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## E344 Assignment 10

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# Contents

<b>Declaration</b>	i
<b>List of Figures</b>	v
<b>List of Tables</b>	vi
<b>Nomenclature</b>	viii
<b>1. Literature</b>	1
1.1. Solar photovoltaic cells and solar modules . . . . .	1
1.2. Lead acid batteries . . . . .	2
1.3. Over-current protection(Fuse) . . . . .	3
<b>2. System design</b>	4
2.1. System Design . . . . .	4
<b>3. Detailed design</b>	6
3.1. Voltage regulation . . . . .	6
3.1.1. Design . . . . .	6
3.1.2. Current limit . . . . .	7
3.1.3. Thermal analysis . . . . .	7
3.2. High side switch on supply side . . . . .	7
3.2.1. Design . . . . .	8
3.3. Undervoltage protection . . . . .	8
3.3.1. Introduction . . . . .	8
3.3.2. 5V rail . . . . .	9
3.3.3. 5V Voltage regulator . . . . .	9
3.4. Voltage monitoring with hysteresis design . . . . .	9
3.4.1. Hysteresis . . . . .	10
3.5. Overcurrent protection . . . . .	11
3.5.1. Introduction . . . . .	11
3.5.2. Design . . . . .	11
3.6. Low-side switch . . . . .	12
3.6.1. Literature . . . . .	12
3.6.2. Design . . . . .	12
3.6.3. Results . . . . .	13
3.7. Supply voltage measurement . . . . .	14
3.7.1. Design . . . . .	14

3.8. Battery voltage measurement . . . . .	15
3.8.1. Design . . . . .	15
3.9. Ambient light sensor circuitry . . . . .	17
3.10. Pilot light control . . . . .	17
3.11. LED load control . . . . .	18
<b>4. Simulated and measured results</b>	<b>19</b>
4.1. Voltage Regulation and high side switch . . . . .	19
4.1.1. Simulation results . . . . .	19
4.1.2. Measured results . . . . .	19
4.2. Overcurrent protection . . . . .	21
4.3. Undervoltage protection . . . . .	23
4.4. Low side switch . . . . .	25
4.5. Supply voltage measurement . . . . .	27
4.5.1. Simulated Results . . . . .	27
4.5.2. Measured Results . . . . .	27
4.6. Battery voltage measurement . . . . .	28
4.6.1. Simulated Results . . . . .	28
4.6.2. Measured Results . . . . .	28
4.7. Ambient light sensor . . . . .	29
4.8. Pilot light . . . . .	29
4.9. LED load control . . . . .	30
<b>5. Firmware</b>	<b>31</b>
5.1. Flow Diagram . . . . .	31
5.1.1. Calibration calculations . . . . .	32
5.1.2. Battery Voltage . . . . .	32
5.1.3. Supply Voltage . . . . .	32
5.1.4. Battery Current . . . . .	32
5.1.5. LightSensor . . . . .	32
<b>6. PC Software</b>	<b>33</b>
6.1. Overview of functional blocks . . . . .	33
6.1.1. updateDisplay() . . . . .	33
6.1.2. openConnection(sc) . . . . .	33
6.1.3. closeConnection(sc) . . . . .	33
6.1.4. buttonConnectHandle(sc) . . . . .	33
6.1.5. buttonLEDHandler() . . . . .	34
6.1.6. buttonChargeHandler() . . . . .	34
6.2. GUI . . . . .	34
6.3. Pseudo . . . . .	35

<b>Bibliography</b>	36
<b>A. GitHub Activity Heatmap</b>	38
<b>B. Social Contract</b>	39

# List of Figures

1.1.	Terminal voltage of a 537-5422 battery discharged at different currents [1] . . . . .	1
1.2.	Charge and discharge figures for a sealed lead acid battery [2] . . . . .	3
2.1.	System diagram . . . . .	5
3.1.	Supply voltage to battery ADC input voltage . . . . .	14
3.2.	Battery voltage to battery ADC input voltage . . . . .	16
3.3.	Ambient light sensor circuitry . . . . .	17
3.4.	Pilot light circuitry . . . . .	17
3.5.	Caption for this figure with two images . . . . .	18
4.1.	The Ltpice results for the designed charging circuit. . . . .	19
4.2.	LTSPice output simulation graph . . . . .	21
4.3.	LTSpice design schematic . . . . .	22
4.4.	MY design and student number . . . . .	22
4.5.	LTspice undervoltage protection design . . . . .	23
4.6.	LTspice undervoltage protection design simulted results . . . . .	23
4.7.	LTspice undervoltage protection circuit . . . . .	24
4.8.	LTspice Low side switch circuit . . . . .	25
4.9.	Low side switch circuit design . . . . .	26
4.10.	The supply input to the beetle vs the PV panel voltage . . . . .	27
4.11.	The supply input to the beetle response to a 1V step . . . . .	27
4.12.	The supply input to the beetle response to a 1V step . . . . .	28
4.13.	Light sensing circuit analog and digital output . . . . .	29
4.14.	Pilot light output . . . . .	29
4.15.	A single LED current vs ligh sensor . . . . .	30
4.16.	A single LED current vs SR latch output . . . . .	30
5.1.	Flow diagram of firmware run on arduino on the beetle . . . . .	31
6.1.	User interface . . . . .	34
6.2.	Python Pseudo code . . . . .	35
B.1.	Social Contract . . . . .	40

# List of Tables

1.1.	PV module measured results . . . . .	2
4.1.	Simulated Results . . . . .	29
4.2.	Lab Result . . . . .	29
4.3.	Simulated Results . . . . .	29
4.4.	Lab Result . . . . .	29
4.5.	Simulated Results . . . . .	30
4.6.	Lab Result . . . . .	30



# Nomenclature

$V$	Voltage over the module
$V_{oc}$	Open source voltage
$V_{STC}$	Standard test condition voltage
$V_{T-coeff}$	Temperature Coefficient of $V_{oc}$
$I$	Current flowing through the module
$I_{sc}$	Short circuit current
$P$	Power output of the module
$P_{max}$	Maximum power
$P_{STC}$	Standard test condition power
$T_{cell}$	Temperature of the cell
$V_{GS}$	Gate to source voltage
$V_{GS(th)}$	Gate to source thevenin voltage
$V_{DS}$	Drain to source voltage
$R$	Resistor
$V_{CM}$	Common mode voltage
$V_{DIFF}$	Difference Input Voltage
$V_{IN}$	Input Voltage
$V_{REF}$	Reference voltage
$V_{OUT}$	Output voltage
$I_D$	Drain current
$V_{BAT}$	Voltage battery source
$I_{LED}$	Current through LED
$V_{LED}$	Voltage over the LED
$V_{GS(th)}$	Gate Threshold Voltage
$V_{cc}$	Voltage source
$I_{LOAD}$	Current through the load
$R_{sense}$	Current sense resistor value
$V_{ref}$	Reference voltage
$mV_{pk}$	milliVolt peak
$V_{DS}$	Drain source voltage
$P_R$	Power dissipation of resistor

## **Acronyms and abbreviations**

PV	Photovoltaic
STC	Standard Test Conditions
MPPT	Maximum power point tracking
OP-AMP	Operational Amplifier
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
NPN	Negative positive negative
MOSFET	Metal–oxide–semiconductor field-effect transistor
LED	Light emitting diode
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
BJT	Bipolar Junction Transistor
NMOS	Negatively Doped Metal Oxide Semiconductor
PMOS	Positively Doped Metal Oxide Semiconductor

# Chapter 1

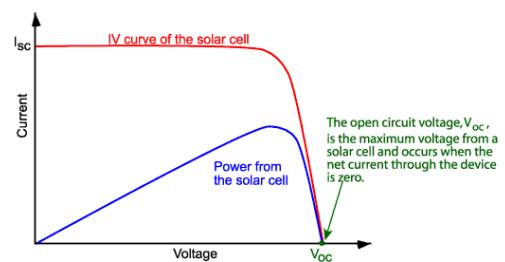
## Literature

### 1.1. Solar photovoltaic cells and solar modules

A PV cell is an energy harvesting technology, that converts solar energy into electricity through the photovoltaic effect (PV). The photovoltaic cell is a specially treated semi-conductor layer [3]. This layer consists of two other layers: the p-type and n-type layer. Thus, forming a pn-junction which converts the sun's energy into useful electricity through a process called the photovoltaic effect. If the pn-junction is connected into a circuit, current will start to flow from the n-type side through the circuit to the p-type side [4]. A photovoltaic cell is however not ideal, because in practise it can only convert a percentage of the solar energy it receives into electrical energy. The average efficiency of a solar panel is between 17 to 19 percent. This could be due to the material of the panel component, reflective efficiency, and Thermodynamic efficiency [5]

A photovoltaic cell has a **I-V curve** that, under certain conditions indicate the relationship between the voltage and the current of the cell. This relationship is almost parallel with the Voltage axis. The knee of this curve drops drastically until the curve is in an open-circuit state and the voltage is equal to the open-circuit voltage. This drop represents the current that is produced if more voltage is introduced [1].

The open-circuit voltage (VOC) is the maximum voltage attainable by a photovoltaic cell. This voltage will be reached when the circuit is in an open circuit configuration. Therefore, the current will be zero as illustrated in Figure 1.2. The value is not fixed for a cell, because many factors may change this value, like discussed in section 1.3. The open circuit voltage of a single cell is typically 0.6V [5]. Our specific solar module has a VOC = 21.6V [6]. The photovoltaic cell has a short circuit configuration where the voltage over the cell is zero, but the maximum current is flowing through the circuit. The maximum current is denoted as Isc in Figure 2.1. The short-circuit current is a result of the light-generated carrier that are gathered by the cell. Ideal solar cells have a short-circuit



**Figure 1.1:** Terminal voltage of a 537-5422 battery discharged at different currents [1]

current which is identical to the light-generated current. There are many factors that influence the short-circuit value like, the area of the cell, the number of photons, the spectrum of the incident light, the optical properties, and the collection probability. The specific solar module has a  $I_{SC} = 0.34A$  [6]. This is not very large, but these cells are connected in series with one another to produce a larger voltage value. These are called solar modules and our module has 36 cells which is in series with each other [5]

Illustrated in Figure 1.2, the equation  $P = IV$  can be used to calculate a power curve. Maximum power will be produced when the voltage is regulated to be at the knee of the IV-curve. However the IV-curve is not static and may change due to many factors as mentioned above. As a result, the maximum power point is not static and has to be tracked to optimise the power efficiency of the solar cell. This is known as maximum power point tracking (MPPT) [7]. Our solar module has a  $P_{max} = 5W$  [6]. The self test done on the PV panel at approximately 12:05 lead to the results below is Table 1.1:

	$V_{OC}$ [V]	$I_{SC}$ [mA]
Dark	0.11	0
Ambient light	13.6	0,7
Sunlight when module is upside down	18.8	28
Direct Sunlight	21.7	180
Oblique Sunlight	20.8	125

**Table 1.1:** PV module measured results

## 1.2. Lead acid batteries

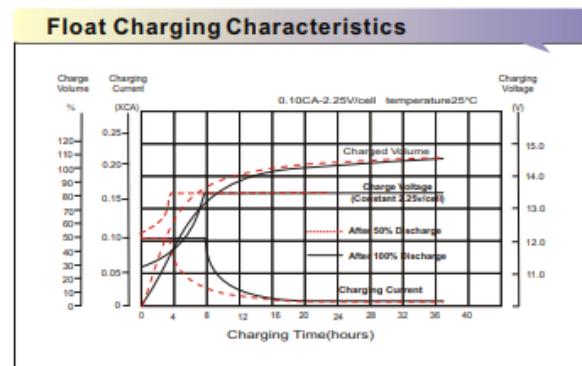
The battery that is being used for this project is the 537-5422(6V4.0Ah) battery. The nominal Voltage is 6V and the amps per hour that should be supplied is 4Ah (4 amps per hour). As a result the battery should supply 24Wh (24 Watts per hour). A amp hour(Ah) is the amount of current amount of amps the a battery can supply to a load over a hour. These are all ideal values that will not be attained in non-ideal cases. Therefore voltage rated values are given of 6.75V - 6.9V. The actual open circuit voltage will appear in this range. My specific battery supplies a voltage of 6.36V [2]. The amp hour rating is also for ideal cases as many factors may influence the rate at which the chemical reaction takes place inside the battery, such as temperature. Internal resistance gets lower when the battery temperature increases. The chemical reaction speeds up as temperature increases and decreases the life time of the battery [8].

