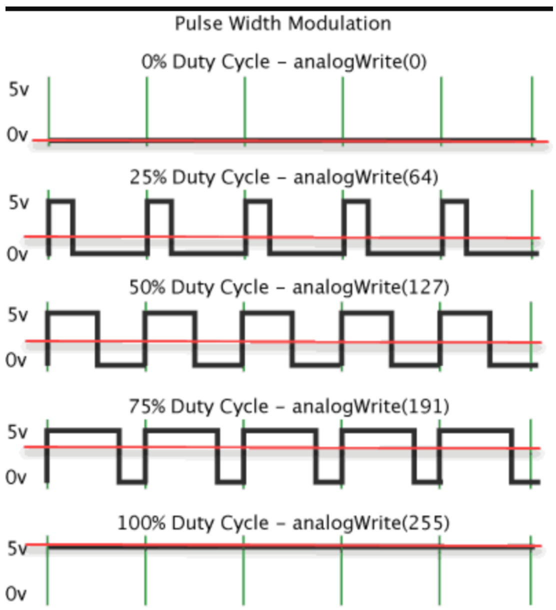

Figure 1.8: Duty Cycle of PWM signals

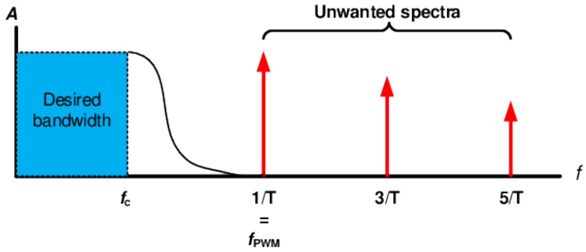

Figure 1.9: Spectra needed to be filtered

1.4. Fundamental operation of the range sensor

There are many ways of detecting the presence of an object. Certain proximity sensors are used for different tasks. Some are suited to detecting ferrous metals, all metals or objects/people. There are magnetic, capacitive, ultrasonic and more. Ultrasonic sensors are useful for detecting objects up to several meters. The way that objects are detected is based on an ultrasonic pulse being emitted from a sensor transmitter at a specific frequency when the trigger is set. This wave is then reflected off the object and received. The amount of time taking from transmitting a pulse signal to the signal being received is called the time of flight. The time of flight is used to measure how far away the object is from the sensor. By powering the sensor and filtering the pulses. An analog signal can be generated with different values based on how close the object is. This value can be read by a microprocessor to detect the object. The reason for the a change in value is due to the pwm. Figure 1.10 shows a diagram of an ultrasonic sensor.

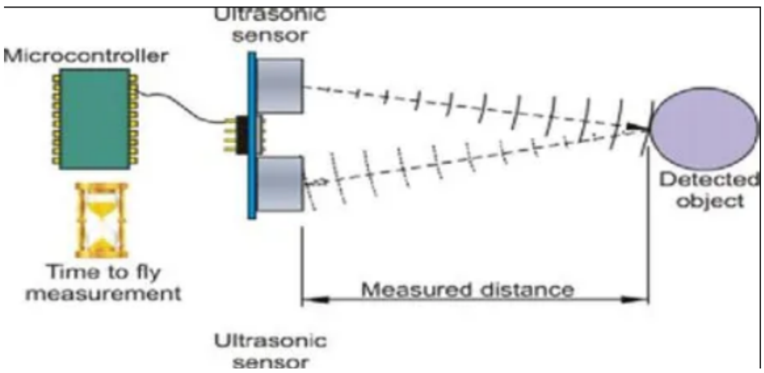

Figure 1.10: Current sensor detection

1.5. Interfacing with an Ultrasonic Range Sensor

The HC-SR04 ultrasonic sensor emits a sound wave at a specific frequency. The waves then bounce off the object and the sensor receives them. The received signal is a PWM signal. This must then be converted to an analog signal, the signal is converted by using a filter. This filter can be a simple RC filter or an active filter. The capacitors discharge causing the pulse signal to smooth out to an analog one. Depending on the width of the pulse the mean voltage of the analog signal changes. When the signal is received the echo pin is sent low. This received signal will correspond to the distance the object is. Closer objects have smaller analog voltage signal and the magnitude increases as the object gets further away.

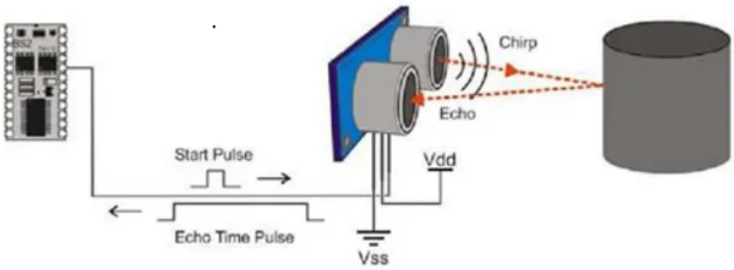

Figure 1.11: Current sensor detection

1.6. Converting Digital to Analog Values

Digital to Analogue converters or DAC's convert binary/non-binary signals into non-discrete analogue signals with the output voltage/current of the the converter being proportional to the input. The most common way of conversion is using a weighted resistors and a summing operational amplifier.

1.6.1. Inverting Summer

Multiple inputs can be connected to the negative terminal of the Op Amp in order to build a summing amplifier. This can be seen in figure 1.12. This is called a summing inverting voltage amplifier. The implication of using is that the negative feedback created biases the inverting input to a zero potential therefor making any input signals electrically isolated from each other.

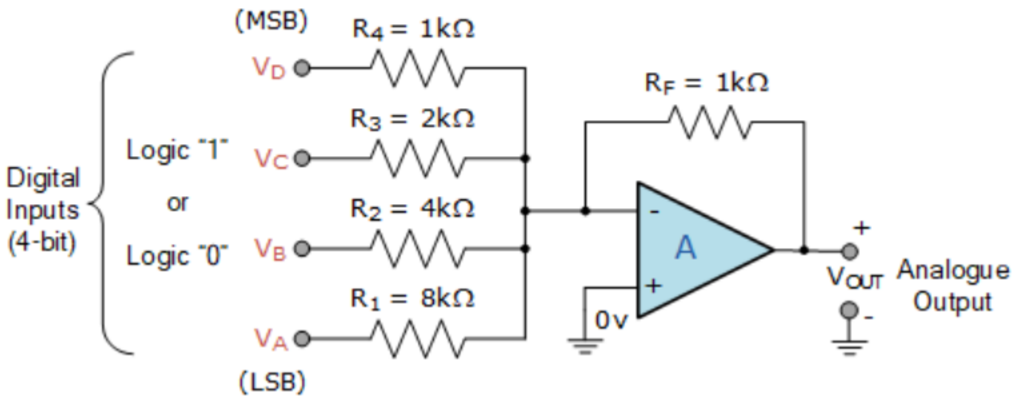

Figure 1.12: Summing Inverting Voltage Amplifier

1.6.2. Impedance Considerations

The resistors need to be large enough to reduce the current and minimize the power consumption of the circuit. The resistors R1-R4 in figure 1.12 produce a negative sum of the of the input voltages due to being connected at the negative terminal.

1.7. Lead Acid Batteries

Lead acid are rechargeable batteries that use lead and sulphuric acid to work. [1] The chemical reaction between lead and sulphuric acid causes the battery to produce electricity. They are a fairly new invention being invented in 1959. Lead acid batteries self discharge meaning that it discharges 1% of its capacity everyday, this can't be stopped entirely. Various factors can cause a lead acid battery to fail. This includes partial discharge. This happens when the electrolyte solution lowers, The lead will then be partially exposed allowing the sulphate to bond to the lead. Deep discharge is another problem which happens when the battery is discharged below 50%. This allows for small pieces of lead to break off from the plate. The last problem is overcharging, overcharging can break the down the electrolyte material.

Lead acid batteries are good for usage as they are smaller in size, have powerful voltage and are excellent for tools, heavy-duty equipment and electric vehicles.

1.7.1. Charging a Lead Acid Battery

From [2]. There are four techniques in which lead acid batteries can be charged.

- Constant Voltage
- Constant Current
- Taper Current
- Two Step Constant Voltage

The best charging method to obtain max battery life, capacity, with decent recharge time time and economy is constant voltage-current limited charging. For taper and constant voltage charging the battery's current acceptance decreases as the voltage and state of charge increases. When the current is fully stable, the battery is fully charged. For constant voltage charging the batteries may either be charged on a continuous or non-continuous basis. For portable equipment non-continuous charging is used. This method applies a constant voltage to the battery and limits the initial charge current.

