UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

E344 Assignment 7

Abraham Albertus Cilliers

23252162

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.

October 10, 2021

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

Plagiaatverklaring / *Plagiarism Declaration*

1. Plagiaat is die oorneem en gebruik van die idees, materiaal en ander intellektuele eiendom van ander persone asof dit jou eie werk is.
Plagiarism is the use of ideas, material and other intellectual property of another's work and to present is as my own.

2. Ek erken dat die pleeg van plagiaat 'n strafbare oortreding is aangesien dit 'n vorm van diefstal is.
I agree that plagiarism is a punishable offence because it constitutes theft.

3. Ek verstaan ook dat direkte vertalings plagiaat is.
I also understand that direct translations are plagiarism.

4. Dienooreenkomstig is alle aanhalings en bydraes vanuit enige bron (ingesluit die internet) volledig verwys (erken). Ek erken dat die woordelikse aanhaal van teks sonder aanhalingstekens (selfs al word die bron volledig erken) plagiaat is.
Accordingly all quotations and contributions from any source whatsoever (including the internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism

5. Ek verklaar dat die werk in hierdie skryfstuk vervat, behalwe waar anders aangedui, my eie oorspronklike werk is en dat ek dit nie vantevore in die geheel of gedeeltelik ingehandig het vir bepunting in hierdie module/werkstuk of 'n ander module/werkstuk nie.
I declare that the work contained in this assignment, except where otherwise stated, is my original work and that I have not previously (in its entirety or in part) submitted it for grading in this module/assignment or another module/assignment.

23252162 Studentenommer / *Student number*	Cilliers Handtekening / *Signature*
AA. Cilliers Voorletters en van / *Initials and surname*	October 10, 2021 Datum / *Date*

Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

V_{out}	Output Voltage
R_{sense}	Current Sensing Resistor
I_{load}	Load Current
V_{ref}	Reference Voltage
T_j	Junction Temperature
T_{amb}	Ambient Temperature

Acronyms and abbreviations

MOSFET	Metal Oxide Semiconductor Field Effect Transistors
LED	light-emitting diode
Op Amp	Operational Amplifier
PV	Photovoltaic
OC	Open Circuit
NEC	National Electrical Code
STC	Standard Test Conditions
Ah	Amp Hour
Wh	Watt Hour
CCCV	Constant Current Constant Voltage
DoD	Depth of Discharge
IC	Integrated Circuit
ADC	analogue-to-digital converter
LDR	Light Dependent Resistor

Chapter 1

Literature

1.1. Solar photovoltaic cells and solar modules

Photovoltaic (PV) technology uses a natural source of energy in the form of sunlight and coverts the sunlight into electrical energy. One PV device is called a cell, and are made from semiconductor materials such as silicon. These cells are quite small and only produce around 1-2 watts. In order to increase the power output several cells are connected together to form a module [7] [8]. Ovear the years the efficiency of solar PV modules have greatly improved, however polycrystalline PV modules which are going to be used in this project are not the most efficient type of PV module. Their efficiency is around 13-16% according to an article by Geotherm [9], however a practical study found it to be closer to 11% [10].

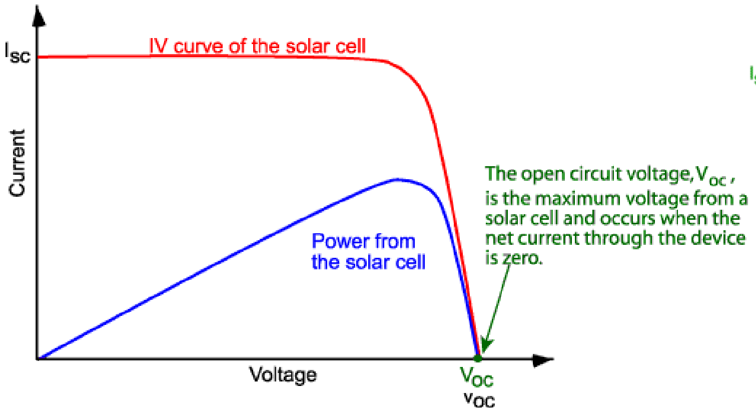
A PV module's performance is judged by its current–voltage (I–V) characteristic curve. As seen in figure 1.1a and figure 1.1b a few interesting points can be seen on the figures, namely the Open Circuit (OC) voltage and the Short Circuit (SC) Current. The open circuit voltage can be defined as the maximum available voltage from one solar cell when no load is connected (this occurs at 0 current). The OC voltage is useful when you want to calculate how many solar modules(panels) you can connect in series which will connect to your inverter or charge controller. SC Current is how much current the solar cell is pulling when the voltage across the cell is 0, this can be measured when the positive and negative terminals are connected directly to each other. This SC current will be the maximum amount of amps that the solar cell will produce and can be used to determine how many amps connected devices can handle by multiplying with a 1.25 times scaling factor according to National Electrical Code (NEC) 80% requirements [11]. Typically a single PV cell has an OC voltage of around 0.5V to 0.7V at room temperature (25°C) [12].

As shown in figure 1.2 the voltage increases and the current stays the same until a certain point. If you have too high a voltage the current will drastically drop, because of this there is a certain sweet spot where the optimal amount of power can be produced, this is called the maximum power point. The maximum power point is where the product of volts x amps gives the highest wattage possible. $P_{mpp} = V_{mpp}I_{mpp}$

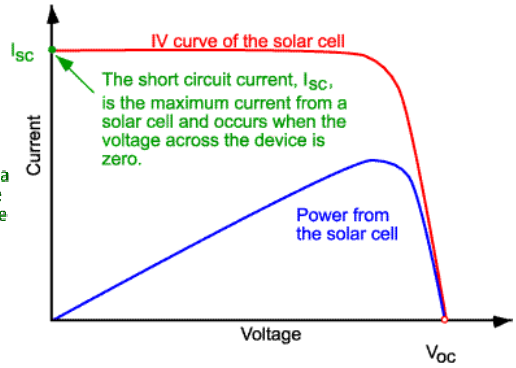
The solar module provided to us has a OC voltage of 21.6V and a SC current of 0.34A according to the ACDC Dynamics datasheet [13]. It appears to have 36 individual solar cells.

Solar PV modules are tested at a certain set of standard conditions because voltage and current varies with temperature. This set of criteria are called the Standard Test Conditions

(STC), these conditions are: the cell's temperature at 25°C, an irradiance of 1000 W/m² and the atmospheric density to be 1.5 [11]. At STC conditions the solar PV module provided to us has a rated power output of 5W. Table 1.1 shows some measurements of our PV module under certain test conditions.



(a) OC Voltage of Solar Cell [14]



(b) SC Current of Solar Cell [15]

Figure 1.1: OC Voltage and SC Current of Solar Cell

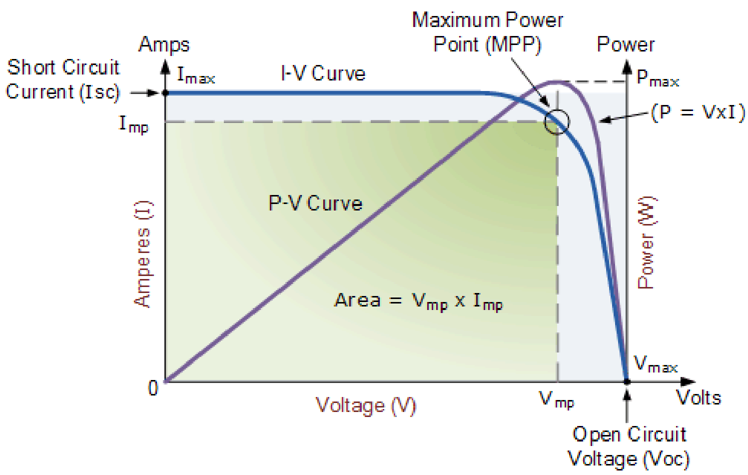


Figure 1.2: Relationship between Current and Voltage Characteristics [1]

Table 1.1: V_{OC}[V] and I_{SC} of PV module under certain test conditions

Test Condition	V_{OC}[V]	I_{SC}[mA]
Dark	0.0006	0
Upside down with sun on back	14.36	2.52
Ambient light indoors	12.46	2.32
Oblique sunlight	19.78	23.8
Perpendicular sunlight	21.8	260

1.2. Lead acid batteries

Lead acid batteries are the most common battery type that is used in PV solar systems. They are low cost, have a very long lifetime and have well documented and researched technology for recharging [16]. Batteries are given a rating based on the nominal voltage of the battery, in the case of the lead acid battery provided to us it is rated at 6V. A lead acid battery is constructed of a few individual cells connected in series. The nominal voltage of a single cell is 2V, thus our battery has a total of 3 cells. The most common way to measure the storage capacity of a battery is in amp hours (Ah), which is define as the total number of hours at which a battery can provide the same amount of current equal to the discharge rate at the nominal voltage of the battery [17]. However, there is another measure called watt hour (Wh), which is determined by multiplying the Ah capacity with the nominal voltage of the battery. Our battery has an advertised capacity of 4Ah, thus the expected Wh capacity is $4Ah \times 6V = 24Wh$. This rated capacity is rated according to discharge rate and temperature of the specific battery, because the capacity is greatly affected by the discharge rate and temperature of the battery. As shown in figure 1.3 we can see that the battery capacity falls by roughly 1% per degree when the temperature of the battery is below 20°. Too high temperatures are not good for the battery either as this can make the battery age faster or self-discharge [2].

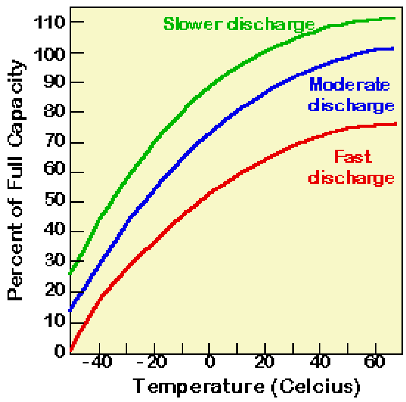


Figure 1.3: Relationship between Battery Capacity, Temperature and Discharge Rate [2]

Testing the OC voltage of the lead acid battery provided to us gives a result of 6.39V, if a load is connected to the battery, the battery will begin to discharge and the voltage of the battery will slowly begin to drop. However there will also be an instantaneous drop in voltage across the terminals of the battery, this is due to the internal resistance of the battery. Internal resistance is the resistance on the inside of the battery and determines the maximum discharge current of a battery [18].

1.2.1. Charging

Lead acid batteries are charged using the constant current constant voltage (CCCV) charge method. With this method the battery is charged in 3 stages as shown in figure 1.4: constant current charge, topping charge and float charge. The constant current charge is where the current is kept at a constant rate and the main portion (70%) of the charging is done and the voltage rises to the peak voltage. The topping charge stage slowly decreases the current, but the voltage stays at the same level. The float charge lowers the voltage to the float charge level in order to compensate for the loss caused by self-discharge. The battery is considered fully charged when the current drops below a certain set level (around 3-5% of the Ah rating), for our battery the current drawn would be around 40mA when the battery is fully charged [3]. According to the datasheet provided by RS Pro [19] the maximum constant current rate at which our battery should be charged is 1.2A when using the constant voltage method. Our battery is fully charged at a voltage of 7.2V when the charger is still connected.

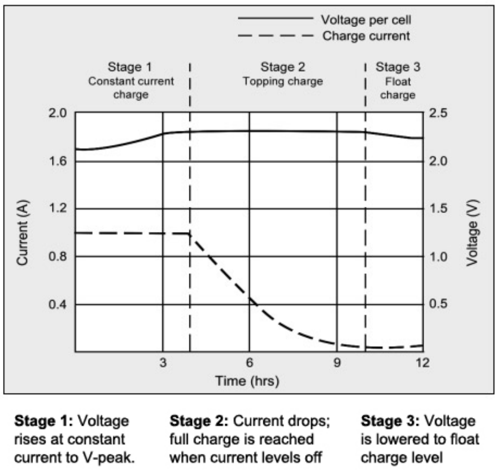


Figure 1.4: Charge States of Lead Acid Battery [3]

1.2.2. Discharging

After being charged the lead acid battery is now ready to be discharged, however there are some important points to consider about discharging a lead acid battery. The amount that a battery has been discharged is measured by the depth of discharge (DoD), which is expressed as a percentage relative to the total capacity of the battery [2]. Discharging a battery to 100% DoD is not recommended as this will decrease the lifetime of the battery [20]. The recommended DoD for longevity is determined by whether your battery is a shallow-cycle or deep-cycle battery. A shallow-cycle battery like ours will get the most cycles with a DoD of 50%. According to the datasheet provided by RS Pro [19] the maximum burst discharge current that our battery can provide is 60A for 5s. If a load resistor was added it would slowly start discharging the battery. The terminal voltage of our battery is 6.35V after 1 hour at 0.05C discharge rate, 6.05V after 4 minutes at 1C discharge rate, 5.45V after 20 hours at 0.05C , and it would take around 11 hours for the battery to reach 2V per cell if it uses 200mA. At 6V (2 per cell) our battery would be considered flat without affecting longevity.