The internal resistance of a battery is a factor of many components. Such as: the size and capacity of the battery. The chemical properties inside as well as the documented discharge rate. The internal resistance of a battery is of interest because it influences the life expectancy of the battery. If the internal resistance increases with age, the battery will supply less current and will heat up more as a result [8].

The batteries charging characteristics will go through four stages before it is charged completely. The maximum amount of current that is allowed to flow through the battery when it is depleted is 1A. When the battery is fully charged, it will absorb a current of 10mA. There are five stages of charging: Bulk, absorption, float, equalization and discharge [9].

### 1.3. Over-current protection(Fuse)

A fuse is an electric component which is designed with the intention of protecting other components, especially against over current conditions. A fuse has a conductive strip built into it that is designed to melt at a specific current value. This stops all current flowing through the fuse as well as the components on the other side. To allow the electric circuit to function again, the fuse would have to be replaced with a new one. Fuses are rated in the unit of current (amperes). When broken a fuse will function as an open circuit. [10].



**Figure 1.2:** Charge and discharge figures for a sealed lead acid battery [2]

# Chapter 2

## System design

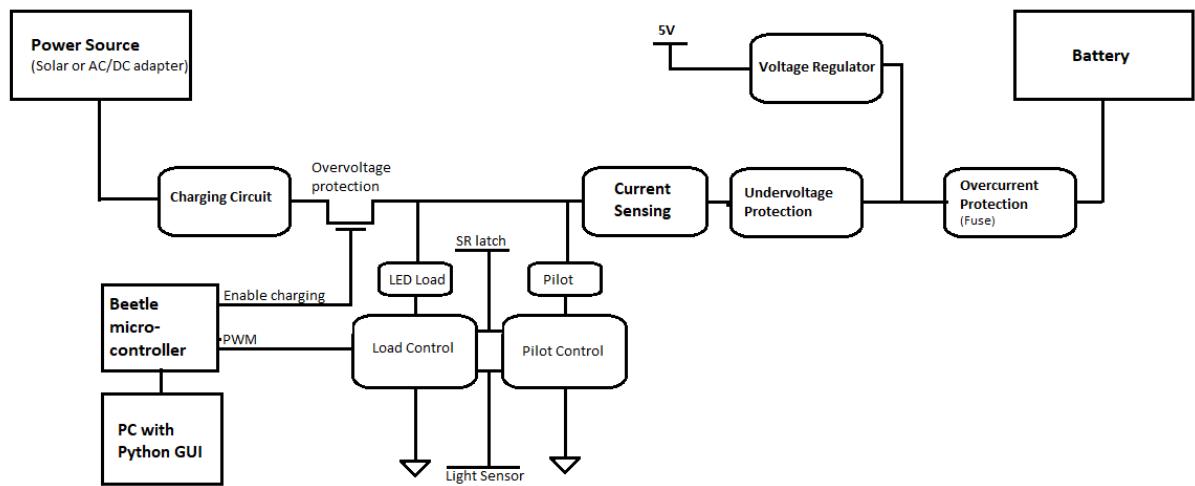
### 2.1. System Design

The goal of this system is to power a LED load with a lead acid-battery. The battery that will be used should be charged with a solar panel or a AC/DC adapter. The main functionality of the system is the charging and discharging of the battery.

Figure 2.1 is a simple diagram of the system. The **charging circuit** block regulates the voltage and current as to not damage the battery. If the battery is charged sufficiently the **overvoltage protection** will be turned off, this will be done by a digital GPIO pin from the beetle, thus disconnecting the power source from the battery and not allowing the battery to charge further. If the battery is discharging and the voltage drops below a certain voltage, The **undervoltage protection** will ensure that the battery doesn't discharge into the LED load by disconnecting it from the circuit. The **current sensing** measures the current flowing from the battery to the load and power source. This information allows the user to know if the systems is charging or discharging the battery. A 5V regulator is also implemented as most of the logic blocks are reliant on a 5V source.

The **load control** and **Pilot control** blocks determine whether the LED load or the Pilot light should be on. The LED load state is determined by the **SR latch** state, the beetle **PWM** and the **light sensor**. The pilot control block is determined by the **SR latch** and the **light sensor**. Both control block function as lowside switches. When all the criteria is met the control block will be short circuited and a voltage drop will exist over the LED load, if all the criteria aren't met, the control blocks will be open circuited and no voltage drop will exist over the LED.

The **beetle** is used to receive the supply voltage, battery voltage, battery current and light sensor. These values are displayed back to the user using python. The beetle also allows the user to change the PWM signal as well as the enable charging signal.



**Figure 2.1:** System diagram

# Chapter 3

## Detailed design

### 3.1. Voltage regulation

A voltage regulator is a electrical component that is placed in a circuit to regulate the output voltage of the component to a fixed voltage value. The LM317 is a very common voltage regulator and is also the regulator that will be used in the circuit. Voltage regulators have 3 pins which is input, output and an adjust pin. If the input voltage is large enough the regulation of voltage will start. The output voltage is fixed but can be any value between 1.2V and 37V. The output current is in excess of 1.5A. The difference between the output and adjust pin is always 1.25V. This relationship can be used to design the output voltage to any desired value that range between 1.2V and 37V. Voltage regulators can be used to design a constant current at the output pin. Using the relationship of 1.25V as the  $V_{REF}$  and placing a resistor between these two pins a desired output current can be designed. When combining the constant voltage source with the constant current source, a efficient battery charger can be designed [11].

#### 3.1.1. Design

The voltage output requirement is to deliver the voltage terminal 7.2 (2.4V per cell). We use R3 and R4 to design the LM317 to deliver the required voltage. Using [?] we see  $R3 = 470$ . This is a good choice as the current through this resistor will be:

$$I_{470\Omega} = \frac{V_{REF}}{R3} = \frac{1.25}{470} = 2.66\text{mohm} \quad (3.1)$$

The power dissipation is thus:

$$P_{R3} = I_{470\Omega}^2 R3 = (2.66m)^2 * 470 = 3.33mW \quad (3.2)$$

This means minimum power loss. To calculate R4 we use the equation:

$$R4 = R3 \frac{V_{out}}{V_{REF} - 1} = 2237.2\Omega \quad (3.3)$$

We will be using  $R4 = 2.2k\Omega$  as found in the labs.

This total power dissipation over R3 and R4 is significantly small and should cause no problems. This means minimum power loss.

### **3.1.2. Current limit**

The current limit requirement is 400mA. This requirement should not influence any of the values that are chosen in section (2.3.1) that designs for the voltage regulation requirements. The resistor  $R_S$  has to be significantly small as to not cause a large voltage drop across it. A low  $R_S$  value will also have no effect on the voltage regulation mathematics as it will be so small that it will be negligible. A value of  $0.3\Omega$  is chosen as this value is significantly small and the output current requirement is met with this resistor.

Designing a resistor this small is problematic. There aren't resistors this small and the voltmeter struggles to measure such low resistor values. The oscilloscope was thus used to measure  $1.2\Omega$  resistors in parallel until the desired value was achieved. In this design a  $0.1\Omega$  resistor and 4  $1.2\Omega$  resistors are placed in parallel.

### **3.1.3. Thermal analysis**

The heat sink improves the power dissipation of the LM317. The heat sink is attached to the voltage regulator with thermal paste in between as to not allow air between the two components. The heat sink allows the LM317 to not overheat. This is required for the circuit because when the LM317 heats up its physical characteristics change and no design choices were made for these changes. Therefore we try to avoid this problem by improving the heat/power dissipation through the heat sink[4].

## **3.2. High side switch on supply side**

MOSFETs could be used as electronic switches instead of mechanical switches. A large enough positive gate voltage will be used to turn "ON" a circuit and a zero to turn the circuit "OFF". To turn "ON" the MOSFET the gate voltage has to be large enough to put the MOSFET in the saturation region.  $I_D$  and  $V_{DS}$  will be larger than zero. To turn off the MOSFET the gate voltage has to be small enough to put the MOSFET in the cut-off region.  $I_D$  will equal zero and  $V_{DS} = V_{CC}$ . By using MOSFETs we can use low gate current to control high voltage circuits [12]. MOSFETs are voltage controlled switches where BJTs are current control switches. MOSFETs are more efficient switches for power supplies, this is why we will be using them [12]. These electronic switches can be placed in two main configurations. High side switch or low side switch. A high side switch has the load between the switch and ground. The load will receive a voltage when the MOSFET is in the saturation region, usually a PMOS. A low-side switch has the load between the power source and the switch. The load will receive a voltage when the MOSFET is in the cut-off region, usually a NMOS [12]. Although MOSFETs make great switches, the gate voltage might not be enough to control the voltage over  $V_{DS}$ . If this is the case the maximum gate voltage will not be enough to put

the switch into the saturation region. We thus use a second MOSFET at the gate of the first to regulate the voltage, known as a driver [3].

### 3.2.1. Design

The high side switch will consist of two mosfets. The IRF9Z24NPBF must be in saturation when the minimum of 6V is supplied to it. For this to be true the gate voltage has to be 4V. We design for 5V for extreme cases. R2 is in parallel with  $V_{on}$  and will have the same voltage drop. by making R1 and R2 large we can ignore  $V_{DS1}$ . By choosing  $R2 = 50k\Omega$  and  $R1 = 10k\Omega$ (to simplify voltage division with 6V over 60k $\Omega$ ) we can use voltage division to calculate that:

$$V_{GS} = V_{out_{min}} \left( \frac{R2}{R2 + R1} \right) = 5V \quad (3.4)$$

and when  $V_{out} = 7.2$  :

$$V_{GS} = V_{out_{min}} \left( \frac{R2}{R2 + R1} \right) = 6V \quad (3.5)$$

By choosing these resistor values  $I_D$ (if not there) will not exceed 0.12mA( $V_{out} = 7.2V$ ):

$$I_D = \frac{V_{out_{min}}}{R1 + R2} = 0.12mA \quad (3.6)$$

The power dissipation is :

$$P_{R1+R2} = I_D^2(R1 + R2) = (0.12m)^2(60k) = 0.864mW \quad (3.7)$$

This is a good choice as this will limit the power dissipation of R1,R2 and the 2N7000(NMOS). A Schottky diode will be place between the IRF9Z24NPBF (PMOS) and the battery terminal as to keep the battery charging when the supply node goes low.

## 3.3. Undervoltage protection

### 3.3.1. Introduction

The undervoltage protector circuit should start charging the battery terminal when the voltage become to low, this will protect the battery and increase the live span of it. The undervoltage circuit will consist of two operational amplifiers, one will function as a Schmidt trigger and will use hysteresis to avoid outputs that oscillate between states. The second operational amplifier will invert the Schmidt triggers output and will be fed into the high side switch design to allow the battery to be charged or dissipate power, depending on the state of the Battery terminal. A 5V regulator will be designed and used to supply a constant 5V to the circuit. Voltage division will be used at both operational amplifiers to avoid the inputs to

hit the 5V rail. The high side switch will consist of a npn driver transistor and a pnp switch transistor.

