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# 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 9, 2021

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# Nomenclature

### Variables and functions

| | |
|---|---|
| $A$ | Amperes: Measurement of current |
| $V$ | Volts: potential difference measurement |
| $V+$ | Positive supply voltage |
| $Vref$ | Reference voltage |
| $\Omega$ | Resistance |
| $R$ | Resistance |
| $mF$ | Micro Farads: measurement of capacitance |

## Acronyms and abbreviations

| | |
|---|---|
| MOSFET | Metal-oxide-semicondutor field-effect transistor |
| Fig. | Figure |
| LED | Light-emitting diode |
| pk-pk | Peak to peak amplitude measurement |
| Ah | Amp hours |
| Voc | Open-circuit voltage |
| Isc | Closed-circuit current |
| mA | Milli Amperes |

# Chapter 1

# Literature

## 1.1. Solar photovoltaic cells and solar modules

A solar PV cell is a cell that contains a material that conducts electricity, specifically a semi-conductor, through energy that is received through sunlight. When the semi-conductor is exposed to light, the semi-conductor absorbs that light and transfers the energy to electrons in the material which can now move freely to form an electric current by the voltaic effect. As long as sunlight is received, an external power source is not needed to induce an electric current. The efficiency at which a polycrystalline module operates ranges from 16% to 18%. This means that out of 100% of sunlight which is captured, only 18% is converted to electricity where the rest is wasted. Many PV cells together form a module. Our specific module seems to have 36 cells.

The open circuit voltage and short circuit current are important aspects to consider when doing circuit design. The Open Circuit voltage is the voltage over the terminals of the PV module when no current is being drawn but there is still radiance. The Short Circuit current is the current that the module can deliver when the 2 terminals are connected to each other. This can be seen in the figure:

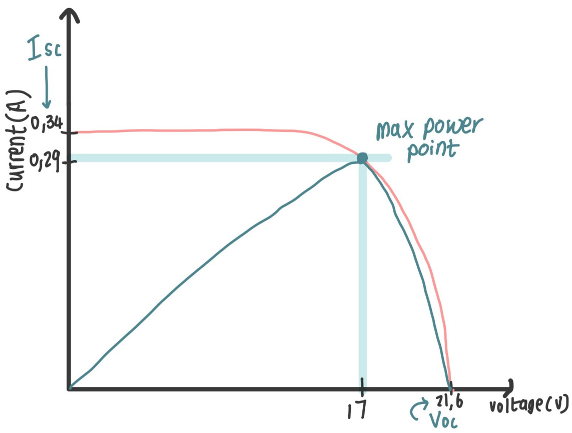



**Figure 1.1:** Relationship between the current delivered by our PV module and the voltage across its terminals. Voc and Isc can also be read from the graph. Max power point is also shown.

According to the datasheet, the Voc and Isc for our specific module is 21.6V and 340mA respectively. This is specifically for 25°C. As the the temperature increases, Voc decreases and Isc increases. This also means that if we have 36 cells, the Voc per cell is 0.6V.

The maximum power point of a PV module is the maximum amount of power which can be drawn from the PV module. This depends on the voltage and the current. To reach the maximum power point, one needs to manipulate the current and the voltage of the PV module. According to the datasheet [2], the maximum power point of our PV module is 5W. The required voltage and current to reach that point can be seen in Figure 1.1.

The Standard Test Conditions for solar module analysis are the industry standard under which all solar PV panels are tested for rated power. These conditions are as follow:

- Cell Temperature: 25°C
- Irradiance: 1000W/m$^2$
- Air mass:1.5 [3]

The rated output power of our solar PV module under STC is 5W according to the datasheet.

## 1.2. Lead-Acid Batteries

For this assignment, we will be using a lead acid battery. This is a battery that uses sponge lead and lead peroxide to convert chemical energy into electrical power. Most of the details about the battery are found either on the battery itself or on the data sheet. Our specific lead acid battery is rated at 6V which can be seen on the side of the battery. The battery also has an internal resistance of 45mΩ. Internal resistance is the resistance that is posed by the cells themself in the battery.

The battery is composed of 3 cells with a nominal voltage of 2V/cell. The capacity of this battery, which is found on the datasheet, is 4.0Ah@20hr-rate. This means that the battery is able to dissipate 200mA for 20 hours at 1.8V/cell. The reason that the capacity is is rating according to discharge rate and temperature is because these are the 2 biggest factors which affect how much voltage and current are available. This can be seen by looking at Figure 1.2, if all the current is dissipated in 1h at 1.8V, then only 2.8A will be dissipated. But if it's dissipated over 20 hours, then a total of 4A will be dissipated. Thus, it is much more efficient to dissipate current over several hours than dissipating all of it within one hour.

With regards to temperature, the temperature has an effect on the life expectancy of a battery and how much a battery will discharge on its own when stored over months. The higher the temperature, the lower the life expectancy and the higher the self-discharge rate.

**Constant Current Discharge Characteristics : A (25°C)** Amps

| F.V/Time | 5min | 10min | 15min | 20min | 30min | 45min | 1h | 2h | 3h | 4h | 5h | 6h | 8h | 10h | 20h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.85V/cell | 7.68 | 5.35 | 4.42 | 3.83 | 3.07 | 2.36 | 1.93 | 1.18 | 0.899 | 0.739 | 0.627 | 0.543 | 0.432 | 0.359 | 0.198 |
| 1.80V/cell | 9.44 | 6.39 | 5.12 | 4.33 | 3.40 | 2.58 | 2.08 | 1.25 | 0.945 | 0.777 | 0.654 | 0.567 | 0.448 | 0.372 | 0.200 |
| 1.75V/cell | 11.2 | 7.22 | 5.65 | 4.72 | 3.63 | 2.74 | 2.19 | 1.31 | 0.979 | 0.801 | 0.672 | 0.581 | 0.460 | 0.379 | 0.202 |
| 1.70V/cell | 12.7 | 7.97 | 6.11 | 5.06 | 3.82 | 2.84 | 2.28 | 1.36 | 1.01 | 0.821 | 0.689 | 0.595 | 0.467 | 0.386 | 0.206 |
| 1.65V/cell | 14.0 | 8.57 | 6.46 | 5.32 | 3.98 | 2.95 | 2.38 | 1.40 | 1.04 | 0.838 | 0.704 | 0.607 | 0.475 | 0.391 | 0.208 |
| 1.60V/cell | 14.7 | 8.93 | 6.74 | 5.48 | 4.09 | 3.02 | 2.43 | 1.45 | 1.06 | 0.859 | 0.718 | 0.619 | 0.485 | 0.398 | 0.210 |

