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E344 Assignment 4

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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 threw 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
$VLED$	Voltage over the LED
$V_{GS(th)}$	Gate Threshold Voltage
V_{cc}	Voltage source
I_{LOAD}	Current through the load
R_{sence}	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. The photovoltaic effect

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] .

1.2. The I-V-curve

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 produce 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,

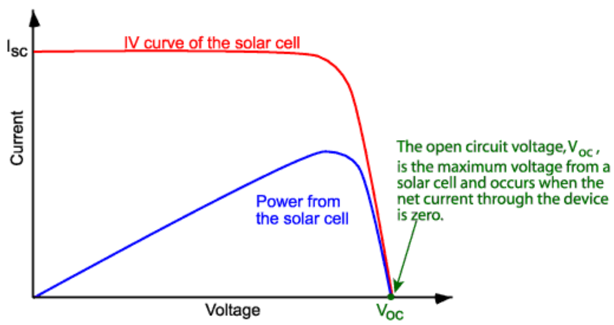


Figure 1.1: Terminal voltage of a 537-5422 battery discharged at different currents [1]

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 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 Isc = 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 Pmax = 5W [6].

1.3. 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].

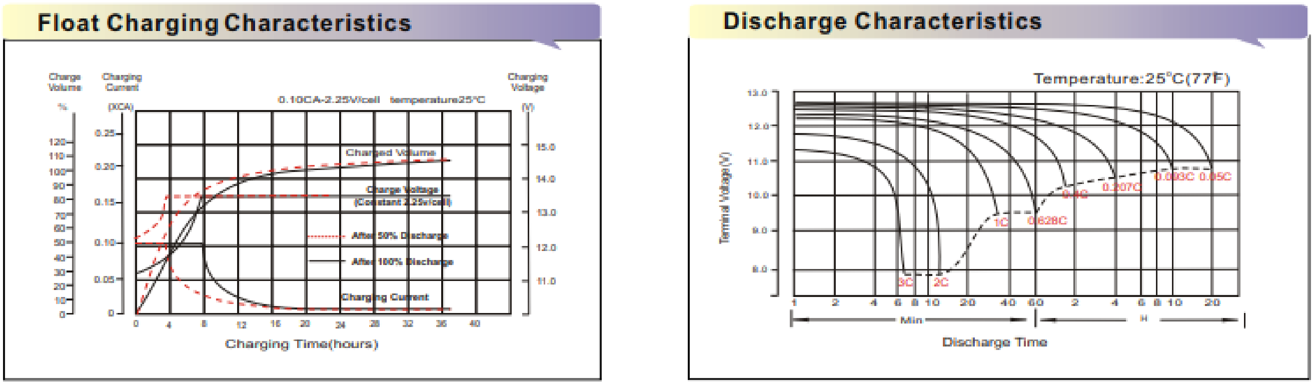


Figure 1.2: Charge and discharge figures for a sealed lead acid battery [2]

1.4. Charging

The battery will wil 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 wil absorb a current of 10mA. There are five stages of charging: Bulk, absorbsion, float, equalization and discharge [9].

1.5. 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 build 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 electic 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 fuction as a opencircuit. [10].

1.6. Design

The recommended maximum charging current limit should be evaluated when designing a fuse to protect the battery [11]. The value for the lead acid battery is sited to be at $I_{max} = 1.2A$. Our fuses which is ampere rating should be lower than I_{max}. The design choice is made to have a fuse with a 1A rating.
As a student we are given 2 options to use RSPro fuses [2] or Littlefuses, but as RSPro fuses only consist of fuses rated higher than our required 1A a $Little_fuse$ will be used. The only little fuse with the correct rating is the black 1A 0287001 fuse. This fuse has a voltage drop of 176mV. This means that for calculation purposes the fuse can be neglected.

Chapter 2

Detailed design

2.1. Voltage regulation

2.1.1. Literature

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 VREF 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 [12].

2.1.2. 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:

$$I_{470\Omega} = \frac{V_{REF}}{R3} = \frac{1.25}{470} = 2.66m\text{ohm} \tag{2.1}$$

The power dissipation is thus:

$$P_{R3} = I_{470\Omega}^2 R3 = (2.66m)^2 * 470 = 3.33mW \tag{2.2}$$

This means minimum power loss.

