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E344 Project

Johann Ruben van Tonder
22569596

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.

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Nomenclature

Variables and functions

V	Volt
I	Current
R	Resistance
P	Power
A	Ampere
Ω	Ohm
$Pmax$	Maximum power
Voc	Open circuit voltage
Isc	Closed circuit current
Wh	Watts per hour
Ah	Ampere hour
r	Internal resistance
F	Farad
Hz	Hertz

Acronyms and abbreviations

SOC	state of charge
DOD	depth of discharge
SOH	state of health
PV	photovoltaics
STC	standard test conditions
MOSFET	metal-oxide-semiconductor field-effect transistor
NMOS	N-channel metal-oxide-semiconductor
PMOS	P-channel metal-oxide-semiconductor
MPP	maximum power point
AC	alternating current
DC	direct current
RDS	static drain-source-on-resistance
KVL	Kirchhoff's voltage law
Op-amp	Operational Amplifier
LED	Light-emitting-diode
ADC	analog-to-digital converter
LDR	Light dependent resistor
OP	Overcharge Protection
IDE	integrated development environment
GUI	Graphical User Interface

Chapter 1

Literature

1.1. Battery

The battery that is used in this project is a 6 V, 4 A h [1] sealed lead acid battery. Lead acid batteries have required charging and discharge specifications, to safely use it and not damage the battery.

Charging - the current rate at which the lead acid battery should be charged with, is determined by its capacity. Our battery has a capacity of 4 A h. The battery should be charged with a maximum current of 0.1 C, which is 10 % of the battery's capacity. The maximum discharge current is therefore 400 mA. The voltage level the battery should be charged to is read from the datasheet. The voltage level is 7.2 V. The voltage regulation circuit is designed according to these voltage and current values.

Discharging - the battery will only be discharged at a rate of approximately 100 mA. This is well within in the limits of safely discharging the battery. Even though the rate of discharge is not very high the battery should not be discharge past 6 V. The battery should also never be discharged past 10 to 20% of its capacity. For every type of lead acid battery this value will be different. Figure 1.1 show the rates of discharge and how long the battery can be discharged at that rate.

Batteries also tend to self discharge over time. If the battery was stored for a long time its open circuit voltage should be measured before it is charged. The storing temperature will

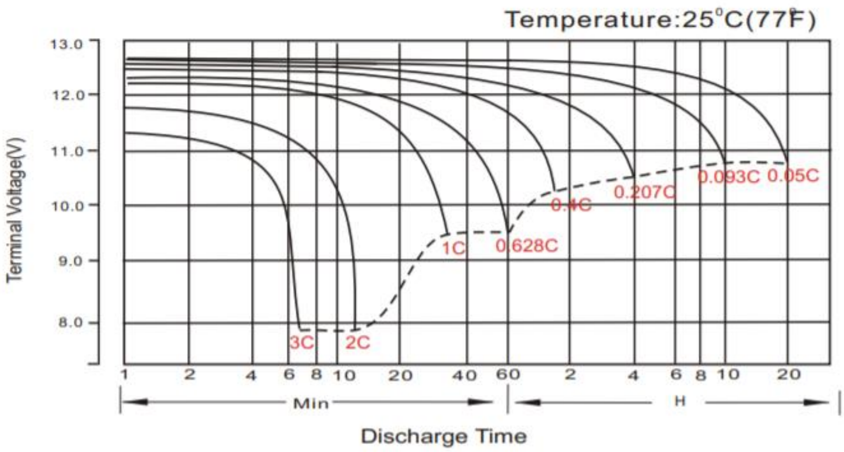

Figure 1.1: Battery Discharge Curve [1]

also have an effect on the battery. Do not store lead acid batteries at very high or very low temperatures, the ideal temperature is 20 to 25°C.

1.2. Solar photovoltaic cells and solar modules

PV cells and solar modules convert sunlight to electricity. In order to harness the generated electricity from the solar modules you need to understand the following concepts. First you need to know how electricity is created inside the PV cells. If sufficient sunlight hits the PV cells the free electrons inside the cells gain energy and can move around. Connecting a PN-junction to the cells causes the electrons to flow in a certain direction. This creates the conventional flow of current inside a PV cell. When connection a circuit/battery to the PV cell the current can be harnessed to charge a battery or power a circuit.

Open Circuit Volatge - Each PV cell inside a solar module has a open circuit voltage. This is the voltage measured when no current is flowing. The open circuit voltage of the solar PV module will be the open circuit voltage of each PV cell superimposed. The amount of PV cells will therefore determine the open circuit voltage of the solar PV module.

Short Circuit Current - The short circuit current is the current flowing from a solar PV module when the voltage over the solar PV module is zero. The short circuit current is the maximum current the solar PV module can supply.

There is a very important relationship between Voc and Isc, this relationship determines the amount of power that can be supplied by a solar module as shown in Figure 1.2

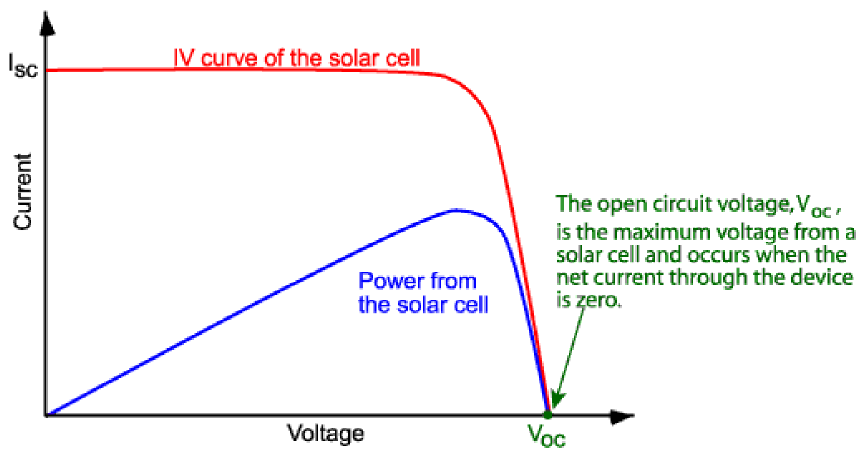

Figure 1.2: The Relationship between Isc and Voc [2].

The blue line in Figure 1.2 indicates the power being supplied by the solar module. If the voltage is too low or too high the power from the solar module will not be sufficient to power any electrical device. The regions in which you want to operate is where the blue line is near its peak. This brings into consideration the MPP [3].

MPP - The MPP is a point on the power curve that has the highest value of the product of the corresponding voltage and current. When operating a solar PV module the current and voltage characteristics of the circuit should be at this point.

All the necessary values of a solar module can be read from the datasheet of a solar module, like the Voc, Isc, $Pmax$, voltage at $Pmax$ and current at $Pmax$. Note that this measurements are done at STC. STC are at 25 °C, an irradiance of $1\,\mathrm{kW\,m^{-2}}$ and air mass of 1.5 AM for all solar PV modules.

1.3. Fuse

When deciding what fuse size will be sufficient to ensure the safety of your battery you need to consider the following. At what temperature is the circuit/battery going to discharge and charge. What is circuit current consumption going to be and at what current rate is the battery going to be charged at. Then also take into account what is the discharge current when the battery is short circuited, because this is what the fuse should protect the battery against.

For this project the battery is charged with a maximum of 400 mA, the current through the load is designed for 100 mA. The fuse should take into account that the maximum current flowing through it will be 400 mA. The rule of thumb is to choose a fuse so that the current flowing through the fuse should never be more than 75 % of its rated value and that when the battery is short circuited, the fuse should blow within 10 ms.

Chapter 2

System Design

The development of the project so far is shown in Figure 2.1. The system consist of a DC power supply either in the form of an AC/DC adapter or a solar PV module. The voltage and current is then regulated by a voltage regulator according to the battery voltage and battery charging current. The load can be powered from the Voltage regulator or the battery. When the power supply is not connected the battery will discharge into the load. The undervoltage protection protects the battery from discharging to much and the overcurrent protection protects the battery from possible shortcircuits. The 5 V regulator is powered from the battery and is used to power the current sensing and undervoltage protection circuits.

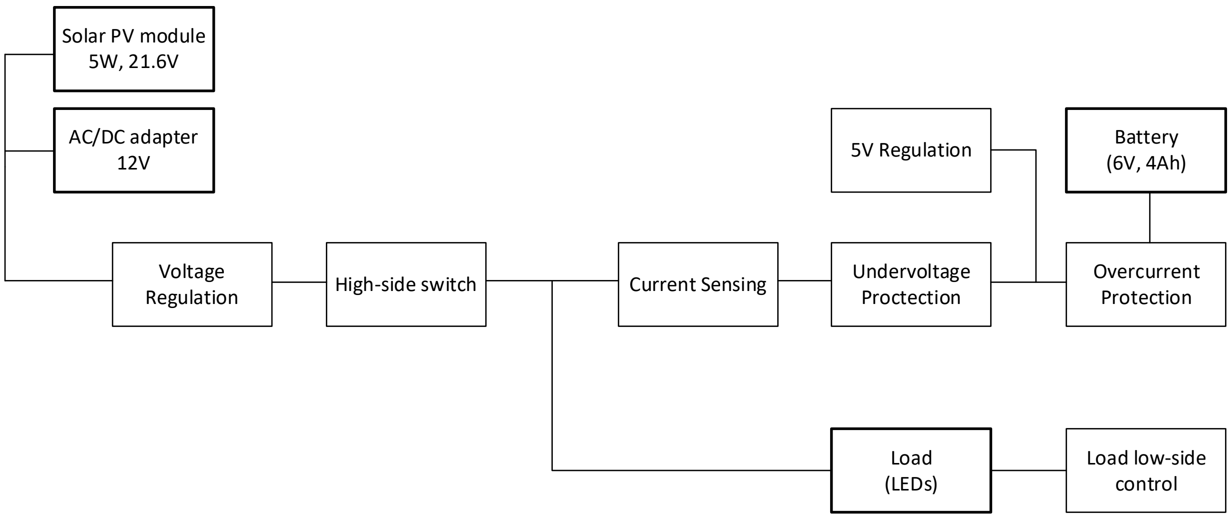

Figure 2.1: System Diagram of Project

2.1. Voltage Regulation

The voltage regulation is done using a LM317T [4] linear voltage regulator. The LM317T takes the input from the AC/DC adapter or the solar PV module and then regulates it to the appropriate voltage and current for the battery.

2.2. High-side and Low-side switching

The high-side and low-side switching is built using NMOS [5] and PMOS [6] transistors. The switches are controlled by external 5 V control signals. For the high-side switch, the NMOS transisotr switches on the PMOS transistor and for the low-side switch only a NMOS is used.

The control signals that control whether the switches are on or off are 5 V signal for on and a 0 V signal for off.

2.3. 5 V Regulation

The 5 V regulator used is the LM2940 [7]. The LM2940 is used due to its low voltage drop and its set output of 5 V. This enables it to be powered from the battery's side, where the battery voltage can drop as low as 6 V. The dropout voltage for the LM2940 is typically 0.5 V. The 5 V is used as die Vcc rail for the op-amps in the protection and sensing circuits.

2.4. Undervoltage Protection and Overcurrent Protection

The undervoltage protection circuit consist of three MCP6241 [8] op-amps. The aim of the undervoltage protection circuit is to protect the battery from discharging below 6 V. The output of the op-amps is connect to a NMOS transistor and the NMOS transistor controls a PMOS transistor. When the voltage over the terminal of the battery is to low the NMOS transistor will turn off and stop the flow of current out from the battery by switching off the PMOS transistor. The switching circuit inside the undervoltage protection will not prevent the battery from charging due to the body diode of the PMOS. For overcurrent protection a fuse is placed in series between the battery and the undervoltage protection circuit.

2.5. Current Sensing

The current sensing measures the current flowing into or out of the battery. This is done through a very low ohmage resistor and then by amplifying the the voltage drop over the resistor using a TSC213 [9] op-amp which has a set gain of 50.

2.6. Load

The load consists of five ultra bright clear LEDs [10]. The LEDs are placed in parallel with each LED having its own current limiting resistor. When the battery if fully charged, or when powered from the voltage regulator, the LEDs will have a current consumption of around 100 mA. Each LED will have a current of 20 mA.

Chapter 3

Detailed Design

3.1. Voltage Regulation

The LM317T will function as a charging regulator as it is capable of regualting current and voltage. The template used for desiging the charging regulator is shown in Figure 3.1. To determine the output voltage of the regulator you need to work back from the battery to the output. The output value should be calculated when the battery is fully charged. From Section 1.1 you know this value is 7.2 V, the voltage drop over the high-side switch will be approximately 0.4 V due to the forward voltage of the diode. The voltage drop Vsg is neglectful. This means the output voltage should be 7.6 V. The current $Iadj$ is define to typically be 50 µA. The minimum load current Io required to keep the LM317T on, is typically 3.5 mA. The $Vref$ voltage is 1.25 V, this is the voltage between the Output and Adjust node. Therefore if there is minimum current flowing to the battery, assume its zero, then the minimum current should flow through the resistor R1 and R2. The value calculated for R1 is 357 Ω. Now using equation 3.1 where the output is chosen to be 7.5 V, R2 is calculated as 1757 Ω.

$$Vo = Vref \times (1 + R2/R1) + Iadj \times R2 \tag{3.1}$$

The maximum charging current should be 400 mA when the battery is empty. The voltage of the battery when empty is 6 V. To limit the current a resistor R3, is placed between the output of the regulator and the node connected to the high-side switch. To calculated the value of R3, start by taking the battery voltage as 6 V, then work back to the node just after R3. The voltage drop over the high-side switch is 0.4 V. This means the voltage at the node,

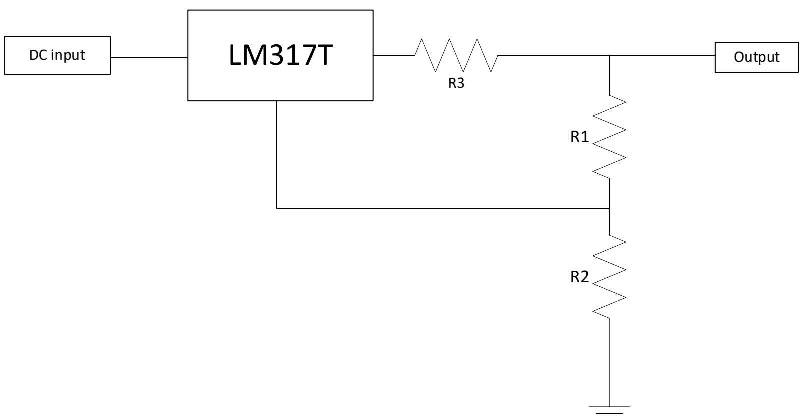

Figure 3.1: Template for charging regulator

above R1, will be 6.4 V. By taking a KVL, resulting in equation 3.2.

$$Vref + VR1 + VR3 = 0 \tag{3.2}$$

Knowing that the maximum current should be limited to 0.4 A. The value R3 is calculated as 0.381 Ω. After simulation the value is adjusted to 0.4 Ω.

The LM317T regulator will dissipate a lot of power. The heat will influence the current and voltage control of the regulator. The power dissipated by the regulator as well as resistors R1,R2 and R3 are shown in Table 3.1. The LM317T will dissipated the most power when the

Table 3.1: V,I and P measurements.