**Figure 1.2:** Constant current Discharge Characteristics at 25°C : A [4]

To calculate the capacity of the battery in Wh, one must look at Figure 1.3 which is from the datasheet. Using the advertised capacity which is at 1,8V/cell, it can be seen that 0.402W can be dissipated per hour over 20 hours. Thus, the rated capacity in Wh will be 0.402x20hours which is 8Wh.

**Constant Power Discharge Characteristics : W (25°C)** Watts

| F.V/Time | 5min | 10min | 15min | 20min | 30min | 45min | 1h | 2h | 3h | 4h | 5h | 6h | 8h | 10h | 20h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.85V/cell | 14.5 | 10.2 | 8.49 | 7.42 | 5.99 | 4.63 | 3.81 | 2.34 | 1.79 | 1.47 | 1.26 | 1.09 | 0.869 | 0.724 | 0.400 |
| 1.80V/cell | 17.6 | 12.0 | 9.76 | 8.33 | 6.59 | 5.02 | 4.07 | 2.47 | 1.87 | 1.54 | 1.30 | 1.13 | 0.896 | 0.745 | 0.402 |
| 1.75V/cell | 20.6 | 13.5 | 10.7 | 9.00 | 6.99 | 5.30 | 4.26 | 2.56 | 1.92 | 1.58 | 1.33 | 1.15 | 0.914 | 0.755 | 0.403 |
| 1.70V/cell | 23.1 | 14.7 | 11.4 | 9.59 | 7.29 | 5.47 | 4.42 | 2.65 | 1.97 | 1.61 | 1.35 | 1.17 | 0.922 | 0.763 | 0.408 |
| 1.65V/cell | 25.1 | 15.6 | 12.0 | 9.96 | 7.53 | 5.65 | 4.57 | 2.71 | 2.01 | 1.63 | 1.38 | 1.19 | 0.933 | 0.770 | 0.412 |
| 1.60V/cell | 26.0 | 16.1 | 12.3 | 10.2 | 7.67 | 5.72 | 4.64 | 2.78 | 2.05 | 1.66 | 1.40 | 1.21 | 0.947 | 0.779 | 0.412 |

**Figure 1.3:** Constant Power Discharge Characteristics at 25°C : W [4]

The measured voltage over the battery is 6.39V, this corresponds closely to the theoretical voltage. The voltage after connecting a load will be slightly different. The voltage will decrease as there will be a voltage drop over the load.

## 1.3. Fuses

A fuse is a device used to protect a device from dangerous levels of current. The current that flows through a conductor's nonzero resistance creates a power dissipation in the form of heat. If the combination of the current's amplitude and duration is enough to raise the temperature above the fuse's melting point, then it becomes an open circuit and current can no longer flow. Each fuse has a set current threshold. [5]

# Chapter 2

# System Design

## 2.1. Charging Circuit Overview

The charging circuit is designed to limit the current and the voltage that is used to charged the battery. It uses an adjustable voltage regulator because we want the current being delivered to the battery to come to a stop when the voltage at the output reaches saturation so that the battery is not damaged. The charging circuit will be placed in between the source voltage (voltage from the AC/DC adapter and from the PV module) and the high-side switch so that the output of the regulator can be turned on and off. This can be seen in diagram 2.1.

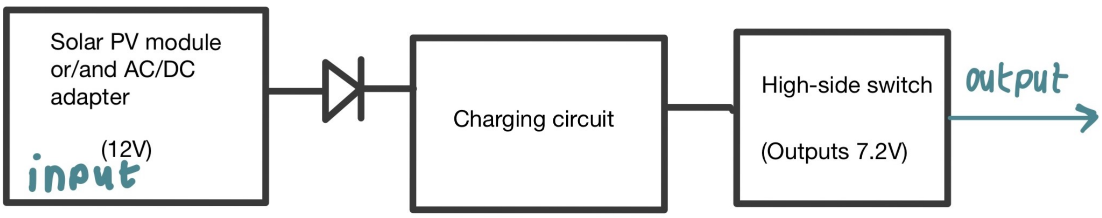



**Figure 2.1:** Overview block diagram of the system for A2

## 2.2. Undervoltage Protection Overview

The undervoltage protection circuit consists of 2 main components: A Shmidt trigger which doubles as a comparator constructed of op-amps and a high-side switch constucted of a pmos MOSFET, keeping in mind that the entire circuit is bidirectional to allow the battery to wither charge or discharge. This layout can be seen in the figure below.