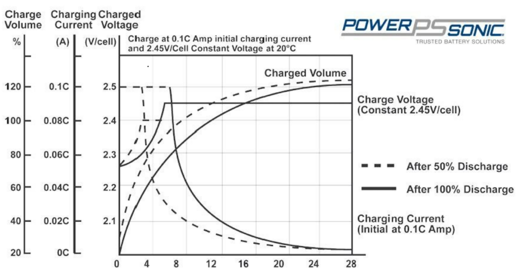

Figure 1.13: Lead Acid Battery charge characteristics

Chapter 2

Detail design

The maximum stall current was found to be 1.01 A. This was found by powering the motor and attaching the wheel. By stopping the wheel and observing the current used by the motor when the wheel was not able to move, the maximum current was observed. This was done quickly as stalling the motor for long will destroy the motor. The measurement and setup can be seen in figure 2.1. When the motor was running with no force stopping it, it used about 150mA. However the motor will have to move the entire vehicle and therefor will consume about 200-300mA.

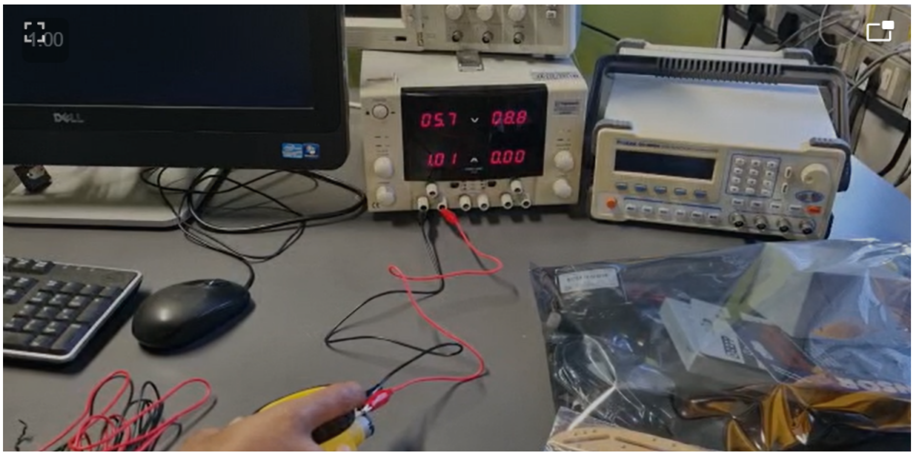

Figure 2.1: Stalling Test

Figure 2.2 was taken from Texas instruments. These were the main implementations of a low side current sensor. 2.2a is simpler to build and implement a filter on but is less stable than 2.2b. Due to disturbances on the sensing resistor 2.2b was chosen. If the motor/load affects the current sensor, the effects will be nullified by the extra resistors in 2.2b. The value of R1 was chosen as 250 Ohm. The gain was chosen 300 in order to get a voltage output of over 3Vs. The rest of the resistor values were worked out using the equation in figure 2.2. These values were tweaked in LTSpice in order to get the best output. The max voltage the ESP can read is 3.3V therefor the circuit was designed to be in this range. This can be seen in 2.4

The frequency response was chosen to be around 20 Hz. The following equation was used in order to work out the correct values for the circuit. This was then changed on LTSpice to get a better smoother curve. By smoothing out the graph shown in figure 2.4, the slew rate increased. A value in the middle was chosen. Figure 2.3 is the final design of the circuit. The resistor values were chosen to use less than 150 uA.

$$\frac{1}{2pi*fsense*10*R2}$$

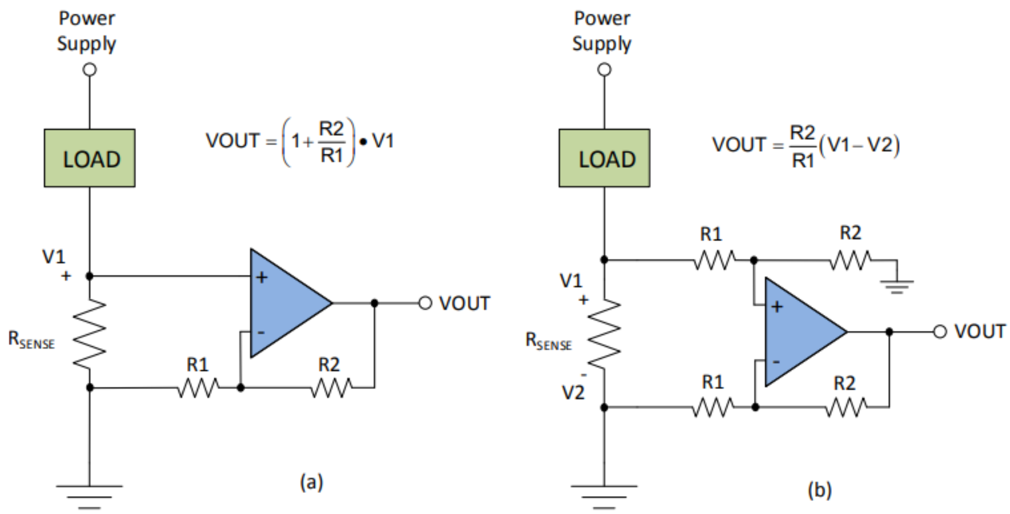

Figure 2.2: Simulation

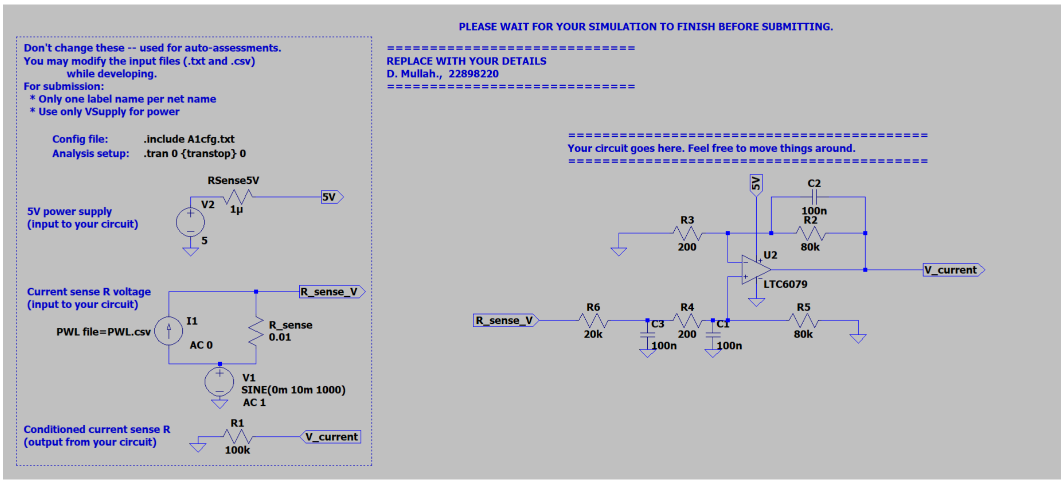

Figure 2.3: Final Design

2.1. Design of PWM to Analog Converter

The filter was initially designed for a frequency of 8Hz. The reason being is that the PWM signal has a frequency of 16Hz and the design must be half of the PWM signal. The circuit consisted of two op amps. The first one was set up as an active filter. The second op amp was used to control the gain. Figure 2.4 shows the final implementation of the circuit.

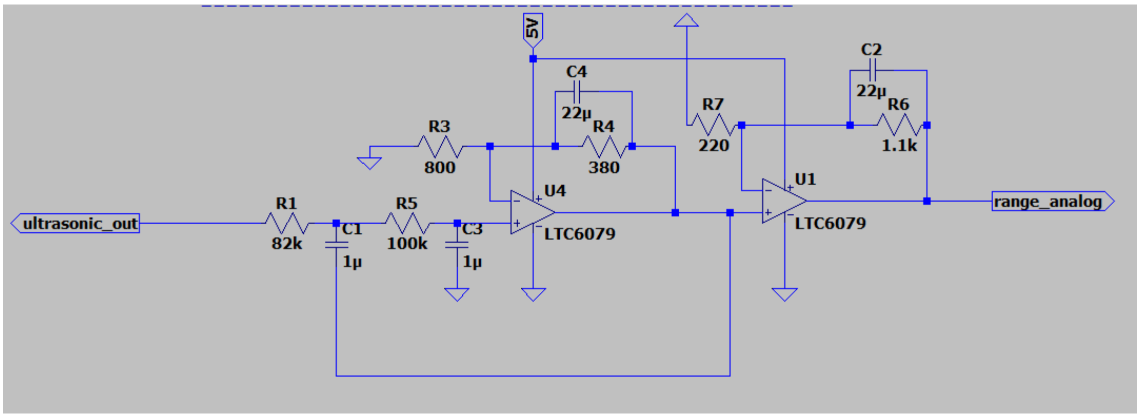

Figure 2.4: circuit diagram of ultrasonic sensing circuit

The following equations show the gain of the each op amp. They were both set up with the same gain equation.

$$Gain = 1 + \frac{R2}{R1}$$

Design of the frequency.