	V [V]	I [A]	P [W]
LM317T with PV module as input	9.5	0.29	2.755
LM317T with AC/DC adapter as input	4.6	0.387	1.7802
R1	0.19	0.0031	0.003
R2	5.35	0.0031	0.017
R3	0.16	0.387	0.062

PV module is used as the input and therefore that power value should be used in thermal analysis. The values for the thermal resistances are found in the datasheets of the components. The safe operating temperuture of the LM317T is −55 to 150°C. The temperature of the LM317T exceeds its safe operating temperature as shown in Table 3.2. It needs a heat sink [11] to better regulate its temperature. In this case we are given a heat sink so we need to calculate if it is sufficient in regulating the temperature of the LM317T. The heat sinks thermal resistance is very dependent on the mounting surface temperature. To accurately calculate the thermal resistance you need to asses the conditions under which your circuit will operate. It is obviously that our circuit will be used mainly in the outdoors due to the solar PV module. The mounting surface temperature can be assumed to reach temperatures as high as 40 °C. This results in a thermal resistance of 10 °C W^{-1} between the sink and the air. The thermal resistance between the case and sink can be approximated by worst case scenario to be 4 °C W^{-1} [12]. The newly calculated temperature of the LM317T regulator is shown in Table 3.2.

Table 3.2: Junction temperature of LM317T

	Temperature [°C]
Before heatsink ($Tamb$ = 40°C)	191.53
After heatsink ($Tamb$ = 40°C)	92.345

For the 5 V LM2940C regulator, the specific regulator is chosen for its low dropout voltage of 0.5 V. The regulators input can be connected to the battery and the voltage regulator will be able to regulate even if the voltage of the battery is below 6 V. Meaning the undervoltage

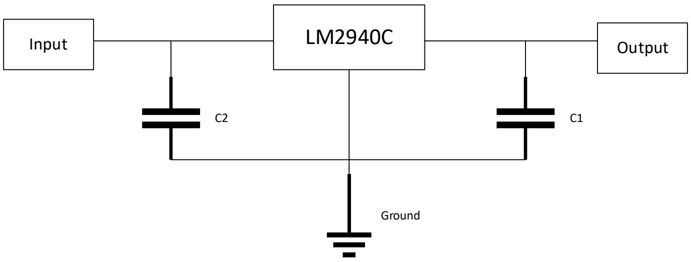

Figure 3.2: 5V regulator circuit

protection circuit will still function normal and protect the battery from discharging below 6 V. The 5 V regulator circuit is shown in Figure 3.2, two capacitors are placed in parallel with the input and output of the regulator to improve transient response of the regulator.

3.2. High-side switch

The design of the high-side switch consist of a PMOS and NMOS transistor. The reason for using two MOSFETs is due to the current capabilities of the NMOS transistor, which can only sustain a current value of 100 mA. However the PMOS can sustain current values as high as 12 A. Because our battery will be charging at currents as high as 400 mA, which is too high for a NMOS transistor to handle a PMOS transistor is used. But due to the structure of a PMOS transistor it requires a voltage drop from the source to the gate. The only way to achieve this is to use a NMOS transistor along side the PMOS transistor.

The NMOS transistor will act as a switch for turning on the PMOS transistor. The NMOS transistor is controlled by a 5 V control signal applied at the gate. In order to turn on the PMOS transitor, a voltage drop over the source to gate should be in the range of 4 to 20 V. The output of the voltage regulator will be designed to be roughly 7.5 V. Therefor a resistor can be placed between the source and gate of the PMOS transistor, that connects to the NMOSs drain. This will cause a sufficient voltage drop when the NMOS transitor is turned on. The circuit is shown in Figure 3.3. The switch is placed between the output of the voltage regulator and the battery. The values for the R1 should be big enough to limit the current to micro ampere. The value can range from 10 to 200kΩ. The value of R2 does not matter that much, the purpose of R2 is to connected the gate of the NMOS transistor to ground in the physical build of the circuit. This ensures that the NMOS transisor will turn off.

A diode is placed between the drain of the PMOS transistor and the output node to stop current from flowing into the high-side switch when the voltage regulator is off. Without the diode the current would have been able to conduct through the body diode of the PMOS transistor. The switch is called a high-side switch because it is connected to the high-side of the circuit and the load is connected in between then PMOS transistor and ground.

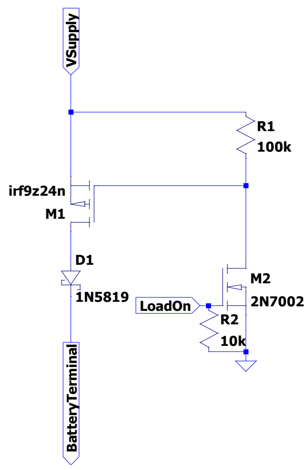

Figure 3.3: High-side switch circuit

3.3. Overcurrent Protection

The temperature at which our battery will discharge is approximately around 40 to 50 °C. The temperature re-rating curve [13], shows how the temperature will effect the fuse rating. At a temperature of 50 °C the fuse will be rated at 95 % of its original rated value. The current draw from the circuit should not exceed 100 mA. The battery is designed to charge at 400 mA and any charge currents higher than that will damage the battery. The short circuit current draw from the battery is 60 A for 5 s. The time it take for the fuse to burnout should be less than 10 ms. Equation 3.3 shows how the time it takes to burn the fuse can be calculated, $Irated$ is the rated ampere obtained from the datasheet of the fuse and $Ishort$ is the short circuit current obtained from the battery datasheet.

$$Time = \frac{Irated^2}{Ishort^2} \tag{3.3}$$

If a 1 A rated fuse is used the time it takes to burn out is, 0.11 ms. If a 5 A rated fuse is used the time is 0.4 ms. This is also acceptable, but this means that the battery will be able to charge at currents as high as 5 A and seeing that our battery will only charge at 400 mA the 1 A rated fuse is the correct size for our battery. Figure 3.4 shows how the fuse will fit in the project and connect to the battery.

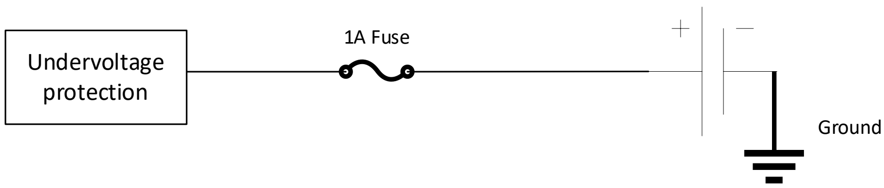

Figure 3.4: Fuse placement in circuit

3.4. Undervoltage Protection

To implement undervoltage protection for the battery it is necessary to develop a circuit that monitors the battery voltage level. When the battery is above the threshold of 6 V the battery should be able to discharge into the load and when the battery terminal is below 6 V it should not be able to discharge until the battery voltage reaches 6.2 V again. To implement this a op-amp circuit is used [14]. The circuit will use the op-amps as voltage comparators. Voltage comparator circuits compares the voltage of Vin, the battery voltage, to a $Vref$ voltage. The op-amp is configured as a schmitt trigger. A schmitt trigger is an op-amp that is either a high of 5 V or a low of 0 V in our implementation of it. The circuit diagram is shown in Figures 3.5,3.6 and 3.7 . Op-amp U1 is a voltage follower with the positive input to the op-amp being the $Vref$ that comes from the voltage division circuit using R1 and R2 resistor to bring the voltage level to 2.5 V, to be within the common and differential mode input voltage ranges. The voltage follower acts as a high impedance so the feedback loop from op-amp U2 does not influence the $Vref$ node.

To stop the battery from discharging at 6 V and only let it resume its discharge at 6.2 V, hysteresis should be implemented. This is when a feedback resistor is connected from the output to the $Vref$ input node. This enable the $Vref$ voltage to swing up and down depending on what the output of the schmitt trigger is. The op-amp U2, in figure 3.6 shows this implementation. The battery voltage at 6.1 V is brought down to match the voltage of $Vref$ of 2.5 V. This is done using resistor R3 and R4. The feedback resistor R6 and the R5 resistor form the feedback ratio β. Equation 3.5 shows the relationship between R5 and R6 for determining the ratio β. The ratio β is then used to determine the value of the hysteresis voltage shown in equation 3.4.

$$Vhysteresis = 2 \times \beta \times Vcc \tag{3.4}$$

In op-amp U2, the $Vhysteresis$ value is added to the $Vref$ when the output is 0 V and will be subtracted when the output is 5 V. The ratio of β is chosen to be 0.005. This means the $Vref$ voltage will swing between 2.45 V, which is equivalent to a battery voltage of 5.978 V and 2.55 V,which is equivalent to a battery voltage of 6.22 V.

$$\beta = \frac{R5}{R5 + R6} \tag{3.5}$$

The last op-amp U3 shown in Figure 3.7 is a inverting schmitt trigger without a feedback resistor. Due to op-amp U2 being an inverting schmitt trigger. The output should be inverted to have the correct logic so that the high-side switch functions correctly. The output of op-amp U2 is connected to the negative of the op-amp U3 and the positive is connect to a $Vref$ of 2.5 V. The output of the op-amp U3 is 5 V when the input $Vout1$ is 0 V and when the input $Vout1$ is 5 V the output is 0 V.

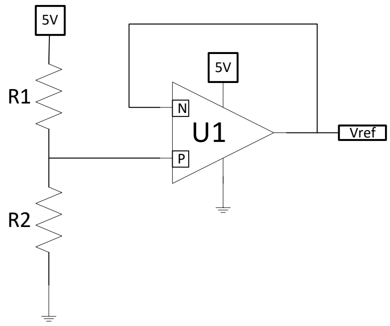

Figure 3.5: $Vref$ conditioning and voltage follower

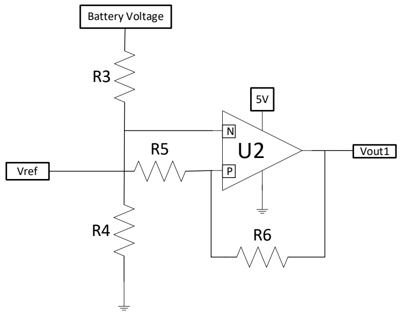

Figure 3.6: Battery voltage conditioning and Schmitt trigger

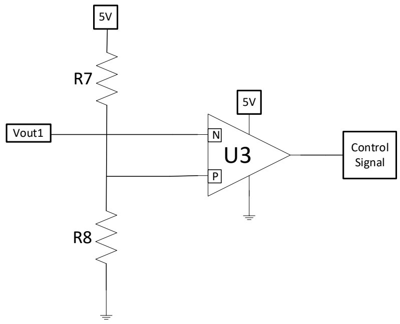

Figure 3.7: Inverting Op-amp

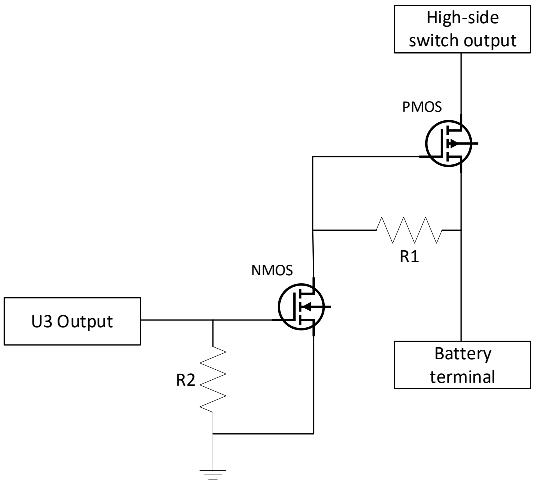

Figure 3.8: High-side switch for undervoltage protection

The output of op-amp U3 is connected to the gate of the NMOS transistor as shown in Figure 3.8. The resistor R2 is there to connect the gate of the NMOS to ground so that the NMOS switches off properly, the value can be in the range of 10 to 100kΩ. Resistor R1 creates the voltage drop between the source and the gate of the PMOS, which is required for the PMOS to turn on. The value of the resistor should be in the kΩ range. The required voltage drop over R1 should be bigger than 4 V for the PMOS to turn on. The voltage drop over R1 will always be bigger than the required Vsg turn on voltage because the voltage drop over the NMOS is neglectable. The body diode of the PMOS allows the battery to charge whenever the high-side switch output is higher than the Battery terminal voltage.

This completes the design for the battery undervoltage protection. The circuits stop the battery from discharging past 6 V and will only allow the battery to start discharging again if the battery reaches 6.2 V. The circuit will still allow the battery to charge independent of the battery terminal voltage as longs as the high-side switch output is high.

3.5. Current Sense

The Vcc voltage of the TSC op-amp is 5 V. The op-amp has a set gain of 50 and the $Rshunt$ resistor was given and is 0.1 Ω. When designing the $Vref$ voltage, it is important to know the current ranges that will flow through the resistor. The maximum positive current, this means current flowing from the charging circuit to the battery, is 400 mA. The maximum negative current, the current flowing from the battery to the load, is 100 mA. To safely operate the TSC op-amp I designed for a current ranges of −150 to 450 mA.

For the output of the TSC op-amp to swing equally close to its rail voltages. The $Vref$ can be calculated by using equation 3.6. If you substitute the $Iload$ into the equation with $Vref$ set to zero. The swing of the output is calculated as 3 V. This means the output needs to be 1 V when −150 mA is flowing through the resistor and be 4 V when 450 mA is flowing through the resistor. The negative swing can be calculated as −0.75 V by adding that to the minimum output voltage, yields 1.75 V, which will be the $Vref$ required for equal swing in the output of the TSC op-amp. The 5 V regulators output is used through voltage division to get the $Vref$ value. The resistor values should be in the kΩ range to limit the current flowing through the circuit.

$$OutputVoltage = Rshunt \times Iload \times 50 + Vref \tag{3.6}$$

The output of the TSC op-amp will also amplify any noise on the $Vref$ or on the positive and negative inputs of the op-amp. To attenuate the noise a bypass capacitor or multiple should be connected to the output of the TSC op-amp. Figure 3.10 shows how the bypass capacitor should be connected. Multiple bypass capacitors can be connected to improve the noise suppression on the output voltage of the TSC op-amp. The noise should be measured and then capacitors should be added until the noise suppression is sufficient. The bypass capacitor was simulated in spice, but the spice model is not a accurate representation of the TSC op-amp so the capacitor value in practical circuit might differ from the capacitor value in spice.