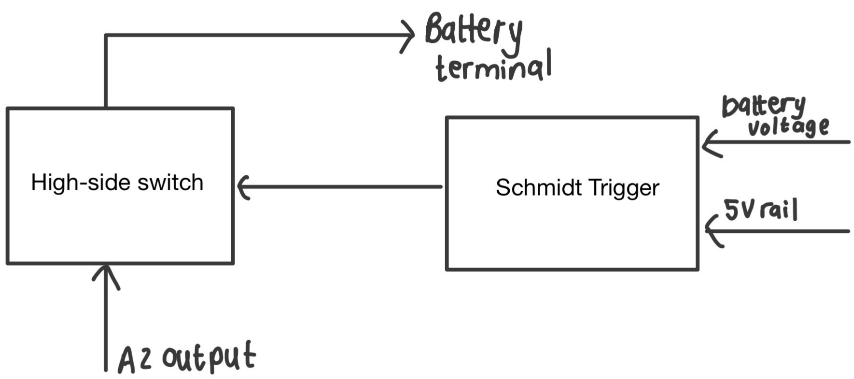



**Figure 2.2:** Block diagram of the undervoltage protection circuit

## 2.3. Bidirectional Current Measuring Circuit Overview

The position of the current sensing circuit relative to the rest of the circuit can be seen in figure 2.3. The current from the High-side switch and the current from the undervoltage protection enter the current sensing circuit making the current sensing circuit bi-directional.

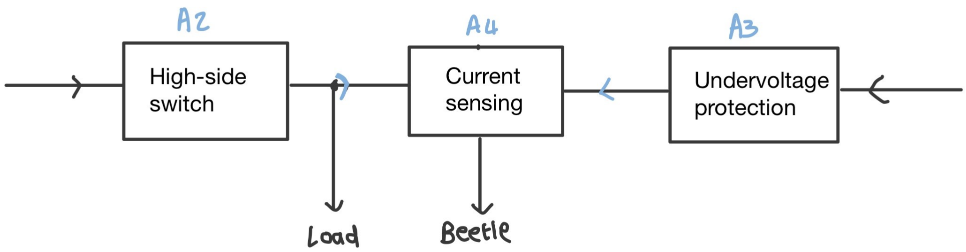



**Figure 2.3:** Current sensing circuit relative to the rest of the circuit.

# Chapter 3

# Detail Design

## 3.1. Voltage Regulation

The voltage regulator needs to be able to output a maximum voltage of 7.2V and a maximum current of 400mA, which is explained in the literature part of the report. I used the circuit diagram named "Battery Charger" on the data sheet [1] as a guide. Then I used a combination of circuit analysis and a formula that I found on the datasheet to calculate the resistor values. These calculations and values can be found in figure 3.2 and 3.3.

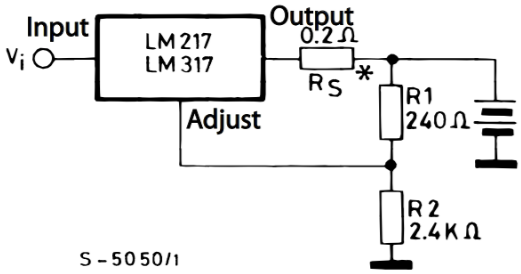



**Figure 3.1:** Battery Charging Circuit. [1]

$$V_0 = V_{ref}(1 + R_2/R_1) + i_{adj} \cdot R_2$$
$$7{,}2 = 1{,}25(1 + R_2/R_1)$$
$$R_2/R_1 = 4{,}76$$
$$\text{Let } R_1 = 240\Omega$$
$$\therefore R_2 = 1142{,}4\Omega$$

**Figure 3.2:** Calculation of R2 using formula from datasheet [1]

### 3.1.1. Current limit

The battery charger needs a current limit because if the current that is being delivered to the battery is too high, the battery will be permanently damaged as the chemistry inside the battery will be altered. The limit that I found for the battery can be derived from figure 3.1. The datasheet [4] specifies that the battery should be charged at 0.1C until the voltage

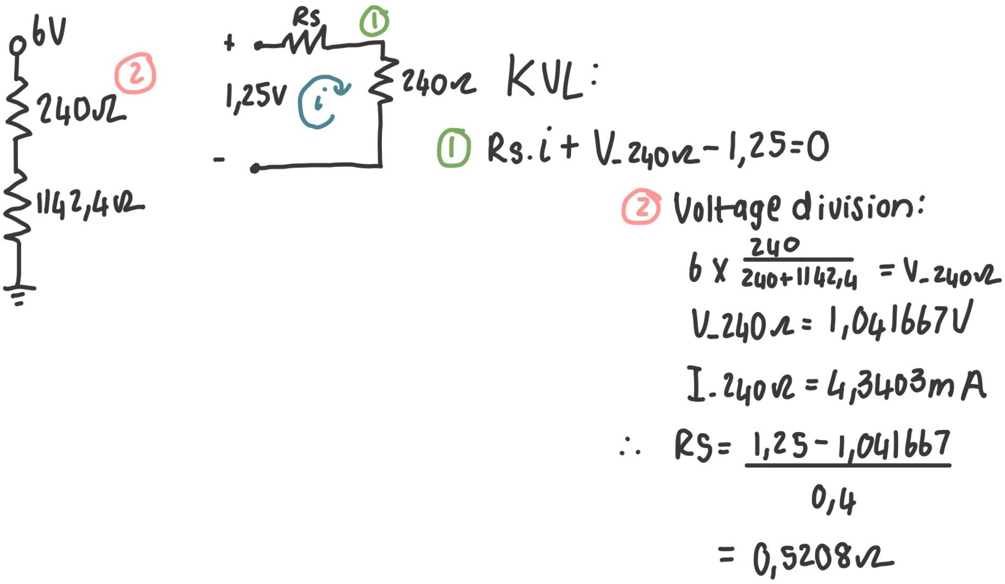



**Figure 3.3:** Circuit analysis calculation of Rs.

reaches 7.2V. This means that 0.1 of the 4Ah per hour should be the maximum charging current. This works out to 400mA. To design for this current I used circuit analysis and kept in mind that the current going into the battery charger is almost equal to the current exiting the battery charger.