1.3. Fuse

A fuse is an electrical device that is used for safety purposes in order to protect against overcurrent. It consists of a metal wire or strip that conducts current but melts when too much current flows through it, thus disconnecting the circuit and stopping current from flowing between the two points where the fuse was connected. Fuses are rated according to a maximum continuous current that the fuse can conduct without melting. The fuse also has a maximum voltage rating, which needs to be greater than what would become the open circuit (OC) voltage, otherwise a voltage arc may occur. Fuse ratings change according to the operational temperature of the enclosure or area in which the fuse is situated. The fuse is then re-rated according to a re-rating curve of rated current vs ambient temperature as seen in figure 1.5. The time it will take for a fuse to blow is determined by it's time-current characteristics as shown in figure B.1. Thus, the higher the ambient temperature the lower the fuses' rated current and the lower the required time to blow.

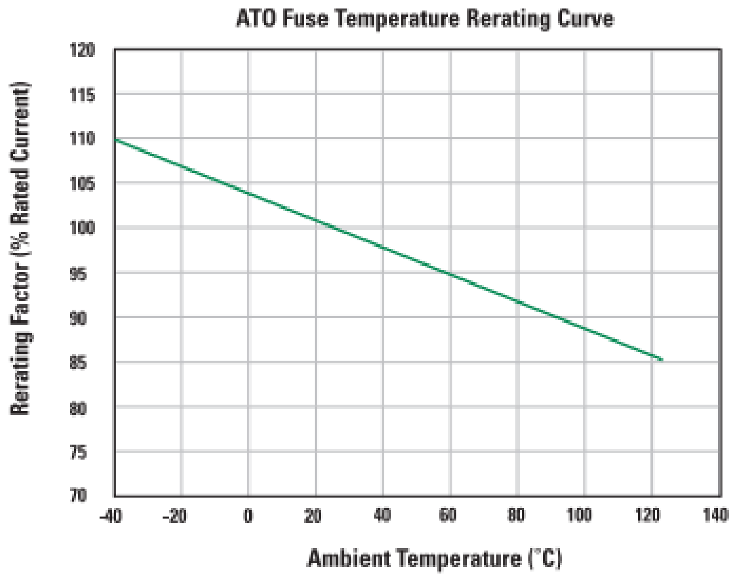


Figure 1.5: Temperature Rerating Curve [4]

Chapter 2

System Design

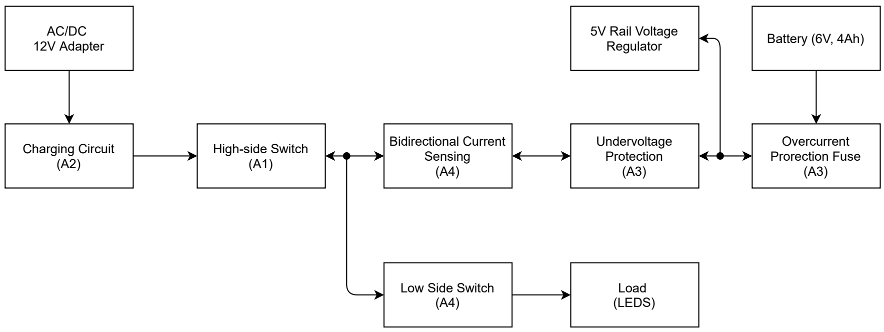


Figure 2.1: Conceptual Block Diagram of System

2.1. High-Side Switch

Metal Oxide Semiconductor Field Effect Transistors (MOSFET) are a voltage controlled field effect transistor. The gate terminal is isolated from the main current carrying channel between the drain and source, as no current flows into the gate terminal [21]. Enhancement type MOSFETs requires a voltage across the gate-source terminals in order to switch the device on. Thus, the enhancement mode MOSFET acts as a normally open switch. In an NMOS (n-channel) MOSFET the device will only switch on and allow current to flow when $V_{gs} > V_{TH}$. For a PMOS (p-channel) MOSFET the opposite is true, a negative gate-source voltage will turn the transistor on, or in other words $V_{sg} > V_{TH}$. We will make use of a high-side switch on the supply side in order to control the charging of the battery. It will be controlled by a control signal which will allow the switch to turn on if the control signal is high(5V) and allow the circuit to start charging and stop charging when the control signal is set to low(0V).

2.2. Charging Circuit

Our battery needs to be able to be recharged when the battery voltage drops below 6V, this will be achieved with a charging circuit. The charging circuit consists of two main parts, the high-side switch and the charging voltage regulator. As shown in figure 2.2 the voltage regulator will receive it's input from either an AC/DC power adapter or from a solar PV module. The voltage regulator will take an input and regulate it down to around 7.4-7.8V. The output from the voltage regulator will be used as the input to the high-side switch which is used to turn the charging circuit on/off. This design will ensure that the output voltage across the battery terminals is 7.2V after all the voltage drops have been taken into account.

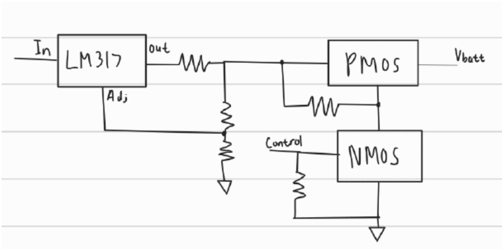


Figure 2.2: Conceptual Block Diagram of Charging Circuit

2.3. Overcurrent Protection

A fuse was added in order to protect the battery and the rest of the circuit in case of shorts or other errors that might cause a big surge of current. In case of a current surge, the fuse will melt and prevent the battery and some of the other components from becoming damaged.

2.4. Undervoltage Protection

Undervoltage protection is added in order to ensure that the battery does not get discharged below a certain voltage level(6V). This will ensure that the battery does not become permanently damaged. The circuit consists of two main parts, the undervoltage protection section and the 5V rail voltage regulator(discussed in section 2.5). As seen in figure 2.3 the circuit receives an input from the node ”A2 Output”, which is the charging voltage as designed in section 3.1.1. Three operational amplifiers (Op Amps) together with a high-side switch are used to implement the undervoltage protection circuit. The main Op Amp implements a schmitt trigger comparator with hysteresis, the comparator will switch and stop the battery from discharging when the voltage of the battery falls below 6V and only allow the battery to discharge again when the battery voltage rises above 6.2V. A voltage follower opamp is used to keep the reference voltage to the comparator constant. The output from the last Op Amp is either a 5V or 0V signal and is used to turn the NMOS MOSFET on or off, which then turns the PMOS MOSFET on/off in order to allow the battery to charge or stop discharging.

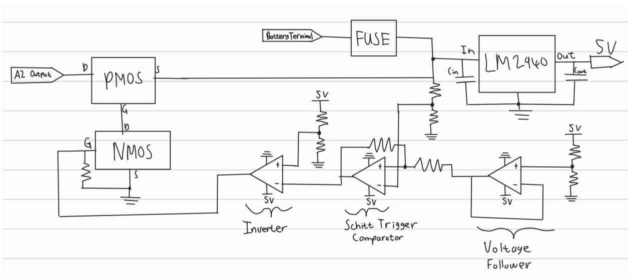


Figure 2.3: Conceptual Block Diagram of Undervoltage Protection Circuit

2.5. 5V Rail Voltage Regulator

Our circuit needs a constant 5V output to power various elements such as the Op Amps and the current sensing circuit. The voltage regulator used is the LM2940 5V voltage regulator which takes input from the battery and provides a constant 5V output. The reason why the LM2940 regulator was chosen rather than the LM7805 regulator is because the LM2940 voltage regulator has a lower minimum input voltage (6V) and a lower minimum voltage dropout (0.5V) [6]. The LM7805 regulator has a minimum dropout voltage of 2V [22] and thus it will not be able to provide constant voltage regulation across the whole battery voltage range. The maximum output current of the LM2940 regulator is 1A [6].

2.6. Bidirectional Current Sensing and Load Control

The circuit can be split into two sub-circuits, namely the TSC213 current sensing amplifier and the load together with it's low side switch. These sub-circuits can be identified in figure 2.4 with subcircuit (a) representing the TSC213 current sensing amplifier and sub-circuit (b) the load together with it's low side switch. The TSC213 is used as a current sensing amplifier, which will provide an analog output voltage proportional to the current flowing through a current sensing resistor connected at its input. This current sensing resistor is called R_{sense} and is chosen to be really small at $100m\Omega$ in order to prevent power losses.

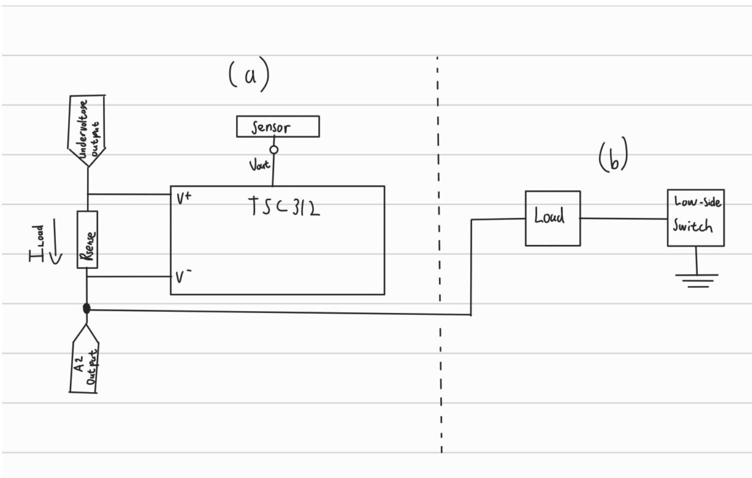


Figure 2.4: Conceptual Block Diagram of Current Sensing and Load Control Circuit

Chapter 3

Detail Design

3.1. Voltage Regulation

3.1.1. Charging Regulator

We will make use of the LM317 adjustable voltage regulator in this project in order to regulate the charging voltage to the required 7.2V at the battery terminals. Thus we can look at our datasheet for the LM317 and we can find an example of a battery charging circuit as shown in figure 3.2. In order to set the output voltage level, voltage dividing resistors R_1 and R_2 are used and in order to limit the current, resistor R_s is used. We can calculate the value of these resistors as follows:
*(for the calculation of V_{out} the voltage drops V_{ds} and V_{Rs} were ignored as they are quite small.)

$$V_{out} = V_{batteryterminal} + V_{diode}$$
$$V_{out} = 7.8V$$

Picking a value for R1 as 240Ω we can then solve for R2.

$$V_{out} = 1.25(1 + \frac{R_2}{R_1})$$
$$\therefore R_2 = 1247.6\Omega$$

Solving for Rs using I_f as 0.4A:

$$I_f = \frac{V_{out} - 1.25(1 + \frac{R_2}{R_1})}{-R_s(1 + \frac{R_2}{R_1})}$$
$$\therefore R_s = 0.72\Omega$$

These resistor values were further fine tuned in LTSpice and then the nearest physically available resistor was chosen or a series/parallel combination for the physical circuit as shown in figure 3.1.

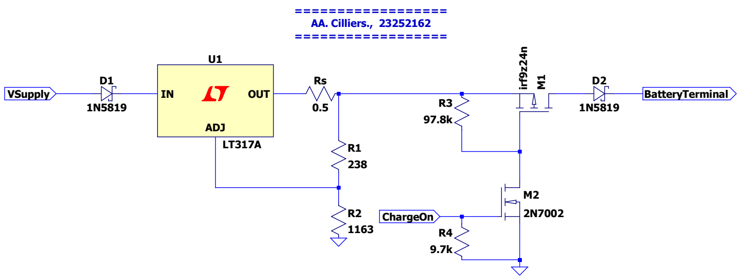


Figure 3.1: Full Circuit Diagram of Voltage Regulator and High-Side Switch

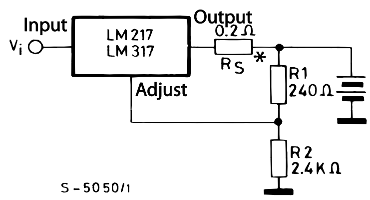


Figure 3.2: Voltage Regulator Battery Charger [5]

Current limit

If the battery is charged at too high a current it will cause decomposition of the water in the electrolyte and cause premature battery aging and may even permanently damage the battery. According to the RS components battery datasheet [19] the charging rate limit for our charging method is 0.1C, which in our case is $0.1(4Ah) = 400mA$. This current limit will be implemented with the use of Resistor R_s shown in figure 3.1. See section 3.1.1 for the calculation of the value of R_s.