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

The values of the capacitors needed to be increased as the circuits initial response was too fast. Increasing the capacitors for the RC filter was selected to be 1u as this value gave a really smooth output with little noise. The resistor values were just chosen to provide a gain which made the output greater than 3V but less than 3.3V. The Op amps have a gain of around 5 when powered by 5V. The 22u F capacitors were chosen to smooth out the response. It filters the ripple. The final signal can be seen in the results.

2.2. Design of Digital to Analogue Converter

The resistors used need to be large in order to reduce the current consumption.

$$I = \frac{V}{R}$$

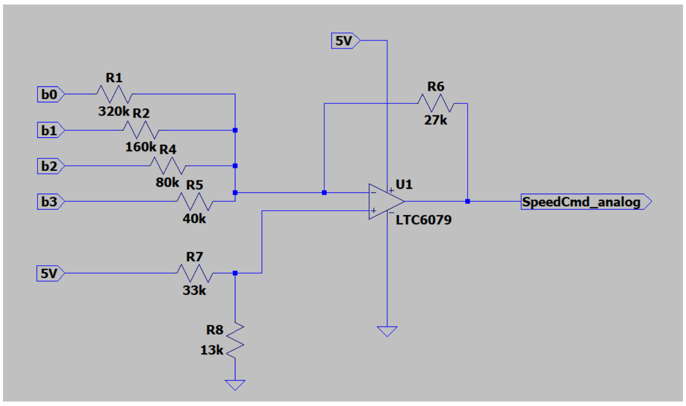

Figure 2.5: Digital to Analogue Converter Circuit diagram

The following voltage output equation shows how the digital signal is converted to an analogue signal. If bit 1 is high and the rest are low then the summer weights it according to the ratios. The resistors value has to be around half of the previous one, and the starting resistor was chosen to be 330kOhm in order to reduce the current. The voltage divider circuit in figure 2.5 produces an output voltage at the positive terminal of 1.9V. This provides the optimal output of the circuit in LTspice and this was chosen so that the circuit can have a voltage of 3.1V. This voltage is multiplied in the ratio shown below and produces the output depending on which bit is high. Potentiometers were used in R8 and the feedback resistor and they were tweaked to allow a maximum output voltage of 3.05V.

$$Vout = \frac{V1}{2} + \frac{V2}{4} + \frac{V3}{8} + \frac{V4}{16}$$

2.3. Design of Low-Side Current Sensor

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2.3.1. Low-side N-MOSFET Switch

A Low-side transistor configuration was used. I chose to use an N-Channel MOSFET. For this configuration the source must connect to ground while the drain terminal connects to the negative side of the load. The reason for this choice is that using a P-MOSFET dissipates much more power than the N-MOSFETS equivalent. As can be seen in figure 2.7 a pull-down resistor is used. The motor voltage is fed into the drain terminal and the combination produces a switch which opens and closes based on the 2.
When the Gate-source voltage is less than the threshold voltage then the MOSFET will be off. No drain current will flow. By having the the gate to source voltage greater than the threshold the MOSFET operates as a closed switch. The voltage fed into the Gate is the motor control.

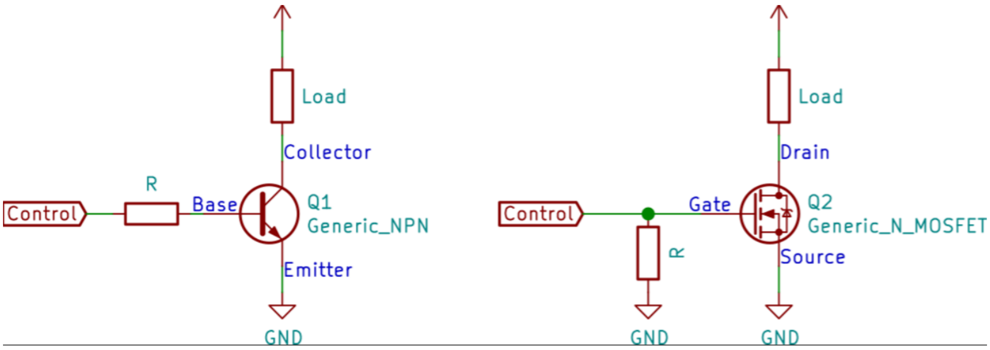


Figure 2.6: Low Side MOSFET

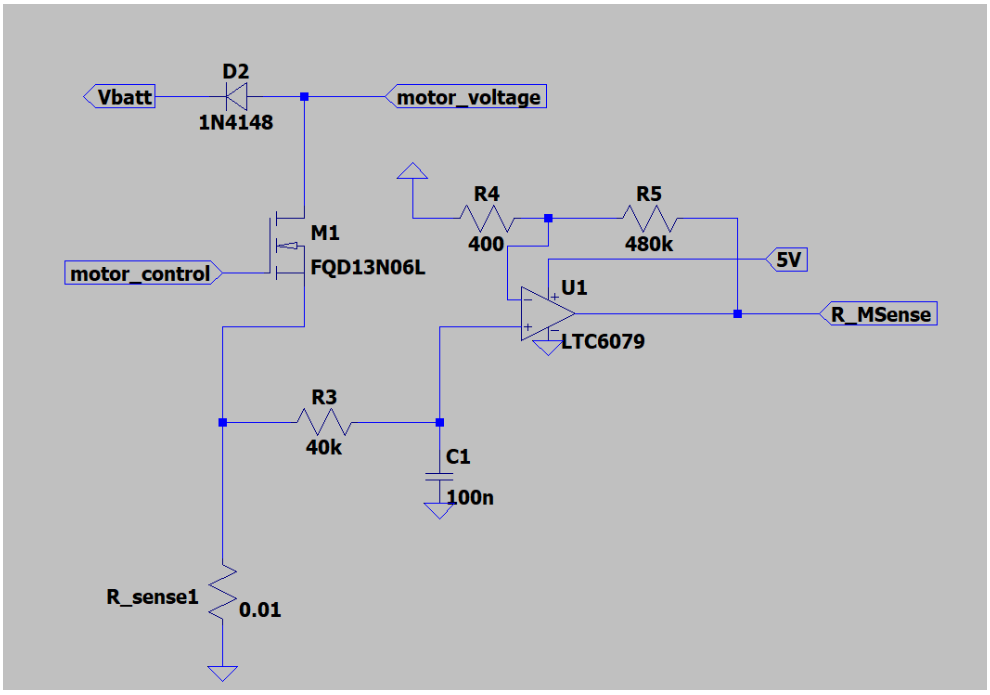


Figure 2.7: Low Side current sensor Design

2.3.2. Current Sensing

The current sensing circuit can be seen in figure 2.7 on the right hand side. The frequency design was calculated using the following equation.

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

This gives a frequency of around 40Hz. This seemed to generate the correct output and was chosen with trail and error as the low side current sensing circuit was built previously.
The gain equation is given by,

$$Gain = 1 + \frac{R2}{R1} = 1201$$

This produced an output which is roughly around 3.3V.