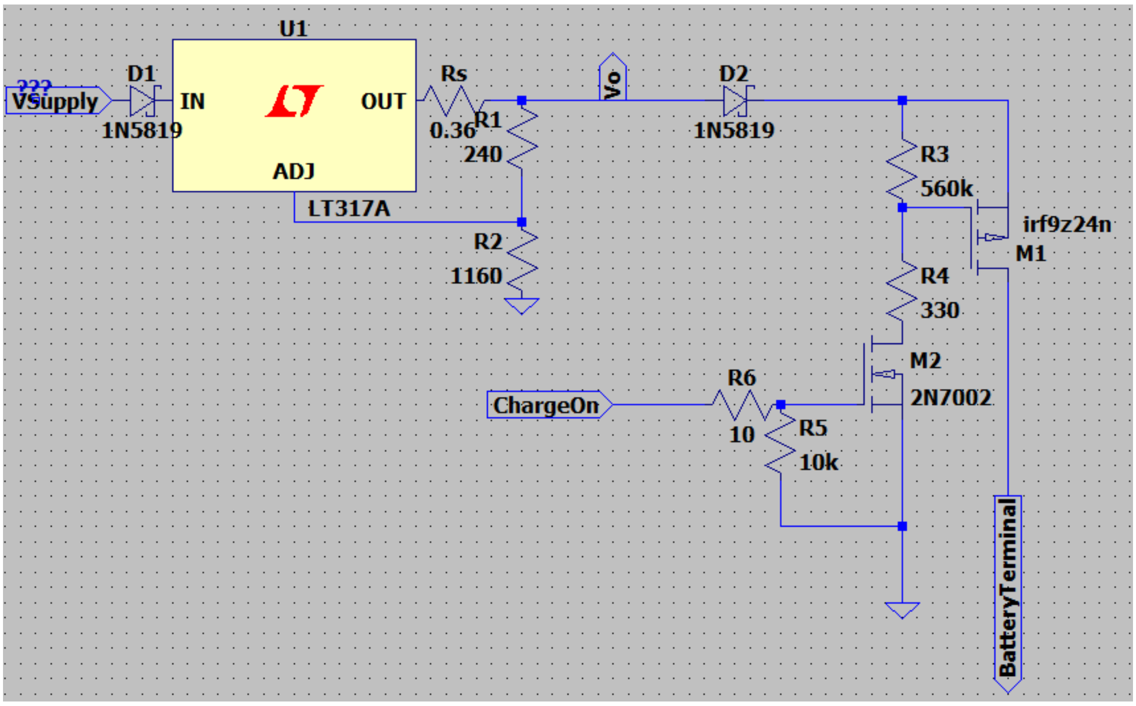



**Figure 3.4:** LTSpice assignment 2 circuit

### 3.1.2. Thermal analysis

Using a heatsink lowers the overall temperature of the regulator and in turn improves the performance of the regulator. According to the datasheet [1], if the temperature of the junction overheats, the reference voltage decreases drastically and the voltage drop over the regulator becomes nonlinear. This makes it very difficult to use mathematical concepts to design for the required output voltage and current.

## 3.2. High side Switch on Supply side

The high side switch that I designed uses a PMOS and NMOS MOSFET. The aim of the design is to have a switch which takes an input that will be read as either a logical high or a logical low, then it allows there to be an output based on whether the switch is on or off. The switch is then used to control when the battery is charging.

I found a template of a high side switch [6] which used a P-MOSFET as the high side switch and the N-MOSFET as the driver. I then simulated and chose my own resistor values. The final circuit can be seen in the figure below:

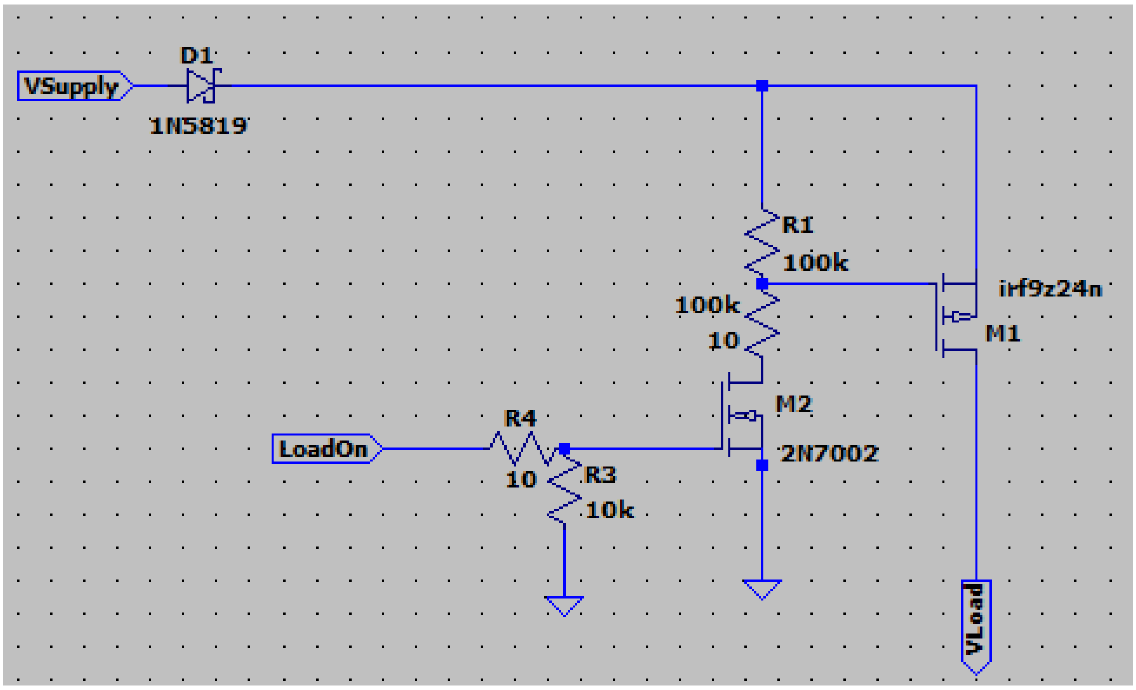



**Figure 3.5:** High-side switch circuit diagram

## 3.3. Under Voltage Protection

### 3.3.1. 5V rail

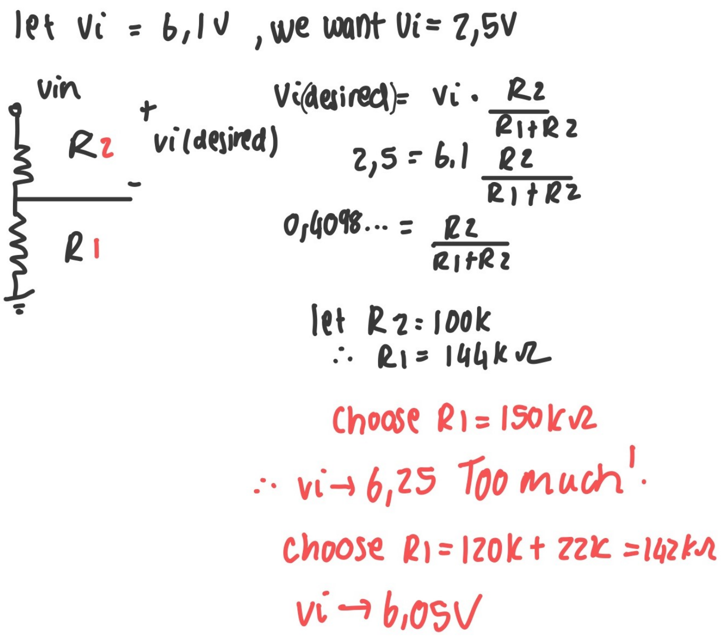
For voltage regulation, I chose to use the LM2940 regulator as opposed to the LM7805 regulator as the former only needs 6V input to work where as the latter needs 7V as input. This makes the LM2940 more suitable for a wider range of input voltages. This then produces a 5V rail which is optimal to power all the OP-AMPS and to use to construct a reference voltage of 2.5V. The LM2940 has a max current which it can withstand when outputting 5V of 20mA. [7] Thus, it is sensible to try designing for a current of less than 10mA to be sure that the device will not fail.

### 3.3.2. High-side switch

When designing the switch, I decided to use only a pmos MOSFET for simplicity. This works because the IRF9Z24NPbF pmos MOSFET has a threshold voltage of between -2V and -4V. [8] If the MOSFET is inverted, then the signal being fed into the MOSFET (the digital 5 or 0V) will have a clear 'ON' for the OV and 'OFF' for the 5V. This is keeping in mind that I used an inverting Schmidt trigger, so the signal logical 'on' and 'off' are inverse. This means that after the comparator/Schmidt trigger has checked if the voltage from the battery terminal is above 6.2V or below 6V, a digital signal is sent to the switch which then either allows the battery to discharge or not to discharge. The battery should discharge if the voltage at the battery terminal is above 6.2V or below 6V.

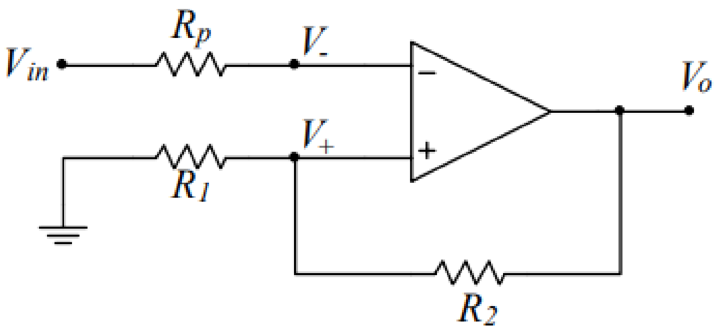
### 3.3.3. Voltage monitoring with hysteresis design

The purpose of the comparator is to compare the voltage of the battery to a reference voltage. The 5V rail is fed into the + terminal of the op amp and using 2 identical resistors (which are chosen high enough to limit the current) to scale it down to 2.5V. The voltage from the battery terminal then needs to be scaled down to 2.5 volts to be compared. If the voltage is less than 2.5V, the output hits the ground rail and if the input voltage is more than 2.5V, the output hits the 5V rail. This then outputs a perfect digital signal. The calculations can be seen in the figure below. The purpose of the Schmidt trigger is to implement hysteresis. Hysteresis is needed when there is a transition from low to in between high and low and we want the state of the battery to stay in the current state until it it fully high. Visa versa from high to low. This is done using a positive feedback with a resistor. A voltage follower is needed to correct the output as the feedback resistor alters the output a bit. I used this example of an inverting Shmidt trigger in the figure below and calculated R2 to be 25 times larger than R1 and I found in spice that they need to be large but also not too large so I settled on choosing R1=5kΩ and R2=150kΩ.




[9]

**Figure 3.6:** Comparator resistor calculations




[9]

**Figure 3.7:** Schmidt trigger design

### 3.3.4. Circuit diagram

## 3.4. Current Sense

### 3.4.1. Design

The objective of the current sensing circuit is output an analogue voltage that represents the current flowing to and from the battery. The current to the battery is a maximum of 450mA and from the battery is 150mA. A reference voltage is needed to shift the output voltage so that the entire voltage is positive. This makes it easier to observe. The calculation of the reference voltage can be seen in figure 3.10.