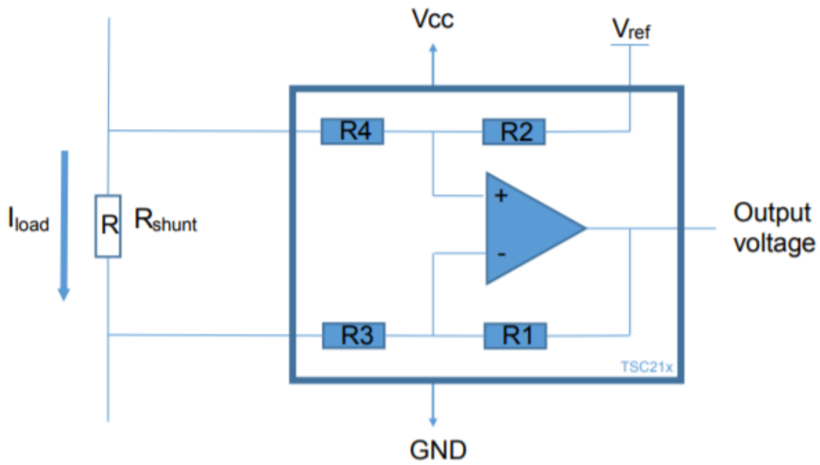

Figure 3.9: TSC213 circuit diagram

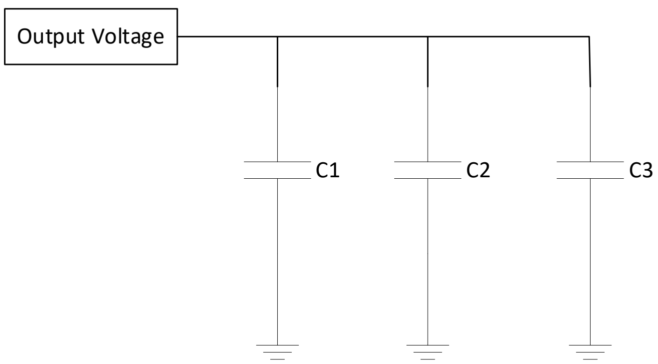

Figure 3.10: Bypass capacitors connected to output

3.6. Low-side Switch

To design for a maximum current of 20 mA, a resistor R2 should be place in series with each LED. The voltage at the positive leg of the LED will be 7.2 V and the forward voltage of the LED at 20 mA will be 3.2 V. The required resistor value is calculated to be 200 Ω. For the low-side load control a simple NMOS transistor can be used as a switch. The NMOS transistor is controlled by 0 to 5V. The Vgs typical turn on voltage is 2.1 V. Thus if a 5 V signal is applied at the gate of the NMOS transistor, the transistor will turn on and allow current to flow through the load. The resistor R1 is added to make sure the NMOS transistor turns off when the control signal is no longer high. The NMOS transistor has a maximum current rating of 200 mA, which is higher than the total load current. Figure 3.11 show the circuit diagram of the low-side switch. The resistor R2 values that was used was 220 Ω instead of 200 Ω due to the availability in the laboratory.

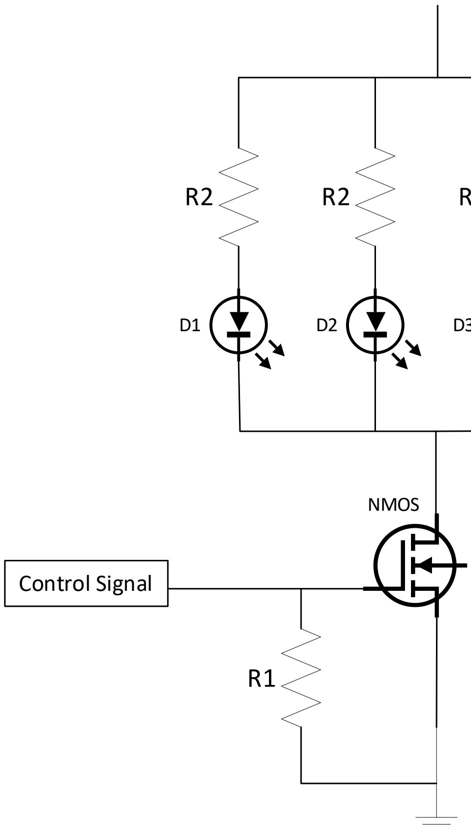

Figure 3.11: Caption

3.7. Supply Voltage Measurements

To design the supply voltage measurements you need to consider what are the range of the supply voltage that needs to be measured and what is the range of the ADC. The supply voltage ranges from 0 to 22.3V, this is the measured value from the solar PV module. The AC/DC adapter has a measured range of 0 to 12.8V. The voltage measurement should be able to measured up to the 22.3 V of the solar PV module. The ADC of the beetle [15] has a range of 0 to 5V. This means that the supply voltage should be scaled down from 0 to 22.3V to 0 to 5V. The ADC has a resolution of 1024 bits. This means the each bit represents a swing of 4.88 mV.

The input voltage is scaled down with a voltage divider circuit shown in Figure 3.12. The lowpass filter is responsible for filtering out any noise that is apparent on the input of the solar PV module or AC/DC adapter. The noise on the input to the ADC should be less than the 4.88 mV, otherwise the ADC measurement will not be accurate. To calculate the resistor values R1 and R2, equation 3.7 is used where $Vadc$ is equal to 4.75 V and $Vinput$ is equal to 22.3 V. By choosing R1 to be any value in the range of kΩ, the value of R2 can be calculated. R1 and R2 should be large enough to limit the amount of current flowing through R1 and R2 to µA.

$$Vadc = \frac{R2}{R1 + R2} \times Vinput \tag{3.7}$$

$$fcut - off = \frac{1}{2 \times pi \times R1||R2 \times C} \tag{3.8}$$

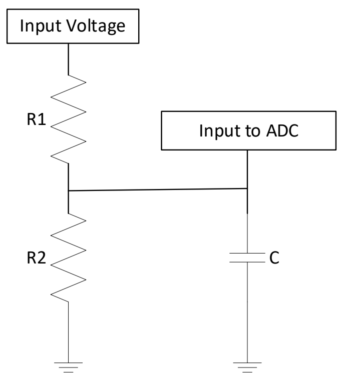

Figure 3.12: Voltage divider and Lowpass filter circuit

The value of the capacitor can be calculated by measuring the noise on the AC/DC adapter and the solar PV module. The switching harmonics of a typical switch-mode power supply, which is apparent when powering the system from the AC/DC adapter, is around 20 to 1000kHz [16]. The noise on the solar PV module can be measured but will be less than the noise on the AC/DC adapter. Thus if the lowpass filter is designed to have a cut-off at 50 Hz it should be sufficient in attenuation the noise on the input. Equation 3.8 shows how the value of the capacitor can be calculated.

3.8. Battery Voltage Measurements

To measure the battery voltage a similar method to Chapter 3.7 is followed, by converting the possible ranges of the battery to a suitable level for the ADC. The battery can be assumed to never be disconnected. This means the battery will typical range from 5.9 to 7.3V. To ensure that the ADC is not clipping the actual voltages of the battery, a 0.2 V is added to the upper and lower limit when calculating the ADC range. The same ADC range of 0 to 5V and resolution of 1024 bits are applicable again as specified in Chapter 3.7. Due to the battery voltage ranging from 5.7 to 7.5V it would be unnecessary to design the measurement circuit to measure below or higher than these values. Therefore the circuit required to measure the battery voltage should zoom in on the range from 5.7 to 7.5V allowing for the ADC resolution to be at its maximum which allows for better signal processing. The circuit used to achieve these specifications is a differential amplifier [17].

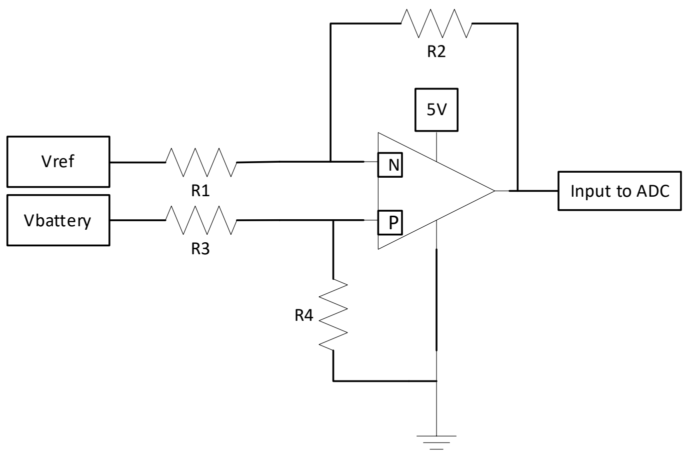

Figure 3.13: Circuit of Differential Amplifier

Figure 3.13 shows the implementation of the differential amplifier. The differential amplifier compares the two voltages at its inputs $Vref$ and $Vbattery$ and then multiplies the output by a gain. To simplify the design of the differential amplifier resistors R1 = R3 and R2= R4. Equation 3.9 shows the simplified equation for the output of the op-amp.

$$Vout = \frac{R2}{R1} \times (Vbattery - Vref) \tag{3.9}$$

The first thing to notice from this implementation of the differential amplifier is that the input voltages is to high for the op-amp to handle. The $Vref$ and $Vbattery$ should be scaled down to lower values that reside inside the op-amps limits. Also the feedback resistor R2 will influence $Vref$ voltage. This can be solved by applying a voltage follower between $Vref$ and the actual reference voltage. The battery voltage $Vbattery$ can be scaled with R3 and R4 or with a different voltage divider circuit before $Vbattery$, which require more resistors but makes for a easier design. But then R3 and R4 will still voltage divide the $Vbattery$ voltage, so stop this from happening a voltage follower can be implemented between the actual scaled down battery voltage and $Vbattery$. Figure 3.14 shows how the $Vref$ and $Vbattery$ voltage is acquired.

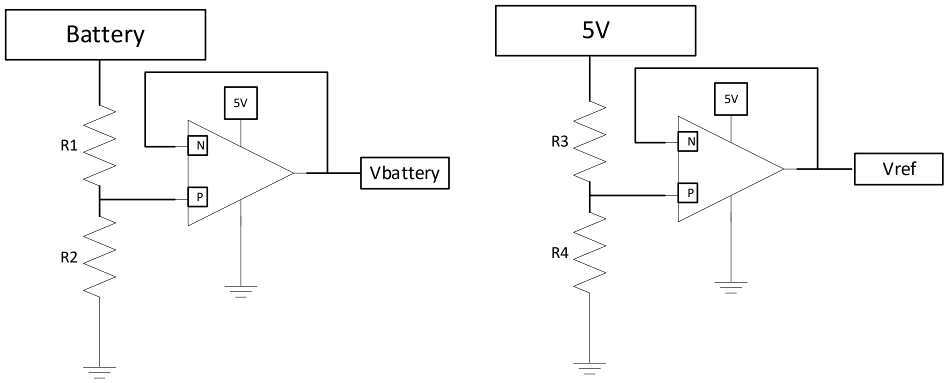

Figure 3.14: Voltage dividing circuits for both $Vref$ and $Vbattery$

The battery voltage can be brought down to any voltage level as long as it falls within the op-amps limits. Bringing the battery voltage down to half of its original value will be sufficient meaning R1 = R2 and should be in the range of kΩ to limit the current to µA. The $Vref$ should match the battery voltage at its lowest limit of 5.7 V, but the voltage $Vbattery$ is halve the battery voltage, thus $Vref$ should be equal to 2.85 V. The ratio between R3 and R4 will then be $R3 = 1.326 \times R4$, again choosing values in the range of kΩ.
Now that $Vbattery$ and $Vref$ is known the gain of the differential amplifier in Figure 3.13 can be calculated. When $Vref$ is equal to $Vbattery$ the output will be 0 V and when $Vbattery$ is at its maximum of 3.75 V the output will be 0.9 V. Thus the output of the op-amp ranges from 0 to 0.9V, to use the maximum range of the ADC the output should be amplified so that the maximum output is equal to 5 V. The gain value is shown in equation 3.10.

$$\frac{R2}{R1} = 5.555 \tag{3.10}$$

All the values in the differential amplifier circuit should be in the range of kΩ. There is no need to use a lowpass filter for the battery measurement because the battery will not generate a lot of noise.

3.9. Ambient Light Sensor

To measure the amount of ambient light a LDR [18] is used. A LDR works as a resistor that has a variable resistance. When the LDR is exposed to light the resistance decreases and when the LDR is not exposed to light, in a dark environment, the resistance increases. A simple series connection of the LDR and a resistor will make for a easy method to measure the ambient light as shown in Figure 3.15. The measured resistance when the LDR is exposed to light levels of the laboratory is $7\,\mathrm{k\Omega}$ and when it is covered, dark, the resistance is measured to be $100\,\mathrm{k\Omega}$. The resistance R1 should be chosen so the swing of the ambient light measurement is at least $2\,\mathrm{V}$. To limit the voltage over the LDR that will be sampled by the ADC, a voltage division calculation can be applied with the *LightToADC* voltage set to $5\,\mathrm{V}$, when the battery is at a maximum of $7.2\,\mathrm{V}$. R1 is calculated as $44\,\mathrm{k\Omega}$. $Vref$ is is set as a third of the maximum voltage that *LightToADC* will be when the battery is a $5.9\,\mathrm{V}$. This results in $R1 = 1.36 \times R2$, the circuit is shown in Figure 3.16.

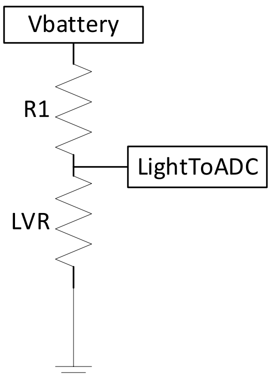

Figure 3.15: Ambient Light measurement circuit

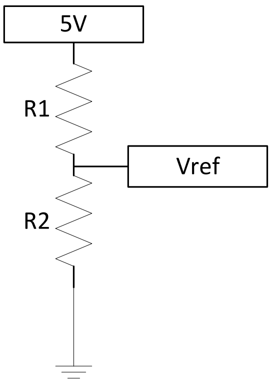

Figure 3.16: Vref conditioning circuit

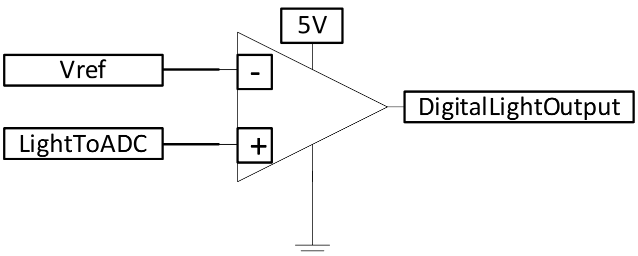

Figure 3.17: Digital Light output circuit

To get a digital voltage signal that indicates if it is dark or light, a voltage comparator is used with inputs $Vref$ and *LightToADC*. The output *DigitalLightOuput* will be $5\,\mathrm{V}$ when it is dark and $0\,\mathrm{V}$ when it is light. This is important to remember when designing the load control. The circuit implementation is shown in Figure 3.17.

3.10. Load Control

The load control is the logic controlling the low side switch that is designed in Section 3.6. Table 3.3 shows the logic where the Light sensors, the *DigitalLightOutput*, 0 represents that light is measured and 1 represents no light is measured. The User input represents a 5 V input signal as a 1 and 0 V signal as a 0. The table shows that the load, which is the output, is simply a AND gate [19] of the Light sensor and User input. This means that the user should be able to toggle the Load only when it is dark. The User input will be a SR Latch [20] implemented using a op-amp. The user can therefore enable the load with a push of a tactile button and then disable it again by pressing the other tactile button. The circuit diagram is shown in Figure B.1.

Light Sensor	User Input	**Load**
0	0	**0**
0	1	**0**
1	0	**0**
1	1	**1**

Table 3.3: Logic table for Load control

The circuit implementation of the AND gate is shown in Figure 3.18. The resistances R is pull-up resistors and should be chosen in the ranges of kΩ. The *Load* signal should be connected to the gate of the NMOS in Figure 3.11.