Thermal Analysis

According to the LM317 datasheet [5] the maximum junction temperature is $T_j = 125°C$. This means that without a heatsink on an average day at an ambient temperature of 45° Celsius (inside an enclosure in direct sunlight) and using the 12 DC power supply the maximum power that the regulator can dissipate is:

$$P_{max} = \frac{(T_j - T_{amb})}{\theta_{j-a}} \quad with\ \theta_{j-a} = 50°C/W$$

$$P_{max} = 1.6W$$

When adding a small TO-220 package heatsink the maximum power dissipated becomes:

$$\theta_{j-c} = 5°C/W;\ \theta_{c-s} = 1.64°C/W;\ \theta_{s-a} = 24.4°C/W$$
$$P_{max} = \frac{(T_j - T_{amb})}{\theta_{j-c} + \theta_{c-s} + \theta_{s-a}}$$
$$P_{max} = 2.58W$$

Thus we can see that adding a heatsink we can dissipate an extra 1W of power.

Without a heatsink:

$$P_{dissipated} = (V_{in} - V_{out})I_{out}$$
$$\therefore T_j = P_{dissipated}(\theta_{j-a}) + T_{amb}$$

Using the 12V DC supply:

$$P_{dissipated} = 1.68W$$
$$T_j = 129°C$$

Using the Solar PV Module (21.6V):

$$P_{dissipated} = 3.68W$$
$$T_j = 229°C$$

With a heatsink:

Using the 12V DC supply:

$$P_{dissipated} = 1.68W$$
$$\therefore T_j = P_{dissipated}(\theta_{j-c} + \theta_{c-s} + \theta_{s-a}) + T_{amb}$$
$$T_j = 97.15°C$$

Using the Solar PV Module (21.6V):

$$P_{dissipated} = 3.68W$$
$$T_j = 159.23°C$$

Thus we can see that adding a heatsink greatly improves the performance of the voltage regulator and keeps the juntion temperature cool when using the 12 DC supply. However if we were to use the solar PV module the voltage regulator would still burn out, so we would need to implement some overvoltage protection in order to limit the amount of voltage the solar PV module can provide.

3.1.2. 5V Rail Regulator

Our circuit needs a constant 5V output to power various elements such as the Op Amps and the current sensing circuit. The voltage regulator used is the LM2940 5V voltage regulator which takes input from the battery and provides a constant 5V output. Two capacitors were added, one at the input and one at the output. These capacitors are used in order to filter out high frequency noise and to ensure a steady and constant 5V output voltage. C_{in} was chosen as 0.47uF and C_{out} as 22uF and are placed as close as possible to the input and output ports as per the recommendations from the LM2940 datasheet [6].

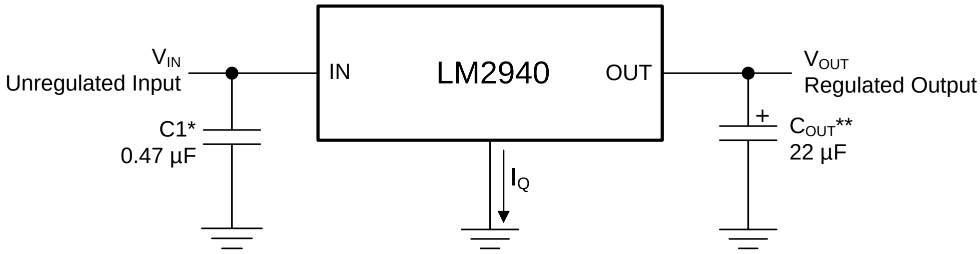


Figure 3.3: Circuit Diagram of LM2940 5V Voltage Regulator [6]

3.2. High-Side Switch

In order to design a high-side switch that uses logic level voltages (0-5V or 0-3.3V) we need to make use of a complementary pair of PMOS and NMOS MOSFETs. Pullup resistor R3 is added to keep to p-channel MOSFET off in unkown floating voltage states and to provide a large enough voltage drop over V_{gs} in order to fully turn the PMOS on when required. Similarly a pulldown resistor R4 is added to the gate of the n-channel MOSFET to keep it off in unknown states. Resistor R3 in figure 3.4 is also used to limit the amount of current that flows through the n-channel MOSFET. If the control voltage ChargeOn is at a high of 5V the n-channel MOSFET will be turned on, thus pulling the gate of the p-channel MOSFET to ground and allowing current to flow. According to the 2N7000 n-channel MOSFET datasheet [23] the maximum current that can flow through the drain-source channel is 200mA, thus the minimum resistor value for R3 can be calculated as:

$$R3_{min} = \frac{7.8V}{200mA} = 39\Omega$$

This value was designed for extremities and would most likely not work in the physical circuit as it is a very small resistor and it is the minimum resistance value that R3 can be, I chose a value of $100k\Omega$ as a design choice in order to limit the amount of current flowing through the resistor. Resistor R4 was also arbitrarily selected as $10k\Omega$.

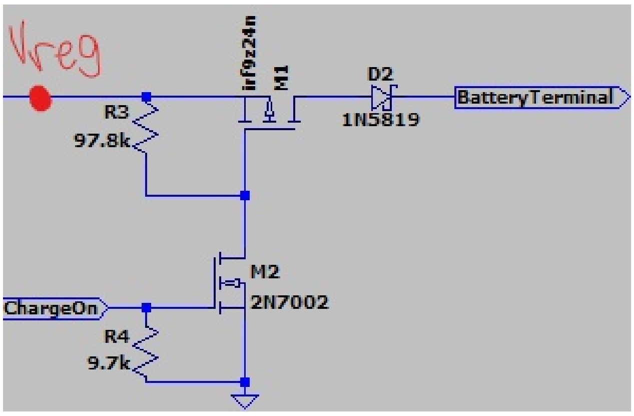


Figure 3.4: Circuit Diagram of High-Side Switch (Vreg is the voltage coming from the charging regulator)

3.3. Overcurrent Protection

The load which our battery will have to power will consist of 5 ultra-bright light-emitting diodes (LEDs), which will draw 100mA in total. We will also allow for 50mA of headroom in order to power some other things in our circuit like the 5V voltage regulator. The maximum current that will enter our battery is during charging which is designed as $400mA$ and is thus the maximum current our fuse should be able to continuously handle. Fuses should only be operated at around 75% of their rated value [24]. Our fuse will typically operate in an enclosure which will be in direct sunlight, thus we need to take temperature rerating into account. Assuming an ambient temperature of 45°C, our fuse has a temperature rerating factor of around 97% [4]. The recommended fuse size can thus be calculated as:

$$Ideal\ Fuse\ Rating = \frac{Nominal\ Operating\ Current}{Temp\ Rerating\ Factor \times 0.75} = \frac{400mA}{0.97 \times 0.75} = 0.55A$$

The next available fuse size should therefore be chosen, thus we will pick a 1A fuse. If something happens and there is a short circuit and the battery discharges 10A or more through the load the fuse will break in 0.01s as seen in figure B.1, thus protecting the circuit from damage.

3.4. Undervoltage Protection

We will make use of three Op Amps in order to design our voltage monitoring circuit. The main Op Amp (U2 in figure 3.5) will be designed as a inverting comparator with hysteresis. Our undervoltage protection circuit needs to allow the battery to discharge when the battery voltage is above 6.2V and not allow it to discharge when the voltage falls below 6V. Hence, we have two threshold switching points, giving a hysteresis deadband of 0.2V. However, because of the common mode input range of -0.3V to 5.3V and the max differential voltage of 5V [25], we need to scale the input voltage and the reference voltage to appropriate levels. We use

voltage dividing resistors R1 and R2 to divide the input voltage from the battery by 2. These resistors need to be large to limit the current through them, so they were arbitrarily chosen as $100k\Omega$. The input voltage will now vary from 3V(V_L) to 3.1V(V_H) and we need to switch at around 3.05V, thus we can use our 5V supply and two voltage dividing resistors R11 and R12 to provide a reference voltage of 3.05V. These two resistors can be calculated as follows (where V_H is the high threshold switching voltage):
*Please refer to figure 3.5 for a visual reference to the mentioned resistors.

$$\frac{R_{11}}{R_{12}} = \frac{V_{cc}}{V_{cc} - V_H} = 1.5789$$
$$\text{pick } R_{12} = 10k\Omega$$
$$\therefore R_{11} = 15.79k\Omega$$

Resistors R9 and R10 provide the positive feedback needed for hysteresis and are calculated as follows:

$$\frac{R_9}{R_{12}} = \frac{V_L}{V_H - V_L} = 30$$
$$\therefore R_9 = 30 \times R_{12} = 300k\Omega$$
$$V_H = V_{ref}(1 + \frac{R_{10}}{R_9})$$
$$\therefore R_{10} = 6.13k\Omega$$

A voltage follower Op Amp was implemented to ensure that the reference voltage would not change due to the hysteresis. The comparator with hysteresis was implemented as an inverting comparator, thus to ensure the required output we implemented another comparator with a reference voltage of 2.5V, which simply inverts the signal from 0V to 5V and vice versa.
All the calculated values were slightly adjusted and the closest real resistor values were picked for the physical building of the circuit

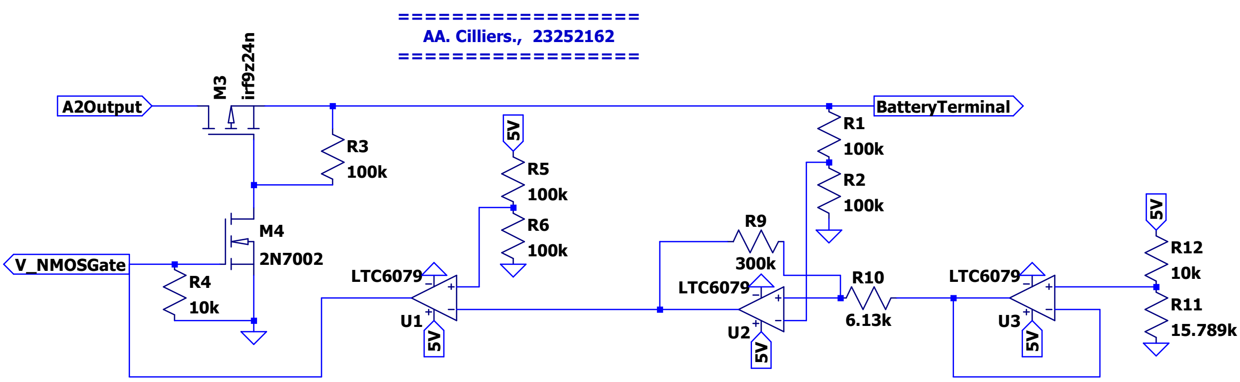


Figure 3.5: Full Circuit Diagram of Undervoltage Protection and Voltage Regulator

3.5. Bidirectional Current Sensing

The voltage drop across the R_{sense} resistor is so small that it would require an OpAmp with a very high common mode voltage. Thus, we were given a TSC213 bidirectional current sensing amplifier which has a common mode voltage of -0.3 to 26V and a gain of 50 [26]. We were required to design for a current input range of -150mA (discharging) to 450mA (charging) and the resulting output voltage had to be biased for optimal output swing.

The output voltage of the TSC213 can range from 0 to 5V, thus the reference voltage can be calculated as follows:

$V_{out} = (R_{sense})(I_{load})(Gain) + V_{ref}$

Set V_{out} =0V and I_{load}=-150mA

$\therefore V_{ref} = 0.75V$

Now set V_{out}=5V and I_{load}=450mA

$\therefore V_{ref} = 2.75V$

Since we need optimal output swing, take the middle of the two voltage references

$\therefore V_{ref} = 1.75V$

This reference voltage results in an output of 1V when the current is at -150mA and an output of 4V when the output is at 450mA.
As seen in the circuit diagram figure 3.6 resistors R_1 and R_2 are used as voltage dividers in order to the the reference voltage at the required level. These resistors are calculated as follows:

$$V_{ref} = \frac{R_2}{R_2 + R_1} Vcc$$

$$\text{Choose } R_2 = 10k\Omega$$

$$\therefore R_1 = 18.571k\Omega$$

The output of the TSC213 needs to be filtered in order to suppress noise. The requirement is that there is less than $2mV_{pk}$ noise on V_{out}, however the circuit must still remain responsive and be able to respond to an abrupt change in current within 2s. The choice of filtering was to make use of a decoupling capacitor on the output and the reference voltage nodes as seen in figure 3.6. Decoupling capacitors can be used as low pass filters and are used to stabilize voltages by preventing quick voltage changes, thus smoothing the output voltage [27]. The reason that the capacitor was placed at the output and not over the R_{sense} resistor is because of impedance mismatching. When selecting a decoupling capacitor for a low-pass filter a low-impedance series component should face a high impedance capacitor [28]. The current sensing resistor is very small and thus would require a very big capacitor in order to provide an appropriate level of filtering. C_2 in figure 3.6 was chosen as 10uF and C_1 was suggested in the TSC213 datasheet [26] to be used as 0.1uF.