### 3.3.2. 5V rail

The first design choice will be the rail voltages when designing a voltage monitoring circuit out of MCP6241 [13] operational amplifiers. Under DC conditions  $V_{ss} = 0V$  according to the data sheet [13] and the  $V_{DD}$  should be between 1.8V and 5.5V. When monitoring the voltage of the battery terminal, binary logic will be implemented where a 5V represents a 1 and 0V represents a binary value of 0. The middle value where a value of 1 and 0 splits is 2.5V. This value is the  $V_{cm}$  of the operational amplifier. Using the equation:

$$V_{cm} = \frac{V_{DD}}{2} \quad (3.8)$$

$$V_{DD} = 5V \quad (3.9)$$

### 3.3.3. 5V Voltage regulator

The 5V regulator was designed using the LM2940 1A low dropout regulator, and using the data sheet. [14] This regulator was chosen because it has a typical output voltage of 5V at  $T_{amb} = 25^{\circ}C$  when the input voltage is between 6.25 and 26V. The input voltage of the regulator should be connected to the battery terminal that will have the required output voltage for the voltage regulator to function properly. A highside switch is build with a driving NPN and PNP switch. This switch is build on the same principles discussed in section(3.2)

## 3.4. Voltage monitoring with hysteresis design

When designing a comparator the rail voltages are designed to be  $V_{DD} = 5V$  and  $V_{SS} = 0V$  as explained in section 2.3. An inverting comparator is designed which has a rail of 5V but, this will not be an issue because it will be seen as the highest value possible, which is about 3.6, when the battery terminal is 7.2V. The battery terminal is compared with 6.2V. However, our source voltage is 5V which is less than 6.2V. Voltage division is thus used to achieve appropriate voltage values. Design choice: 6V will be turned into 3V by making  $R4 = 200k\Omega$  and  $R5 = 200k\Omega$ . 6.2V will be turned into 3.1V.  $R2 = 100K\Omega$  is a design choice made. Using voltage division:

$$R1 = \frac{R2}{\frac{3.1}{5}} - R2 \quad (3.10)$$

$$R1 = 61.3k\Omega \quad (3.11)$$

This means:

$$V_{cm} = V_{DD}/2 \quad (3.12)$$

$$V_{cm} = 2.5V \quad (3.13)$$

This is less than  $V_{cm(max)}=2.75$ . The  $V_{Diff(max)} = |V_{DD} - V_{SS}|$ :

$$V_{Diff(max)} = 5V \quad (3.14)$$

Our voltage difference is:

$$V_{diff} = 3.1V \quad (3.15)$$

at maximum difference.

### 3.4.1. Hysteresis

When the input voltage comes really close to the reference voltage the output of an op amp can begin to oscillate between states. This is especially true when the input can be effected by noise. Hysteresis solves this issue by making use of a feedback resistor connected to the  $V_{ref}$  node called a hysteresis resistor. When the input voltage is low the output of the operation amplifier will be high. This voltage at the  $V_{ref}$  node is slightly higher than it would have been without hysteresis. For the same reason when the output voltage is low  $V_{ref}$  will be lower than it would've been without hysteresis. By changing the reference voltage when the input voltage is made, it creates a bigger difference between the two voltage not allowing oscillations in the output to occur.

For the design of this circuit the hysteresis resistor is calculated to be  $2M\Omega$

The comparators output is pulled high through a  $100k\Omega$ resistor connected from the operational amplifiers output to 5V.

The operational amplifier that has been designed so far is known as a Schmitt trigger. It switches at different voltages depending if the input voltage is moving from 0 to 1 or 1 to 0 [15].

A second operational amplifier is also used. This will be an inverting operational amplifier. Voltage division is again used to choose the reference voltage as  $V_{REF} = 2.5V \cdot R7 / (R7 + R8) = 200k\Omega$ and  $R8 = 200k\Omega$ to satisfy this requirement.  $R9 = 100k\Omega$ and functions as a pull up resistor to not leave the output hanging. The output terminal of this operational amplifier is then connected the 2N7002 npn transistor. The goal of this operational amplifier is to invert the Schmitt trigger.

## 3.5. Overcurrent protection

### 3.5.1. Introduction

The RS -4Ah battery [16] has 4 different phases of charging, it should also be allowed to discharge over a load. The battery therefore have many modes it goes through. These modes need to be tracked to determine how the battery is behaving and how other components should behave according to the battery and users desires. A bidirectional current circuit is a circuit that measures the current flowing through a current sense resistor. A resistor so small that the voltage drop over it can be neglected. Amplify the voltage drop by using an amplifier and then send out an output voltage that correlates to the current flowing through the sense resistor.

### 3.5.2. Design

The TLC213 [17] and current sensing resistor [18] was used to design a current sensing resistor. The TLC213 is selected because it has n build in gain of 50V. The TLC213 amplified the voltage difference over the current. The sensing current would have a voltage output  $V_{out}$  between 5V and 0V to determine if the battery is charging or discharging. The TLC213 has a gain of 50V/V and the following resistors where build into the component we received: R1=R2=1MΩ, R3=R4=20kΩ. The reason these components have the same values are to minimize errors such as noise.

The current over the current sensing resistor(1mΩ) will range from -150mA to 450mA and thus the center current (150mA) has to be at the center of the Voltage range. This will allow the best output swing. The following equations are used to determine the reference voltage( $V_{ref}$ ) to achieve the goal above:

$$V_{out} = I_{LOAD} * V_{diff} * \text{gain} + V_{ref} \quad (3.16)$$

Because we want the center current at the center voltage:

$$V_{out} = I_{LOAD} * R_{sense} + V_{ref} \quad (3.17)$$

$$2.5 = (0.1) * (0.15) * (50) + V_{ref} \quad (3.18)$$

$$V_{ref} = 1.75V \quad (3.19)$$

Because a  $V_{cc} = 5V$ , voltage division will be used to achieve the desired reference voltage. This means:

$$V_{ref} = V_{cc} * \frac{R6}{R6 + R5} \quad (3.20)$$

$$\frac{R6}{R6 + R5} = 0.35 \quad (3.21)$$

Choose  $R6 = 100k\Omega$ . This value is large enough to minimize current through the resistor and therefore minimizing power dissipation over the resistor as well.

$$R5 = \frac{R6}{0.35} - R6 \quad (3.22)$$

$$R5 = 185.7k\Omega \quad (3.23)$$

The output should be connected to a capacitor that will filter out the high frequency noise, however this capacitor should also be small enough to not effect the transient response of the TLC213 too much. By running through many simulations in spice and seeing what is available in the labs, a capacitor of  $4.7\mu F$  has been chosen.

## 3.6. Low-side switch

### 3.6.1. Literature

A load will be connected to the battery, which will allow the battery to discharge over the load. We want to be able to control this behaviour and thus need a switch. A low side switch will be build by using a NPN MOSFET to control the discharge over the load.

### 3.6.2. Design

The load consists of 5 ultra bright LED's connected in parallel with each other. The LED's will be connected to the 7.2V source and the switch. The ultra bright LED's data sheet [19] specifies a forward voltage drop of 3.2V. The maximum current that will flow through the load is 150mA, if 150mA flows through the load, each LED will receive a current of 30mA. This is the maximum rated forward current for the ultra bright LED's according to the data sheet [19] this shouldn't damage the LED's. The typical current of 100mA(20mA per LED) The NPN that will be used has a  $V_{GS(th)} = 2.1V$ . 5V will be sufficient to turn on the transistor [20].

To design for one LED we use circuit analysis to do the following calculations:

$$V_{cc} = I_{LED} * R + V_{(LED)} \quad (3.24)$$

$$7.2 = (20m) * R + 3.2 \quad (3.25)$$

$$R = 200\Omega \quad (3.26)$$

I decided to use  $R = 220$  for safety and labs restrictions.

### **3.6.3. Results**

The circuit worked as intended. The load could be controlled by the signaler NPN MOSFET but, because of the resistor tolerance the voltage drop over the LEDs where not exact as the equation anticipated. For the following conditions:  $V_{cc} = 7.3V$ ;  $I = 100mA$ ;  $R = 220\Omega$ ; the LED voltage was 2.91V. This is less than the typical forward voltage. This means that the LED would be as bright as they could be. But it also means that the LED are more protected against higher currents.

## 3.7. Supply voltage measurement

To use the PV panel properly the system needs to be able to track the output voltage of the panel. This will be done by allowing the beetle [21] to receive a 0V to 5V ADC input voltage. This will correlate to the PV panels 0V and 22V.

### 3.7.1. Design

The PV panel's highest voltage value (22V in this system) will be read as 5V by the beetle and 0V will stay 0V. R2 is chosen to be  $10\text{k}\Omega$

R1 can be calculated by:

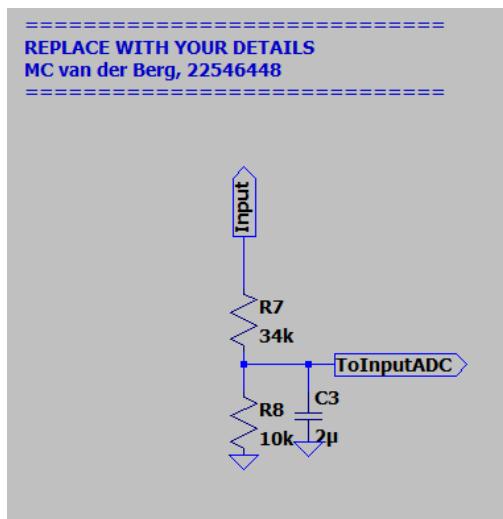
$$R1 = \frac{V_{in}}{V_{out}} * R2 - R2 \quad (3.27)$$

$V_{in} = 22\text{V}$  should lead to  $V_{ADCInput} = 5\text{V}$ :

$$R1 = \frac{22}{5} * 100k - 100k \quad (3.28)$$

leading to  $R1 = 34\text{k}\Omega$

The PV panel's output voltage will be unstable thus, a low pass filter also has to be implemented. The system requires the output to respond within 100ms. A capacitor of  $2\mu\text{F}$  is used to achieve this requirement.



**Figure 3.1:** Supply voltage to battery ADC input voltage

## 3.8. Battery voltage measurement

### 3.8.1. Design

To properly handle the battery, the system needs to know what the current voltage of the battery is. This will be done by allowing the arduino beetle to receive a 0V to 5V ADC value. Therefore, we need to convert the active voltage range of the battery to a ADC voltage that is readable for the beetle [21].

The range that will not harm the battery is 6V to 7.2V, we want to be able to read values higher and lower to know if the battery is being harmed. Thus, 5.5V and 7.5V is chosen. The beetle needs a 0V to 5V as input. Only scaling will lead to 7.5V correlating to 5V and 5.5V to 3.67V making 73.4% unusable. Thus, a differential operational amplifier will be used to make 5.5V correlate to 0V, but 7.5 and 5.5 are higher than 5V (the high side voltage rail), thus the  $V_{in}$  has to be scaled down. The voltage has to be properly scaled as to not hit the operational amplifier voltage rails.

#### Voltage scaling

The input voltage will be scaled from 5.5V and 7.5V to 2.75V and 3.75V making the common mode voltage 1V. The opamp [7] has a common mode of 2.5V thus making these values acceptable. R4 is chosen to be 100k $\Omega$ to limit current flow.

$$R3 = \frac{V_{in}}{V_{out}} * R2 - R2 \quad (3.29)$$

We want  $V_{in} = 7.5V$  to correlate to 3.75V:

$$R3 = \frac{7.5}{3.75} * 100k - 100k = 100k \quad (3.30)$$

The differential operational amplifier will have a reference voltage that should be the equal to scaled 5.5V(2.75V). So 5V has to be scaled to 2.75V

R2 is chosen to be 100k $\Omega$ to limit current flow and thus increasing power efficiency. R1 can thus be calculated by:

$$R1 = \frac{5}{2.75} * 100k - 100k = 81.81k\Omega \quad (3.31)$$

A 82k $\Omega$ will be used.