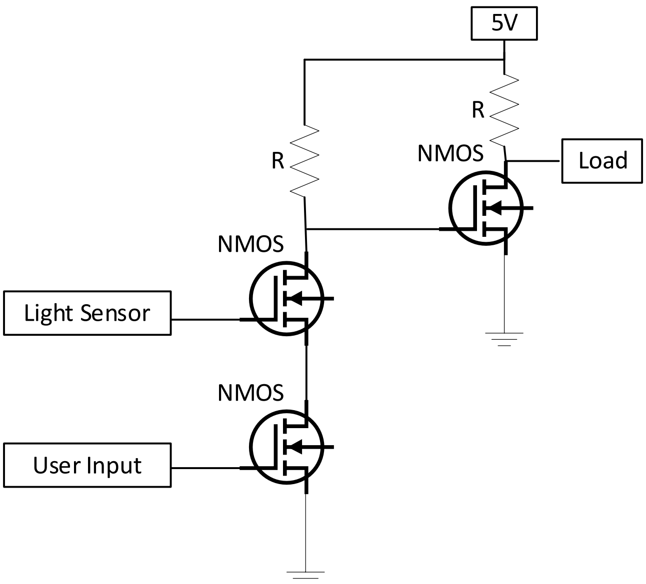

Figure 3.18: Circuit implementation of Load control logic

3.11. Pilot Light Control

The Pilot will be an indication whenever the environment is sufficiently dark that the load can/should be turned on. The pilot light will be a red LED. The pilot should then turn off whenever the load is turned on and turn on again when the load is turned off, given that there is sufficient darkness. Table 3.4 shows the logic in determining the states of the pilot light. The same logic for the Light Sensor is used as in Section 3.10. The output is the Pilot Light. Form the table the logic can be interpreted as follows, the Light Sensor is an enable signal that when it is 0, the Pilot Light will be 0. When the Light Sensor is 1, the Pilot Light will be the opposite of the Load. The circuit representation is shown in Figure 3.19. To get the inverted of the Light Sensor, the *DigitalLightOutput* is inverted using a voltage comparator with $Vref$ the same as in Section 3.9.

Light Sensor	Load	**Pilot Light**
0	0	**0**
0	1	**0**
1	0	**1**
1	1	**0**

Table 3.4: Logic table for Pilot Light Control

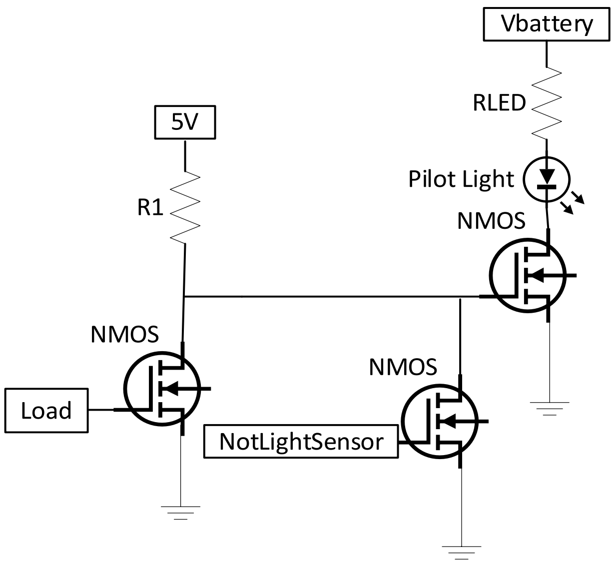

Figure 3.19: Pilot Light Circuit

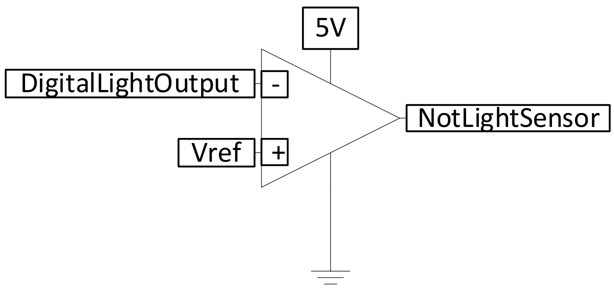

Figure 3.20: Inverting Light Sensor Output

Chapter 4

Subsystem Results

4.1. Voltage Regulation

The charging circuit that was built using the LM317T voltage regulation was simulated and the results are shown in Figure 4.1. The current at which the batter will charge when the battery voltage is at 6 V is 387 mA. The battery charges to a voltage of 7.24 V. Both these specifications are within 5 % of the designed values. The battery also does not discharge into the voltage regulation when the input is turned off. This is because of the diode placed between the high-side switch and the battery terminals.

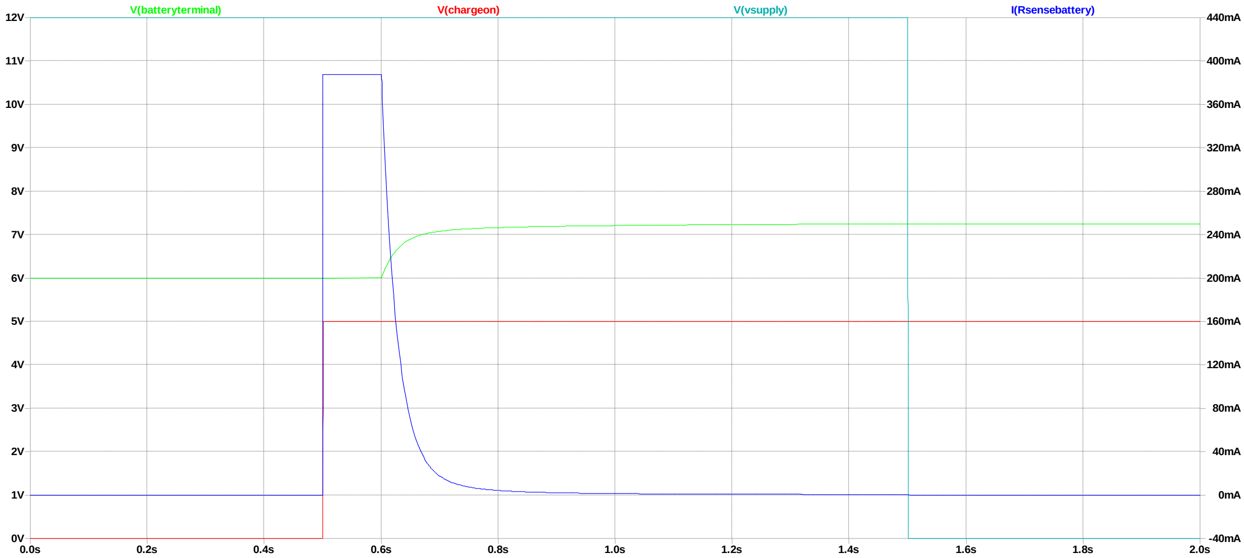

Figure 4.1: Simulation results for the LM317T voltage regulator

The measured results for the LM317T voltage regulator is shown in Table 4.2. The measured open circuit voltage of the voltage regulation is a bit higher than the simulation value, but the current value is quite accurate. The LTspice simulation circuit is shown in Figure 4.2 To

Table 4.1: Voltage regulation Voc and battery charging current when battery voltage at 6.35 V

	Voc [V]	$Icharge$ [A]
LM317T simulation	7.35	0.260
LM317T measured	7.457	0.248

test if the 5 V LM2940C regulator works it can be powered from a power supply and the the output can be measured as the power supply goes from 5.9 to 7.2V to see if the regulator has a steady output of 5.

Table 4.2: LM2940C output voltage with varying input voltage

	$Vout$ [V]
LM2940C, input 7.2 V	5
LM2940C, input 5.9 V	5

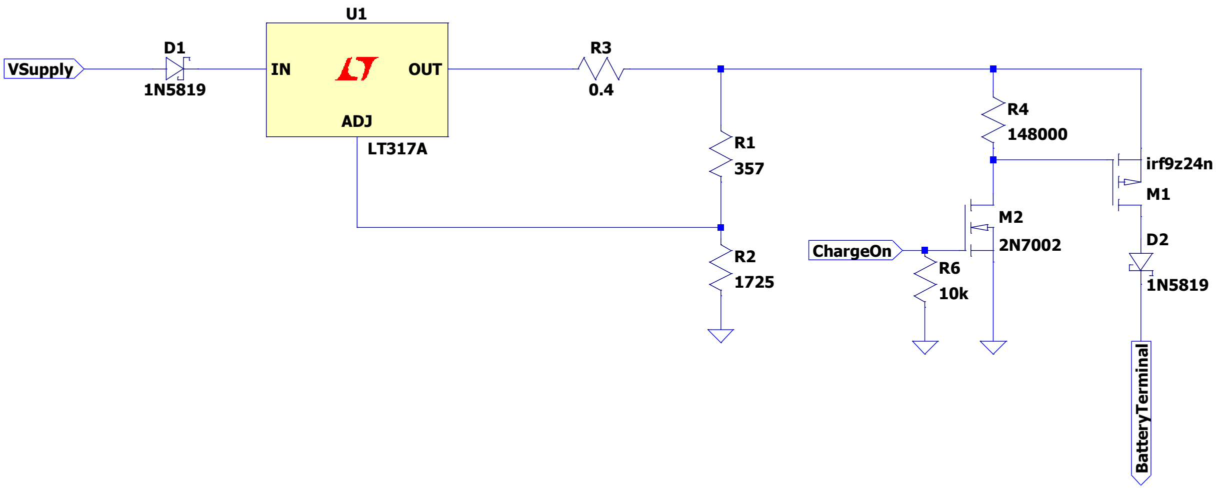

Figure 4.2: LM317T voltage regulator LTspice simulation circuit

4.2. High-side switch

The high-side switch simulation is shown in Figure 4.3. The high-side switch only turns on when the 5 V control signal $Vloadon$ is turned high. The high-side switch does not allow current to flow back into the supply as shown after 1.5 s when the $Vsupply$ goes low and the battery terminal voltage does not drop.

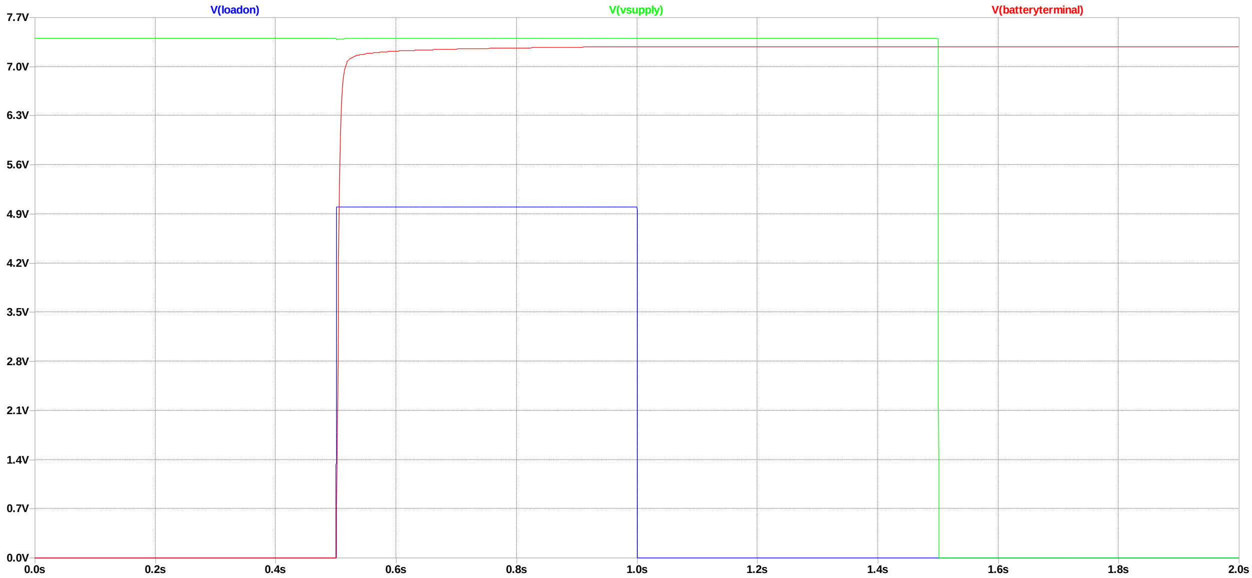

Figure 4.3: High-side switch simulation

The practical circuit that is measured is the high-side switch connected to the output of the LM317T voltage regulator. A load of 1 kΩ is connected to the high-side switch and then the control signal is varied from 0 V to 5 V. There should be a voltage when the control signal is high and current flows through the load resistor. Table 4.3 shows the measured results. The results is as expected and shows that the high-side switch works correctly. The circuit simulated in spice is shown in Figure 3.3.

Table 4.3: High-side switch output

	$Vout$ [V]
$Vout$, control signal 0 V	7.45
$Vout$, control signal 5 V	7.21

4.3. Undervoltage Protection

The output of the undervoltage protection circuit is shown in Figure 4.4. The battery voltage is simulated to move down from 6.3 V to 5.7 V and then back up again to 6.3 V. The output is plotted in green. The battery voltage and current is shown in Figure 4.5, positive current is measured as current flowing into the battery and negative current is when the battery discharges. From Figure 4.5 it is clear that the battery stops to discharge when the voltage drops below 5.9 V and then starts discharging again when it reaches 6.2 V. The circuit simulated in LTspice is shown in Figure 4.6.