To calculate R4 we use the equation:

$$V_{out} = V_{REF}(1 + \frac{R4}{R3}) \tag{2.3}$$

this equation leads to:

$$R4 = R3\frac{V_{out}}{V_{REF} - 1} = 2237.2\Omega \tag{2.4}$$

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

This total power dissipation of R3 and R4 is thus:

$$I_{R3+R4} = \frac{V_{out}}{R3 + R4} = \frac{7.2}{2200 + 470} = 2.697mA \tag{2.5}$$

and thus:

$$P_{R3+R4} = I^2_{470+2200\Omega}(R3 + R4) = (2.66m)^2 * 470 = 19.42mW \tag{2.6}$$

This is significantly small and should cause any problems.

This means minimum power loss.

2.1.3. 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 Rs 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 0.3Ω 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 measures such low resistor values. The oscilloscope was thus used to measure 1.2Ω resistors in parallel until the desired value was achieved. In this design a 0.1Ω resistor and 4 $1,2\Omega$ resistors are placed in parallel.

2.1.4. 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 was made for these changes. therefore we try to avoid this problem by improving the heat/power dissipation through the heat sink[4].

2.2. High side switch on supply side

MOSFETs could be use 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. ID and VDS 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. ID will equal zero and VDS = Vcc. By using MOSFETs we can use low gate current to control high voltage circuits [13]. MOSFETS are voltage controlled switches where BJTs are current control switches. MOSFET are more efficient switches for power supplies, this is why we will be using them [13]. These electronic switches can be placed in to 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 [13]. Although MOSFETs make great switches, the gate voltage might not be enough to control the voltage over VDS. 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].

2.2.1. 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 60kΩ) we can use voltage division to to calculate that:

$$V_{GS} = V_{out_{min}}(\frac{R2}{R2 + R1}) = 5V \tag{2.7}$$

and when $V_{out} = 7.2$:

$$V_{GS} = V_{out_{min}}(\frac{R2}{R2 + R1}) = 6V \tag{2.8}$$

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

$$I_D = \frac{V_{out_{min}}}{R1 + R2} = 0.12mA \tag{2.9}$$

The power dissipation is :

$$P_{R1+R2} = I_D^2(R1 + R2) = (0.12m)^2(60k) = 0.864mW \tag{2.10}$$

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.

2.3. Undervoltage protection

2.3.1. 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.

2.3.2. 5V rail

The first design choice will be the rail voltages when designing a voltage monitoring circuit out of MCP6241 [14] operational amplifiers. Under DC conditions $V_{ss} = 0V$ according to the data sheet [14] 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:

$$V_{cm} = \frac{V_{DD}}{2} \tag{2.11}$$

$$V_{DD} = 5V \tag{2.12}$$

2.3.3. 5V Voltage regulator

The 5V regulator was designed using the LM2940 1A low dropout regulator, and using the data sheet. [15] This regulator was chosen because it has a typical output voltage of 5V at $T_{amb} = 25°C$ 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)

2.4. 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 is 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 = 200kΩ. 6.2V will be turned into 3.1V.R2 = 100KΩis a design choice made. Using voltage division:

$$R1 = \frac{R2}{\frac{3.1}{5}} - R2 \tag{2.13}$$

$$R1 = 61.3k\Omega \tag{2.14}$$

This means:

$$V_{cm} = V_{DD}/2 \tag{2.15}$$

$$V_{cm} = 2.5V \tag{2.16}$$

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

$$V_{Diff(max)} = 5V \tag{2.17}$$

Our voltage difference is:

$$V_{diff} = 3.1V \tag{2.18}$$

at maximum difference.

2.4.1. 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 2MΩ

The comparators output is pulled high through a 100kΩresistor 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 [16].
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 $V_{REF} = 2.5V$.R7 =200kΩand R8 = 200kΩto satisfy this requirement. R9 =100kΩand 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.

2.5. Overcurrent protection

2.5.1. Introduction

The RS -4Ah battery [17] 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.