## Differential Amplifier

The equation that will be used is:

$$V_{out} = \frac{(R_1 + R_f) * R_g}{(R_2 + R_g) * R_1} - \frac{R_f}{R_1} * V_1 \quad (3.32)$$

found on electronics-lab [22]

To simplify the equation  $R_1 = R_2$  and  $R_f = R_g$ . Then:

$$V_{out} = \frac{R_f}{R_1} * (V_2 - V_1) \quad (3.33)$$

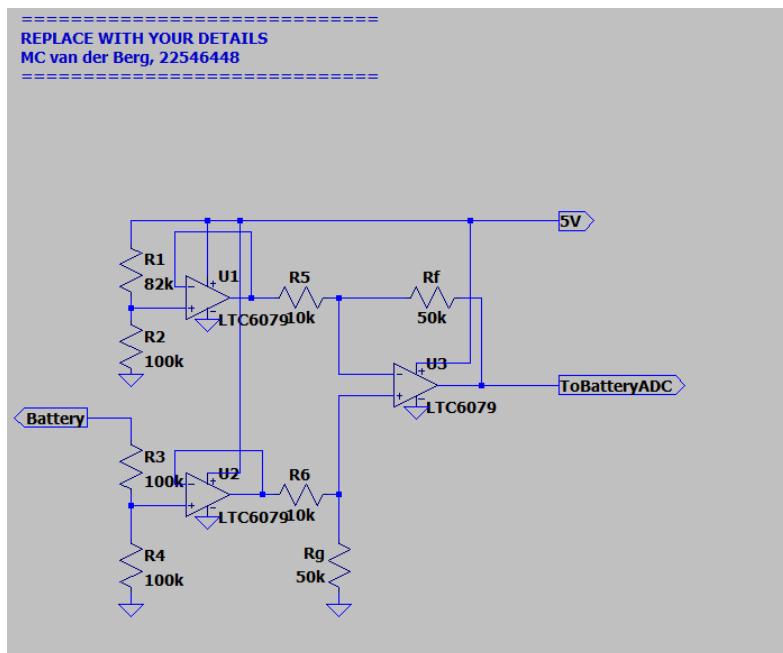
$V_{out} = 5V$  when  $V_2 = 3.72$  and  $V_1 = 2.75$ :

$$A = \frac{R_f}{R_1} = 5 \quad (3.34)$$

$R_1$  is chosen to be  $100k\Omega$  to limit current flow. Leading to  $R_5$  and  $R_6$  equal to  $10k\Omega$ . Then  $R_f = 50k\Omega$ . Leading to  $R_7$  and  $R_8$  to equal  $50K\Omega$ .

## Voltage followers

Two voltage followers are used. When scaling the input voltage and when scaling the reference voltage. This is done to maintain the correct scaling as  $R_5$ ,  $R_6$  and  $R_7$  may change it. The input impedance of the voltage followers is very large and thus limiting current and making the circuit more power efficient.

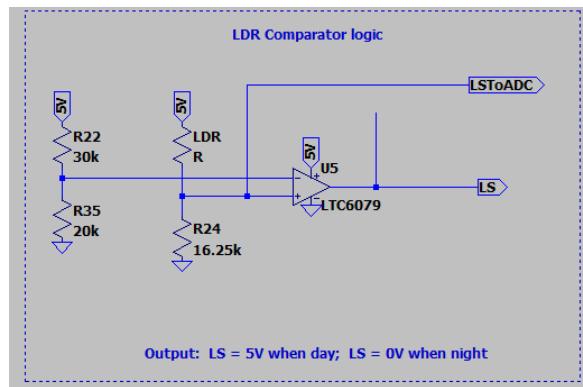


**Figure 3.2:** Battery voltage to battery ADC input voltage

### 3.9. Ambient light sensor circuitry

The goal of this circuit is to output an adc voltage between 0V and 5V that will be read by the arduino beetle [21], as well as a digital output that will be used by the load control and pilot light circuitry.

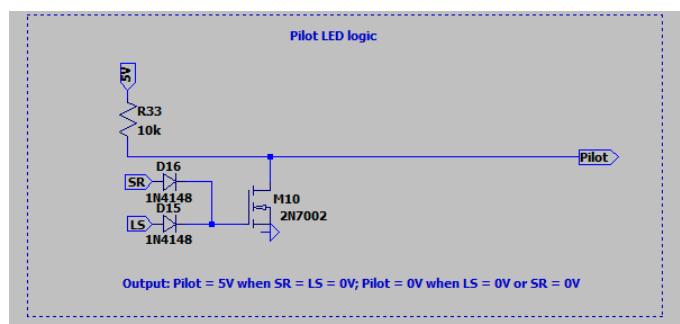
By voltage scaling 5V with a light dependent resistor (LDR) [23]. The output voltage will increase as the brightness outside increases. Lab conditions lead to resistor values of  $7.5\text{k}\Omega$ - $25\text{k}\Omega$ . Choosing lab conditions as 2.5V and thus  $R_g = 16.25\text{k}\Omega$ . A comparator is used for a digital output with a reference voltage of 2V. When the scaled input voltage is higher than 2 the opamp output will be 5V and 0V when the input voltage is lower. The output will be called LS (light sensor)



**Figure 3.3:** Ambient light sensor circuitry

### 3.10. Pilot light control

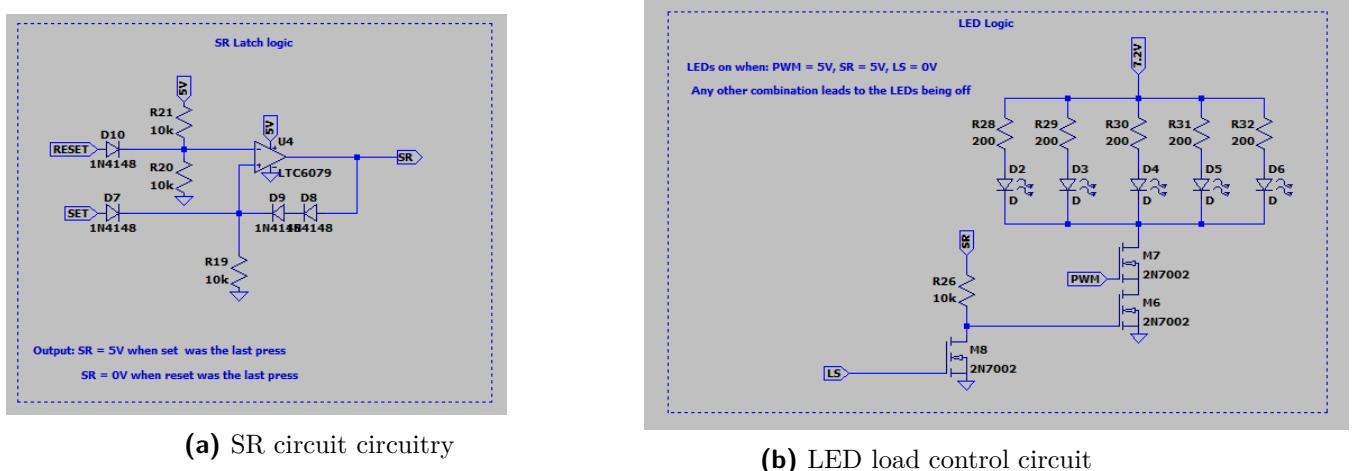
The pilot light should be controlled to be on when it is dark and when the load LEDs are off. The pilot lights can thus be controlled by using the light sensor output and the SR latch as these two inputs control the load LED and when its day or night. A XOR gate is build and used in parallel with the pilot light. By doing this the pilot lights are pulled low when they should be off and pulled high when they should be on. Diodes(1N4148) are used to separate the circuits from one another.



**Figure 3.4:** Pilot light circuitry

### 3.11. LED load control

The LED load should be controlled by LS, the SR latch and the beetle [21] should control the brightness of the LED load through PWM. The LEDs should only be on when the SR latch output and PWM inputs as mentioned above, are high and when LS is low. A low side switch can be build for the PWM and the SR output will be the  $V_D$  for a inverting switch with  $V_B$  as LS.



**Figure 3.5:** Caption for this figure with two images

The SR latch will take two button inputs for a user. One will set the output of the SR latch to high (SET button) and the other will set the output of the SR latch to low (RESET button). The SR latch will function as 1 bit of ram, saving the user input and outputs accordingly until the user input changes. The SR latch will be built using an operational amplifier, resistors and diodes.

A  $10k\Omega$  is placed between 5V and reset input as well as between reset input and ground. When the reset input is floating (no user inputs) the operational amplifier will receive a scaled voltage of 2.5V. This will function as a reference voltage,  $V_-$  will not be able to be pulled lower than 2.5V, due to D10 being reverse biased. When the set input goes high, the voltage will be higher and the operational amplifier will receive 4.4V due to D7. This reference voltage leading to a change in the SR latch output. The set input is connected to a pull down resistor of  $10k\Omega$ . This will lead to the set input to be 0V instead floating when there is no user input. Diodes are used in the feedback of the operational amplifier so that the non-inverting input signal will be 3.8V when no user input is given.

# Chapter 4

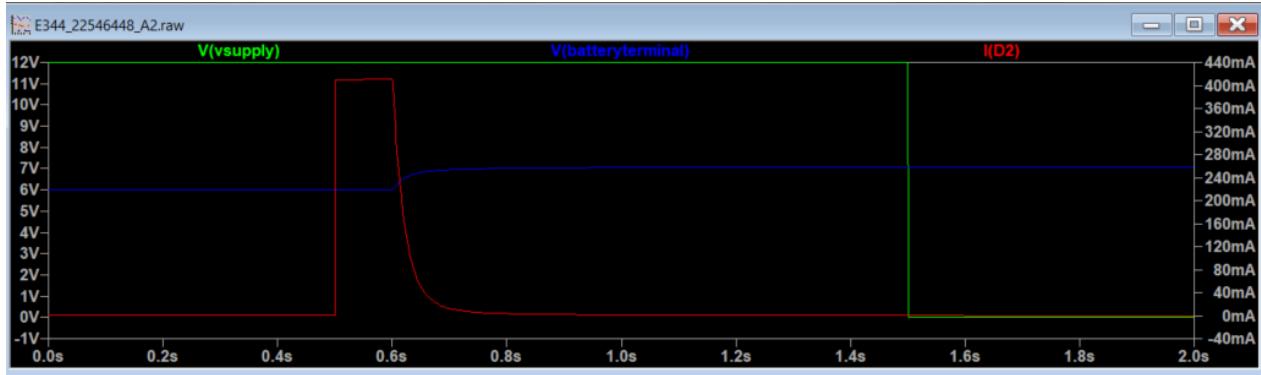
## Simulated and measured results

### 4.1. Voltage Regulation and high side switch

#### 4.1.1. Simulation results

The circuit works as intended. The regulated voltage at the battery terminal is 6V at first. This is why we designed IRF9Z24NPBF to be on and its voltage  $V_{GS} = 5V$  at 6V output. At six second the voltage increases from 6 to 7.2V at the exact same time the current spikes to 400mA for about half a second. This is due to the charge on node that increased from 0V to 5V. At this point the Battery is being charged at a optimal voltage and current. The circuit therefore meets all the design requirements. The current drops down to 0A again after no more than a second. When the supply voltage drops to zero the battery terminal keeps on charging, and the voltage delivered to the battery remains 7.2V. This is due to the 1N5819 Schottky diode.

**Figure 4.1:** The Ltpice results for the designed charging circuit.



#### 4.1.2. Measured results

Convince the reader that your circuit performed as expected using measured results. Same principle as for the simulation results, but now with measurements (e.g. oscilloscope plots).