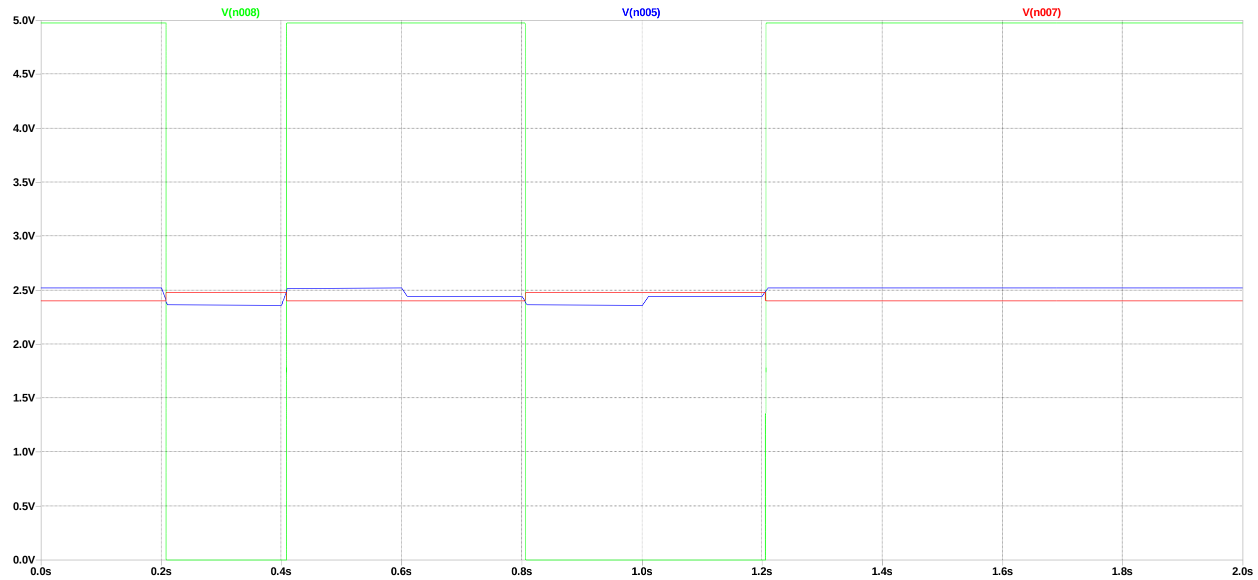

Figure 4.4: Undervoltage protection circuit output

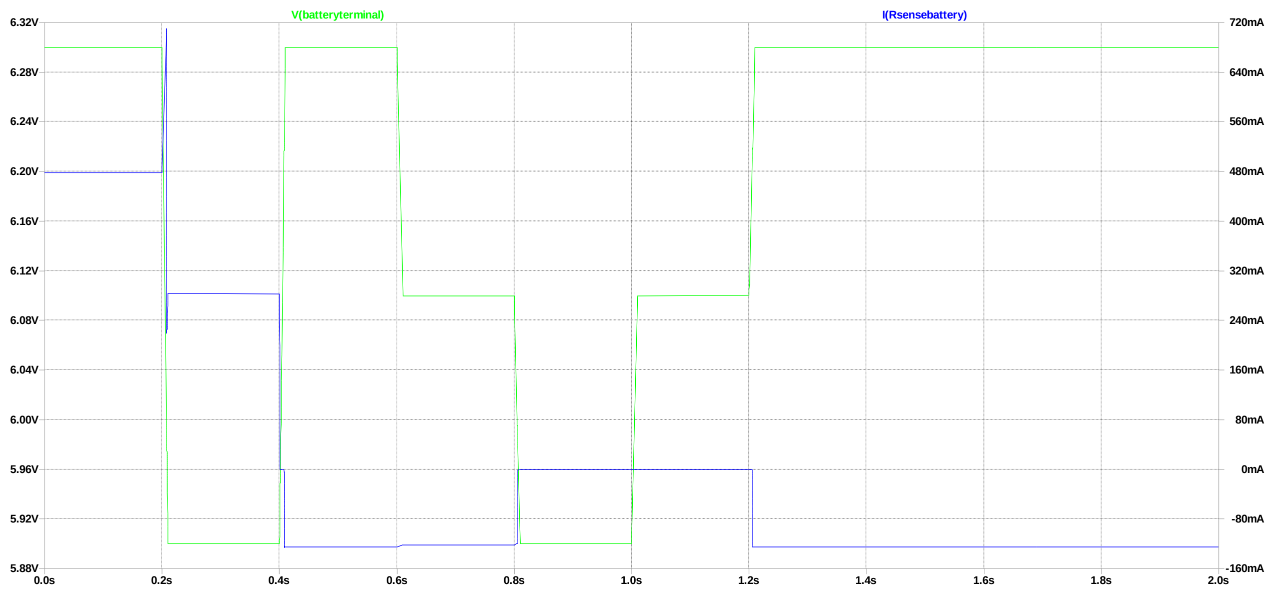

Figure 4.5: Battery voltage and current

The undervoltage protection circuit was measured practically where a DC power supply simulated the voltage of the battery, Table 4.4 shows the results. The power supply voltage was changed the same as the battery voltage was simulated in the simulation.

Table 4.4: Undervoltage protection circuit output

	$Vout$ [V]
$Vout$, battery voltage 6.3 V	5
$Vout$, battery voltage 6.2 V	5
$Vout$, battery voltage 6.1 V	5
$Vout$, battery voltage 6.0 V	5
$Vout$, battery voltage 5.9 V	0
$Vout$, battery voltage 6.0 V	0
$Vout$, battery voltage 6.1 V	0
$Vout$, battery voltage 6.2 V	5

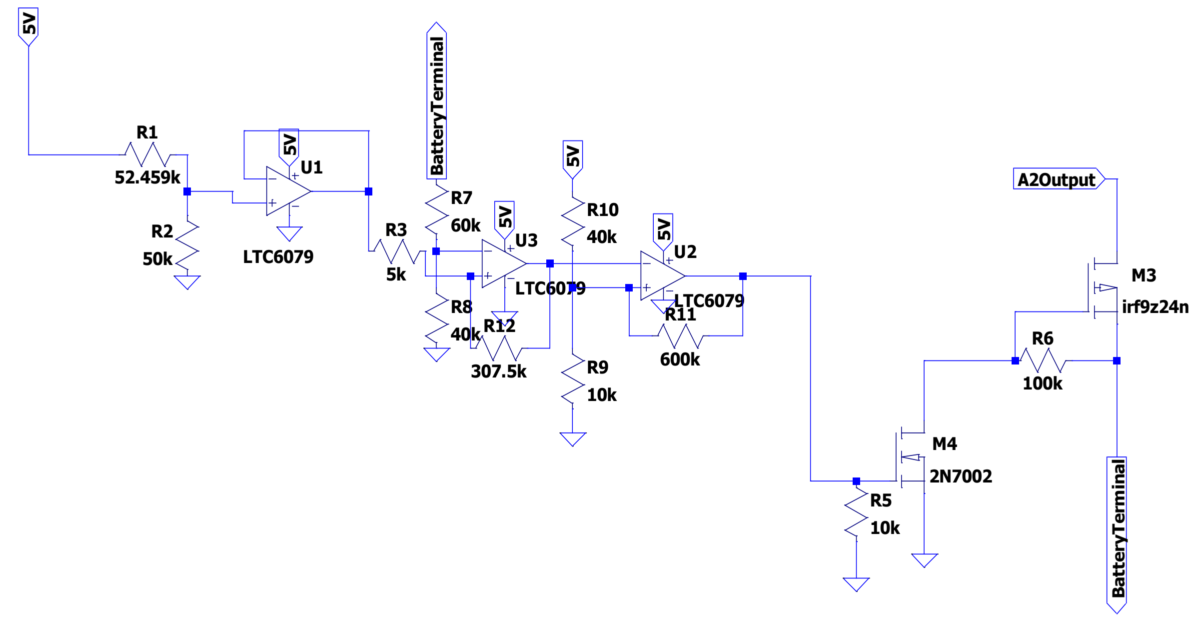

Figure 4.6: LTspice simulation for undervoltage protection circuit

4.4. Current Sense

The TSC op-amp is measured at minimum and maximum current through the shunt resistor. The output voltage noise is then also measured, while simulating a noise at the input. Figure 4.7 shows the output ranges of the TSC op-amp. The limits measured from the simulation is 1 V and 4 V as designed for. Figure 4.8 shows that the capacitor is attenuating the noise so that the output has less than a 2 mV pk-pk swing. Table 4.5 shows the measured voltage of the TSC op-amp as well as the current through the shunt resistor. The battery voltage was at 6.42 V.

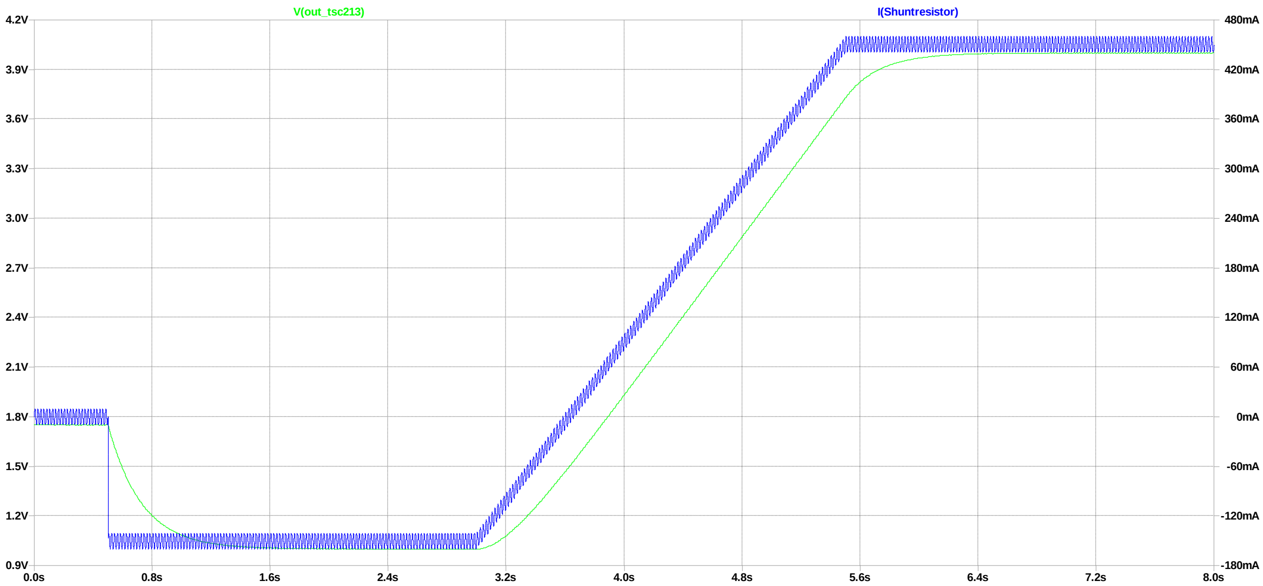

Figure 4.7: Output of TSC op-amp and current through Rshunt

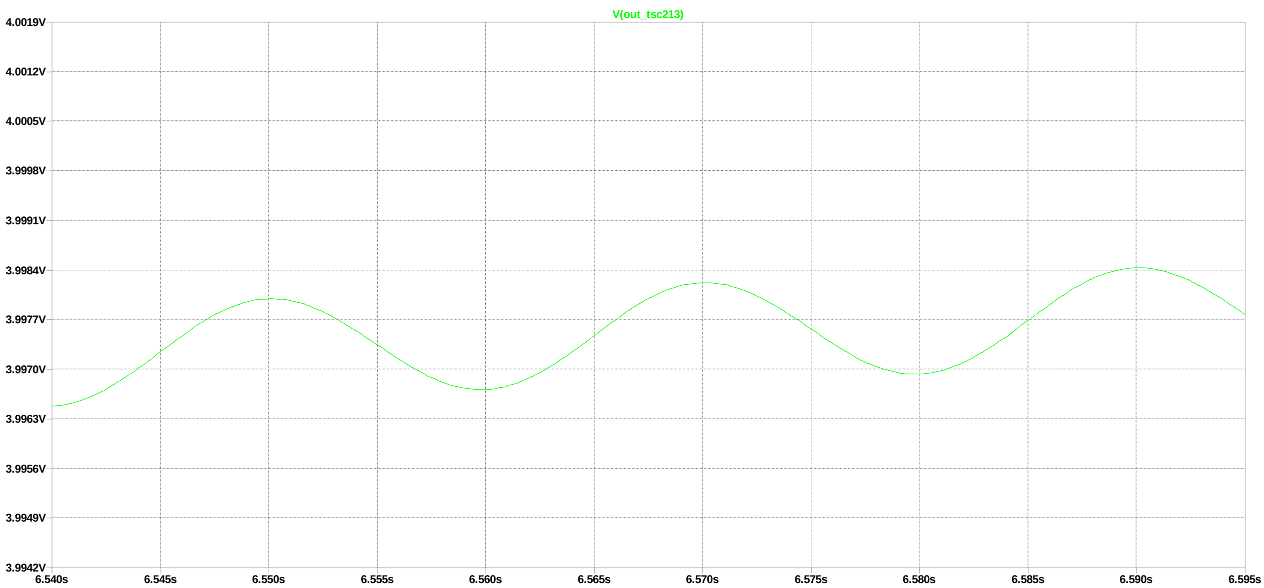

Figure 4.8: Noise attenuation

Table 4.5: Output voltage of TSC and current through shunt resistor

	Ishunt [mA]	*Vout* [V]
Battery Charging	212.4	2.812
Battery Discharging	-75.6	1.372

Figure 4.9 shows the measured noise on the TSC op-amp output. The pk-pk noise voltage is too big, the biggest capacitor, in the laboratory, was used. A different approach should be used in attenuating noise like a sallen-key lowpass filter.

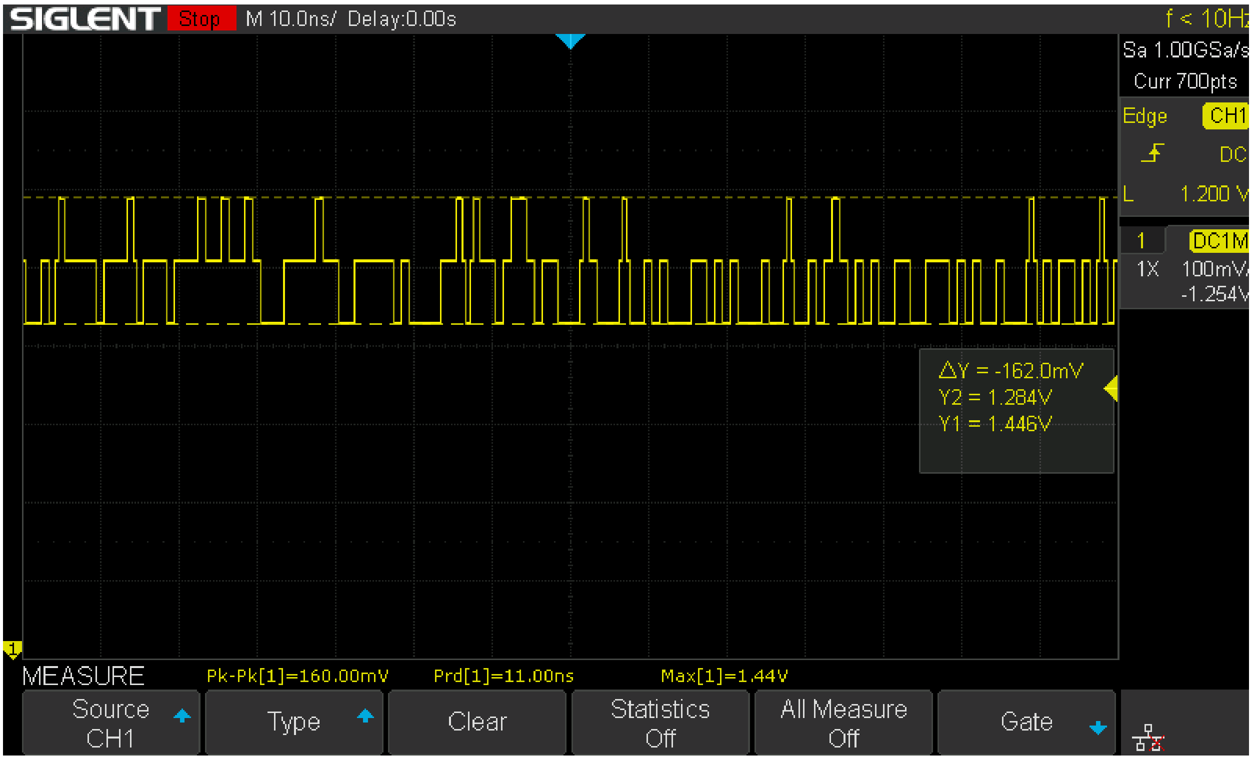

Figure 4.9: Noise measurements on TSC213 output

4.5. Low-side Switch

The low-side switch was measured by applying a 7.2 V at the load and then measuring the current through the all five LEDs. The 7.2 V came from a DC power supply. The positive of the power supply was attached to the multitmeter's positive probe and the negative probe was attached the the ends of the load resistors. The gate of the NMOS transistor is then held low at 0 V. The power supply is turned on. Then the gate voltage at the NMOS transistor is varied to 5 V which should allow current to flow. The measured values are shown in Table 4.6. The current of 97.6 mA is very close to the design current of 100 mA.