2.5.2. Design

The TLC213 [18] and current sensing resistor [19] 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:

$$V_{out} = I_{LOAD} * V_{diff} * gain + V_{ref} \tag{2.19}$$

Because we want the center current at the center voltage:

$$V_{out} = I_{LOAD} * R_{sense} + V_{ref} \tag{2.20}$$

$$2.5 = (0.1) * (0.15) * (50) + V_{ref} \tag{2.21}$$

$$V_{ref} = 1.75V \tag{2.22}$$

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

$$V_{ref} = Vcc * \frac{R6}{R6 + R5} \tag{2.23}$$

$$\frac{R6}{R6 + R5} = 0.35 \tag{2.24}$$

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

$$R5 = \frac{R6}{0.35} - R6 \tag{2.25}$$

$$R5 = 185.7k\Omega \tag{2.26}$$

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 4.7u has been chosen.

2.6. Low-side switch

2.6.1. 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.

2.6.2. 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 [20] 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 [20] 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 [21].

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

$$Vcc = I_{LED} * R + V_(LED) \tag{2.27}$$

$$7.2 = (20m) * R + 3.2 \tag{2.28}$$

$$R = 200\Omega \tag{2.29}$$

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

2.6.3. 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: Vcc = 7.3V;I = 100mA; R = 220Ω; 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.

Chapter 3

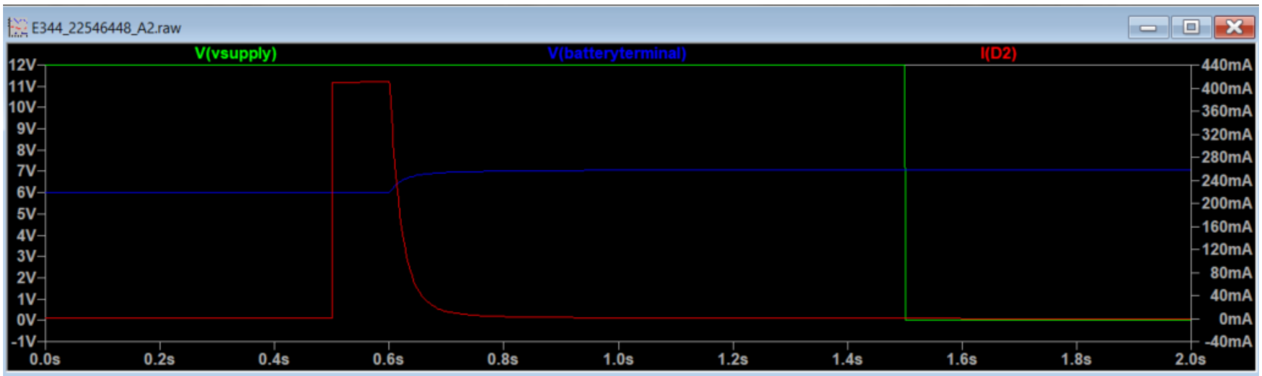
Simulated and measured results

3.1. Voltage Regulation and high side switch

3.1.1. 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 therminal keeps on charging, and the voltage delivered to the battery remains 7.2V. This is due to the 1N5819 Schottky diode.

Figure 3.1: The Ltpice results for the designed charging circuit.



3.1.2. 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 vlaue 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 save design. The difference in output voltage and current could be do to the 0.3Ω resistor as it was extremely difficult to design this it. 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.