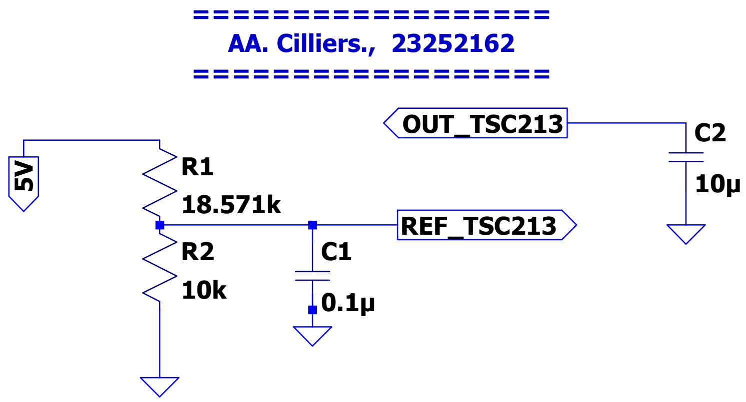


Figure 3.6: Full Circuit Diagram of Bidirectional Current Sensor Only

3.6. Low-side Switch

In order to design a low-side switch that uses logic level voltages (0-5V or 0-3.3V) we can make use of a NMOS MOSFET. Pull-down resistor R1 in figure 3.7 is added to provide a large enough voltage drop over V_{gs} in order to fully turn the NMOS on when required and to keep the NMOS off in unkown states. If the voltage at the gate of the NMOS is at a high of 5V the n-channel MOSFET will be turned on, thus allowing current to flow through the drain-source channel, which means the load is now active. If the voltage at the gate of the NMOS is at a low, the NMOS will turn off and the load will be disconnected. According to the 2N7000 n-channel MOSFET datasheet [23] the maximum current that can flow through the drain-source channel is 200mA, however the maximum current that will flow through the NMOS in our circuit is 100mA (from the 5 super-bright LEDs), thus a current limiting resistor is not required.

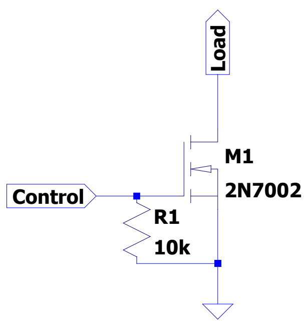


Figure 3.7: Circuit Diagram of Low-Side Switch Portion

The pull-down resistor R3 was arbitrarily selected as $10k\Omega$. Each super bright LED will be current limited by using a resistor connected in series, thus each LED will draw a maximum of 20mA each, giving a total of 100mA that will flow through the load and through the NMOS drain-source channel.

3.7. Supply Voltage Measurement

Since the supply voltages can range from 0-22V we will first scale the input voltage down by using a voltage divider in order for the voltage to stay between the maximum input voltage to the beetle (0-5V) [29]. I chose the range to be from 0-4.5V in order to have a small safety margin. The resistor values for the voltage division R_1 and R_2 in figure 3.8 can be calculated as follows:

$$\text{Choose } R_1 = 47k\Omega$$
$$\frac{R_2}{R_1 + R_2}(22) = 4.5$$
$$\therefore R_2 = 12.085k\Omega$$

If the system receives power from the PV module it will not be very noisy, however if the 12V AC/DC adapter is used it will introduce a lot of noise due to the switch-mode regulator that it uses. We want to use the supply voltage measurement with the beetle so we are going to convert the analogue voltage level to a scale of digital bits using a analogue-to-digital converter (ADC). The ADC has a resolution of 2^10 bits and the beetle's maximum input is 5V, thus the voltage range of a single bit is $\frac{5}{2^10} = 4.88mV$. Thus, we need to implement a passive RC filter in order to reduce the noise to below the threshold otherwise the noise will cause the bit reading to fluctuate between different bit values and can cause errors when working with those values in code later on. The RC filter was designed as follows:

$$\text{Choose } F_L = 50Hz$$
$$\text{Choose } C_1 = 4.7uF$$
$$F_L = \frac{1}{2\pi R_3 C_1}$$
$$\therefore R_3 = 677.256\Omega$$

An OpAmp U1 was used as a voltage follower in order to keep the voltage division node voltage constant.

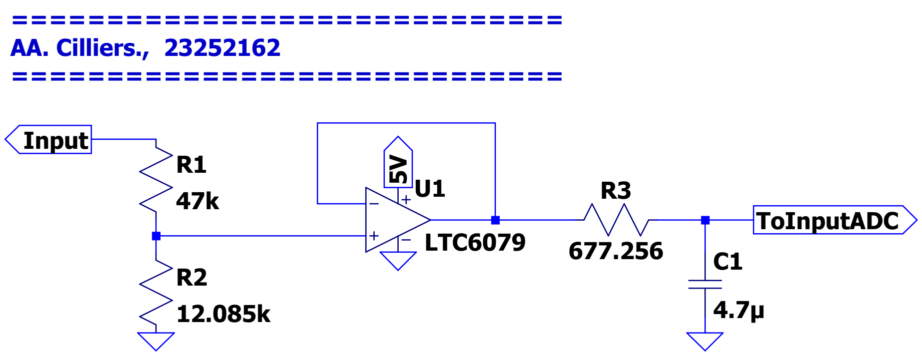


Figure 3.8: Circuit Diagram of Supply Voltage Measurement

3.8. Battery Voltage Measurement

Our battery's ideal operating range is from 6-7.2V, however we will allow for some leeway in order to give some safety margin in the even that the battery goes beyond this range and thus we will define the allowable battery range as 5.5-7.5V. Since the beetle has a maximum of 5V input voltage we will design the output voltage for our battery voltage measurement to range from 0-4.5V in order to not exceed the maximum voltage of the beetle. We will halve the battery voltage using two resistors R_4 *and* R_5 in order to stay within the common mode of the OpAmp, which are chosen to be arbitrarily large at $100k\Omega$ in order to limit the current that flows through them and power dissipation. We will thus design our reference voltage to the differential amplifier U4 as 2.75V. This will ensure that when the battery is at 0V the ToBatteryADC voltage as indicated in figure 3.9 will be 0V. The differential amplifier takes the battery voltage and subtracts the reference voltage from it and then multiplies the resultant voltage by a gain. I am designing for an output voltage range of 0-4.5V where the battery being at 5.5V gives 0V and at a battery voltage of 7.5V the ToBatteryADC value is 4.5V. The differential amplifier resistors are calculated as follows:

$$
\begin{aligned}
&\text{choose } R_8 = R_9 \ and \ R_{10} = R_{11} \text{ then} \\
&V_{out} = \frac{R_{10}}{R_8}(V_{batt_{scaled}} - V_{ref_{scaled}}) \\
&\text{in the worst case } V_{batt_{scaled}} - V_{ref_{scaled}} = 3.75 - 2.75 = 1V \\
&\text{thus in order to get an output range of} \\
&\text{up to 4.5V we need to design our gain} = 4.5V \\
&\therefore gain = 4.5 = \frac{R_{10}}{R_8} \\
&\text{Choose } R_8 = R_9 = 10k\Omega \\
&\therefore R_{10} = R_{11} = 45k\Omega
\end{aligned}
$$

Now in order to design the reference signal as 2.75V we use voltage division and use the 5V rail as a supply.

$$
\begin{aligned}
&R_6 = 10k\Omega \\
&\frac{R_7}{R_7 + R_6}(5) = V_{ref} = 2.75 \\
&\therefore R_7 = 12.222k\Omega
\end{aligned}
$$

Two voltage followers U2 and U3 were implemented in order to keep the voltage division node voltages constant and to prevent the reference voltage from changing.

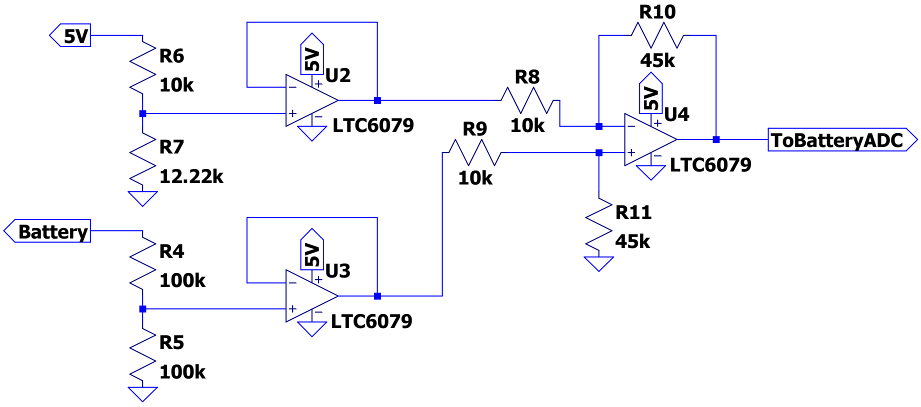


Figure 3.9: Circuit Diagram of Battery Voltage Measurement

3.9. Ambient Light Sensor Circuitry

In order to measure the ambient light level, we are going to make use of an Light Dependent Resistor (LDR). The LDR will decrease it's resistance with an increase in light intensity and vice versa. In order to create an analog output that will be sampled by the ADC of the Beetle we can make use of a voltage divider circuit. As seen in Section 3.11 Figure 3.10 sub-circuit (a) the analog output voltage can be calculated as follows:

$$V_{out} = \frac{R_{LDR}}{R_{LDR} + R_1}(5)$$

Resistor R_1 in the physical circuit was chosen to be a $10k\Omega$ resistor in series with a $220k\Omega$ variable resistor. The light sensor circuit needs to output a logic High voltage when the ambient light is dark enough, thus a non-inverting comparator is implemented. The reference voltage to the comparator is set at 4V using another voltage divider.

$$V_{ref} = \frac{R_3}{R_3 + R_2}(5)$$

Choose $R_3 = 100k\Omega$ and using $V_{ref} = 4V$

$$\therefore R_2 = 25k\Omega$$

The comparator compares the analog output voltage with the 4V reference voltage and as soon as the analog voltage is greater than 4V the output of the comparator ($V_{digital}$ in Section 3.11 Figure 3.10) will saturate to the positive rail of the OpAmp (5V) and when the analog voltage is less than the reference voltage the output of the comparator will be 0V. This output of the comparator is the digital output ($V_{digital}$) that is a 5V when the ambient light level is dark enough and 0V when it is light enough. This threshold can be fine tuned by adjusting the variable resistor R_1.

3.10. LED Load Control Design

The Load Control circuitry will make use of the light sensor circuitry and user input in order to control the load LED lights and the pilot light. I set up a logic truth table as seen in Table 3.1 which encapsulates all the requirements of the load circuit.

Light/Dark 0-Light/1-Dark	**Latch Output 1-On/0-Off**	**Load Control 1-On/0-Off**	**Load LEDS 1-On/0-Off**	**Pilot LED 1-On/0-Off**
0	0	0	0	0
0	1	0	0	0
1	0	0	0	1
1	1	1	1	1

Table 3.1: Load Control Logic Truth Table

The Latch Output column is the output of the user input SR latch seen in Section 3.11 Figure 3.10, sub-circuit (b), which is built using an OpAmp and four 1N4148 diodes as follows: Set the OpAmp's inverting input to 2.5V using a voltage divider with $R_4 \& R_5$. The diodes D1 and D2 in series apply positive feedback to the OpAmp's non-inverting input, which is pulled low by the pull-down resistor R3 if both the output and the SET input are low. When the output is low, if the user applies a 5V pulse to the SET input by pressing a push button, diode D3 becomes forward-biased and thus a 4.4V voltage is applied at the non-inverting input of the OpAmp. This resulting 4.4V at the non-inverting input drives the output high, thus forward-biasing diodes D1 & D2 and latching the non-inverting input to 3.2V due to the positive feedback loop. This is higher than the inverting input voltage of 2.5V, even after the SET input returns to low, because then diode D3 reverse-biases and the voltage at the non-inverting input will stay at 3.2V. If you then drive the RESET input high diode D4 becomes forward-biased and thus a 4.4V voltage is applied at the inverting input of the OpAmp, which is then higher than the 3.2V of the non-inverting input voltage, thus driving the output of the OpAmp low. If the RESET input returns to low then diode D4 reverse-biases and the 2.5V reference voltage at the inverting input will hold the output low [30]. Thus, the SR latch holds the value of the SET input until RESET is pressed or vice versa so that the user does not have to hold the pushbutton down for the duration of time that they want to have light.