In reality these values differ slightly from the simulated values on let spice, but the key ideas and design ideas stay intact. The output voltage of the LM317 is slightly lower than the intended value. This report designed for 7.2V but in reality the physical circuit delivered a 7.1V output voltage when no load attached to the battery terminal. The maximum output

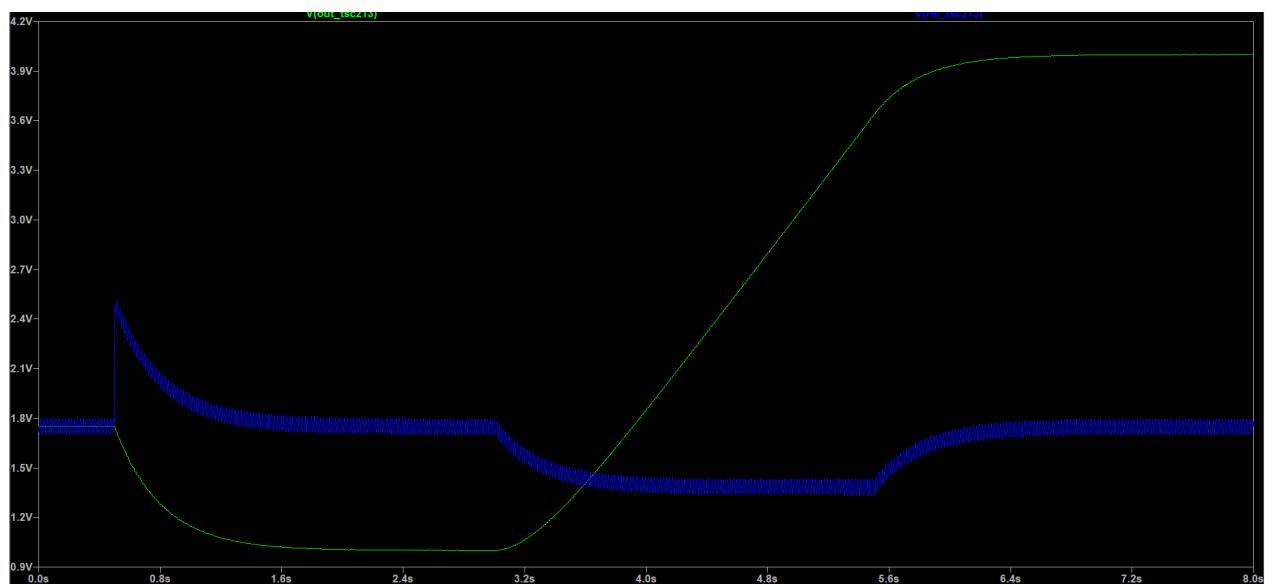
current is also a bit larger than intended for. This report designed for a 400mA maximum output current but in reality the physical circuit value was 430mA. These minor changes in circuit value should not harm the battery in any way as these values are well in the range of safe design. The difference in output voltage and current could be due to the  $0.3\Omega$  resistor as it was extremely difficult to design this. It could also be due to any of the other resistors tolerance range.

But except for the minor value changes in output voltage and output current. The circuit works as intended. And goal was achieved. The battery will be charged safely when attached to the battery terminal of this circuit.

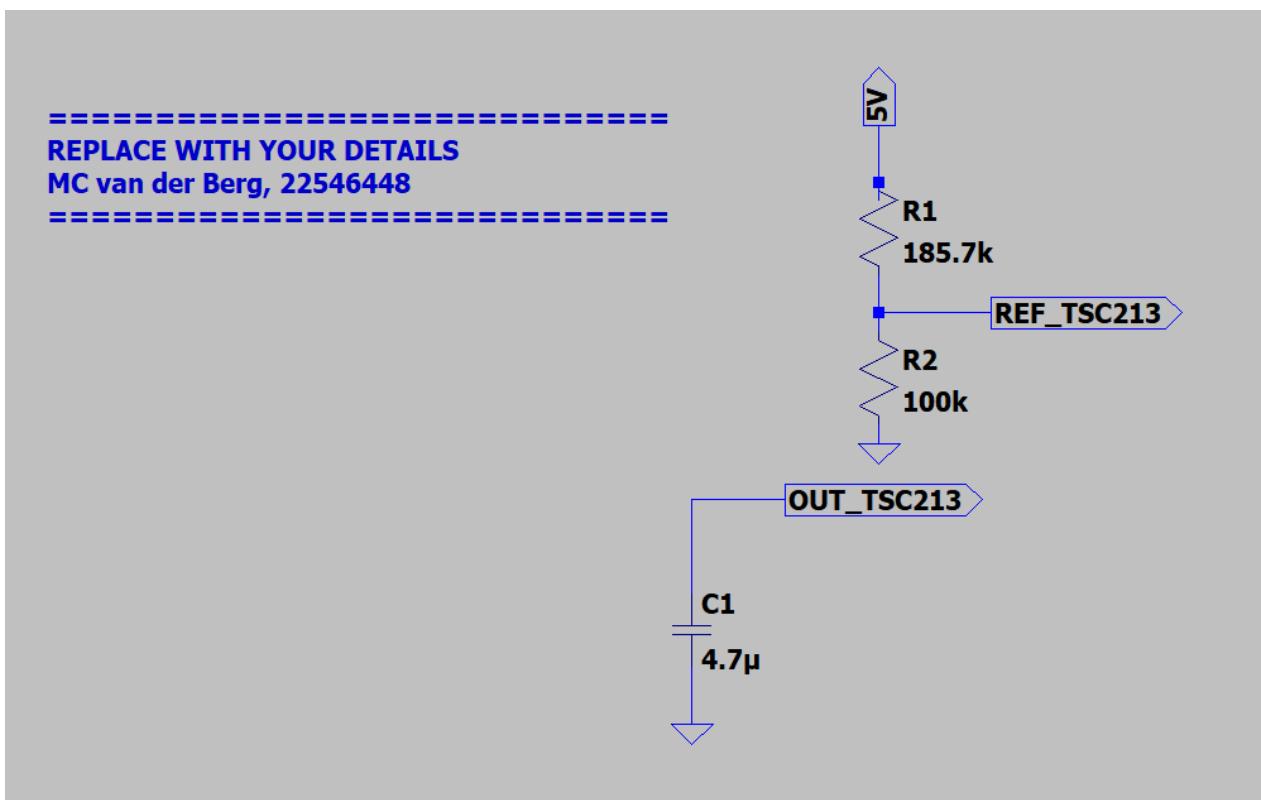
## 4.2. Overcurrent protection

The design requirement state the following:

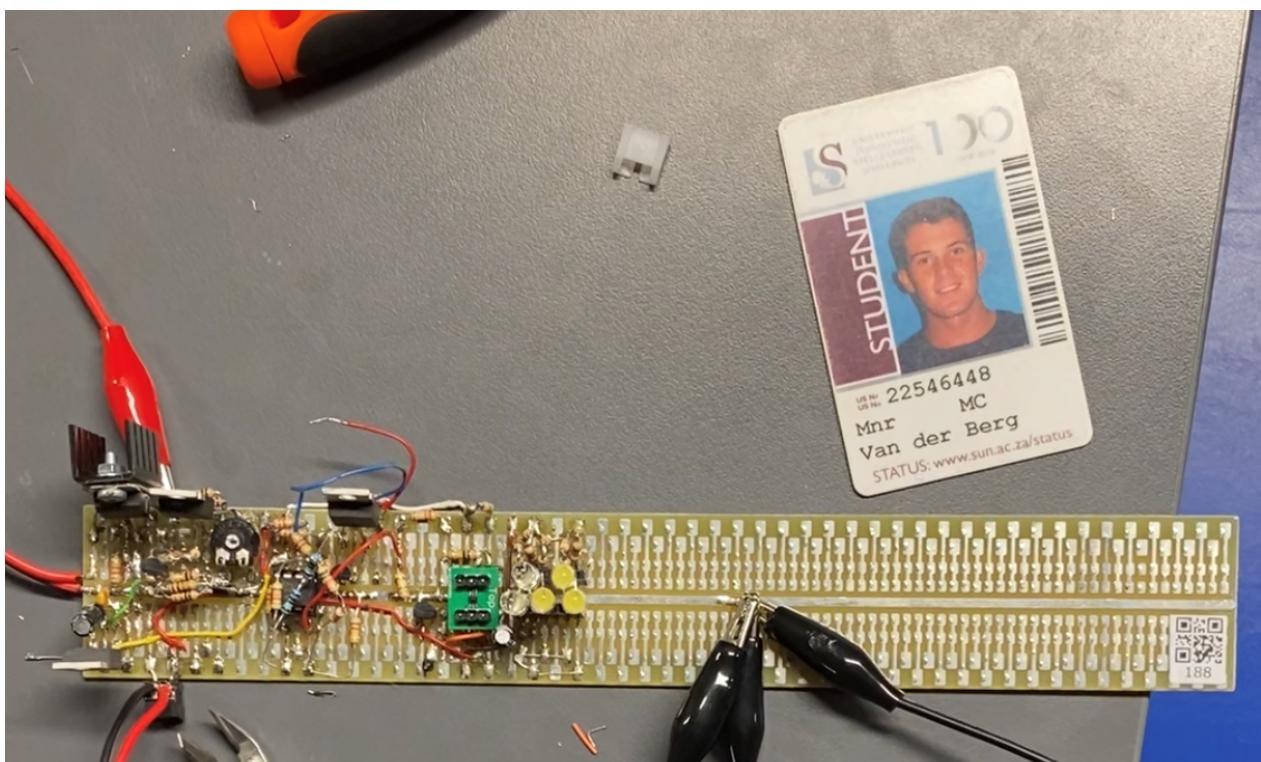
1. The output voltage must be less than  $2mV_{pk}$ : The  $4.7\mu F$  capacitor is large enough to filter out high frequency noise the TLC213 might face. The maximum noise measured and seen on spice is  $1.6\text{mV}$  which is less than  $2mV_{pk}$
2. The circuit response should respond to a change of  $150\text{mA}$  in  $2\text{s}$ : The capacitor is small enough to achieve this requirement. The measured response is  $1.79\text{s}$ , this is less than  $2\text{s}$ .
3. Output voltage should be  $3\text{V}$  for the given current range: The highest  $V_{out} = 4\text{V}$  and the lowest  $V_{out} = 1\text{V}$ , this means the output swing is  $3\text{V}$ .
4. The voltage range must be  $5\text{V}$  to  $0\text{V}$ : This range was designed, as indicated above.  $V_{out}$  will never achieve  $5\text{V}$  or  $0\text{V}$  as the output swing does not allow it and this is also undesirable as this would hit the TLC213 Rail voltages.