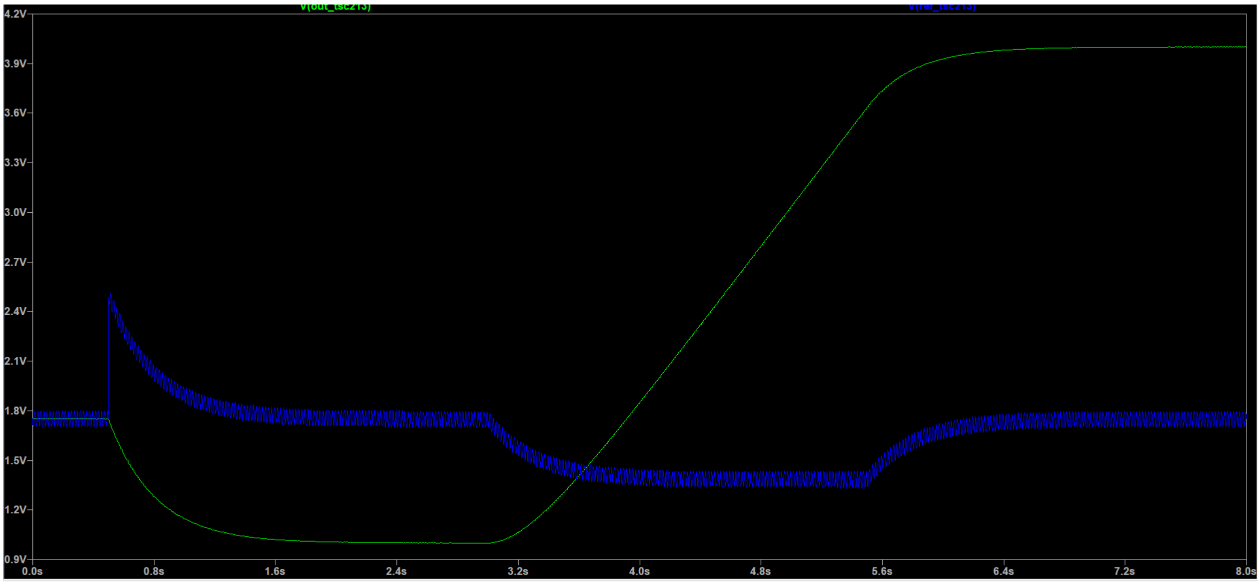


Figure 3.2: LTSPice output simulation graph

3.2. Overcurrent protection

The design requirement state the following:

1. The output voltage must be less than $2mV_{pk}$: The 4.7u capacitor is large enough to filter out high frequency noise the TLC213 might face. The maximum noise measured and seen on spice is 1,6mV which is less than $2mV_{pk}$

2. The circuit response should respond to a change of 150mA in 2 seconds: The capacitor is small enough to achieve this requirement. The measured response is 1.79s, this is less than 2s.

3. Output voltage should be 3V for the given current range: The highest $V_{out} = 4V$ and the lowest $V_{out} = 1V$, this means the output swing is 3V.

4. The voltage range must be 5V to 0V: This range was designed, as indicated above. V_{out} will never achieve 5V or 0V as the output swing does not allow it and this is also undesirable as this would hit the TLC213 Rail voltages.