2.3.3. Software Flow Diagram

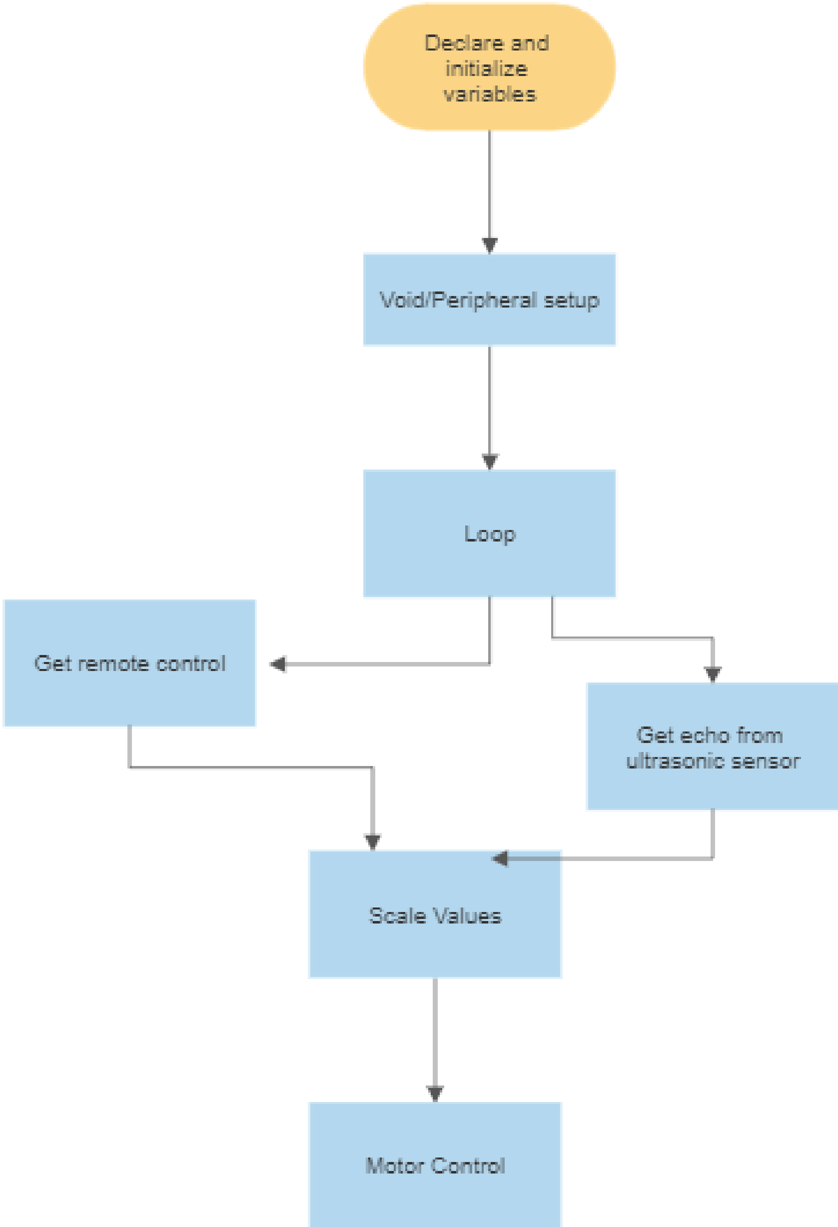


Figure 2.8: Flow Diagram

2.4. Battery Design

2.4.1. Battery Charger Design

By using the LM317T voltage regulator and other MOSFET's, we must create a battery charger than can turn on and off with a switch. A constant voltage of 2.45V/cell needs to be applied to the terminals of the battery in order to charge it. The battery is used in cycle mode as the car we are designing is portable and therefor makes use of non-continuous cyclic charging. The total voltage applied need to be equal to the max rating of the battery. From the data sheet we can find this to be between 7.3V and 7.4V. Therefor by using 2.45V/cell for 3 cells. Therefor a constant voltage of 7.35V can be applied to the battery while charging. The LM317T needs to act as both a current limiter and a constant voltage source. The completed circuit can be seen in figure 2.9 below.

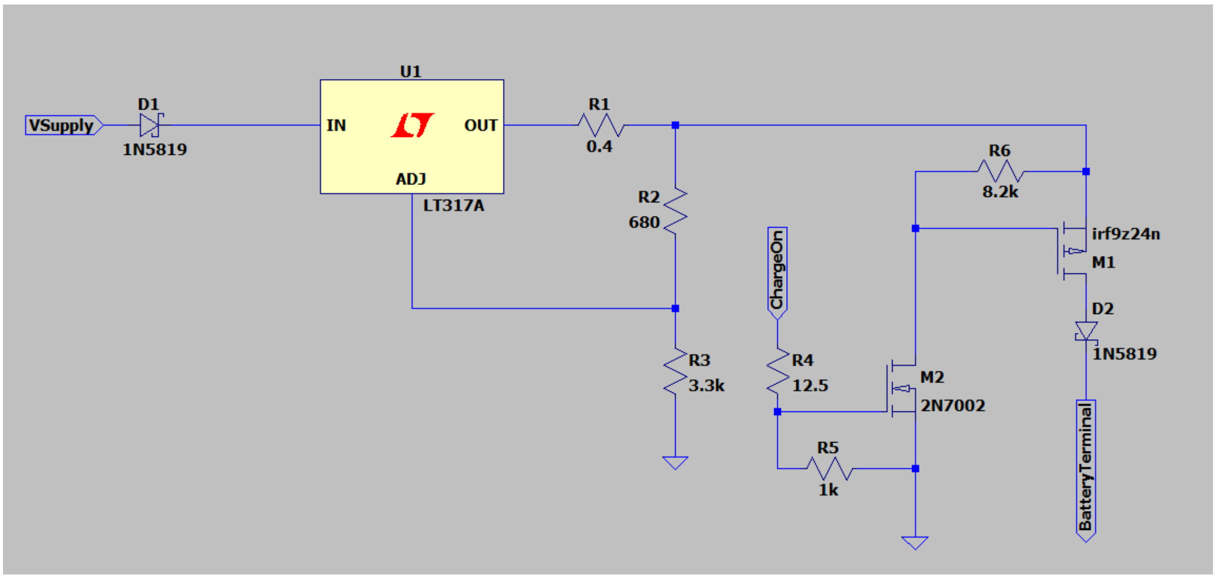


Figure 2.9: Battery Charging Circuit Schematic

The circuit must limit the current into the battery to 0.1C. Due to the battery having a nominal capacity of 7 AH, we must limit the current into the batter to be 700mA. However we were told to limit the current to around 400mA. Thus by measuring the current through the diode in SPICE R1 was chosen to be 0.4Ω . The value of R1 and R2 were chosen by making the gain around 7.3V. The values chosen was 680Ω and 3.3kΩ. These were chosen using the following equation. This gives an output of 7.3V.

$$V = 1.25 * (1 + \frac{R2}{R3})$$

R6 and R5 are simple pull down resistors and don't affect the circuits output. I therefor used resistors I had on hand already. These resistors ensure excess charge is removed from the gate when the charging circuit is applied to the battery. Both capacitors used are decoupling capacitors and they isolate the the battery charging circuit from the voltage supply. The two Schottky diodes also provide protection and don't allow current to travel in the wrong way.

2.4.2. Under-Voltage Protection

The point of the under-voltage protection circuit is to turn off the circuit when the battery voltage is lower than 6.0V and only turn on when the voltage is 6.1V. The design can be seen in figure 2.10. A Schmitt Trigger is used to control the battery supply to the motor. The Schmitt trigger takes the battery voltage and compares the battery voltage and outputs a digital signal corresponding to the batteries voltage. If the voltage is over 6V, the Schmitt trigger outputs a digital high and if it is below 6V it will output a digital low. The digital high signal needs to be 5V and therefor a voltage divider circuit needs to be used.

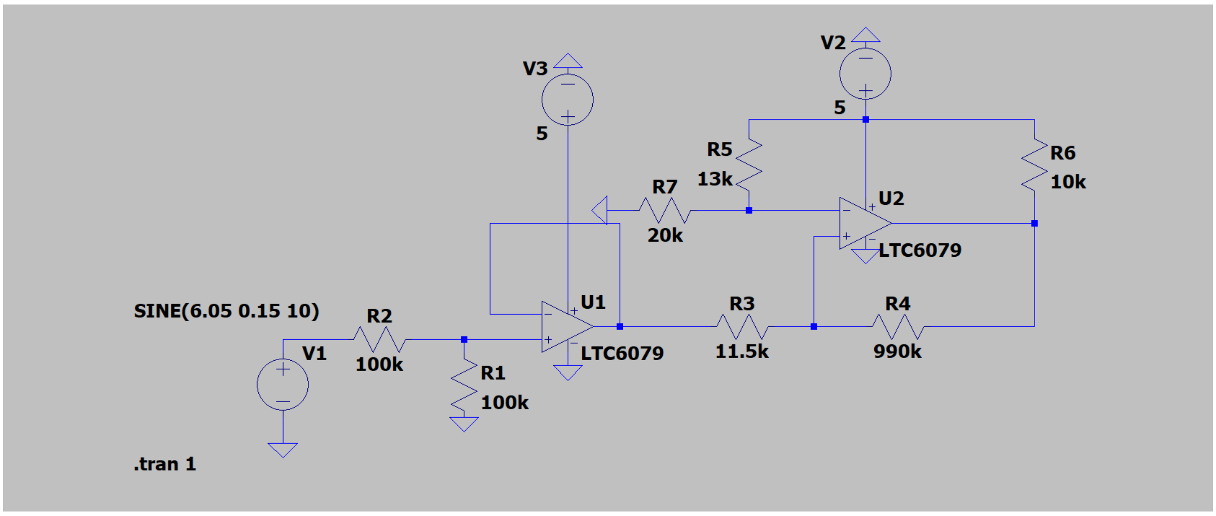


Figure 2.10: Under-voltage Protection

2.4.3. Battery Voltage Signal Conditioning

Chapter 3

Results

3.1. Current sensor

The simulated result of low side current sensing circuit is shown in figure 3.1. The slew rate and smoothness of the output both meet the requirements. The measured stalling test is shown in figure 2.1 above. The outcome of the stalling test was within the expected range.