**Figure 4.2:** LTSPice output simulation graph



**Figure 4.3:** LTSpice design schematic



**Figure 4.4:** MY design and student number

## 4.3. Undervoltage protection

Figure 4.5: LTspice undervoltage protection design

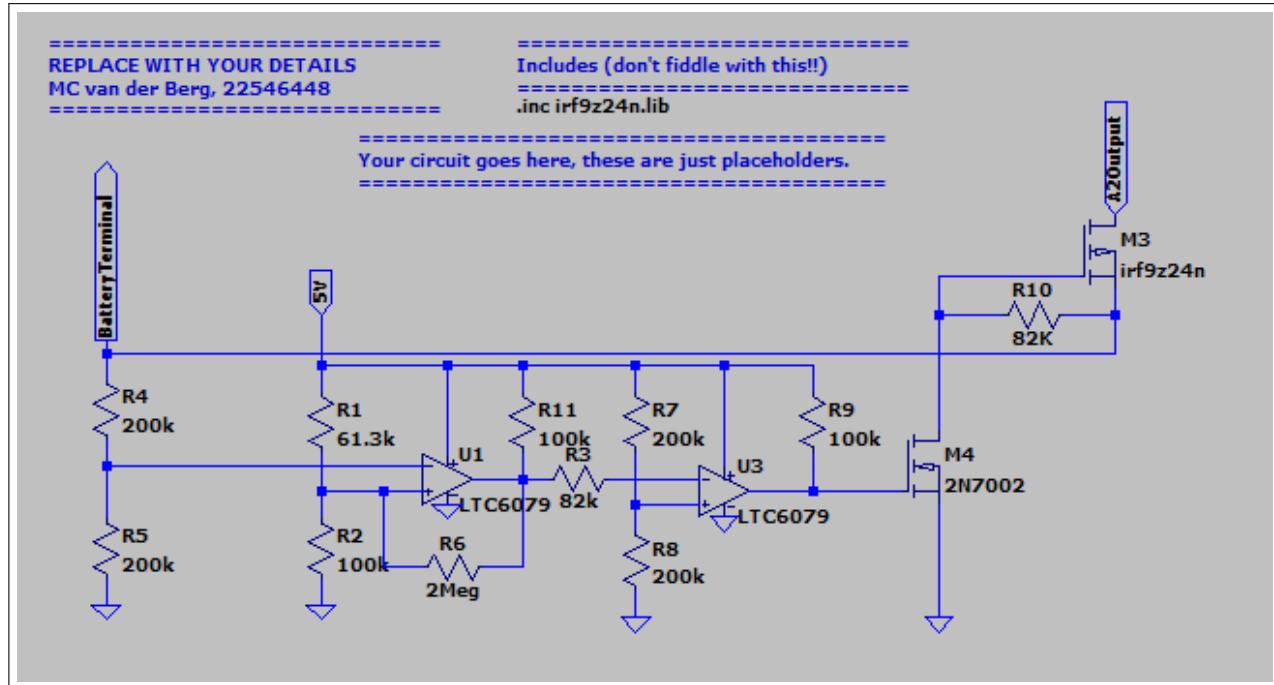
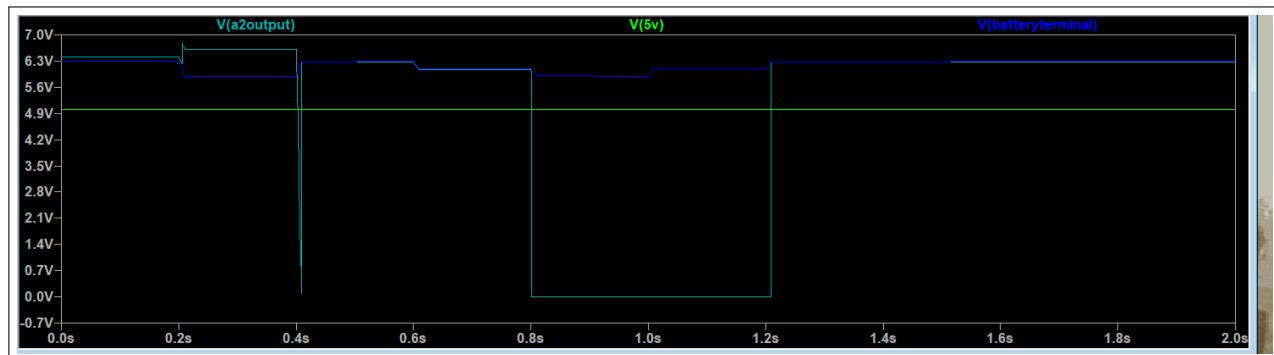
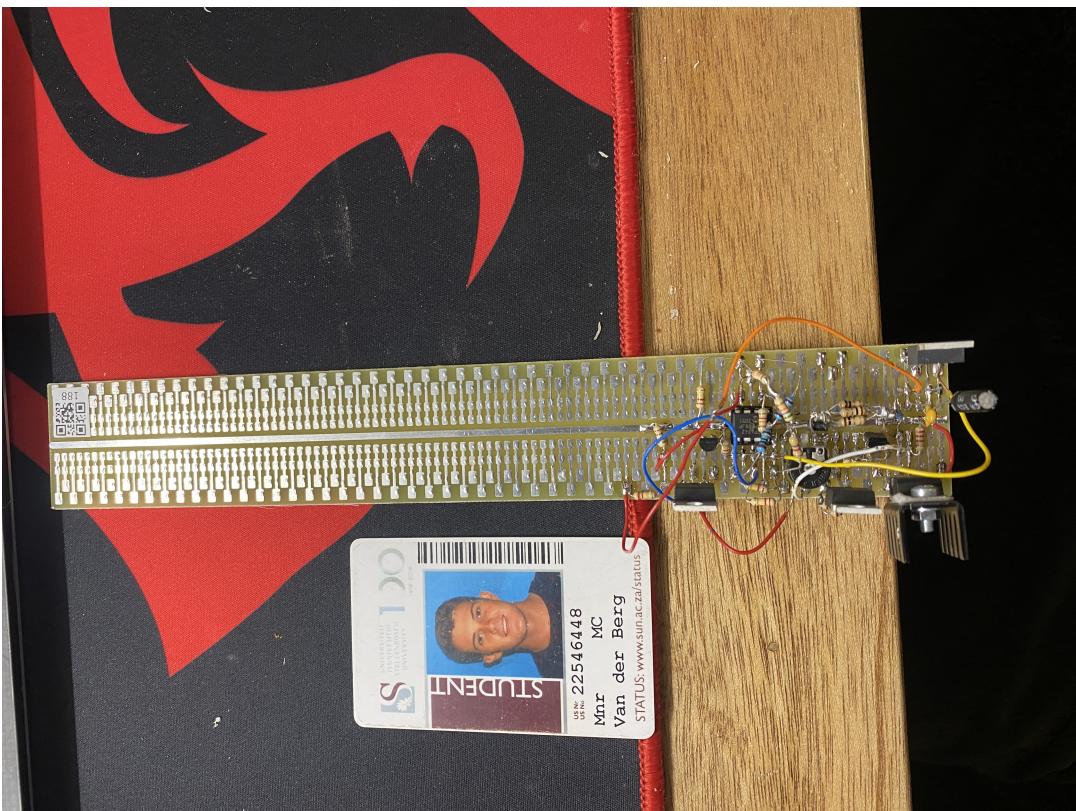


Figure 4.6: LTspice undervoltage protection design simulated results



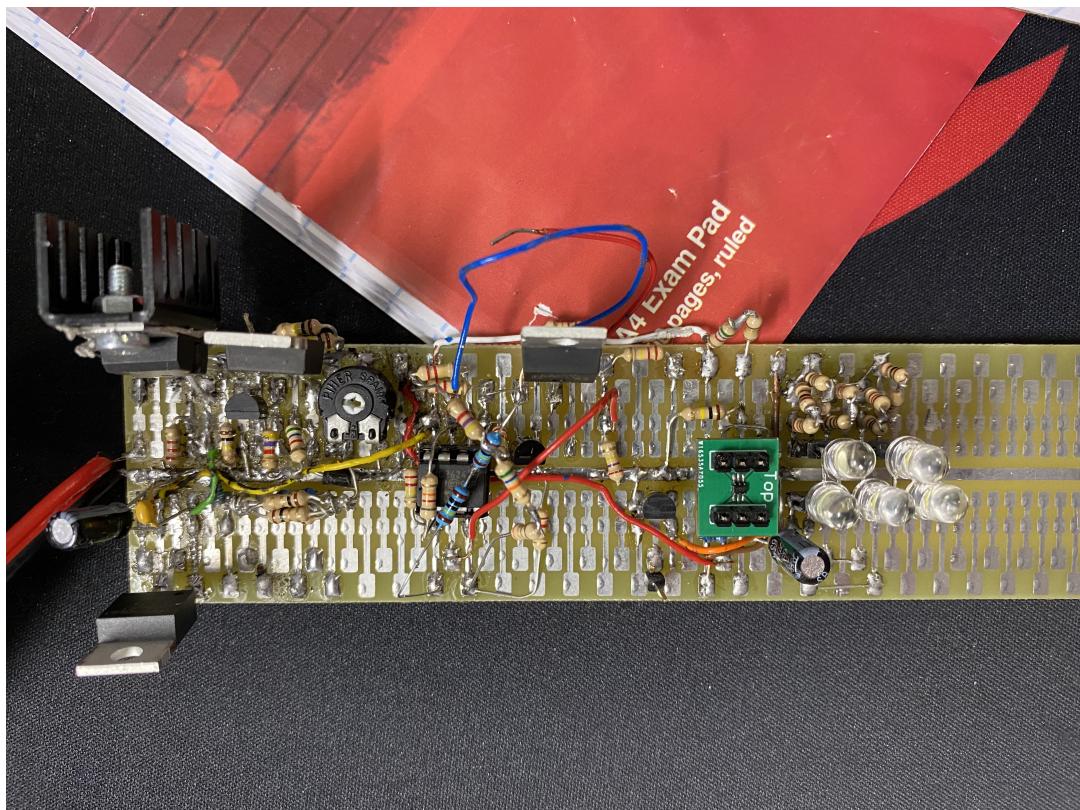
The results are as expected. The battery terminal switches off at 6.2V as designed. The current is limited and almost zero.

**Figure 4.7:** LTspice undervoltage protection circuit

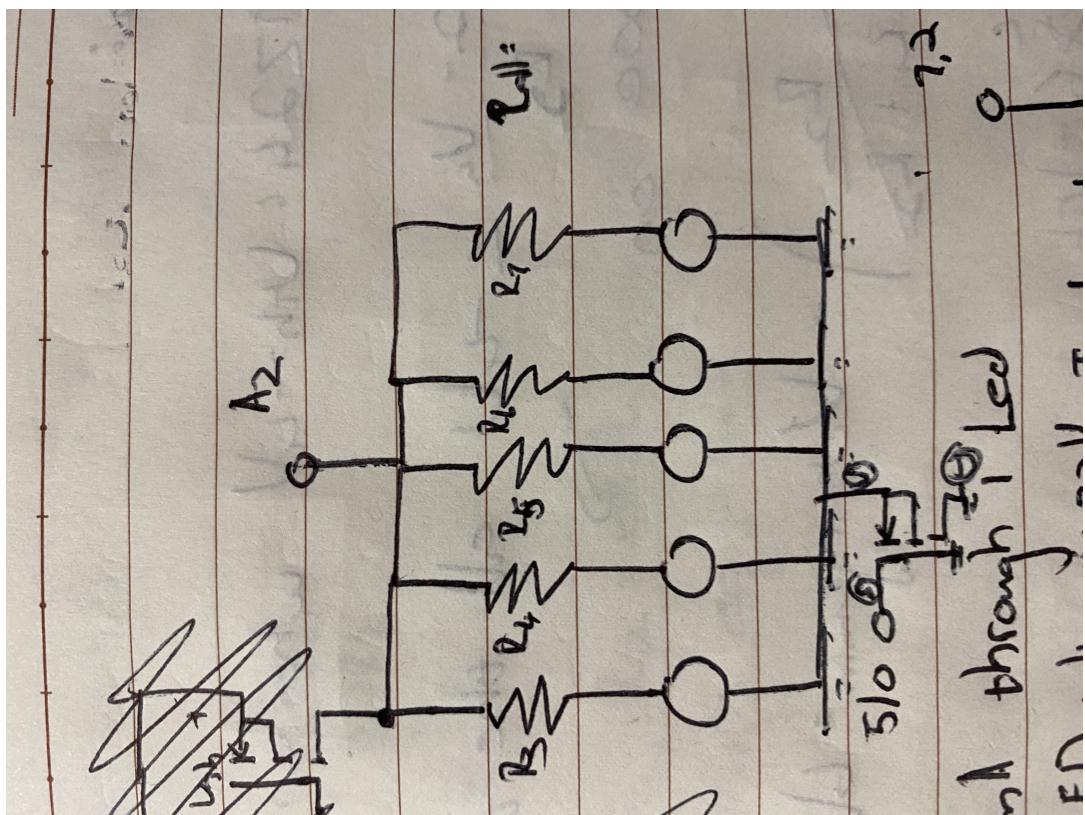


## 4.4. Low side switch

**Figure 4.8:** LTspice Low side switch circuit



**Figure 4.9:** Low side switch circuit design



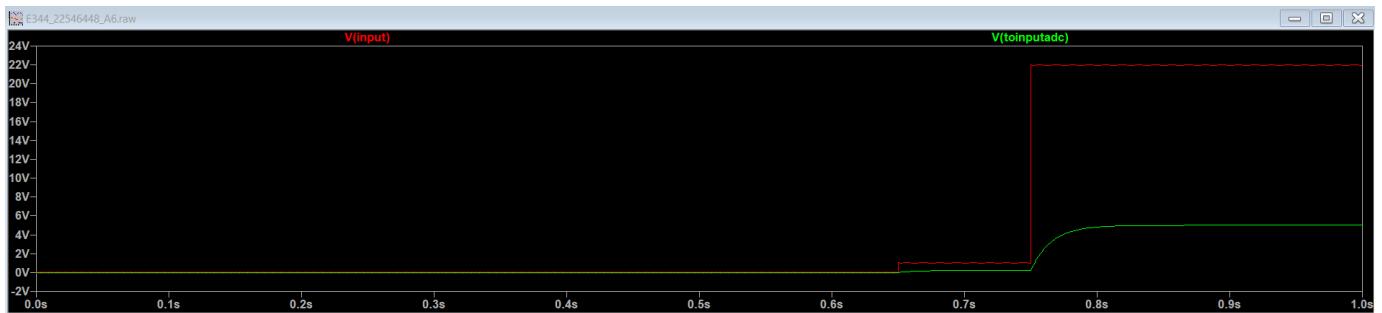
## 4.5. Supply voltage measurement

### 4.5.1. Simulated Results

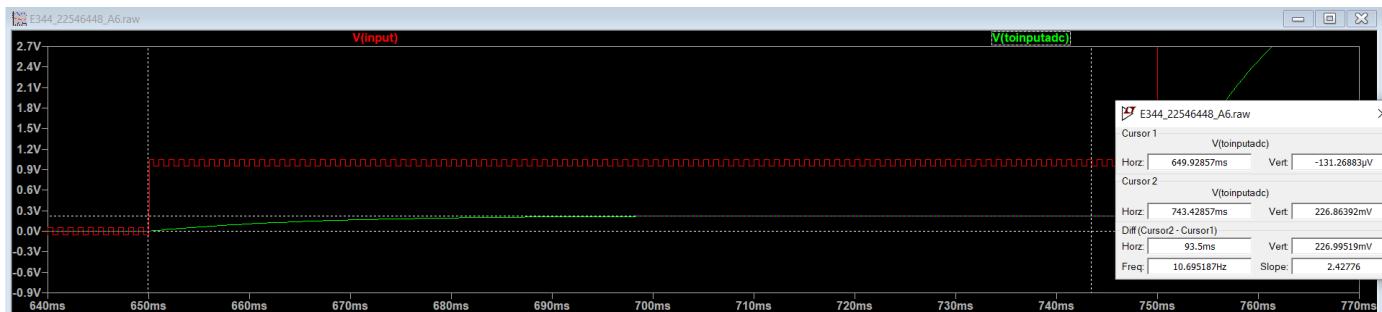
PV panel voltage(V)	ADC voltage(V)
0	0
1	227m
21.95	5

The response a 1V step is 93.5ms. This is below 100ms that is required.