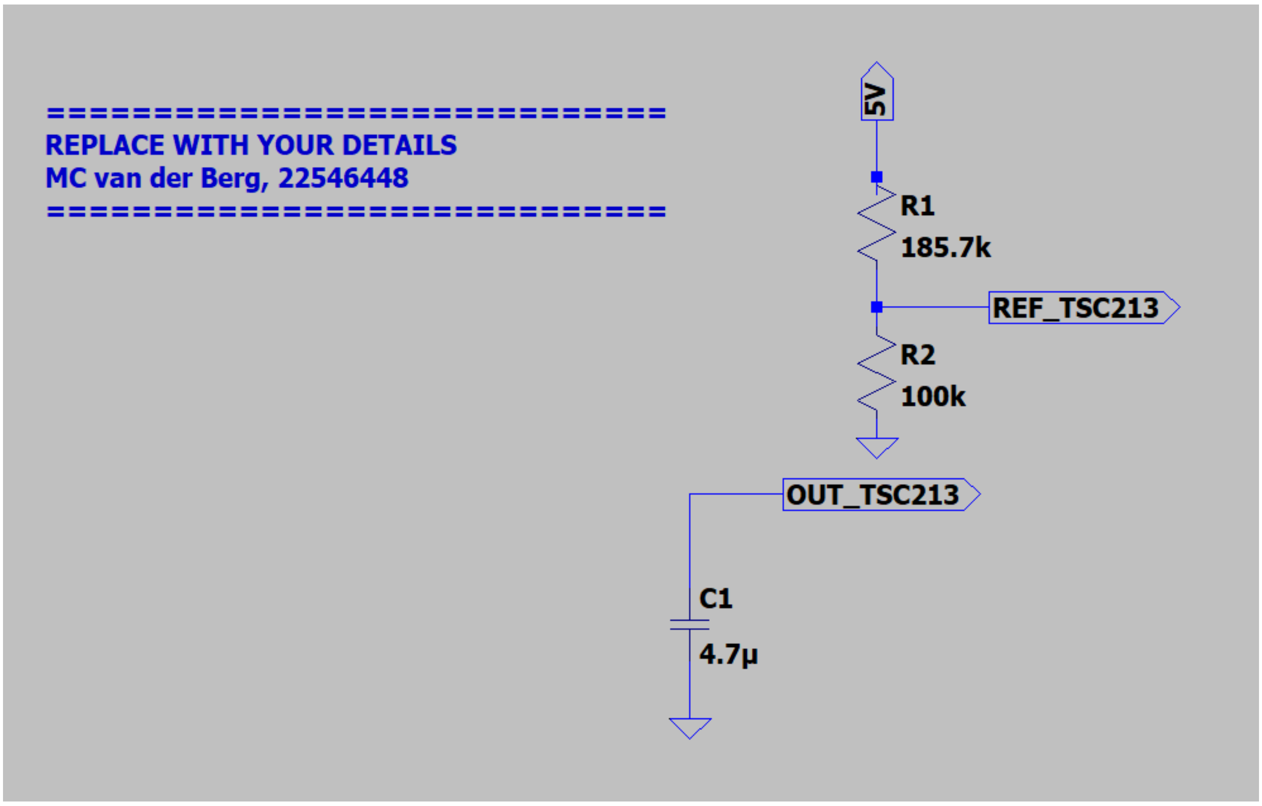


Figure 3.3: LTSpice design schematic

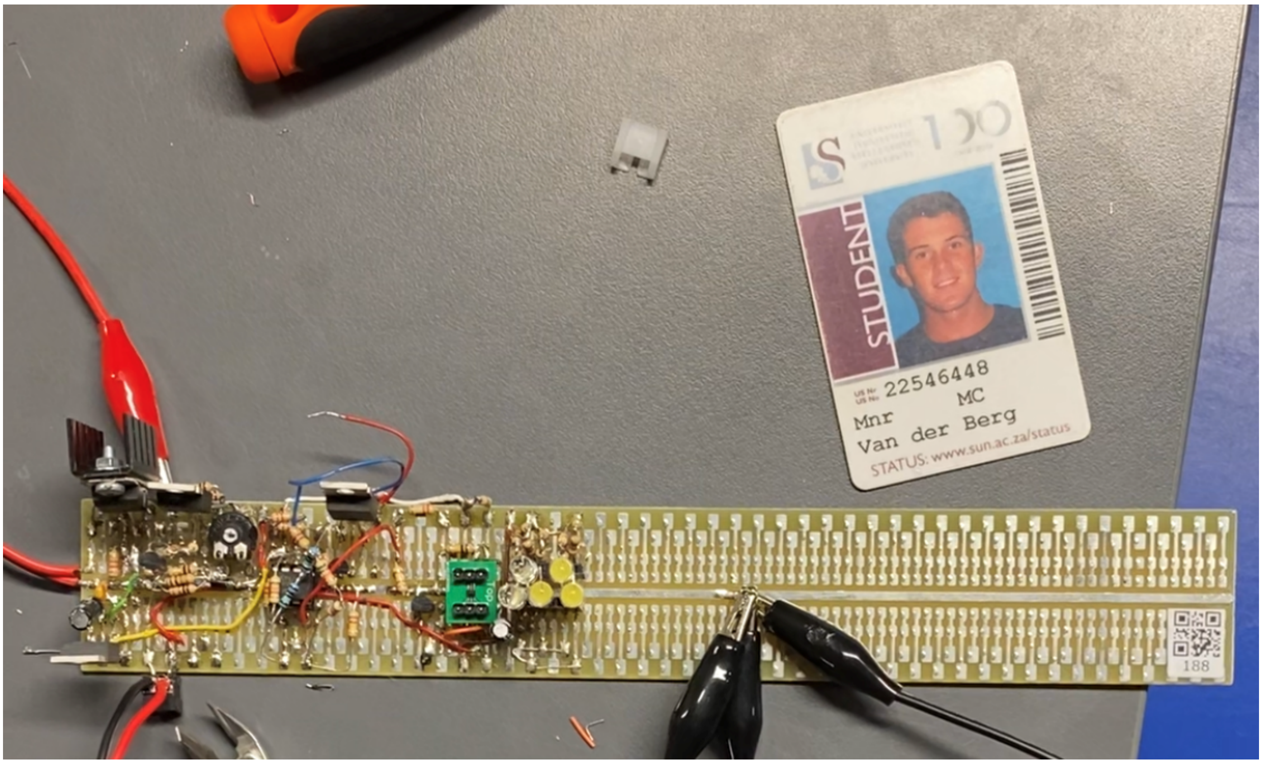


Figure 3.4: MY design and student number

3.3. Undervoltage protection