As seen from the first 3 columns of the truth table, Table 3.1, we can see that a 2 input AND gate is required for the logic of the signal that drives the low-side Load Control circuit. However, we need to provide another input for a PWM signal, which will be implemented in the future, thus a 3 input AND gate is required. Since we are only allowed to use discrete components, a design choice was made to build the 3 -input AND gate using NMOS MOSFETs. This design can be seen in Section 3.11 Figure 3.10 sub-circuit (d) [31].

3.11. Pilot Light Control Design

The pilot light is used as an indication of when the Load LEDS are able to be turned on, thus the pilot light must turn on when the ambient light level is low enough and off again if it is bright enough. The logic for the pilot light can be seen in Section 3.10 Table 3.1.

The pilot light has a maximum continuous allowable current of 20mA, however it should consume much less power than the ultra-bright load LEDs, thus a resistor $R_7 = 1k\Omega$ as seen in Figure 3.10, sub-circuit (c) was chosen, which is bigger than the minimum resistance of 150Ω, but large enough to ensure low power draw.

$$R_{min} = \frac{5V - 2V}{20mA}$$
$$R_{min} = 150\Omega$$

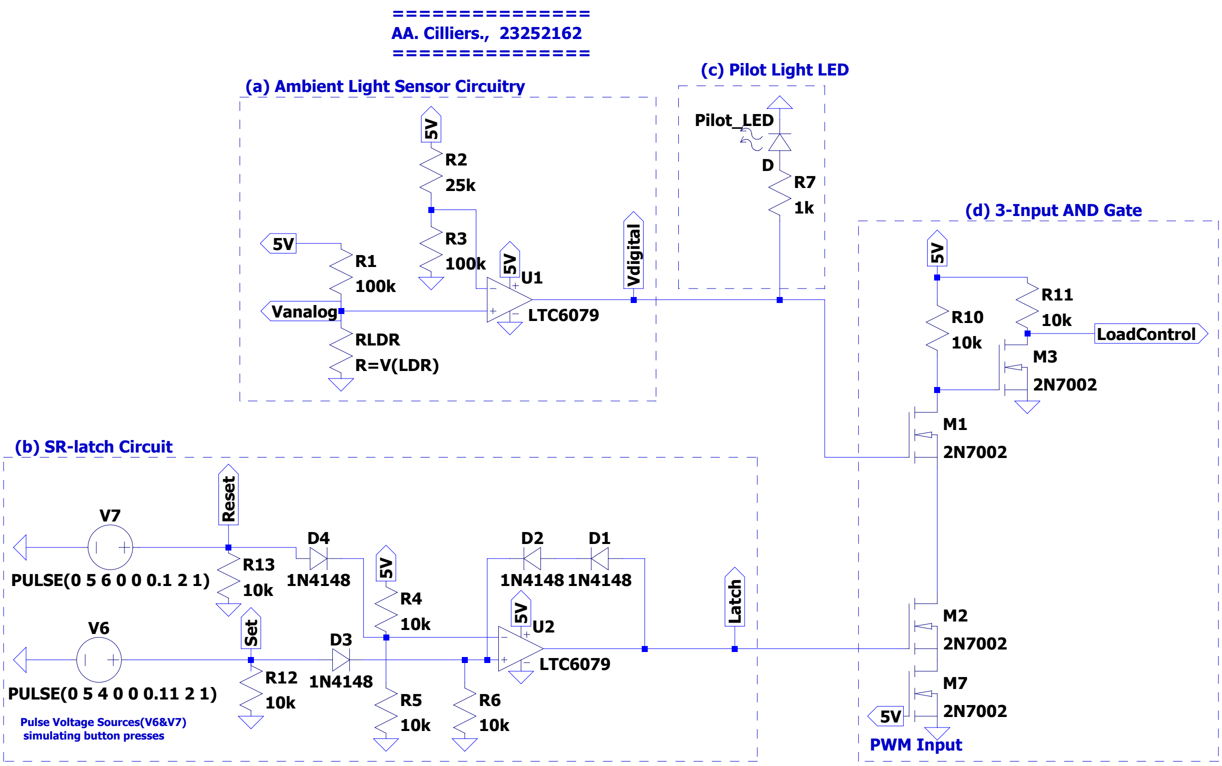


Figure 3.10: Circuit Diagram of Supply Voltage Measurement

Chapter 4

Subsytem Results

4.1. Voltage Regulation

4.1.1. Simulated Results

Figure 4.1 shows the output of the simulated circuit where V(batteryterminal) is the voltage at the battery terminals and I(Rsensebattery) is the output current through the battery terminal. The charging circuit only switches on when the $5V$ logic control signal (Vchargeon) is set high and the battery does not discharge when V_{supply} is switched off. The current requirement of less than $400mA$ when the battery is flat(at $6V$) is fulfilled since the circuit only pulls $326.82mA$. The final voltage when the battery is fully charged is $7.28V$, thus also meeting the required design specifcation of $7.2V$ (with a 5% tolerance). Thus this design is working as intended and meets all the requirements during the simulation.

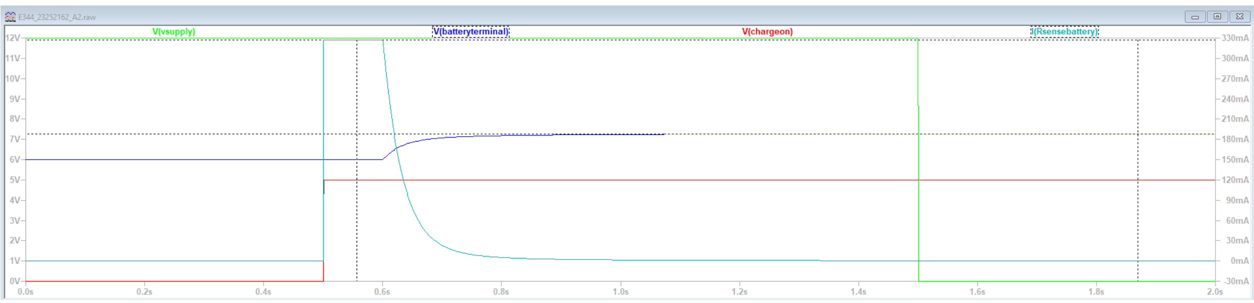


Figure 4.1: Output Graphs of LTSpice Simulation

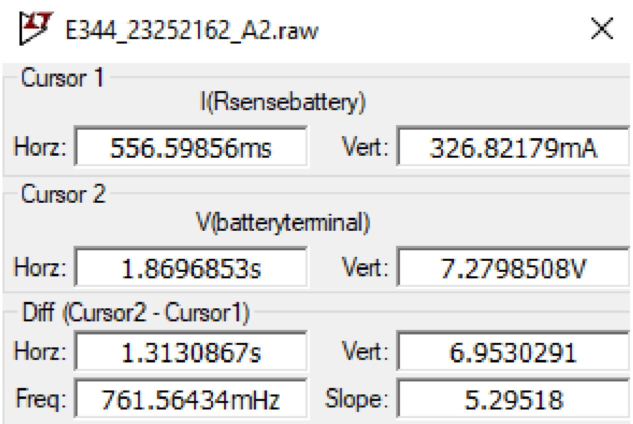


Figure 4.2: Cursor Measurements of the Output Current through Battery and the Battery Terminal Voltage

4.1.2. Measured Results

Figures 4.3 to 4.5 show the measured results of the OC voltage, the voltage over a 1k load and over a 10k load.

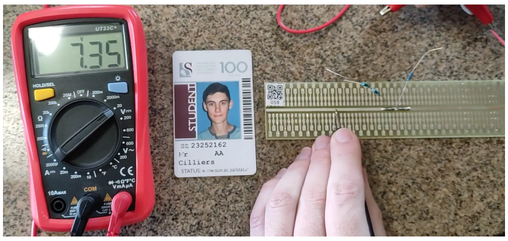


Figure 4.3: Multimeter measurement of the Open Circuit Voltage at the Battery Terminal

Figure 4.4: Multimeter Measurement of the Voltage over a 1k Load

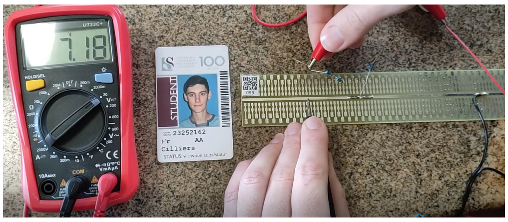


Figure 4.5: Multimeter Measurement of the Voltage over a 10k Load

4.2. High-Side Switch

4.2.1. Simulated Results

As shown in figure 4.6 we can see that the switch is switching an output voltage of 24.89V. It turns on when the external control signal is high (5V) and that it does not allow current to flow back from the load into the supply.

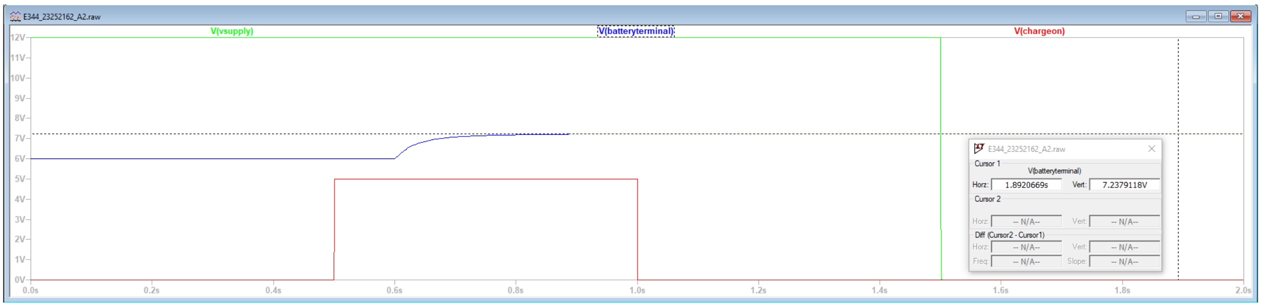


Figure 4.6: Circuit Diagram of High-Side Switch

4.3. Undervoltage Protection

4.3.1. Simulated Results

Figure 4.7 shows the output of the simulated circuit where V(batteryterminal) is the voltage at the battery terminals and I(Rsensebattery) is the output current through the battery terminal and V(NMOSGate) is the output voltage from the schmitt trigger at the gate of the NMOS MOSFET. As shown the circuit is discharging when the battery voltage is higher than 6.2, this can be seen be the negative current of I(Rsensebattery) and stops discharging when the battery voltage is lower than 6V.

Figure 4.8 shows that the 5V regulator only draws around $849\mu A$, which meets the requirement that it should not draw more than 10mA.

Figure 4.9 shows that the circuit switches in $7.84ms$ after a threshold is exceeded, which is below the requirement of $10ms$.

Thus this design is working as intended and meets all the requirements during the simulation.