**Figure 4.10:** The supply input to the beetle vs the PV panel voltage



**Figure 4.11:** The supply input to the beetle response to a 1V step



### 4.5.2. Measured Results

PV panel voltage(V)	ADC voltage(V)
0	0
1	22m
21.95	4.96

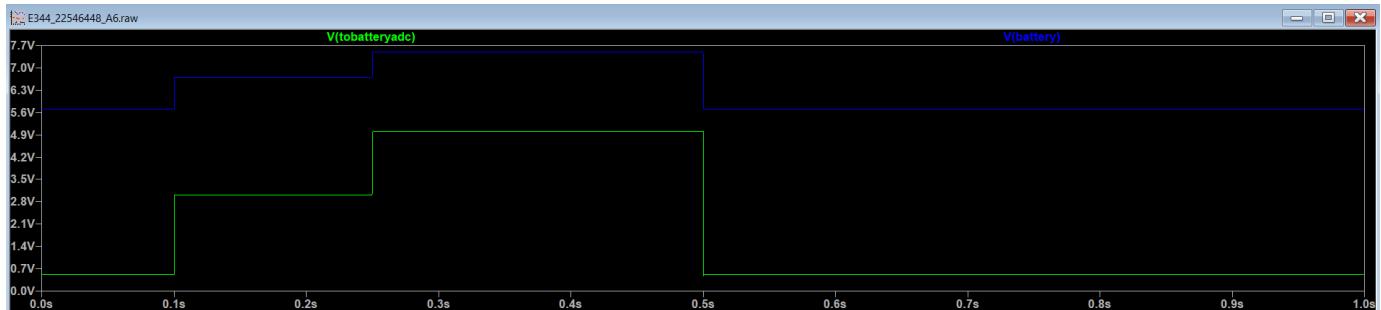
The step response is in reality 97.6ms. This is due to a 2.2uF that was used instead of a 2uF as done in spice. This is however still lower than 100ms.

## 4.6. Battery voltage measurement

### 4.6.1. Simulated Results

Battery voltage	ADC voltage
4.3	0
5.7	500m
6	1.25
6.6	2.75
6.7	3
7.2	4.25
7.5	4.998

**Figure 4.12:** The supply input to the beetle response to a 1V step



### 4.6.2. Measured Results

Battery voltage	ADC voltage
4.3	0
5.7	870m
6	1.57
6.6	2.97
6.7	3.33
7.2	4.36
7.5	4.98

The difference in the measured and simulated results is due to resistor tolerance range. The reference voltage is suppose to be 2.75V ,but when measured it is 2.68V. This will change the peak value from 7.5V to 7.6V. This is not a problem but the beetle software will have to take this into account.

The response time is not effected as no capacitor is placed in the circuit.

## 4.7. Ambient light sensor

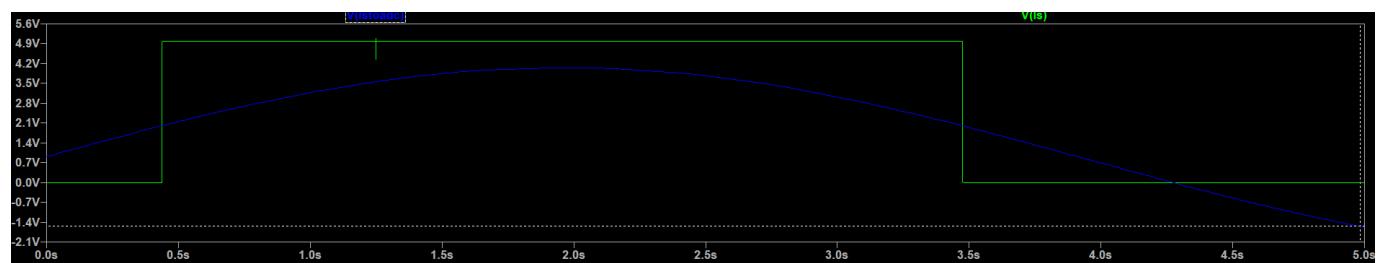
LS digital output	LS ADC output
0	0.8
0	1.8
1	2.8
1	3.8
1	4.8

**Table 4.1:** Simulated Results

LS digital output	LS ADC output
0	0.8
0	1.8
1	2.8
1	3.8
1	4.8

**Table 4.2:** Lab Result

**Figure 4.13:** Light sensing circuit analog and digital output



The simulated results transition at 2V and the lab results transition at 2.1V

## 4.8. Pilot light

Light sensor(V)	SR latch	Pilot light(V)
0	0	0.8m
5	0	0
0	5	0
5	5	0

**Table 4.3:** Simulated Results

Light sensor(V)	SR latch	Pilot light(V)
0	0	0.78m
5	0	0
0	5	0
5	5	0

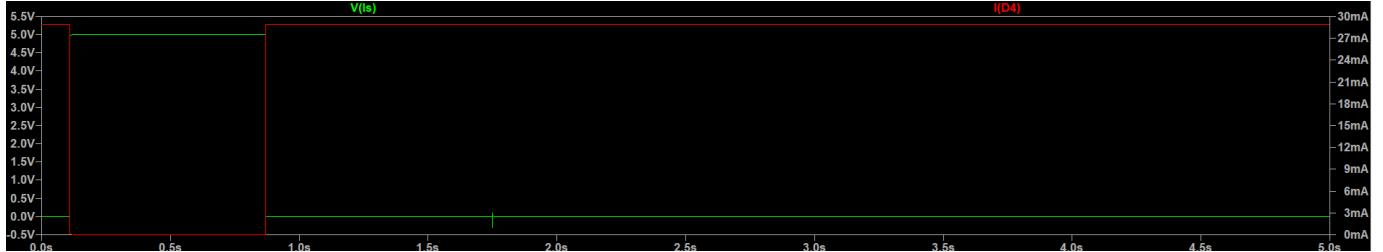
**Table 4.4:** Lab Result

**Figure 4.14:** Pilot light output

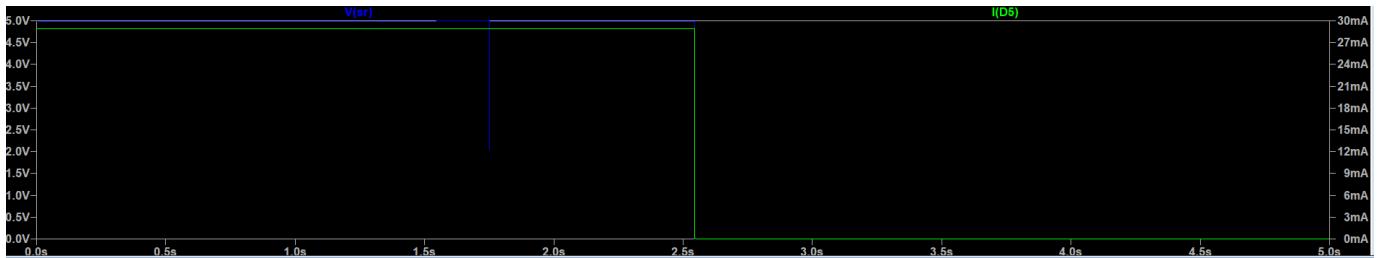


## 4.9. LED load control

**Figure 4.15:** A single LED current vs light sensor



**Figure 4.16:** A single LED current vs SR latch output



Light sensor(V)	SR latch (V)	LED Load (V)
0	0	0
5	0	0
0	5	2
5	5	0

**Table 4.5:** Simulated Results

Light sensor(V)	SR latch (V)	LED Load (V)
0	0	0
5	0	0
0	5	1.75
5	5	0

**Table 4.6:** Lab Result

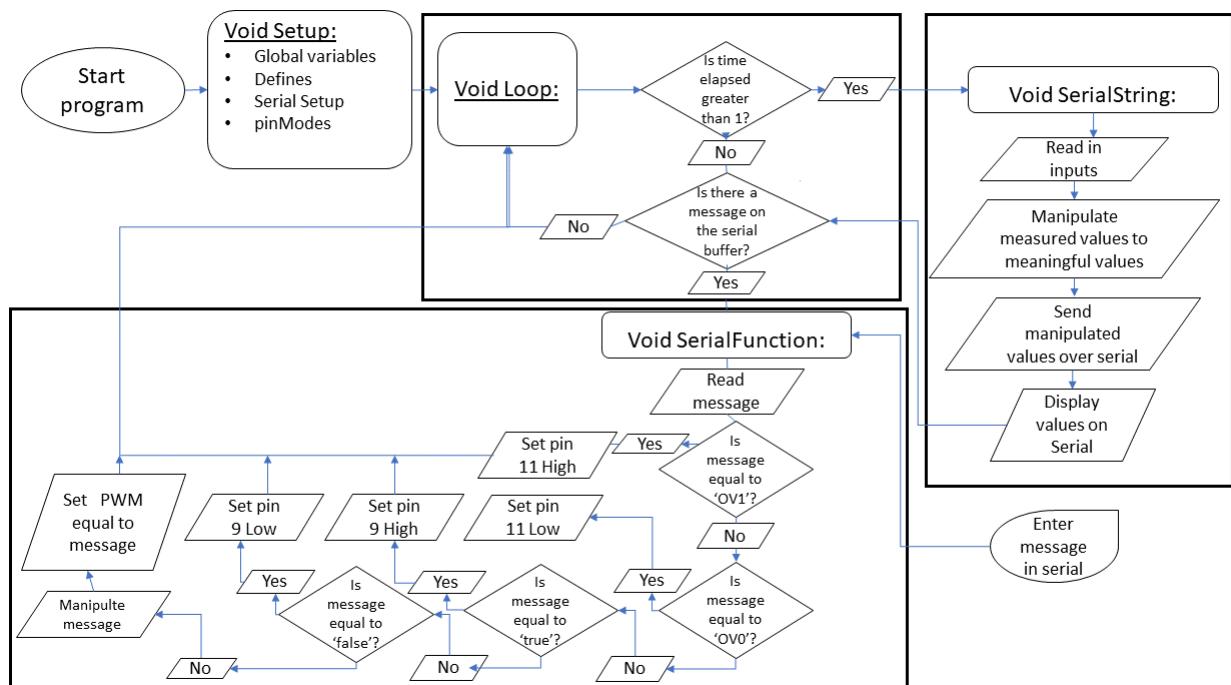
The PWM signal is kept high (5V) for all measurements as this signal will come from the beetle to not only turn the LoadLEDs on but also adjust their brightness. This PWM has not yet been built into the current design.