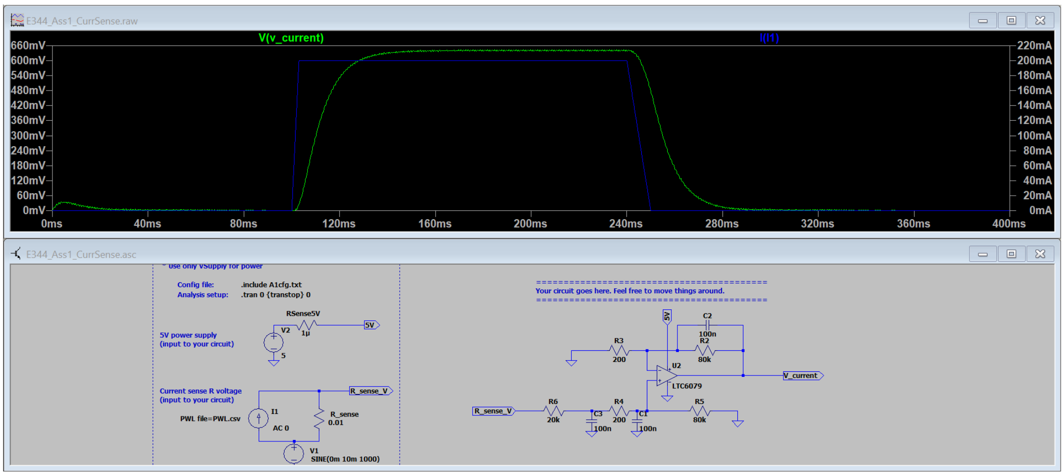


Figure 3.1: Circuit and Output

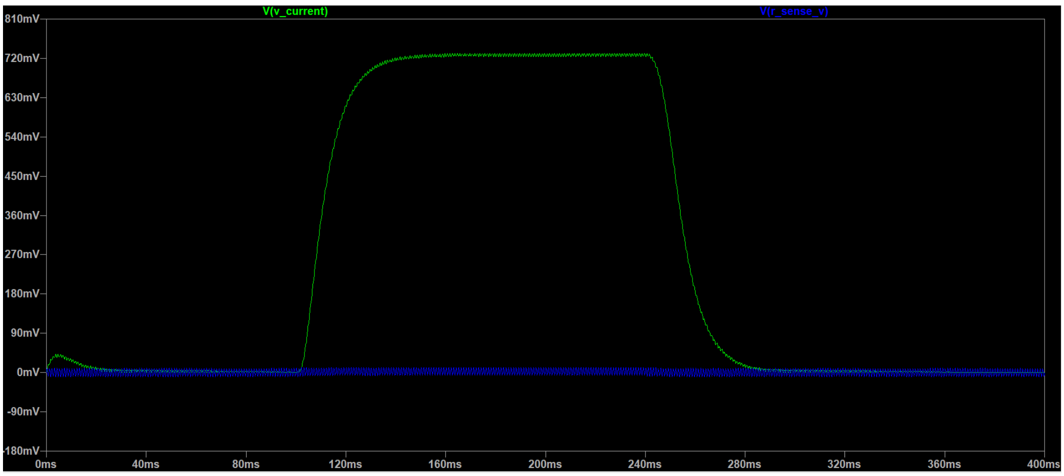


Figure 3.2: Input Vs Output

3.2. Current sensor Physical Measurements

The circuit performed well during regular running and when the wheel was stalled. However when the supply current was set to zero the circuit had a voltage output of 0.35V which is above the requirement. This is due to incorrect biasing with the resistor values. The solution would be to add a voltage clipping circuit at the input or recalculate the resistor values. The solution was not implemented due to time and the circuit did respond correctly to all the other specifications.

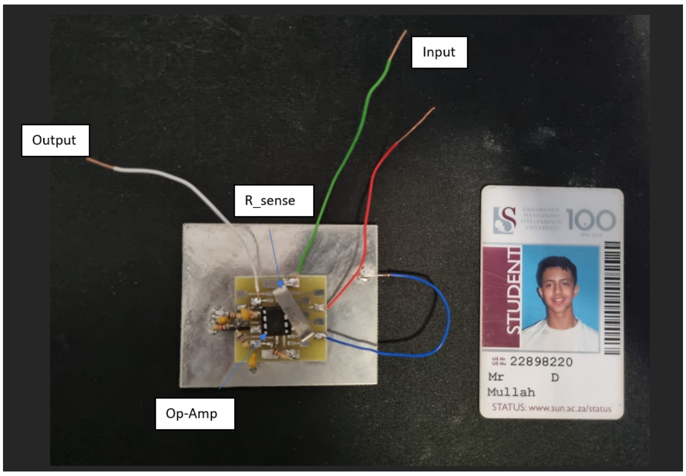


Figure 3.3: physical circuit

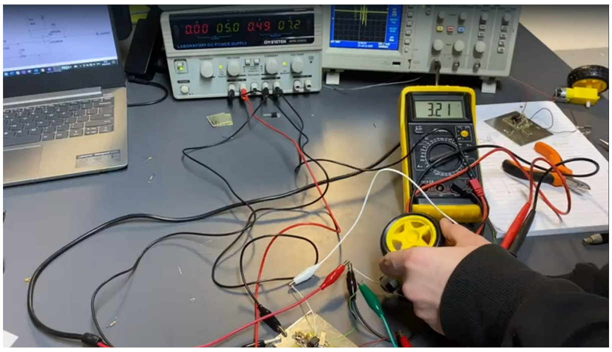


Figure 3.4: stalling test

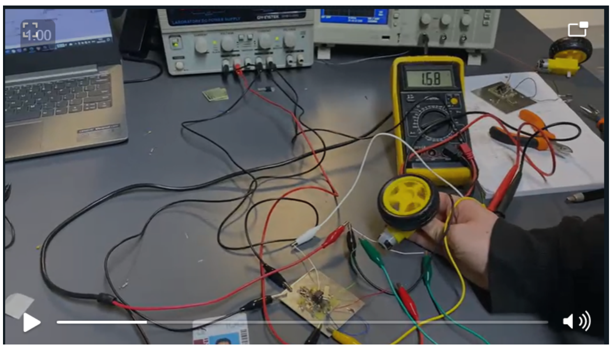


Figure 3.5: running test

3.3. Ultrasonic Sensor Physical Measurements

The circuit performed well and met all the requirements.The output is never above 3.3V and the voltage measured at 1m is 3.18V.