Table 4.6: Load current through the five LEDs

	$Iload$ [mA]
Load current, gate of NMOS at 0 V	0
Load current, gate of NMOS at 5 V	97.6

4.6. Supply Voltage Measurements

Figure 4.10 shows the simulated circuit in LTSpice. The input is simulated as a voltage that changes from 0 to 22V with a input noise of 100 mVpk-pk at a frequency of 1 kHz. Figure 4.11 shows that the range of the input signal is 4.68 V, the swing is big enough to cover the input range of the ADC. Figure 4.12 shows the noise on the input signal, the noise is less than 2 mVpk-pk, which is sufficient attenuation.

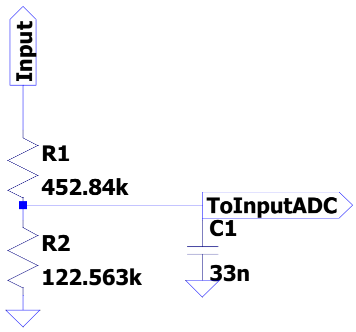

Figure 4.10: Simulated Circuit in LTSpice

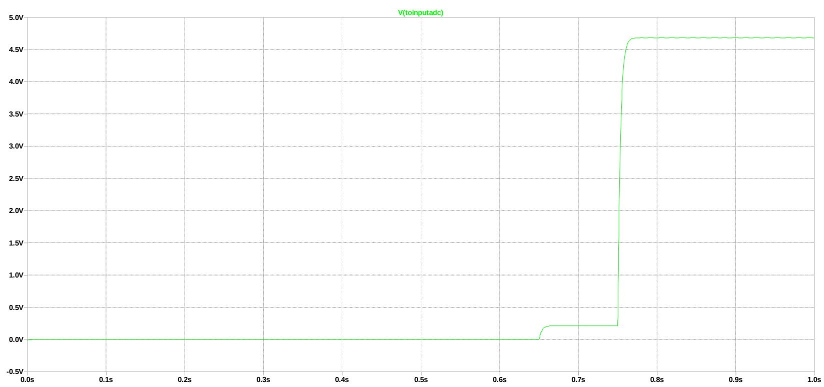

Figure 4.11: Input voltage to the ADC of the beetle

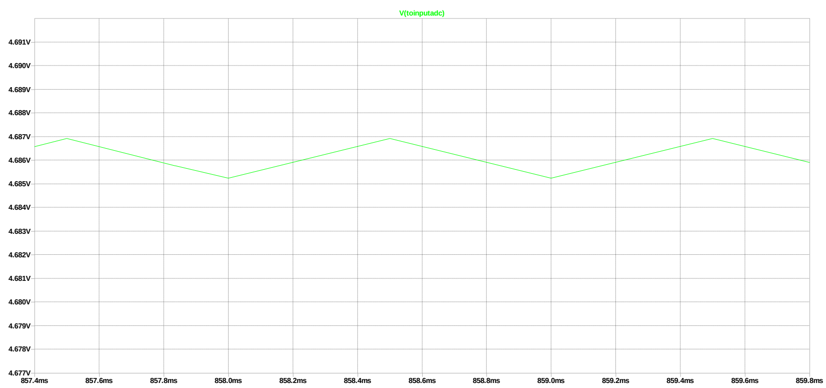

Figure 4.12: Noise on the input voltage to the ADC of the beetle

4.7. Battery Voltage Measurements

Figure 4.13 shows the simulated circuit in LTSpice. The input to the ADC of the beetle is shown in Figure 4.14. The battery voltage is simulated to move up from 5.7 V up to 6.6 V and then up to 7.5 V. The swing of the input voltage to the ADC is 5 V which covers the whole range of the ADC.

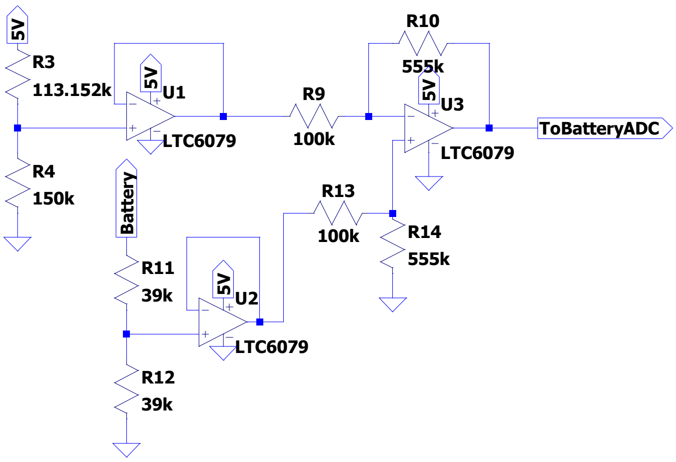

Figure 4.13: Simulated Differential Amplifier circuit in LTSpice

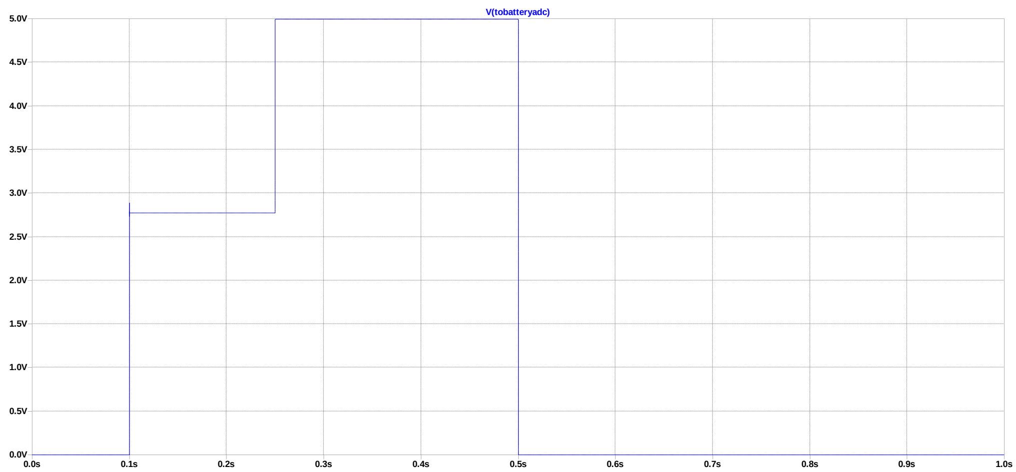

Figure 4.14: Battery voltage to ADC of the beetle

The measured results are shown in Table 4.7. The results show that the battery measurement system works accordingly to its design.

Table 4.7: Battery voltage to ADC

	$VtobatteryADC$ [V]
$VtobatteryADC$ at battery voltage 5.7 V	0.09
$VtobatteryADC$ at battery voltage 6 V	1.03
$VtobatteryADC$ at battery voltage 6.6 V	2.77
$VtobatteryADC$ at battery voltage 7.2 V	4.45

4.8. Ambient Light Measurements

The circuit is simulated with the battery voltage varying, the LDR is simulated in dark environment, meaning the resistance is set to 100 kΩ. The results are shown Figure 4.15, then the simulation is done again with the LDR resistance set to 7 kΩ, light environment, shown in Figure 4.16. The digital output is as expected. Also the ADC range is within 5 V and a swing of around 3 V. $Vref$ is measured as 1.32 V, a variable resistor is used so the value can easily be adjusted. The measured Ambient light sensor, in dark environment, when the battery is a 6.35 V is 3.75 V and light environment is 0.8 V. This is lower than designed for, but this is due to the LDR not reaching 100 kΩ, but closer to 80 kΩ when covered. Still the resultant swing is around 3 V. The simulated circuit is shown in Figure B.1.

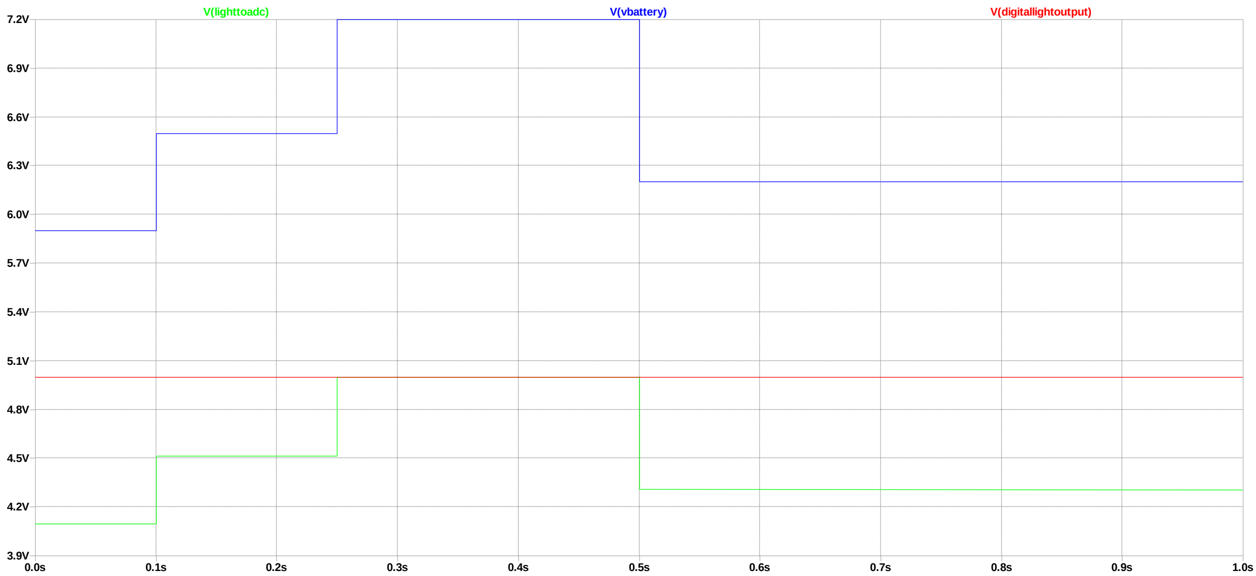

Figure 4.15: Ambient Light Sensor circuit simulation in dark environment

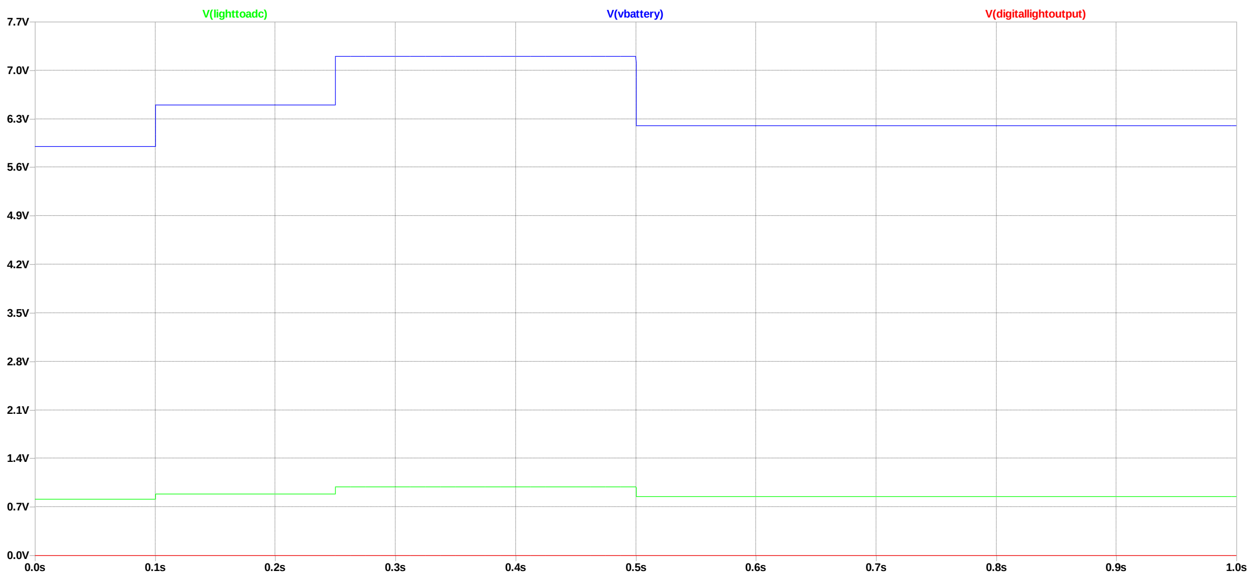

Figure 4.16: Ambient Light Sensor circuit simulation in light environment

4.9. Load Control

The Load control is simulated in two ways, one when the LDR is covered thus the *DigitalLightOutput* will be 5 V and then when the LDR is uncovered thus the *DigitalLightOutput* is 0 V. In both these cases the *UserInput* is varied between 0 V and 5 V. Figure 4.17 shows the case when the LDR is covered and Figure 4.18 shows the case when the LDR is uncovered. The load control was also tested with practical circuit and it work exactly as expected. The simulated circuit is shown in Figure B.1.