The resultant output swing is to be 3V centered at 2.5V. To suppress noise I am using a 4.7uF capacitor as I decided passive filtration is easier to implement than active filtration. I never designed the circuit, I simply implemented it in spice and played around with the

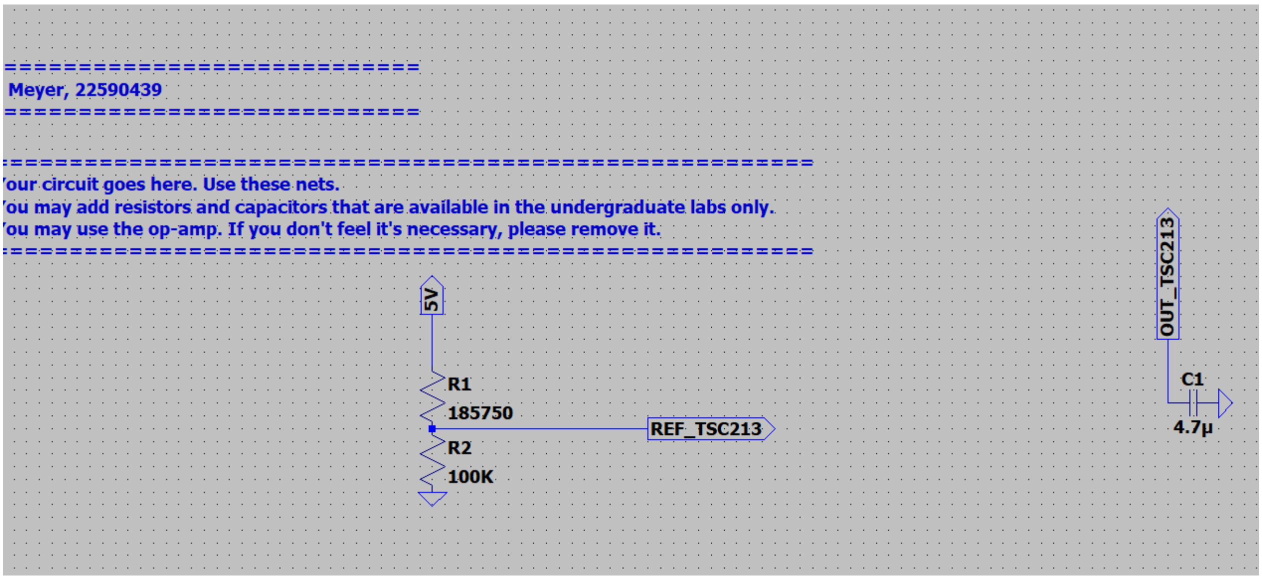



**Figure 3.8:** Spice diagram

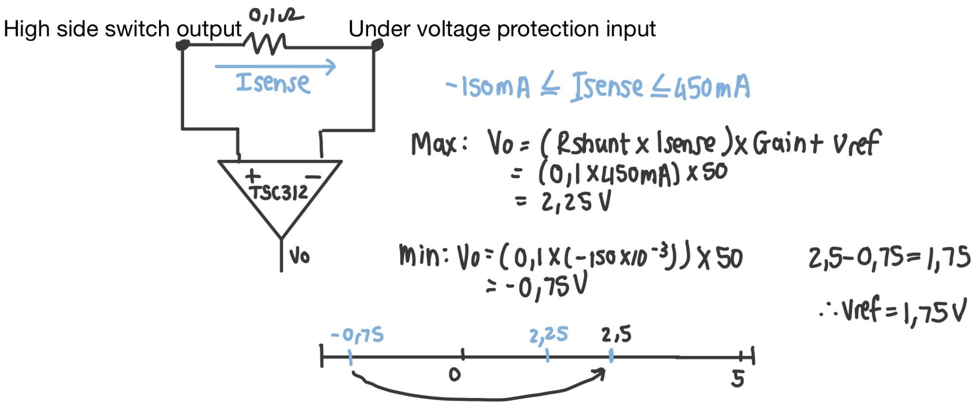



**Figure 3.9:** Calculation of Vref [?]

capacitor value until the noise on the output was less than 2mV pk-pk.

## 3.4.2. Circuit diagram

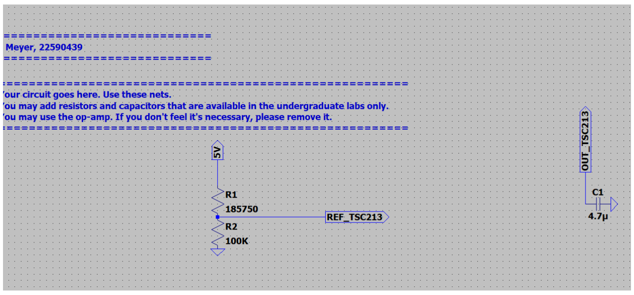


**Figure 3.10:** Spice diagram that was submitted

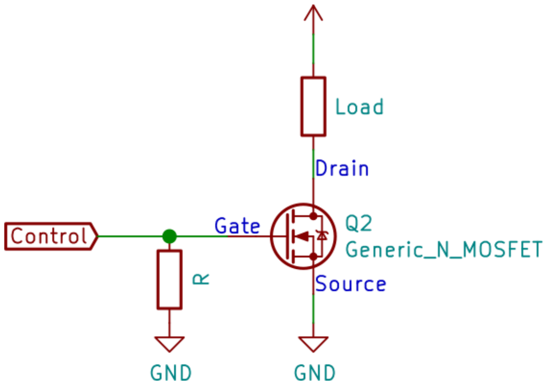



**Figure 3.11:** Lowside switch configuration
[11]

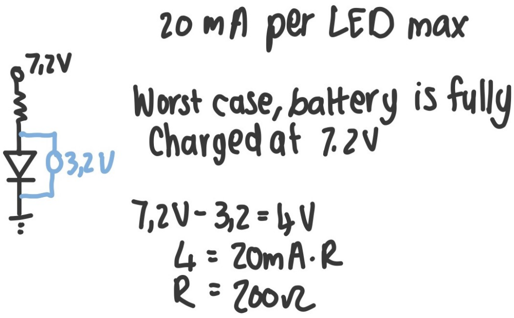



**Figure 3.12:** LED resistor calculations

## 3.5. Low-side Switch

When the MOSFET is connected to ground, the load is between V+ and the MOSFET, in our case V+ will be the signal coming from the A2 output and the signal entering the Bidirectional current sensing circuit. This makes the switch a lowside switch.