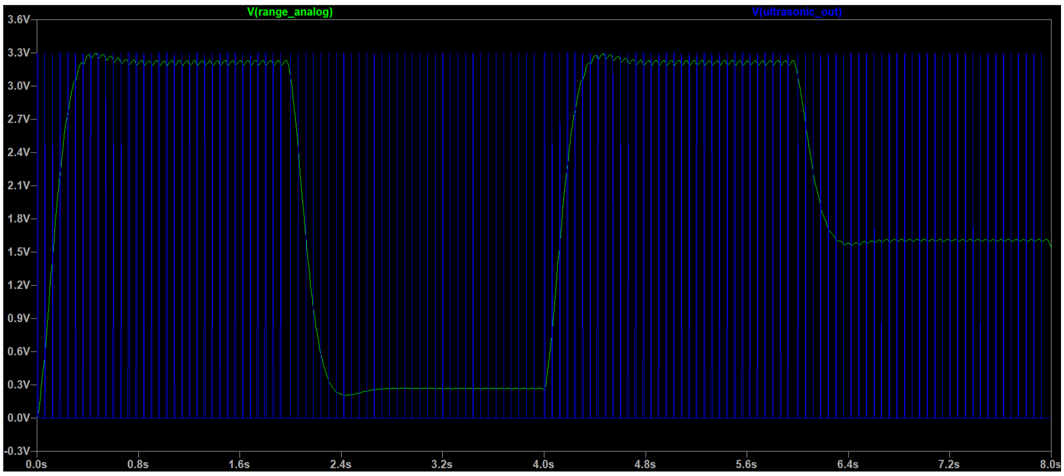


Figure 3.6: Output of ultrasonic sensor

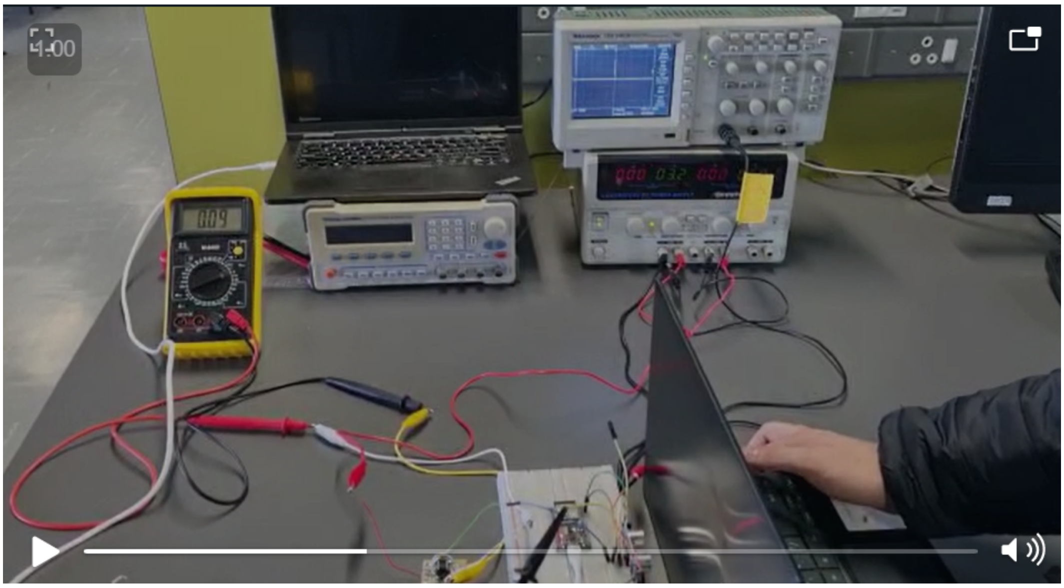


Figure 3.7: Voltage level at 5cm

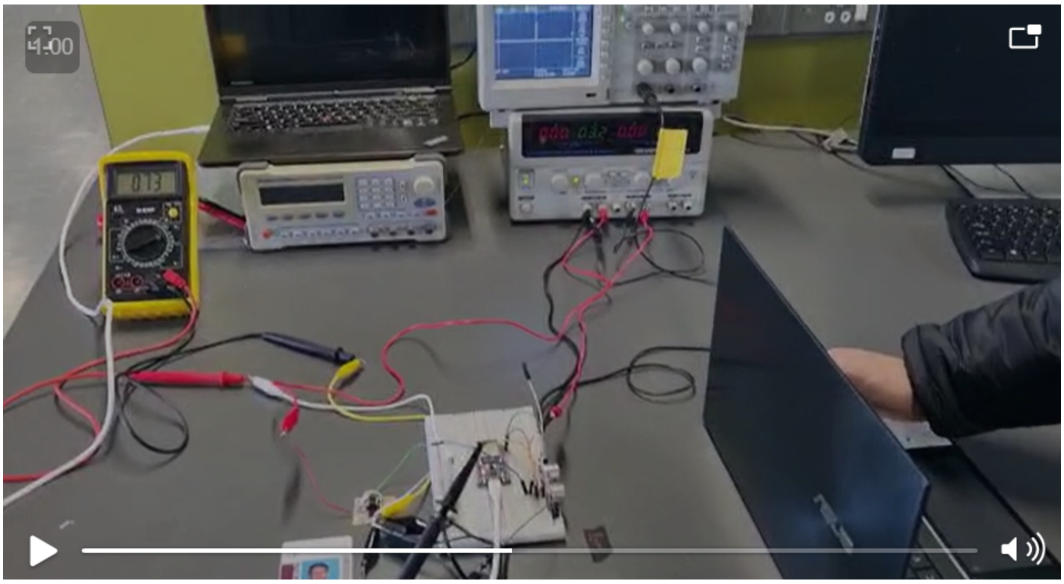


Figure 3.8: Voltage level at 10cm

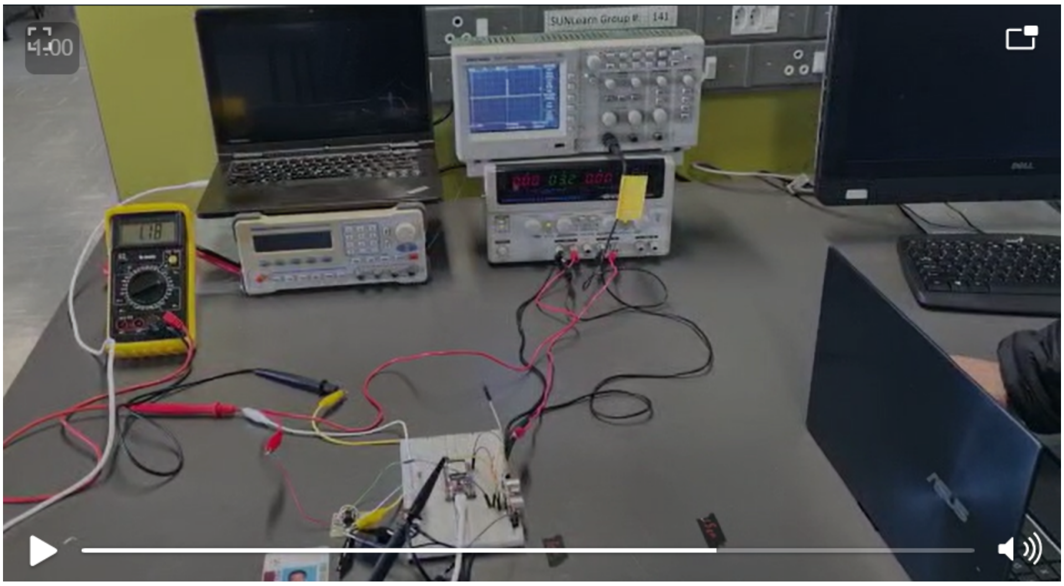


Figure 3.9: Voltage level at 30cm

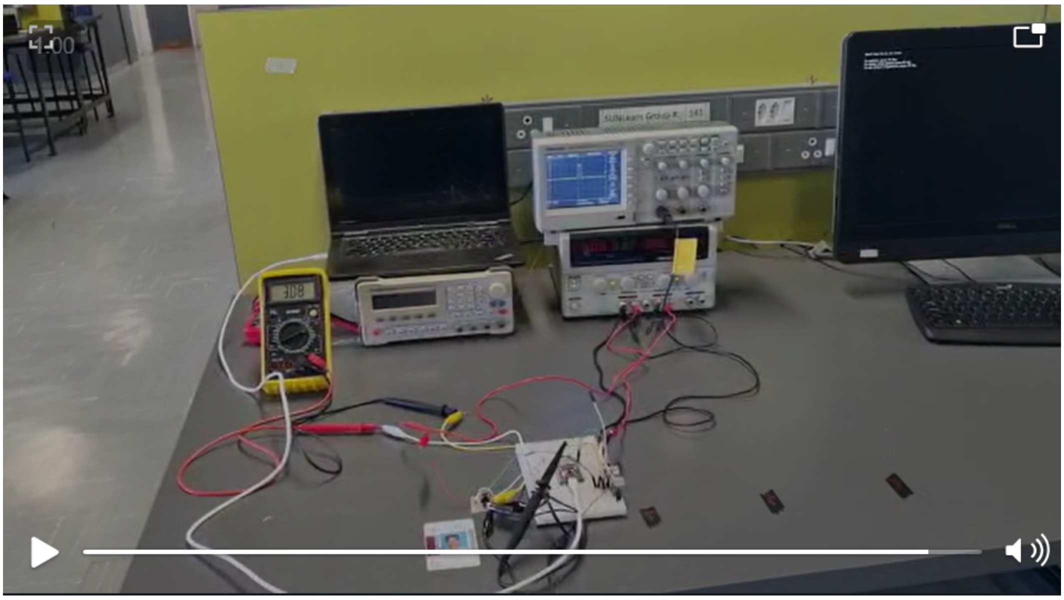


Figure 3.10: Voltage level at 1m

3.4. Digital to Analogue Converter Measurements

The circuit didn't meet all the requirements but it performed close to the specifications given. The results of the current consumption and spice simulations is shown in figure 3.11.