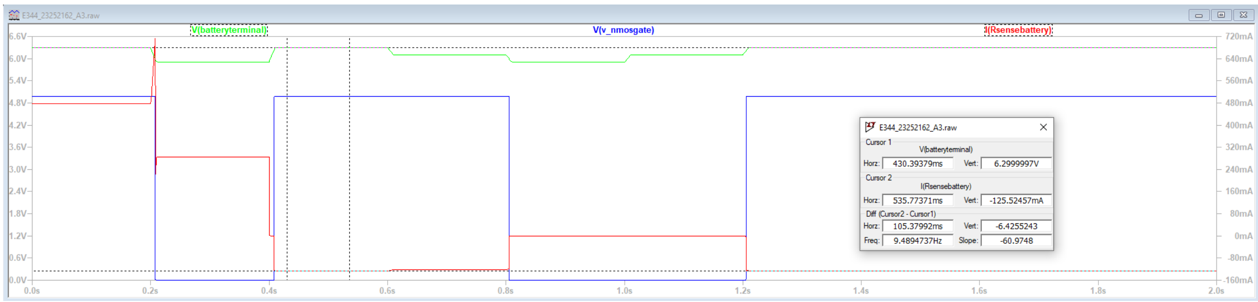


Figure 4.7: Output Graph of LTSpice Simulation Showing Voltage Switching and Discharge Current

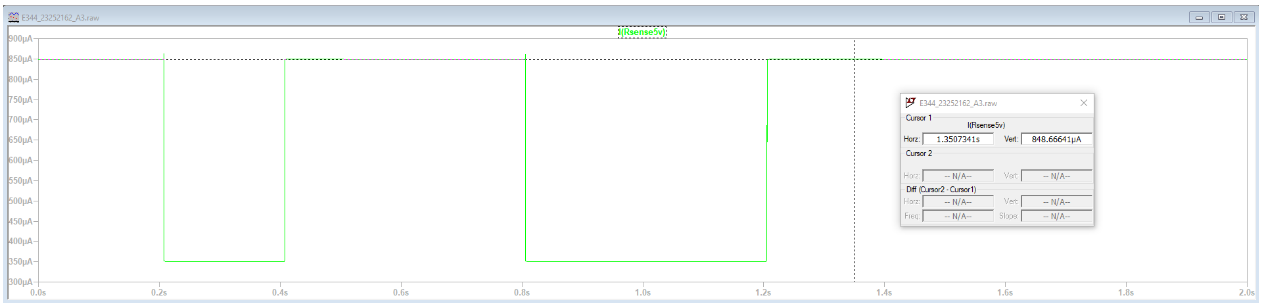


Figure 4.8: Output Graph of LTSpice Simulation Showing Current Used by 5V Regulator

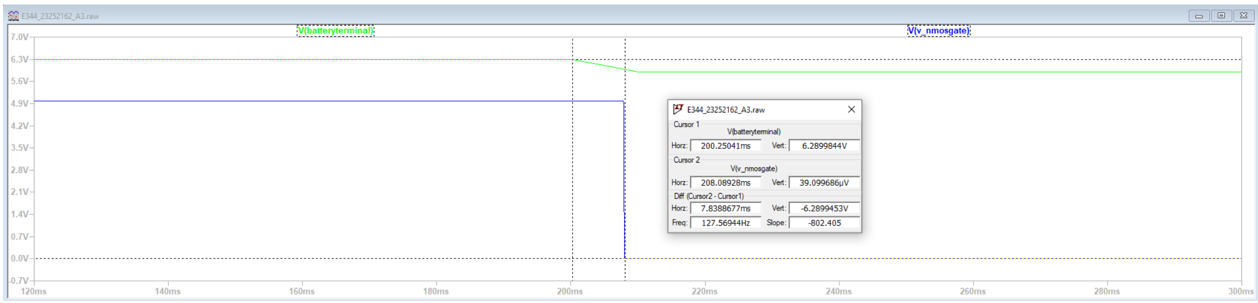
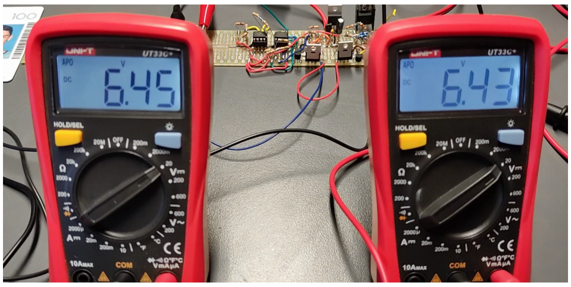


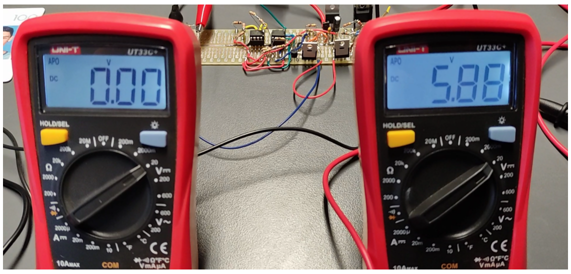
Figure 4.9: Output Graph of LTSpice Simulation Showing Voltage Switching Time

4.3.2. Measured Results

Figure 4.10a shows the voltage over the 10k load while the battery terminal voltage is above 6.3V on the left multimeter and the battery terminal voltage on the right multimeter. Decreasing the battery voltage to below 5.9V prevents the battery from discharging and causes a 0V over the 10k load as seen in figure 4.10b.



(a) Multimeter Measurement Showing Voltage Over 10k Load and Battery Terminals (Battery Voltage Above 6.2V)



(b) Multimeter Measurement Showing Voltage Over 10k Load and Battery Terminals (Battery Voltage Below 5.9V)

Figure 4.10: Outputs Of Multimeters Measuring Voltage over 10k Load and Battery Terminals

4.4. Bidirectional Current Sensing

4.4.1. Simulated Results

Figure 4.11 shows the output of the TSC213 versus the current I1 flowing through R_{shunt} and it also shows the response time after an abrupt change in current as 479.20ms. Figure 4.12 shows the noise of the TSC output to be $4.93mV_{pk-pk}$, which is $2.465mV_{pk}$, which is under the $5mV_{pk}$ specification.

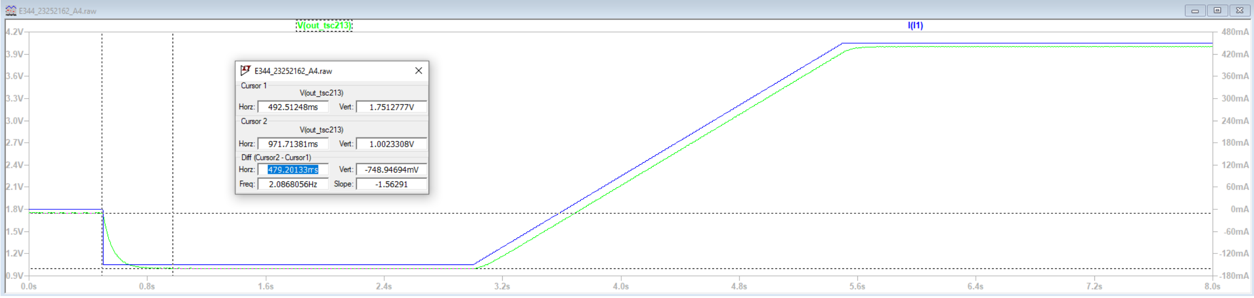


Figure 4.11: TSC213 Output vs Current and Response Time

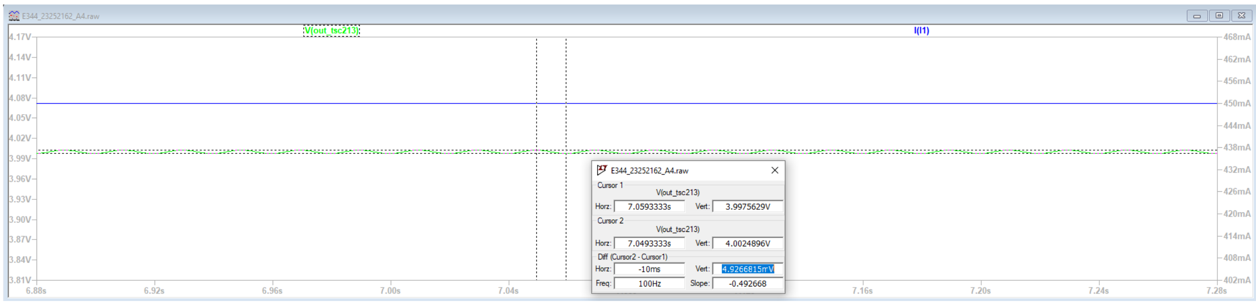
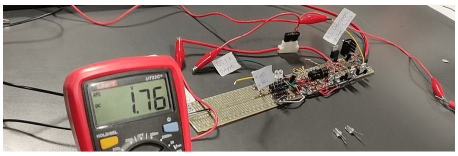


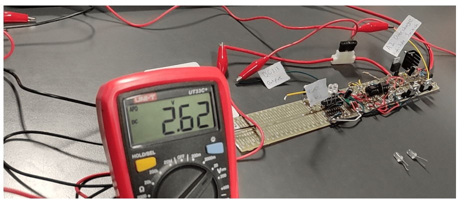
Figure 4.12: Output Graph of LTSpice Simulation Showing Noise of TSC Output

4.4.2. Measured Results

Figure 4.13a shows the multimeter reading of the TSC213 output while no current is flowing through the current sensing resistor and figure 4.13b shows the output while the battery is charging. Switching the load on is shown in figure 4.14a with 3 LEDs and figure 4.14b with 5 LEDs.

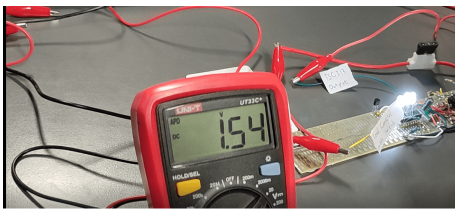


(a) Multimeter Measurement Showing Voltage of TSC213 (No Current)

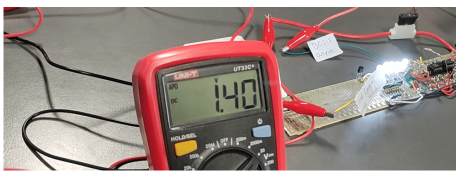


(b) Multimeter Measurement Showing Voltage of TSC213 (While Charging)

Figure 4.13: Multimeter Measurement Showing Output Voltages of TSC213 While Charging/No Current



(a) Multimeter Measurement Showing Voltage of TSC213 (3LEDs)



(b) Multimeter Measurement Showing Voltage of TSC213 (5LEDs)

Figure 4.14: Multimeter Measurement Showing Output Voltages of TSC213 Under Load

4.5. Supply Voltage Measurement

4.5.1. Measured Results

The noise was measured with an oscilloscope to be 1.59mV, which is far below the required noise threshold of 4.88mV and thus the RC filter is doing its job and is working as expected. Figure 4.15 shows the response time of the Supply Voltage Measurement Output when a 1V Input is applied and is measured to be 9.6ms, which meets the specification of under 10ms and thus works as designed.

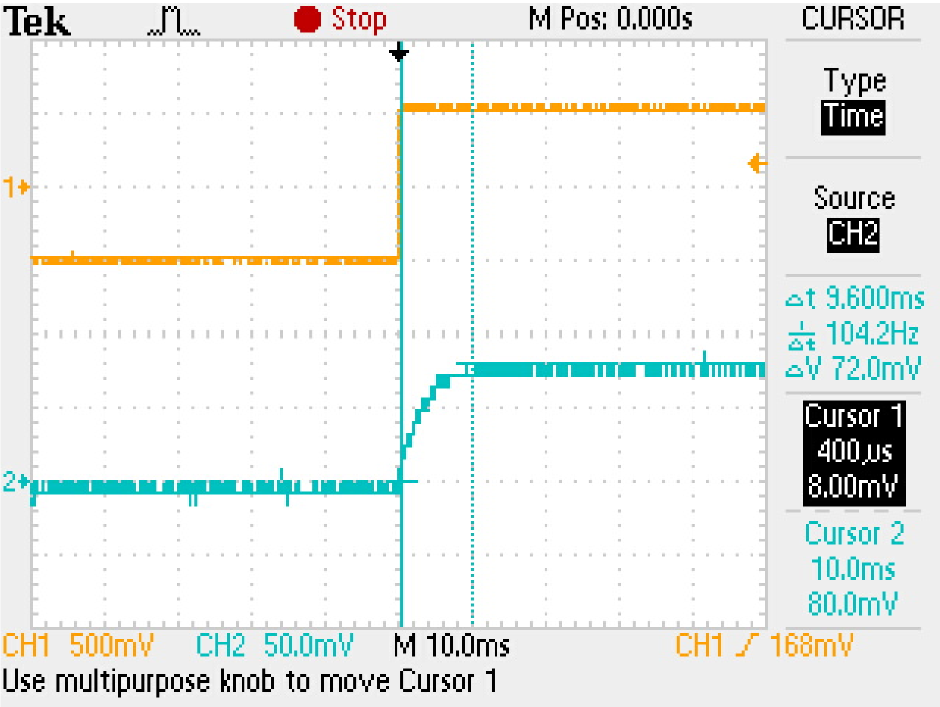


Figure 4.15: Oscilloscope Screenshot of ToInputADC Output Voltage Response Time to 1V Input change

Table 4.1 shows the input supply voltage vs the ToInputADC output voltages, as seen it reaches a maximum of 4.16V when the supply voltage is 22V, we designed for it to be 4.5V at this input voltage, but it is close enough and thus we can conclude that it is working as intended.