We are using an NMOS MOSFET as it has a typical threshold voltage of 2.1V [10]. This is perfect for the lowside switch as the control signal that we'll be using is a logical 0V or 5V.

I based my design off figure 1.1. I chose the pull down resistor to be 100kΩ. The digital 5 or 0V signal is inputted at the gate. The drain is connected to the negative side of the parallel LEDs and the positive side of the LEDS is connected to the signal that does to the load from the battery/power source.. The source of the transistor is connected to ground.

# Chapter 4

# Subsystem (Results)

## 4.1. Voltage Regulation

### 4.1.1. Simulation results

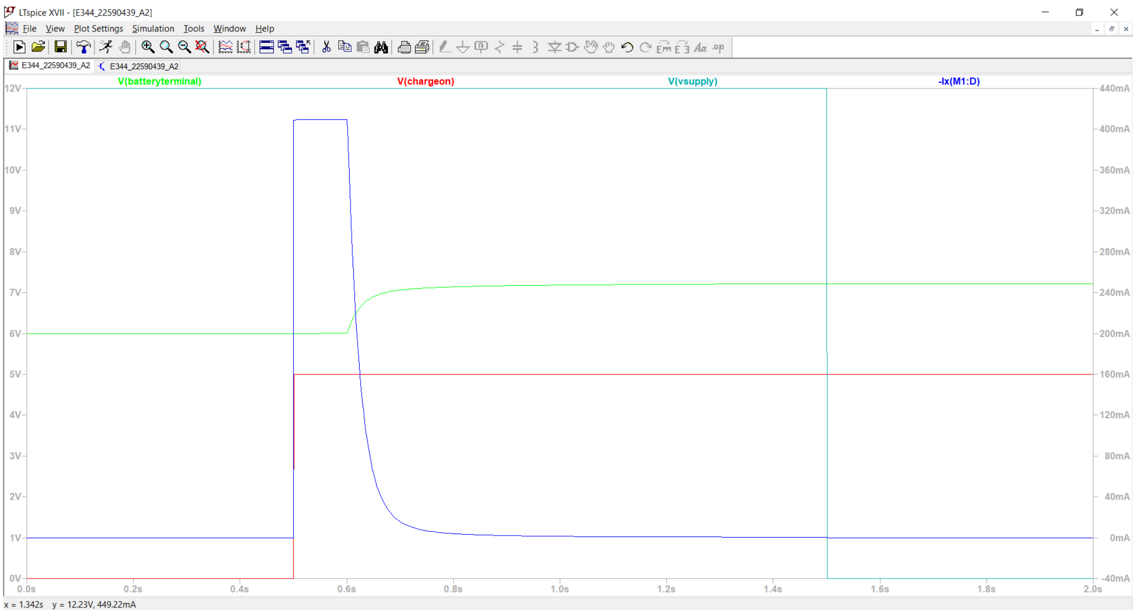



**Figure 4.1:** LTSpice assignment 2 circuit results

After building the circuit in LTSpice, the output did not behave exactly as it was designed, so I had to tweek the resistances. As it can be seen in the circuit diagram in figure 2.5, I had to lower Rs and increase R2 to get the desired output.

The output in figure 3.1 shows that when the switch has a digital-high signal applied to it, then the output current spikes and reaches its maximum, and quickly jumps back to zero. The voltage does the inverse and so the open circuit voltage and the closed-circuit current can be seen. The simulation shows that the design is ready to build because the current is limited to 400mA.

### 4.1.2. Measured results

After implementing the circuit and taking measurements, the open-circuit voltage was very close to what it should be, off by 0,07V. This is because of the tolerance of the resistors. This should still be acceptable and considered a successful design and implementation. The voltage drops when a load is added, which is expected.


**Figure 4.2:** Voltage reading over a 1k ohm resistor.


**Figure 4.3:** Voltage reading over a 10K ohm resistor.

## 4.2. High Side Switch on Supply side

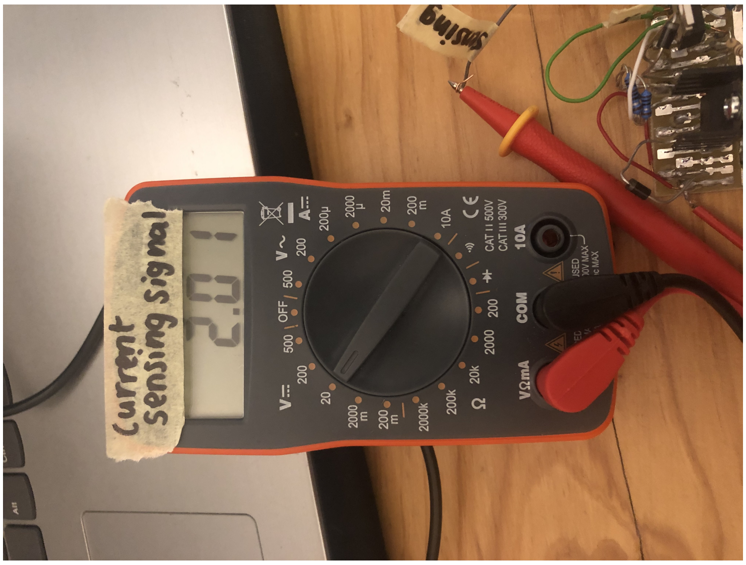



**Figure 4.4:** High-side Switch Spice Output

It can be seen from the figure above that the switch works as designed. When the control signal (Vloadon) goes from a low to a high, the voltage from the input (vload) goes high and stays high, even when the supply voltage goes low.

The physical results can be seen in the voltage regulation results as the switch was only implemented in A2.