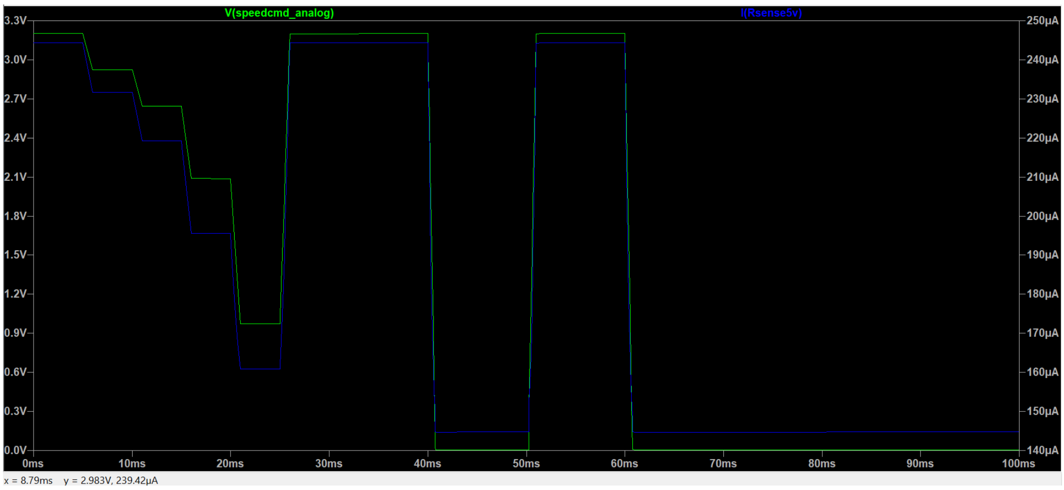
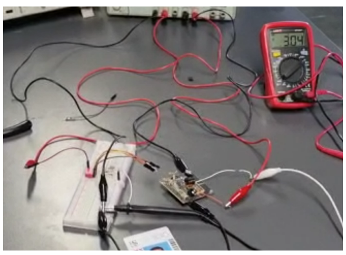
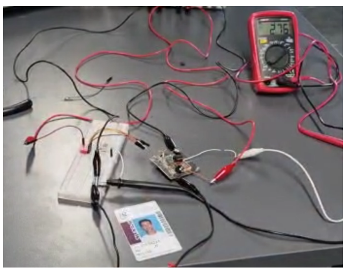


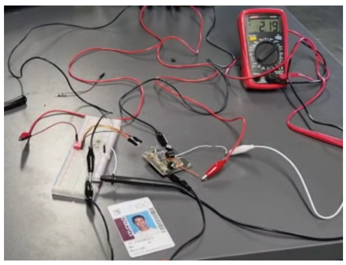
Figure 3.11: Current and voltage simulation