Measured Supply Voltage [V]	**Measured ToInputADC Output Voltage [V]**
0	0
1	0.168
11	2.07
22	4.16

Table 4.1: SubSystem Results Showing Measured Supply Voltage vs ToInputADC Output Voltage

4.6. Battery Voltage Measurement

4.6.1. Simulated Results

Figure 4.16 shows the simulated battery voltage vs the ToBatteryADC Output voltage and as seen in Table 4.2 the output voltage is 0V at a 0V input and 7.5V the output voltage is 4.501V as designed, thus our design is working as intended.

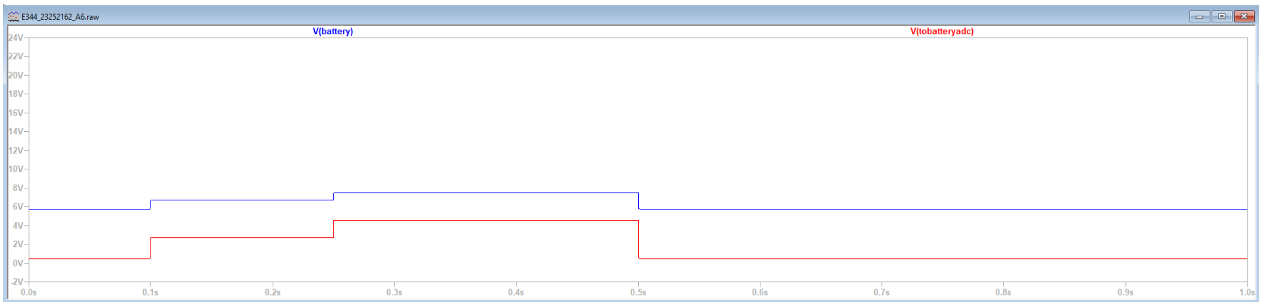


Figure 4.16: LTSpice Graph of Battery Voltage vs ToBatteryADC Output Voltage

Simulated Battery Voltage [V]	Simulated ToBatteryADC Voltage [V]
5.5	0
5.7	0.451
6.7	2.701
7.5	4.501

Table 4.2: SubSystem Results Showing Simulated Battery Voltage vs ToBatteryADC Output Voltage

4.6.2. Measured Results

Table 4.3 shows the simulated battery voltage vs the ToBatteryADC Output voltage and as seen in Table 4.2 the physical circuit and simulated circuit's output voltages match very closely, thus we can conclude that our physical circuit is working as designed.

Measured Battery Voltage [V]	Measured ToBatteryADC Voltage [V]
5.5	0.029
6	1.32
6.6	2.64
7.2	4.06
7.5	4.56

Table 4.3: SubSystem Results Showing Measured Battery Voltage vs ToBatteryADC Output Voltage

4.7. Ambient Light Sensor Circuitry

4.7.1. Simulated Results

Figure 4.17 shows the analog output voltage changing over a range of voltages as the LDR resistance is changed in spice, as soon as the voltage crosses the designed 4V threshold, the digital output voltage toggles on and then off again when it falls below 4V again as designed.

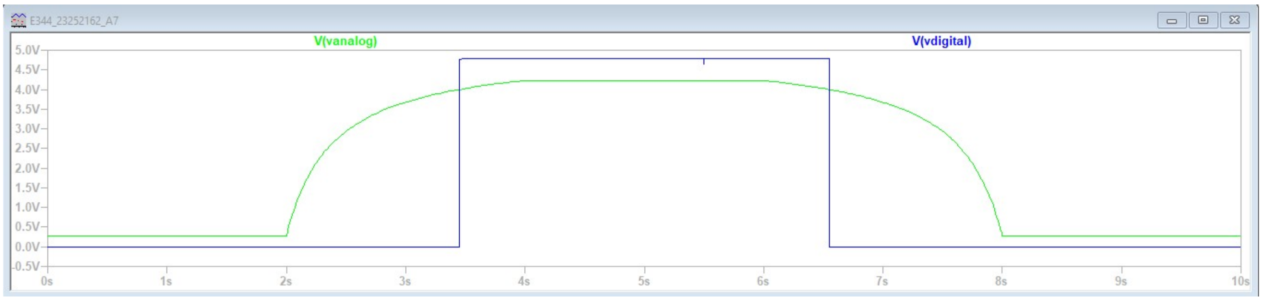


Figure 4.17: LTSpice Graph of Analog Output Voltage vs Digital Output

4.7.2. Measured Results

Table 4.4 shows the measured analog output voltage at different light levels vs the digital output voltage. As designed the analog output voltage is above 4V in light conditions where I would want a lamp on in order to see/read and thus the digital output signal at these conditions is a high.

Light Level	**Analog Output Voltage [V]**	**Digital Output Voltage [V]**
Very Dark	4.88	5.01
Dim	4.06	5.01
Ambient Light	2.97	0
Well-Lit	1.56	0
Very Bright	0.53	0

Table 4.4: SubSystem Results Showing Measured Analog Output Voltage at Different Light Levels vs Digital Output Voltage

4.8. LED Load Control

Figure 4.18 shows that once the light level has become dark enough (indicated to V(digital) going high at around 3.5s) we can now use the user input portion in order to turn on the Load Control signal, thus turning on the Load LEDs. This can be seen by observing that once V(set) goes high the V(loadcontrol) goes high, but the user can also turn off the load LEDs, by pressing the Reset Input and then V(loadcontrol) goes low again.

4.8.1. Simulated Results

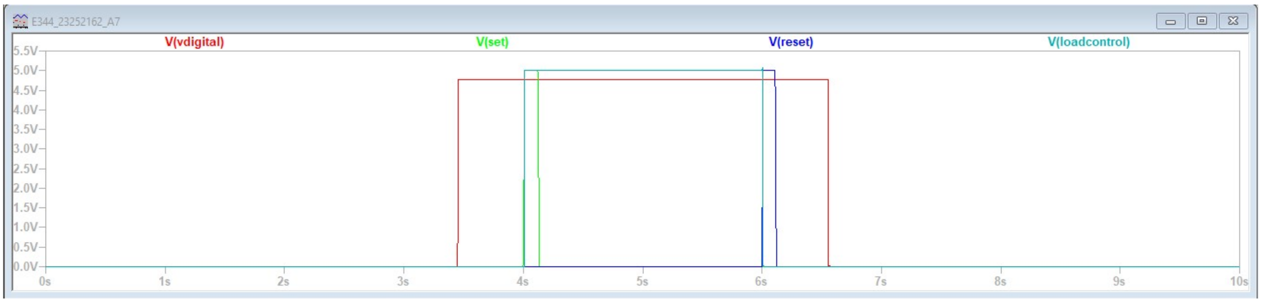


Figure 4.18: LTSpice Graph of Load Control Signal

4.8.2. Measured Results

Table 4.5 show the output of the Load Control Voltage under light/dark conditions and various user input conditions. The Load Control voltage only turns on when it is dark enough and the user input Set button has been pressed. Thus we can see that our design is working as intended.

Light/Dark 0-Light/1-Dark	Set Input [V]	Reset Input [V]	Load Control Voltage [V]
0	0	0	0
0	5.01	0	0
0	0	5.01	0
1	0	0	0
1	5.01	0	5.01
1	0	5.01	0

Table 4.5: Load Control Logic Truth Table

4.9. Pilot Light Control

4.9.1. Simulated Results

Figure 4.19 shows the analog output voltage changing over a range of voltages as the LDR resistance is changed in spice, as soon as the voltage crosses the designed 4V threshold, the pilot light turns on and uses roughly 4mA of current. The pilot led then turns off again once the analog output voltage drops below 4V as designed.

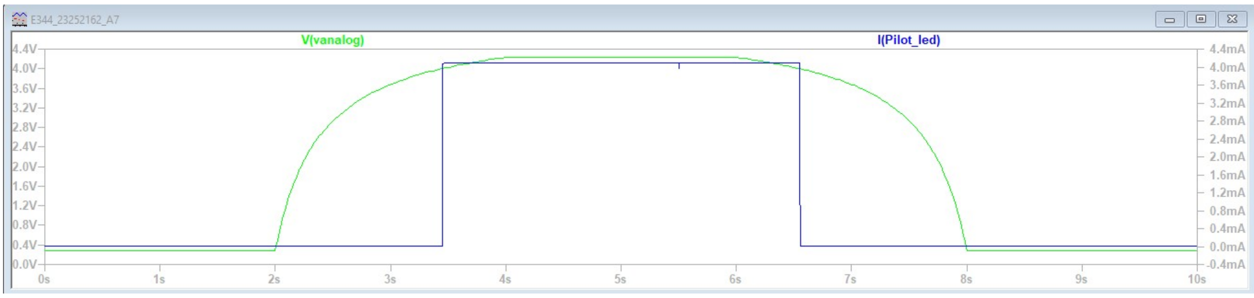


Figure 4.19: LTSpice Graph of Pilot Light Current vs Analog Output Voltage

4.9.2. Measured Results

Light/Dark 0-Light/1-Dark	**Current [mA]**
0	0
1	3.2

Table 4.6: Load Control Logic Truth Table

Chapter 5

System Results

Our system at its core is essential a type of battery management system which will implement charging, discharging, battery protection and measurements. Table 5.1 shows the results of the system's undervoltage protection, hence not allowing the battery to discharge once the voltage falls below 6V. Table 5.2 shows the output of the system measuring the current sensing output in order to determine when the system is charging or discharging and the charging regulator output. Figure 5.1 shows a picture of the complete physically built circuit.

Battery Terminal [V]	**Voltage Over Load [V]**
6.43	6.45
6.2	6.23
5.88	0

Table 5.1: System Results Showing Undervoltage Protection

Charging [Y/N]	**Discharging [Y/N]**	**Current Sense Output [V]**	**Charging Regulator Output [V]**	**LEDs On [Y/N]**
Y	N	2.62	7.18	N
N	Y	1.40	7.18	Y

Table 5.2: System Results Showing When Battery is Charging vs Discharging

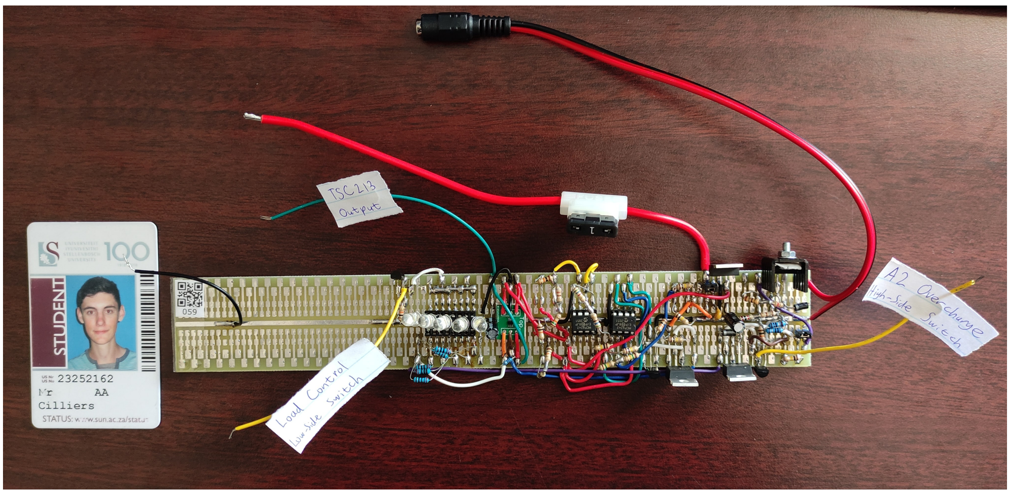


Figure 5.1: Photo of Physical Circuit

Bibliography

[1] A. E. Tutorials, "Solar cell i-v characteristic," https://www.alternative-energy-tutorials.com/photovoltaics/solar-cell-i-v-characteristic.html, 2016.

[2] C. Honsberg and S. Bowden, "Battery characteristics," https://www.pveducation.org/pvcdrom/lead-acid-batteries/characteristics-of-lead-acid-batteries, 2020.

[3] B. University, "Bu-403: Charging lead acid," https://batteryuniversity.com/article/bu-403-charging-lead-acid, Nov. 2019.

[4] *ATOF® BLADE FUSE RATED 32V*, ATOF® BLADE FUSE RATED 32V datasheet, Littelfuse, 2012.

[5] *1.2 V to 37 V adjustable voltage regulators*, LM317 Datasheet, STMicroelectronics.

[6] *LM2940x 1-A Low Dropout Regulator*, LM2940x Datasheet, Texas Instruments.

[7] U. D. of Energy, "Solar photovoltaic cell basics," https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics.

[8] ——, "Solar photovoltaic technology basics," https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics.

[9] Geotherm, "Polycrystalline solar cells vs monocrystalline: Which is better?" https://geothermhvac.com/mono-vs-poly-better/#:~:text=Polycrystalline%20panels%20have%20lower%20efficiency,less%20power%20per%20square%20foot.