# Chapter

5

## Firmware

### 5.1. Flow Diagram



**Figure 5.1:** Flow diagram of firmware run on arduino on the beetle

The system will log and display important data that will allow the user to know in what the state the system is. The program will start by initializing global variables, defines, the serial and configuring the pin that are being used. The **loop function** consists of two if statements, one checking whether enough time has elapsed to read new values from the input pins (**SerialString**) and another checking whether the user has entered a message into the serial buffer (**SerialFunction**). If the elapsed time is greater than one the **SerialString** is called. This function reads, manipulates, sends and displays the GPIO pin input values on the serial output display for the user to interpret. Then the program checks if there is a message available on the serial buffer. If no, the loop will start from the beginning. If yes, a message on the serial buffer is read as either 'OV1', 'OV0', 'true', 'false' or a new PWM value. 'OV1' sets the overvoltage protection pin to on, allowing the battery to charge. 'OV0' sets the overvoltage protection pin to off, disconnecting the battery from the power source. 'true' allows the PWM output to be on. 'false' does not allow the PWM output to be on, thus turning

off the LED load. If a value between 100 and 200 is entered the PWM value will change. The range is from 0 to a 100 but is shifted with a 100 to allow easy manipulation of characters in the array without worrying about the length of the message. After the SerialFunction is completed the program will return to the start of the loop and start repeating itself again.

### 5.1.1. Calibration calculations

All ADC values that have to be calibrated first represent values in a 10bit ADC (0 to 1023). The values have to be recalibrated to the read word values to be able to make sense of them.

### 5.1.2. Battery Voltage

The voltage battery will first be scaled to 0 and 5V where 0V represent 5.5V and 5V represent 7.5V. This adc voltage is a input to the beetle that will read the voltage value as 0 represents a value of 0 and 1023 represents 5V. Due to resistor tolerances the 5.5V staring voltage is in reality 5.3V, thus:

$$V_{battery} = \frac{5}{1023} * ADC_{value} + 5.3 \quad (5.1)$$

### 5.1.3. Supply Voltage

The supply voltage will be scaled down as to protect the beetle. a voltage of 22V will correlate to 5V and 0V will stay 0V. The beetle still samples the supply volatge as a 10bit value. Due to resistor tolerances the 0V staring voltage is in reality 0.3V, thus:

$$V_{supply} = \frac{22}{1023} * ADC_{value} + 0.3 \quad (5.2)$$

### 5.1.4. Battery Current

The current can differ between 450mA to -150mA. These values are represented by voltage between 5V and 0V. This voltage value is sampled as a 10bit value. Due to resistor tolerances the -150A staring current is in reality 148A, thus:

$$I_{Battery} = \frac{450 + 150}{1023} * ADC_{value} - 148 \quad (5.3)$$

### 5.1.5. LightSensor

The value is represented as a persentage between 0 and 100. The light sensor is seen to have a voltage of 1V when it is very dark and a voltage of 3.8V when is is very bright, therefore:

$$LightSensor = \frac{\left(\frac{5}{1023} * ADC_{value} - 1\right) * 100}{3.8} \quad (5.4)$$

# Chapter

6

## PC Software

The software of this systems serves as a interface between the user and the circuitry discussed in previous chapters. The Graphical User Interface that will be displayed on the PC screen will communicate with the Beetle via the serial port. The GUI will display analogue readings that is read from the beetle GPIO pins. The GUI will also allow the user to control to pins on the beetle. The overcharge protection pin and the PWM pin. THe GUI will be created using Tkinter and a Serial Communication class called SerialComms.py that was provided.

### 6.1. Overview of functional blocks

#### 6.1.1. updateDisplay()

This is the main function that handles all the information that is being communicated over the serial interface. This function is called every 100ms to update the information displayed to the user. The PWM adc value is also updated every 100ms.

#### 6.1.2. openConnection(sc)

This function opens the serial connection. This function is called by buttonConnectHandler(). To call this function the instance sc has to be passed as a paramater. sc contains the comPort in use as well as the selected baudrate.

#### 6.1.3. closeConnection(sc)

This function closes the serial connection. This function is called by buttonConnectHandler(). To call this function the instance sc has to be passed as a parameter. sc contains the comPort in use as well as the selected baudrate.

#### 6.1.4. buttonConnectHandle(sc)

This function either opens or closes the serial connected depending on its current state. It also displays error messages in the terminal if the command is unable to be completed.

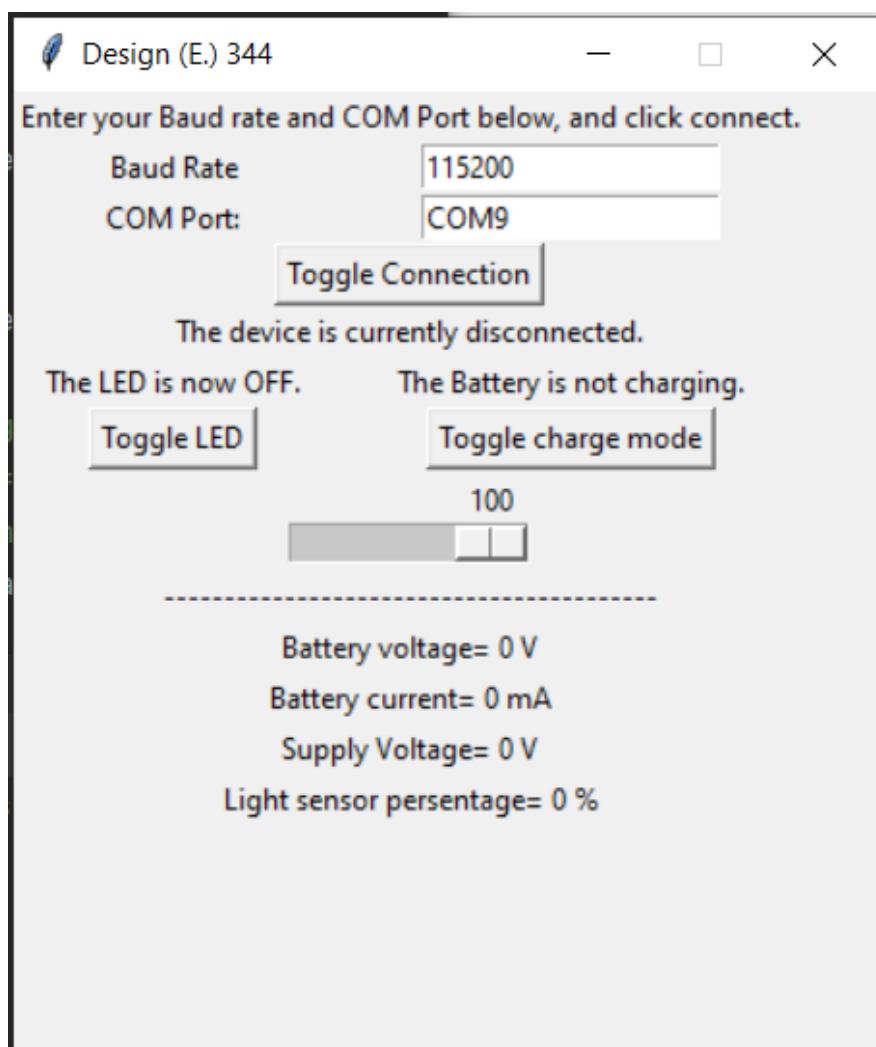
### **6.1.5. buttonLEDHandler()**

This function either allows or disallows the LED to receive a pwm signal. If the LED is ON the slider value will be the percentage value of the PWM signal. If the LED is off the PWM value will be 0.

### **6.1.6. buttonChargeHandler()**

This function toggles the overcharge protection circuit. If ON 'OV1' is send over the serial connection allowing the battery to be charged by a power source. If off 'OV0' is send over the serial connection, disconnecting the battery from the power source.

## **6.2. GUI**



**Figure 6.1:** User interface

### 6.3. Pseudo

```
Import tkinter
Import SerialComms
Import SerialExceptions

Setup Window

Setup connection label
Setup LED Label
Setup up LED button
Setup PWMADC slider
Setup battery Voltage label
Setup Supply Voltage label
Setup battery current label
Setup light sensor label
Setup charging label

void updateDisplay:
    if issc.isOpen == True:
        rawData = sc.receive()

        if length of rawData == 1
            set data[] = split rawData by ','
            set OVstatus = data[0]
            if data[0] == 1
                chargelabel = charging
            else
                chargelabel = not charging

            battery Voltage label = data[1]
            supply Voltage label = data[2]
            battert Current label = data[3]
            Light Sensot label = data[4]
            data[5] = PWMADC.get() + 100

        reset rawData

void openConnection
void closeConnection
void buttonConnectHandler

void buttonLEDHandler
    if com is being used:
        if OVstatus == '0'
            sc.send("OV1")
        else
            sc.send("OV0")
```

Figure 6.2: Python Pseudo code

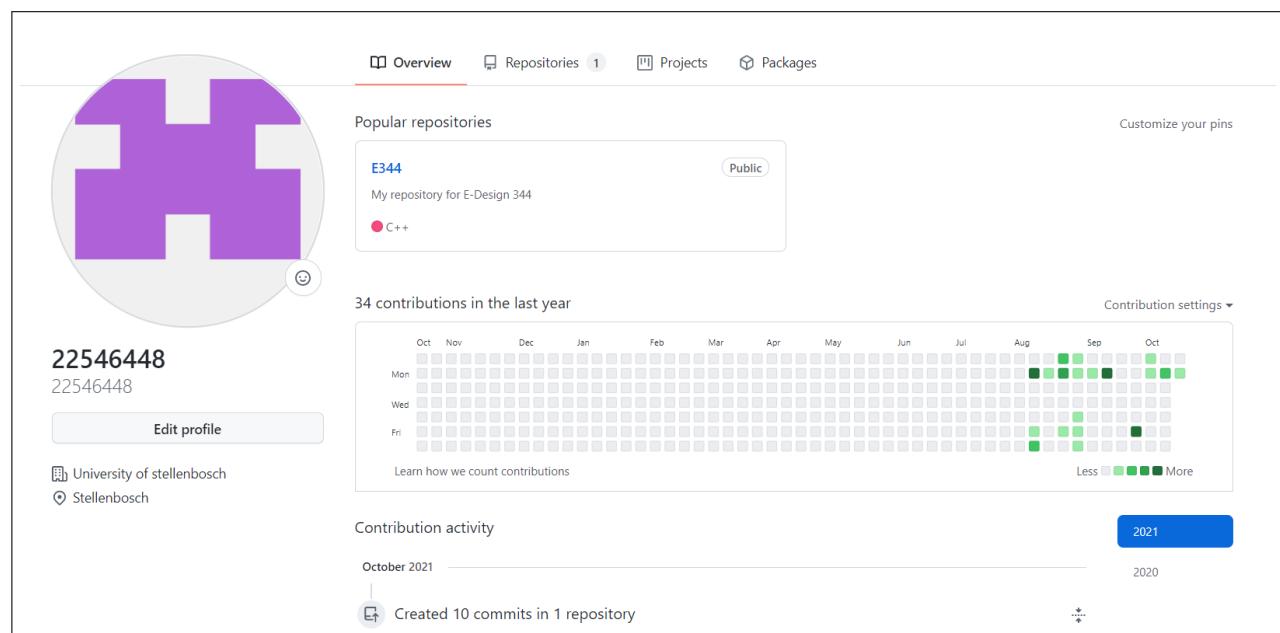
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# Appendix A

## GitHub Activity Heatmap



# **Appendix**

**B**

## **Social Contract**



### E-design 344 Social Contract

2021

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

In the months preceding the term, the lecturer (Thinus Booyens) and the Teaching Assistant (Kurt Coetzer) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare the assignments, to set the tests and assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

**MC van der Berg**

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

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

Prof. MJ Booyens

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22:12:45 +02'00'

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Christiaan van der Berg  
Date: 2021-08-04  
08:26:10 +02'00'

Signature: ..... Signature: .....

Date: 4 Aug 2021

15 Augustus 2021

Date: .....

**Figure B.1:** Social Contract