(a) Max voltage output

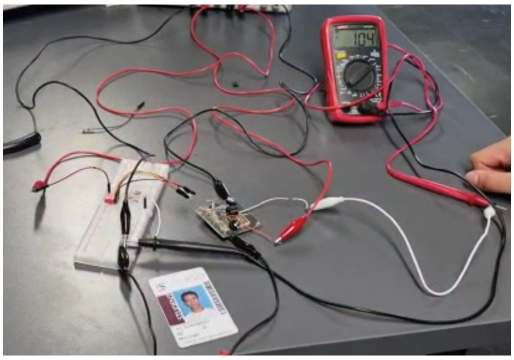


(b) Value at 1000

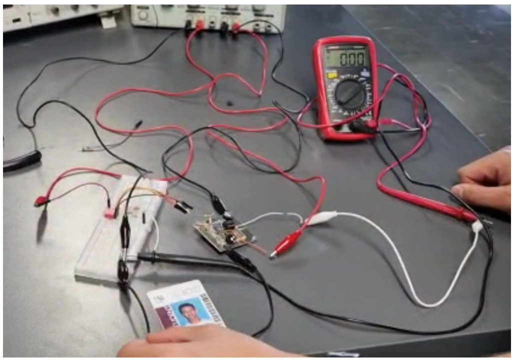


(c) Value at 1100

Figure 3.12



(a) Value at 1110



(b) Minimum voltage output

Figure 3.13: Voltages with different inputs

3.5. Left Wheel Control

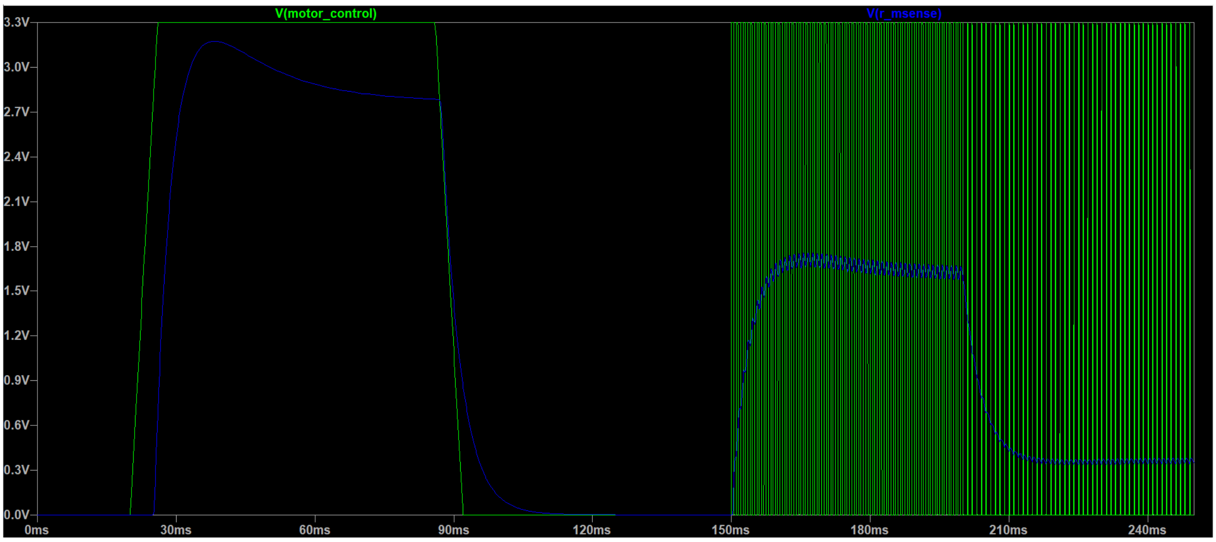


Figure 3.14: Low side Current sensor SPICE output

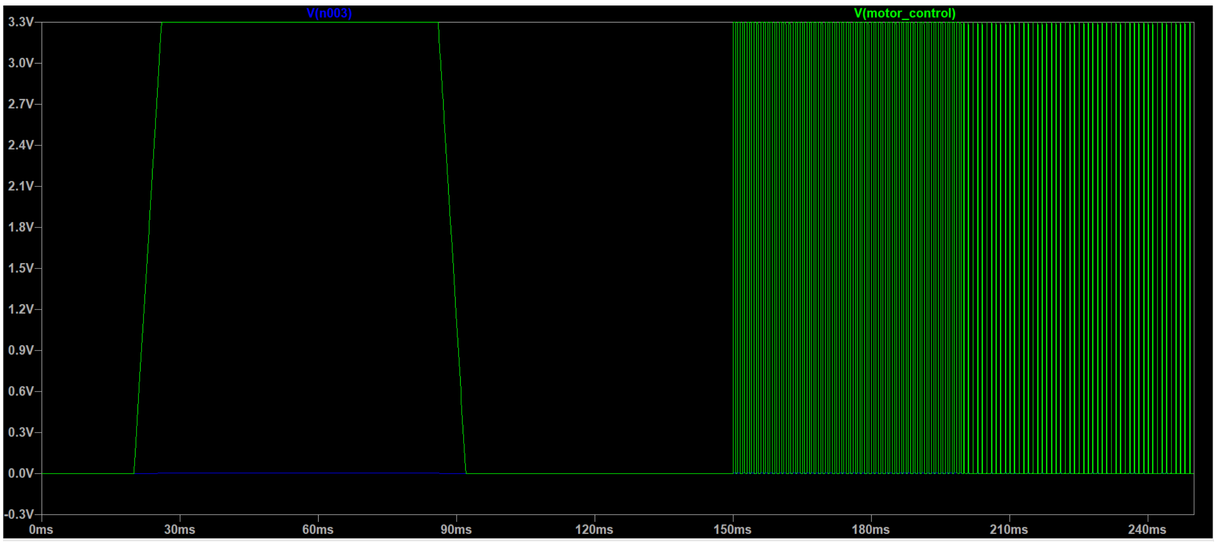


Figure 3.15: Motor Control

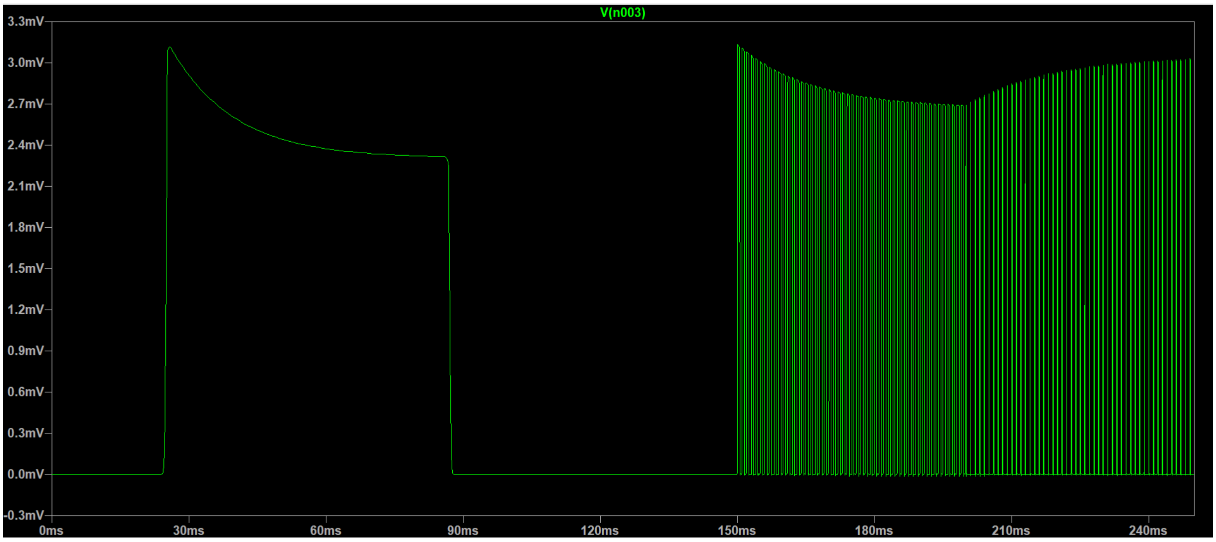


Figure 3.16: Simulated voltage at the source terminal

3.6. Battery

3.6.1. Battery Charger

Figure 3.17 shows the simulated results of the battery. The current is measured to be 420mA which is less than the 0.1C requirement. The voltage also peaks at 7.35V which matches the design.

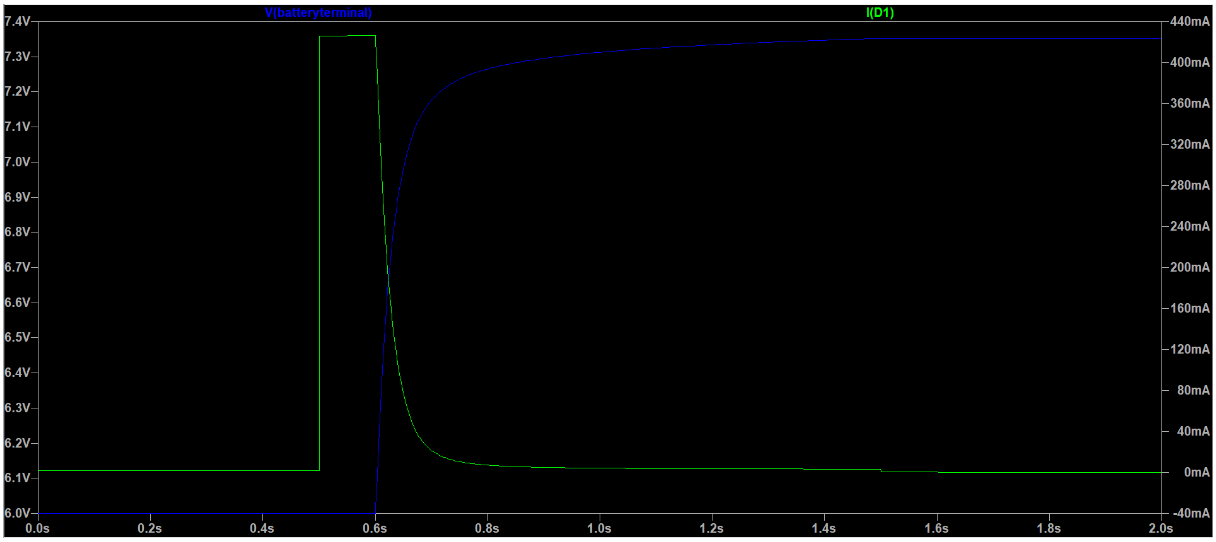


Figure 3.17: Simulated battery output circuit

3.6.2. Under-Voltage Protection

The simulated output of the Schmitt trigger is shown below. When the voltage is lower than 6V, the output is low and when it is above 6V it outputs a high.

(a) Battery Output with 1k Resistor

(b) Batteries Output with 50 Resistor

Figure 3.18: Battery Output with 50 Resistor

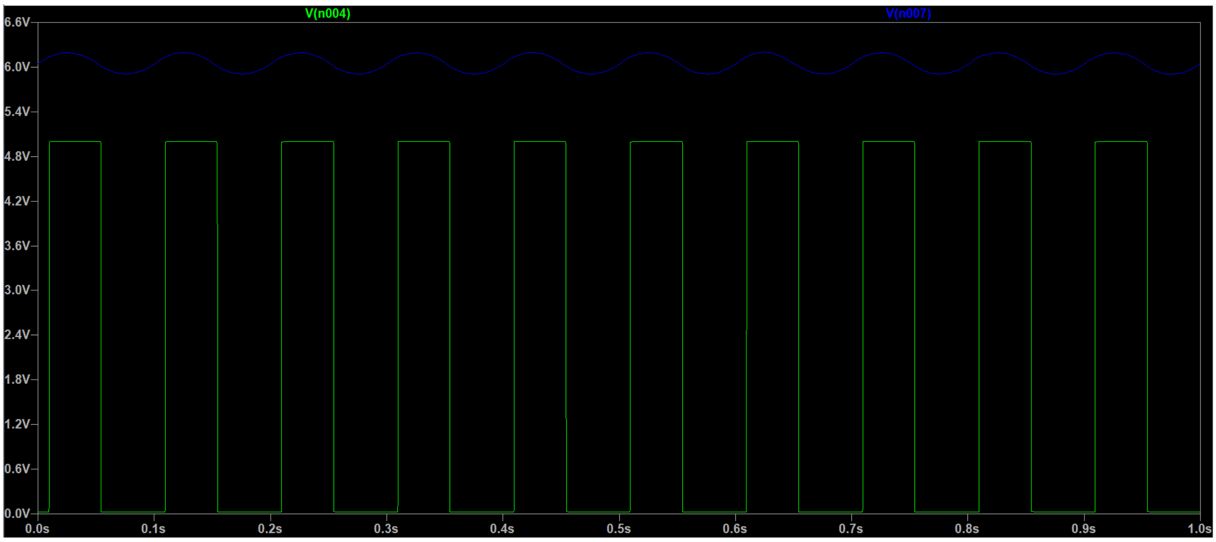


Figure 3.19: Simulated Schmitt Trigger

Bibliography

[1] L. A. Experts, "How does a lead acid battery work?" Sep 2021. [Online]. Available: https://batteryaccessories.net/blogs/news/how-does-a-lead-acid-battery-work

[2] "Complete guide on how to charge a lead acid battery," Mar 2021. [Online]. Available: https://www.power-sonic.com/blog/how-to-charge-a-lead-acid-battery/

Appendix A

Social contract

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E-design 344 Social Contract

2022

The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and a few paid helpers (Rita van der Walt, Keegan Hull, and Michael Ritchie) spent countless hours to prepare for E344 to ensure that you get your money's worth, that you are enabled to learn from the module, and demonstrate and be assessed on your skills. We commit to prepare the assignments, to set the assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

I, Daanyaal Mullah have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication online of supplementary videos on specific topics, I acknowledge that I am expected to attend the scheduled lectures to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Prof. MJ (Thinus) Booysen	Student number: 22898220
Signature: MJ Booysen (Digitally signed by MJ Booysen Date: 2022.07.02 13:22:09 +02'00')	Signature:
Date: 1 July 2022	Date: 31 July 2022

1

Appendix B

GitHub Activity Heatmap