[10] Kurpaska, Slawomir, Knaga, Jaroslaw, Latala, Hubert, Sikora, Jakub, and Tomczyk, Wieslaw, "Efficiency of solar radiation conversion in photovoltaic panels," *BIO Web Conf.*, vol. 10, p. 02014, 2018.

[11] A. Beaudet, "How do i read the solar panel specifications?" https://www.altestore.com/blog/2016/04/how-do-i-read-specifications-of-my-solar-panel/, Apr. 2016.

[12] A. E. Tutorials, "Solar photovoltaic panel," https://www.alternative-energy-tutorials.com/photovoltaics/photovoltaic-panel.html, 2014.

[13] *SLP005-12 PV Module Product Specification Sheet*, SLP005-12 PV Module datasheet, ACDC Dynamics.

[14] C. Honsberg and S. Bowden, "Open-circuit voltage," pveducation.org/pvcdrom/solar-cell-operation/open-circuit-voltage, 2020.

[15] ——, "Short-circuit current," https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current, 2020.

[16] ——, "Lead acid batteries," 2020.

[17] ——, "Battery capacity," https://www.pveducation.org/pvcdrom/battery-characteristics/battery-capacity, 2020.

[18] ——, "Other electrical battery parameters," https://www.pveducation.org/pvcdrom/battery-characteristics/other-electrical-battery-parameters, 2020.

[19] *Sealed Lead-Acid Battery General Purpose Specification*, Sealed Lead-Acid Battery 537-5422(6V4.0Ah) datasheet, RS Pro.

[20] F. Batteries, "What is depth of discharge and why is it so important?" https://federalbatteries.com.au/news/what-depth-discharge-and-why-it-so-important, May 2019.

[21] E. Tutorials, "The mosfet," https://www.electronics-tutorials.ws/transistor/tran_6.html, Jul. 2021.

[22] *μA7800 SERIES POSITIVE-VOLTAGE REGULATORS*, LM7805 Datasheet, Texas Instruments.

[23] *N-Channel Enhancement Mode Field Effect Transistor*, 2N7000 / 2N7002 / NDS7002A Datasheet, ON Semiconductors.

[24] *FUSEOLOGY*, FUSEOLOGY, Littelfuse, 2012.

[25] *50 μA, 550 kHz Rail-to-Rail Op Amp*, MCP6242 Datasheet, Microchip.

[26] *High/low-side, bidirectional, zero-drift current sense amplifiers*, TSC210, TSC212, TSC213 Datasheet, STMicroelectronics.

[27] P. B. Components, "Capacitor selection for coupling and decoupling applications," https://passive-components.eu/capacitor-selection-for-coupling-and-decoupling-applications/, Apr. 2020.

[28] ——, "What-electronics-engineer-needs-to-know-about-passive-low-pass-filters," https://passive-components.eu/what-electronics-engineer-needs-to-know-about-passive-low-pass-filters/, Dec. 2018.

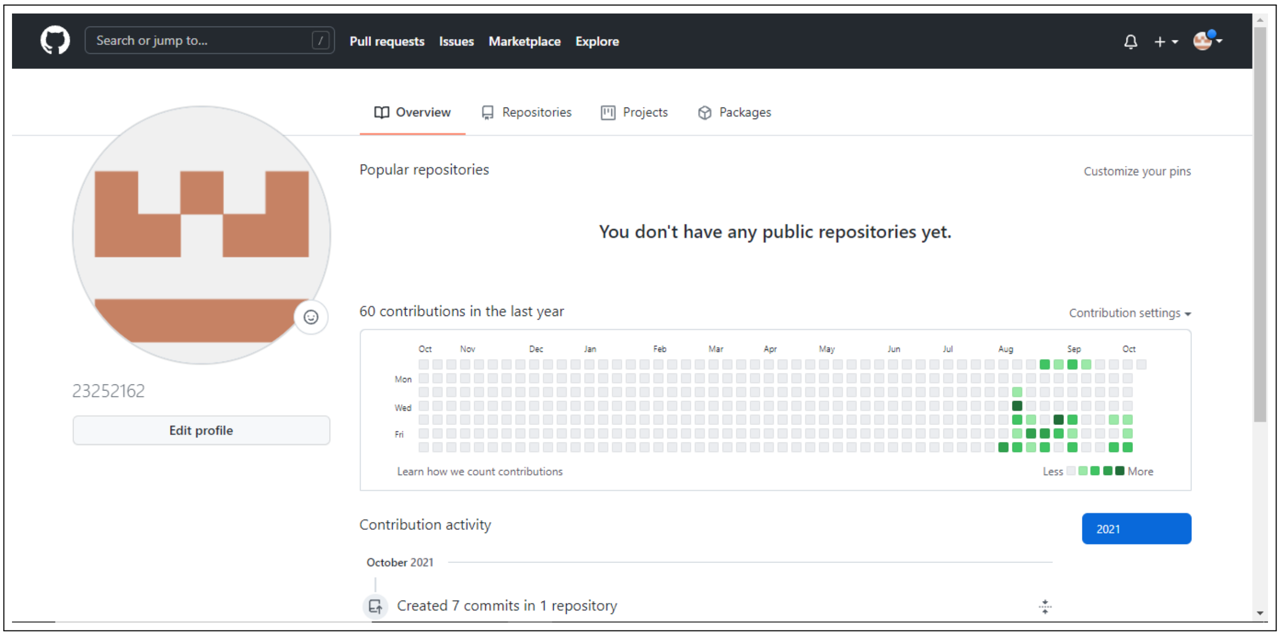
[29] *Beetle SKU:DFR0282*, Beetle Datasheet, DFROBOT, 2017.

[30] A. RUBASINGHE, "Use an op amp as a set/reset flip-flop," https://www.edn.com/use-an-op-amp-as-a-set-reset-flip-flop/, May 2014.

[31] mert (https://electronics.stackexchange.com/users/17120/mert), "And gate design using mosfets," Electrical Engineering Stack Exchange, uRL:https://electronics.stackexchange.com/q/51837 (version: 2013-01-05). [Online]. Available: https://electronics.stackexchange.com/q/51837

Appendix A

GitHub Activity Heatmap



Appendix B

Additional Diagrams

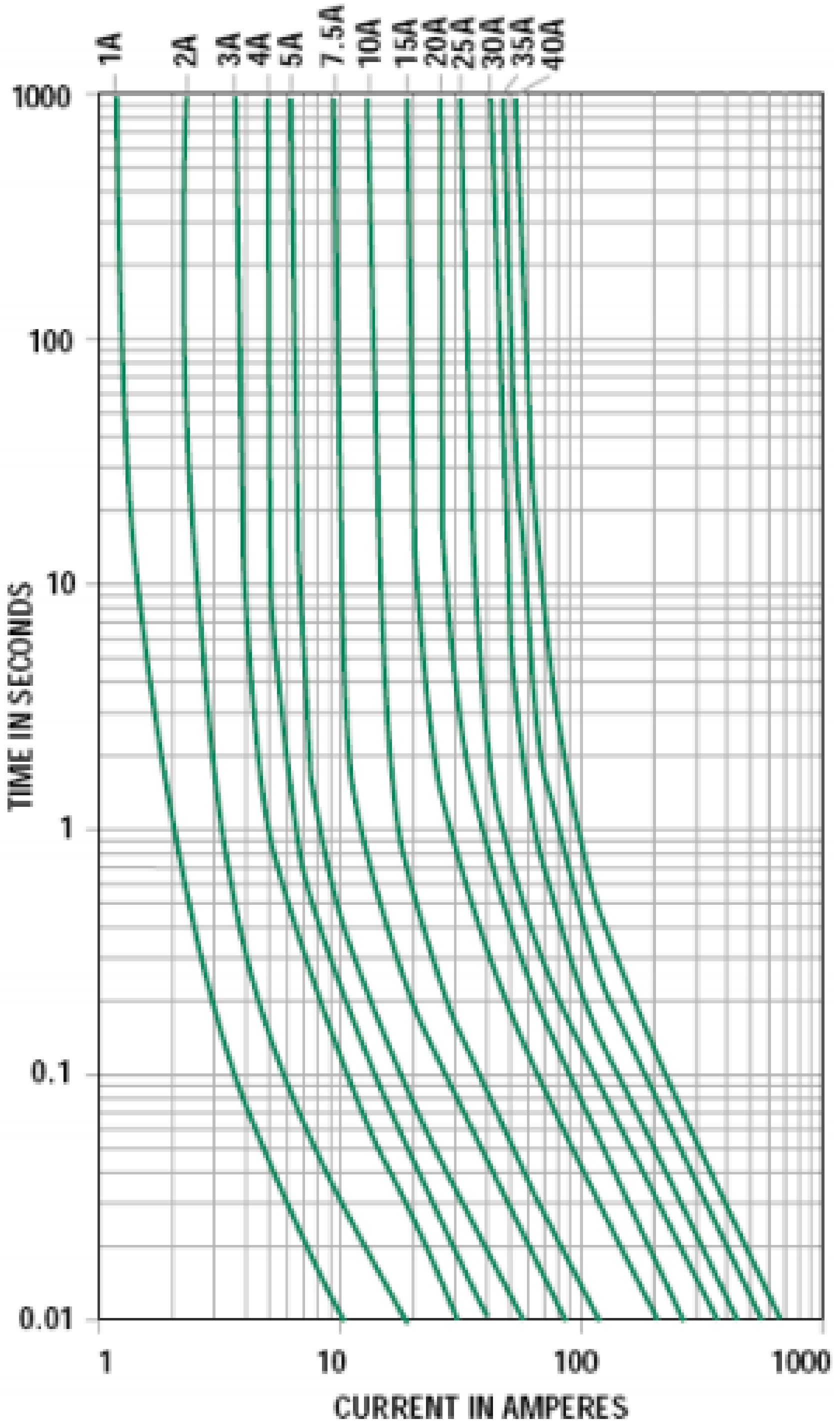


Figure B.1: Time-Current Characteristics [4]

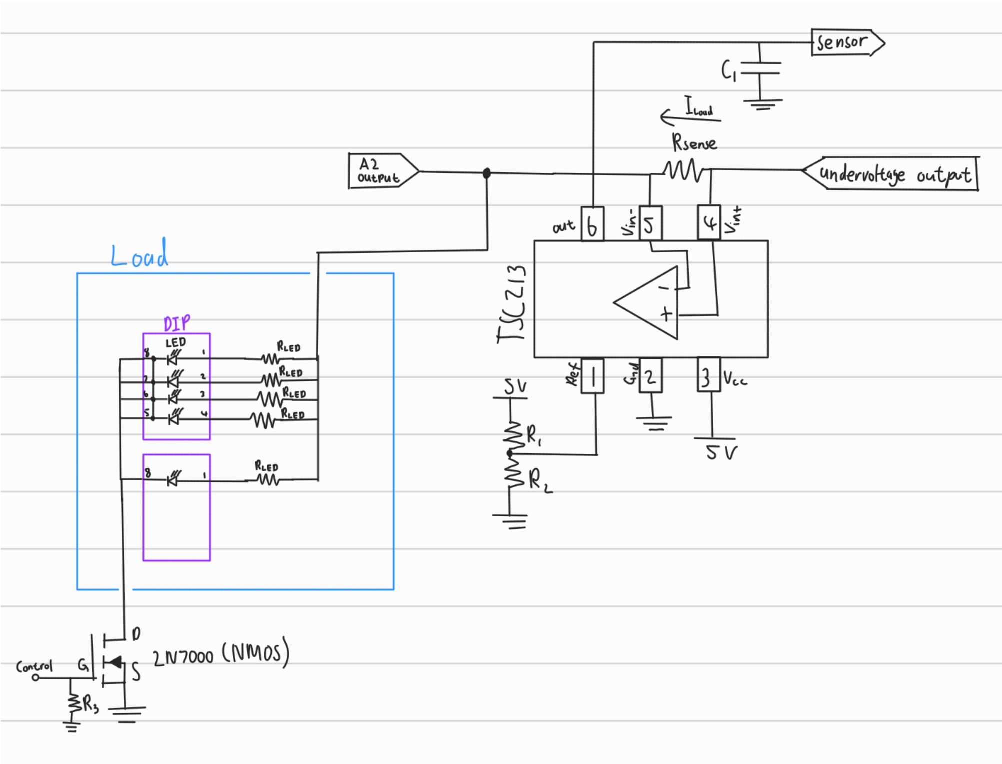


Figure B.2: Full Circuit Diagram of Bidirectional Current Sensor and Load