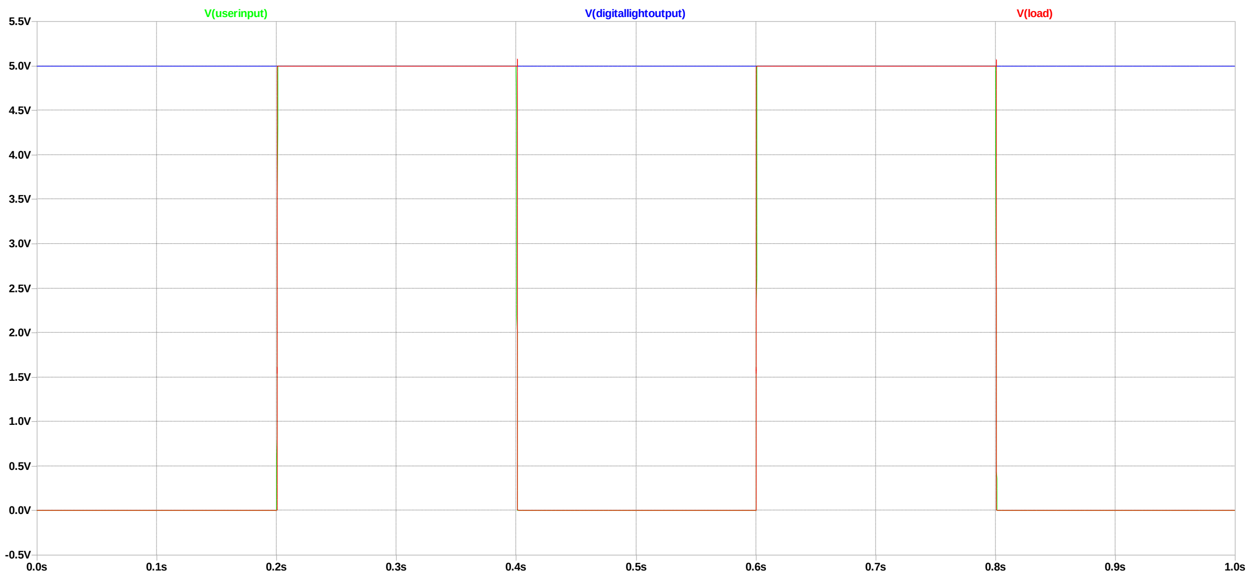

Figure 4.17: Load Control simulated in Dark environment

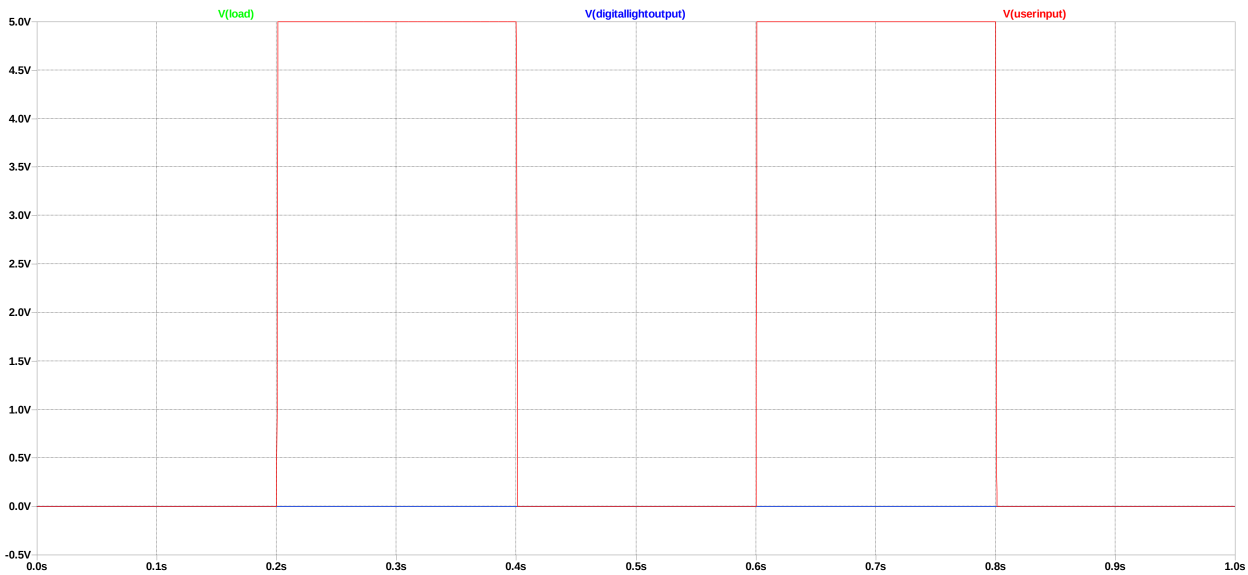

Figure 4.18: Load Control simulated in Light environment

4.10. Pilot Light Control

The Pilot Light control was also simulated for two cases, the same cases as in Section 4.9. Figure 4.19 shows the results when the environment is dark. The result are as expected with the Pilot Light only turning on only when the Load is off. Figure 4.20 shows the results when the environment is light. The Pilot light in this case never turns on independent of the User Input. This was also tested with a practical circuit and the circuit performed exactly as expected. The simulated circuit is shown in Figure B.1.

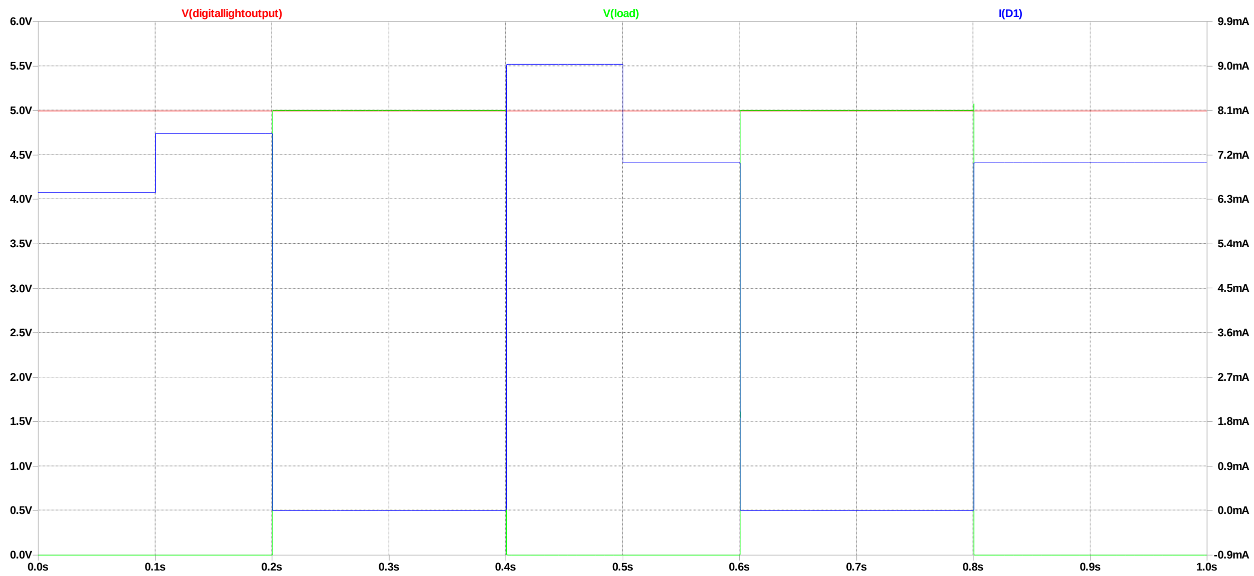

Figure 4.19: Pilot Light control in dark environment

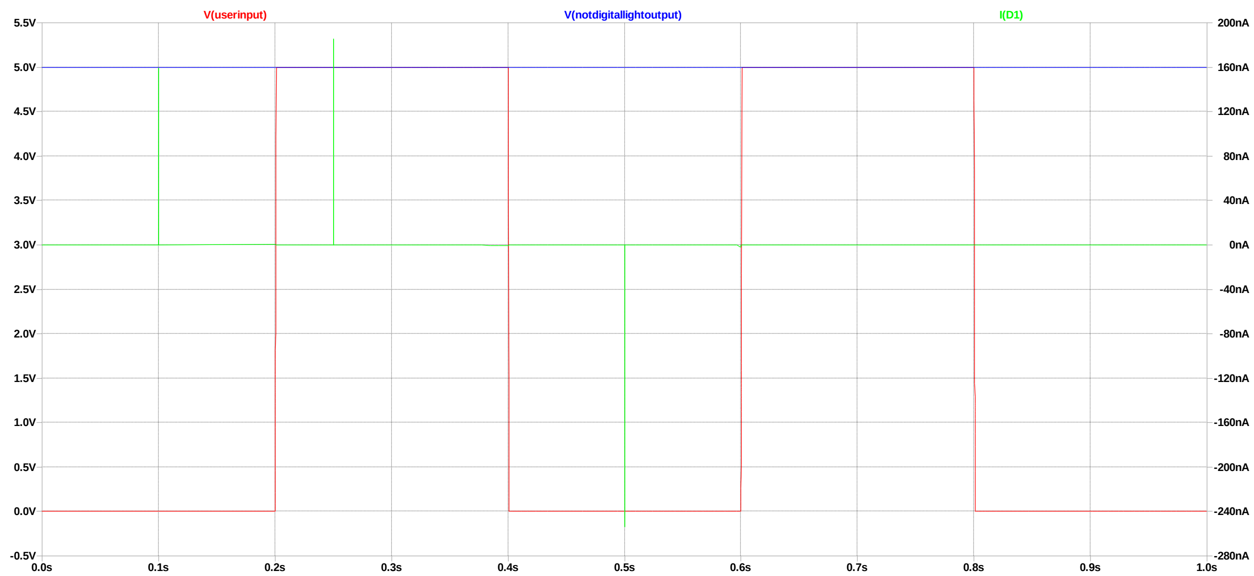

Figure 4.20: Pilot Light control in light environment

Chapter 5

System Results

The complete system is shown in Figure 5.1 and the barcode for my circuit is shown in Figure 5.2. The system as a whole performed accordingly to the designed specifications in Chapter 3. The high-side switch can be controlled via a 5 V control signal. The same can be said about the low-side load control switch. The current sensing works and resulted in accurate readings, but with a fair amount of noise that should be looked into before using the analogue to digital converter of the micro controller. The undervoltage protection performed well and protected the battery from discharging below 6 V. The hysteresis were implemented correctly. The undervoltage circuit did not prevent the battery from being charged. The load is capable of being powered from either the battery or the power supply. The load is easily variable with the LEDs being removeable and not soldered on.

Most of the resistor values that was used in building the circuit is variable resistors. This allowed for more accurate resistor values than that of the laboratory resistors that can have up to ±5 % deviation in their values. The fuse is placed inside a fuse holder, this allows for easy replacement of the fuse if it is blown.

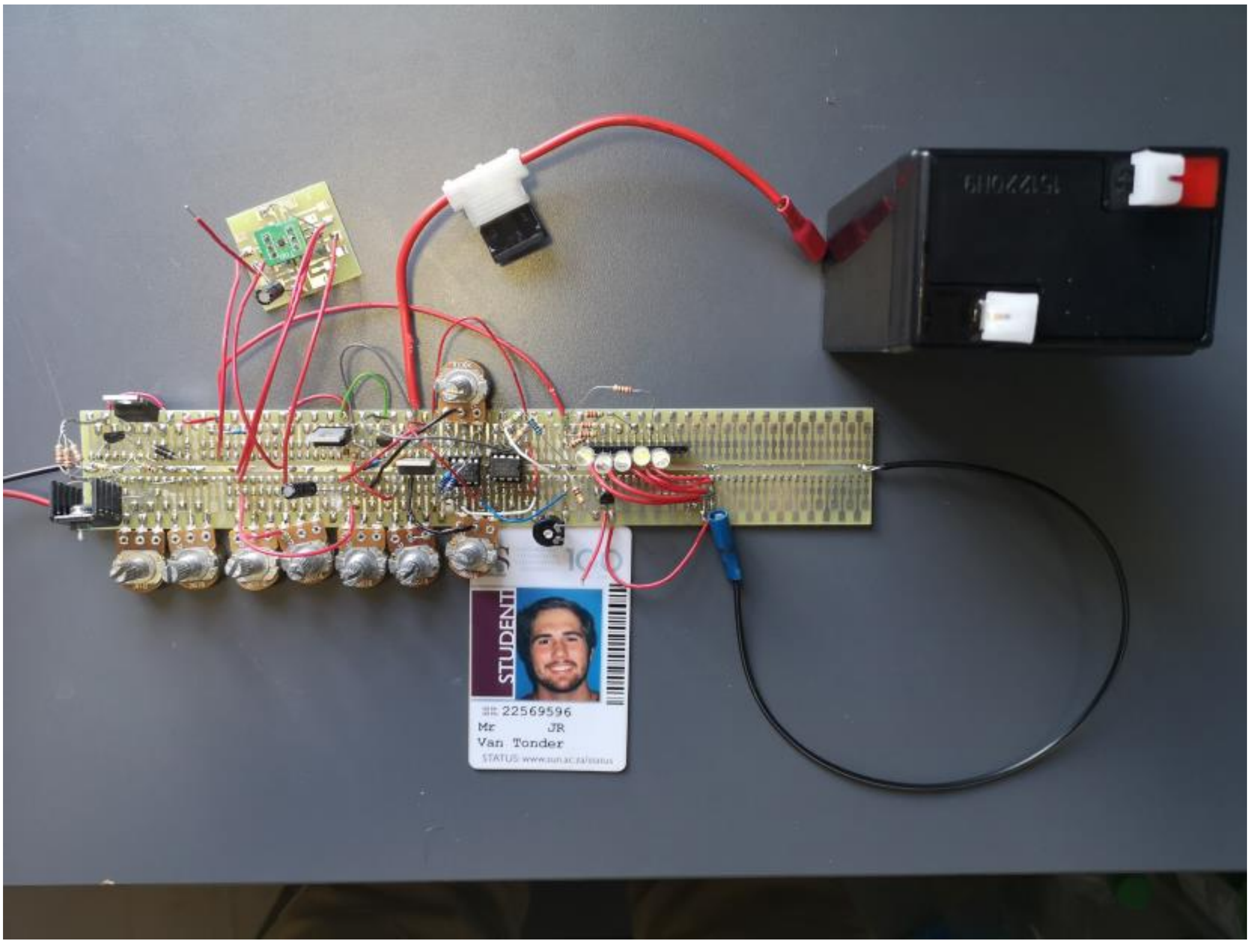

Figure 5.1: Full practical circuit

Figure 5.2: Barcode

Chapter 6

Firmware

The system will be monitored via a Arduino Beetle [15], a small version of the Arduino Leonardo microcontroller. The Beetle monitors the supply voltage level, the battery voltage level, the battery current and the ambient Light Level. The Beetle will also control the High-Side switch, designed in Section 3.2. The supply voltage, battery voltage, battery current and ambient light will be measured with an ADC, the measurements will then be conditioned and the printed onto the serial monitor, to be displayed on the PC. The High-Side switch is controlled via the input of the serial monitor. The command "$OV1$", will turn ON the High-Side switch and the command "$OV0$" will turn OFF the High-Side switch. The flow diagram for the code is shown in Figure 6.1.

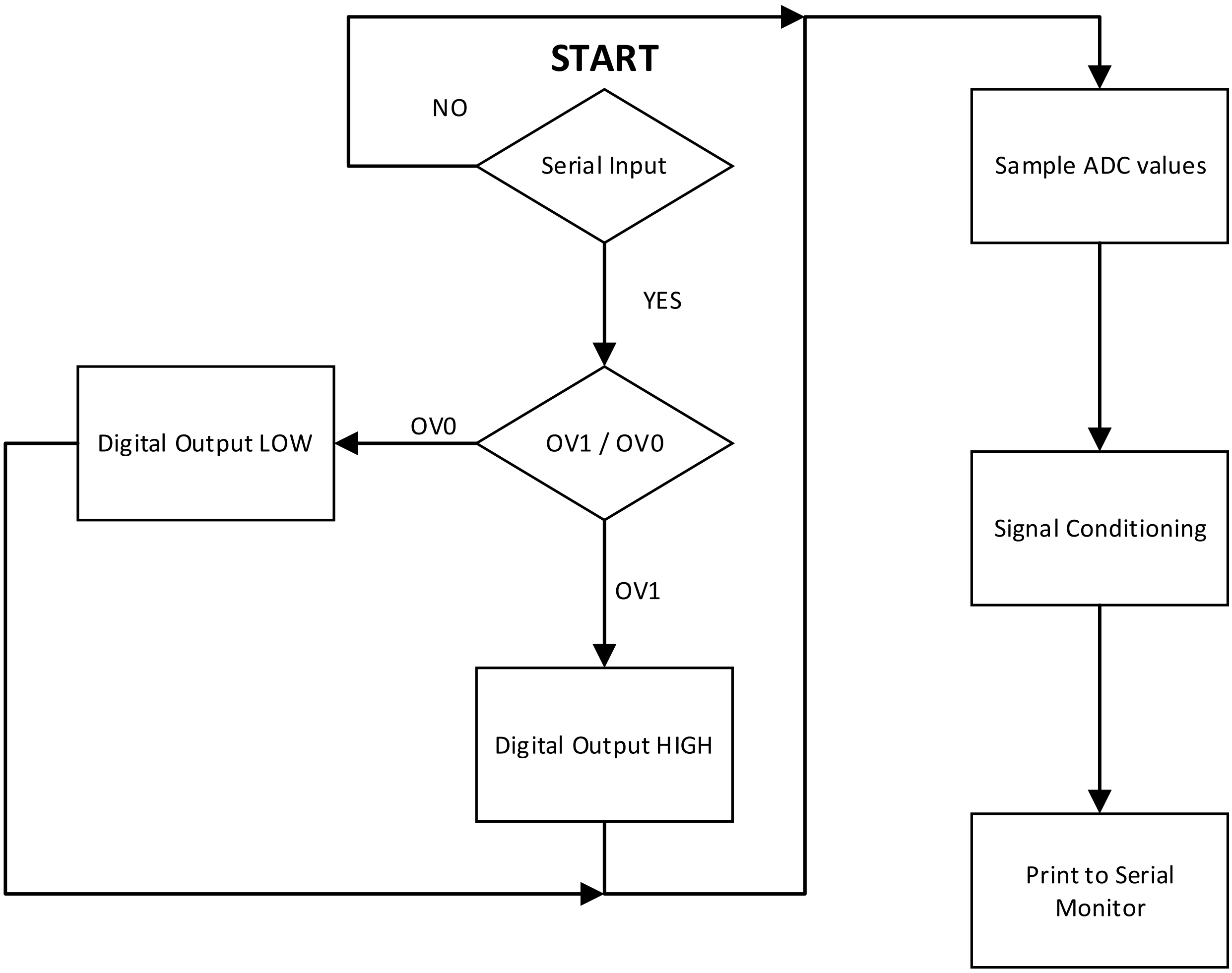

Figure 6.1: Flow Diagram of code

To calibrate the ADC measurement before printing to the serial monitor, signal conditioning is applied to the measured values. The print protocol is shown in Table 6.1. The OP status should be 0 when the switch is open and 1 when the switch should be closed. This is controlled via the user input of the serial monitor as explained already.
The battery voltage, a float representation,ADC value should be divided by 1023, the total ADC bit count. The value should then be multiplied by five to get the measured value in volts. Then the value should be divided by 5.555, which is the designed gain of the differential amplifier in Section 3.8. The value should then be multiplied by two before adding the 5.7 V, to get the measured result. After running the code a 0.09 V error was seen and it was resolved in software, by subtracting the 0.09 V.
The supply voltage, also a float representation, ADC value is also divided by 1023, then multiplied by five to get measured result in volts. Then the value is multiplied by the scaling factor 4.6947, of the resistor dividing circuit, to get the supply voltage. After running the code a 0.7 V error was seen and was resolved in software, by adding 0.7 V.
The battery current, also a float representation, ADC value is divided by 1023 and then multiplied by five to get the measure result in volts. Equation 6.1 is then used to get the battery current in A:

$$OutputVoltage = Rshunt \times Iload \times 50 + Vref \tag{6.1}$$

$OutputVoltage$,$Rshunt$ and $Vref$ is known, therefore subbing in the values the battery current can be calculated. The value is then multiplied by 1000 to convert the A to mA.
The ambient light is a byte representation ranging from 0 to 100. Zero when there is no light measured and 100 when there is maximum light measured. The measured ADC value from the LDR is divided by 700, due to the measured value never reaching past 4 V. This will increase the sensitivity of the ambient light. The value is then multiplied by 100 and then subtracted from a 100 due to the measured value being the inverse of what the light measurement is supposed to be. When there is maximum light 0 V will be measured and a 100 should be displayed on the serial monitor therefor it should be inverted.
The code constructed in the Arduino IDE is shown in Figure B.2,B.3 and B.4.

OP Status	Battery Voltage	Supply Voltage	Battery Current	Ambient Light
bool	float(V)	float(V)	float(mA)	byte(0-100)

Table 6.1: Serial Monitor Printing Protocol

Chapter 7

PC Software

The Arduino's serial monitor will be used to communicate with the PC. A GUI will show the values and allow a user to interact with the system that is designed. The GUI is programmed in python. The user will be able to see the battery voltage, supply voltage, battery current, ambient light level, control the over voltage protection control and to toggle the brightness of the Load. The pseudo code for the the program is shown below.

```
******************************************************************************
..Build GUI
..Monitor the connect button
..If the button is pressed
........Try to connect to the beetle
........If connected display connected
.............Start reading values from serial monitor
.............Update GUI
.............If over voltage protection button pressed
...................Toggle over voltage protection
.............If load brightness button pressed
...................Toggle brightness of load
.............If connect button pressed
...................Disconnect from beetle
.........Else display unable to connected
******************************************************************************
```

A python file is used to simplify the communication between the serial monitor and the PC. The following functions were used to communicate with the serial monitor through Python.
$sc.setCOMPort(x)$
This functions sets the communication port that is used when communicating with the beetle.
$sc.setBuadrate(x)$
This functions sets the baud rate at which the serial port and PC will communicate. This should be equal to the baud rate set in the Arduino IDE. $sc.open()$
This function opens the connection between the PC and the serial monitor of the beetle.
$sc.close()$
This function closes the connection between the PC and the serial monitor of the beetle.
$sc.receive()$
This function reads the data that is sent to the serial monitor and stores the data in a String

type array with each element in the array separate by a new line character.
sc.send()
This function takes data from the PC and sends it to the Arduino. The data is needs to be type String to send it to the serial monitor.
s The GUI is created with Tkinter, a GUI toolkit, the GUI contains labels and buttons. The Layout of the GUI is shown is below in Figure 7.1.

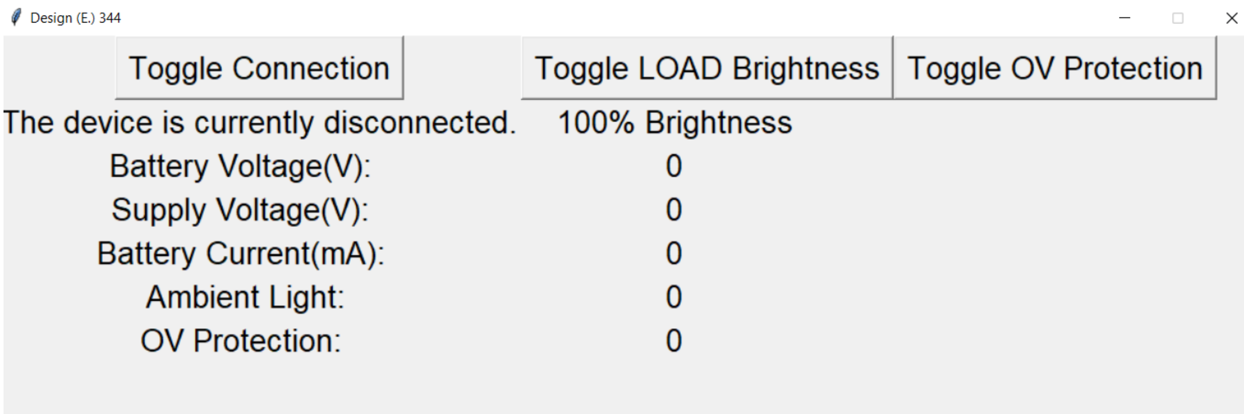

Figure 7.1: GUI layout

Each button when press calls a function. The *ToggleConnection* button calls the following function shown in pseudo code:
****
....If device is disconnect
........Try to connect with current baud rate and COM port
........If connected
............Display the device is connect
........Else
............Display the device is disconnected
....Else if device is already connect
........Disconnected the device
****
The *ToggleLOADBrightness* button's pseudo code that executes when the button is pressed is shown below:
****
....If the brightness is at 100 and button is pressed
........Send a 1 to the serial monitor and change label to 50%
....else if brightness is at 50
........Send a 2 to the serial monitor and change label to 100%
****

The *ToggleOVProtection* button's pseudo code that executes when the button is pressed is shown below:

****

....If the OV protection switch is open

........Send a 3 to the serial monitor and change the label to show a 1

....Else

........Send a 4 to the serial monitor and change the label to show a 0

****

Then to update the GUI every second an *updateDisplay* function is used that calls itself every second, the pseudo code is shown below.

****

....If the device is connected

........Read data from serial monitor

........If the length of the data is 5

............Change the appropriate labels to the new values

....Recall *updateDisplay* after one second

****

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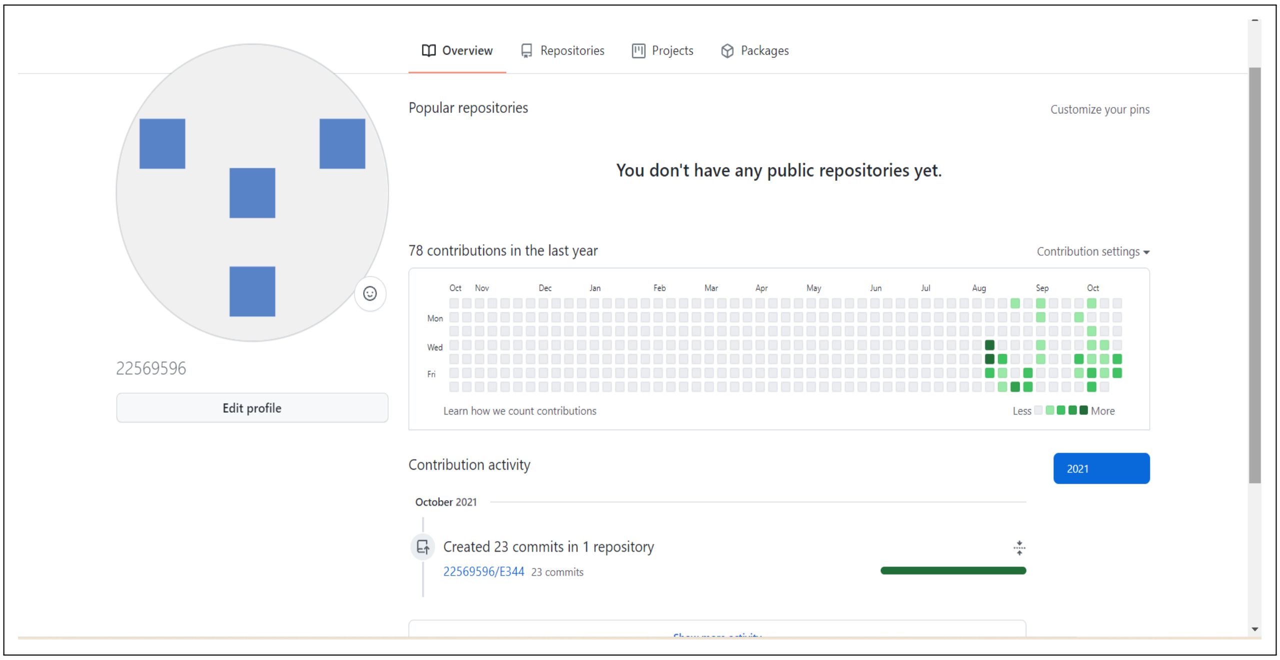
Appendix A

GitHub Activity Heatmap



Appendix B

Simulated Circuits and Software Code

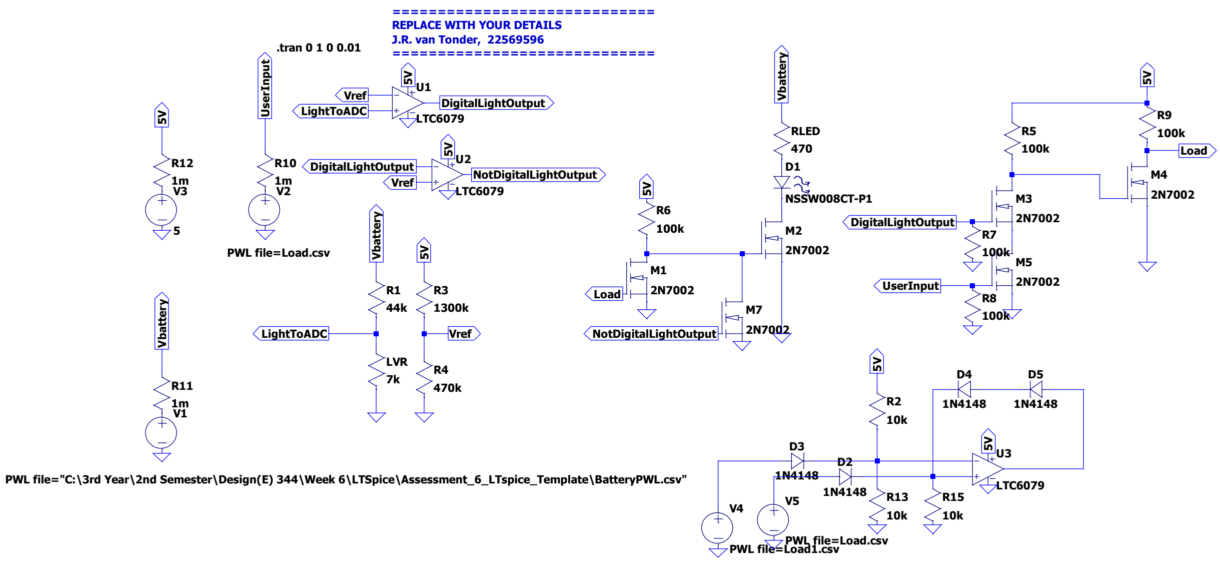


Figure B.1: Simulated Circuits for Ambient Light sensor, Load Control, Pilot Light Control and SR Latch for User Input

```
 bool chargeControl = false;
 float batteryVoltage;
 float supplyVoltage;
 float batteryCurrent;
 byte ambientLight;
  float x0;
  float x1;
  float x2;
  float x9;
  float y0;
  float y1;
  float y2;
  float y9;
void setup() {
  // put your setup code here, to run once:
 Serial.begin(112500);
 // ADC config
 pinMode(A0,INPUT); // Battery Voltage (V)
 pinMode(A1,INPUT); // Supply Voltage (V)
 pinMode(A2,INPUT); // Battery Current (mA)
 pinMode(A9,INPUT); // Ambient Light Level (0-100)
 // Over Voltage protection circuit
 pinMode(A10,OUTPUT); // High-Side switch control
}

void loop() {
  // put your main code here, to run repeatedly:

  // Overcharge protection
  if (Serial.available() > 0 ){
   int input = Serial.parseInt();
   if (input==1){
    chargeControl = true;
   }else if (input==0){
    chargeControl = false;
   }
   if(chargeControl == true){
```

Figure B.2: Page one of code

```
   digitalWrite(10,HIGH);
  }
  if(chargeControl == false){
   digitalWrite(10,LOW);
  }
 }

 //read battery voltage from ADC
 x0 = analogRead(A0);
 y0 = x0/1023;
 y0 = y0*5;
 y0 = y0/5.555;
 y0 = y0*2;
 y0 = 5.7 + y0-0.09;//0.09 error
 batteryVoltage = y0;
 //read supply voltage from ADC
 x1 = analogRead(A1);
 y1 = x1/1023;
 y1 = y1*5;
 y1 = y1*4.6947;
 supplyVoltage = y1+0.7;
 if (supplyVoltage<5){
   supplyVoltage=0;
 }
//read battery current from ADC
x2 = analogRead(A2);
y2 = x2/1023;
y2 = y2*5;
y2 = y2 - 1.75;
y2 = y2/5;
y2 = y2*1000;//mA
if(y2<-110){
 y2=0;
}
batteryCurrent = y2;
// read ambient light sensor from ADC
x9 = analogRead(A9);
```

Figure B.3: Page two of code

```
 y9 = x9/700;
 y9 = y9*100;
 y9 = 100 - y9;
 ambientLight = (int)y9;
 //serial print
 Serial.print(chargeControl);
 Serial.print(", ");
  Serial.print(batteryVoltage);
 Serial.print(", ");
  Serial.print(supplyVoltage);
 Serial.print(", ");
  Serial.print(batteryCurrent);
 Serial.print(", ");
  Serial.print(ambientLight);
 Serial.print("\n");
 delay(1000);
}
```

Figure B.4: Page three of code