## 4.3. Current sense

### 4.3.1. Results

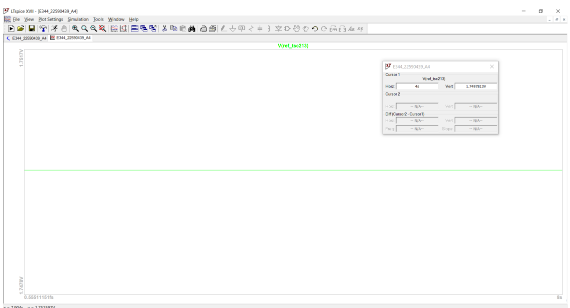


**Figure 4.5:** Correct reference voltage implementation
[11]

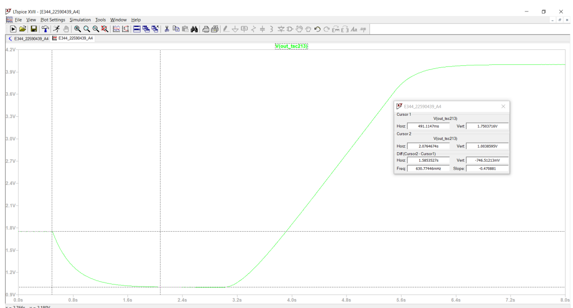


**Figure 4.6:** Correct output voltage shifted by Vref

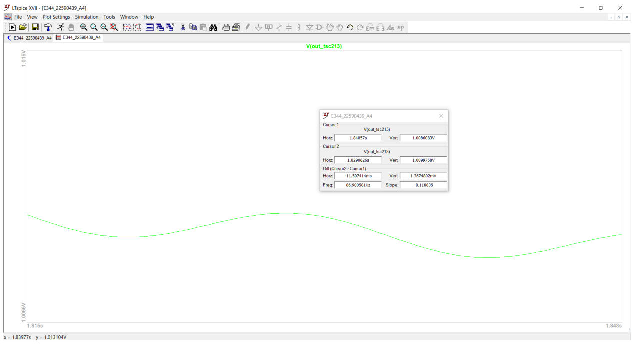


**Figure 4.7:** Sense resistor noise of lass than 2mV pk-pk


**Figure 4.8:** Current sensing voltage when neither the battery nor the source current switches are open

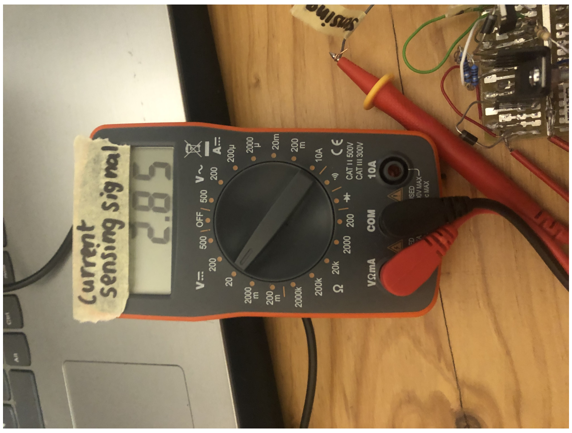



**Figure 4.9:** Current sensing voltage when battery switch is open, but source switch is closed


**Figure 4.10:** Current sensing voltage when both battery and source are connected

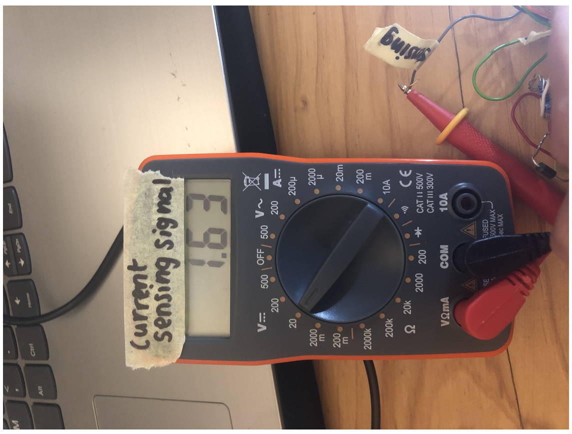



**Figure 4.11:** Current sensing voltage when just the battery is connected

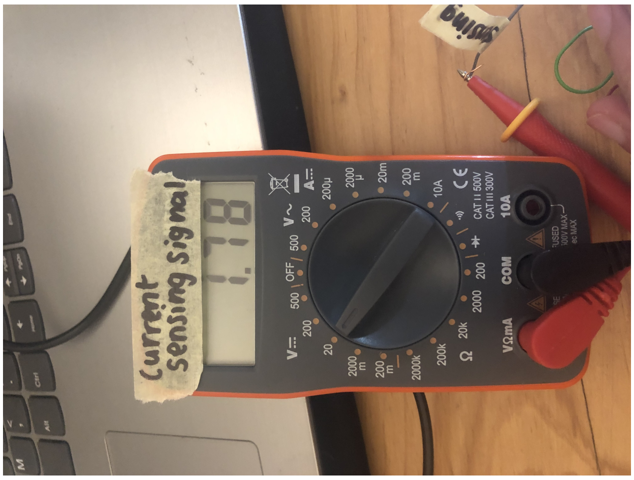



**Figure 4.12:** Current sensing voltage when 3 LEDs are connnected

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# Appendix A

# Social contract

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E-design 344 Social Contract

2021

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 the Teaching Assistant (Kurt Coetzer) spent countless hours to prepare for E344 to ensure that you get your money's worth and 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 tests and 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, Jay-Dee Meyer 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 Booysen | Student number: 22590439 |
| Signature: Digitally signed by MJ BOOYSEN Date: 2021.08.04 22:12:45 +02'00' | Signature: Jmeyer |
| Date: 4 Aug 2021 | Date: 11 August 2021 |

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# Appendix B

# GitHub Activity Heatmap