Figure 3.5: LTspice undervoltage protection design

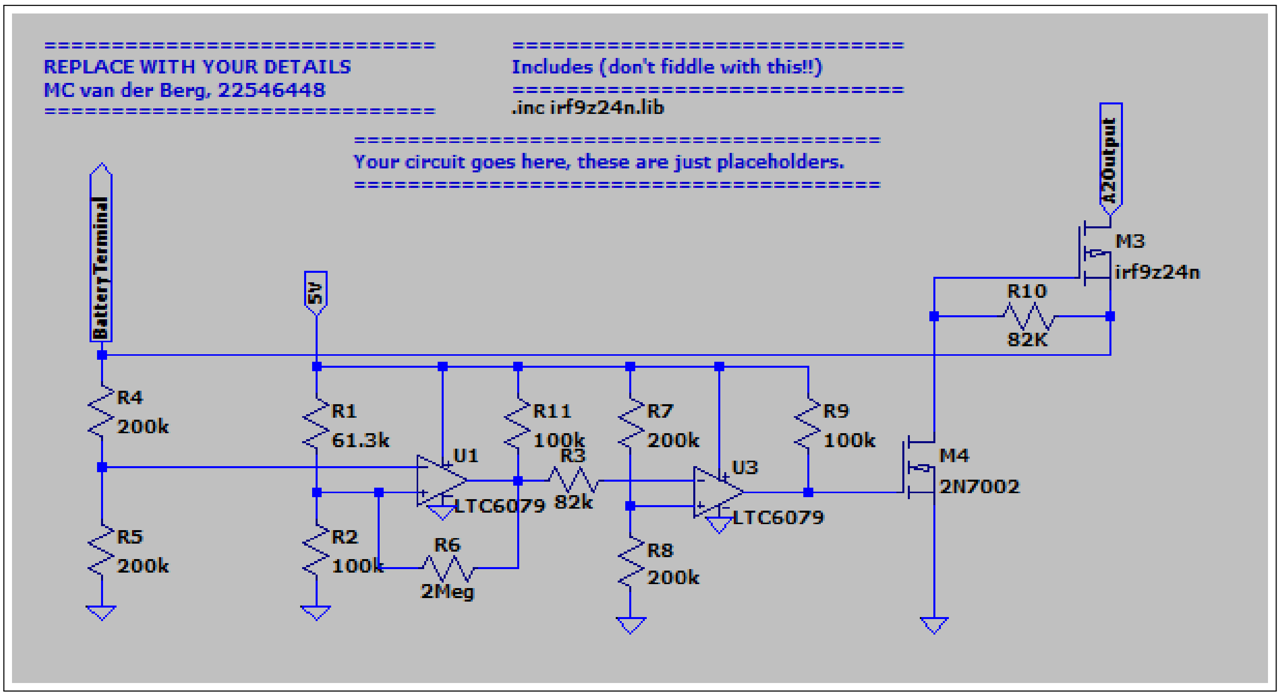
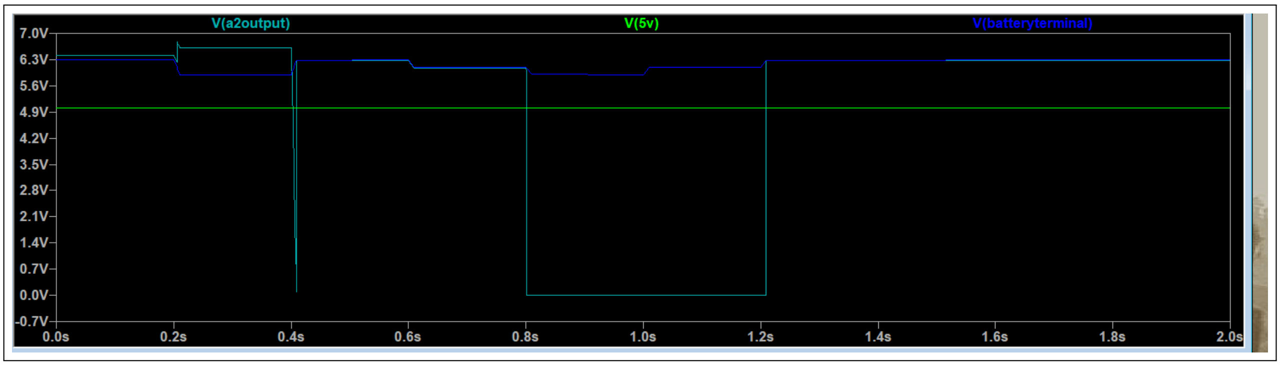
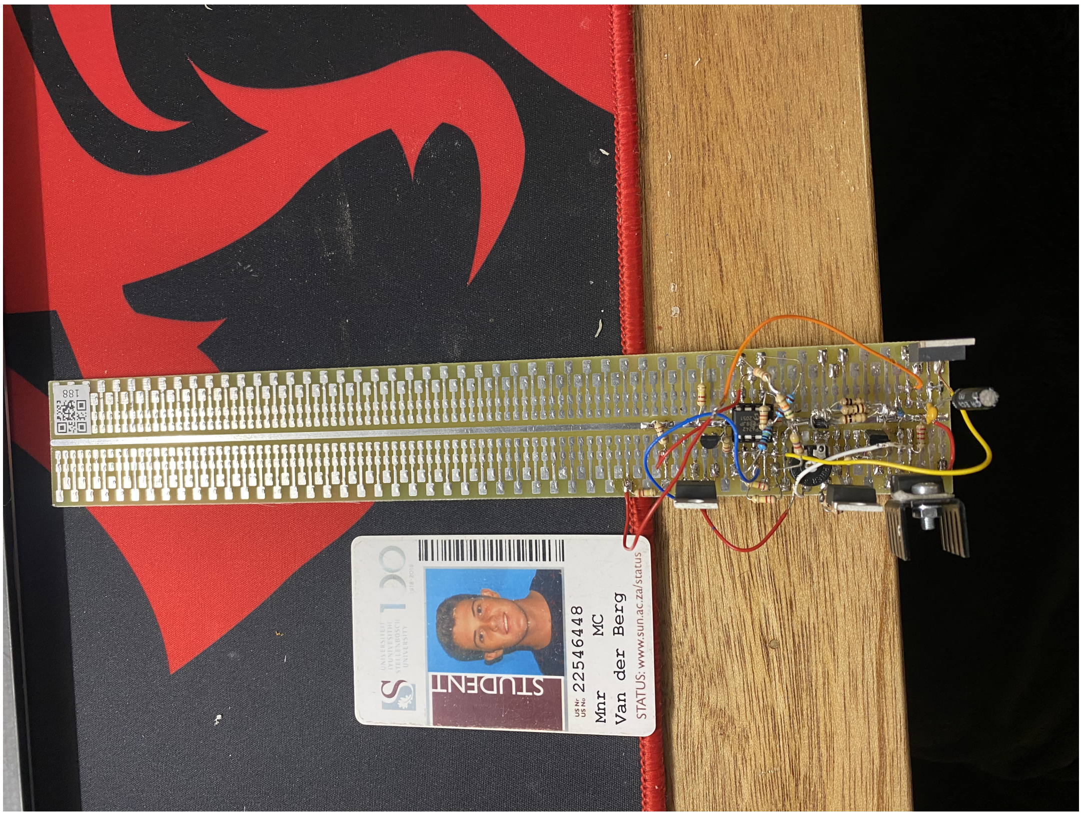


Figure 3.6: LTspice undervoltage protection design simulted results



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

Figure 3.7: LTspice undervoltage protection circuit



3.4. Low side switch

Figure 3.8: LTspice Low side switch circuit

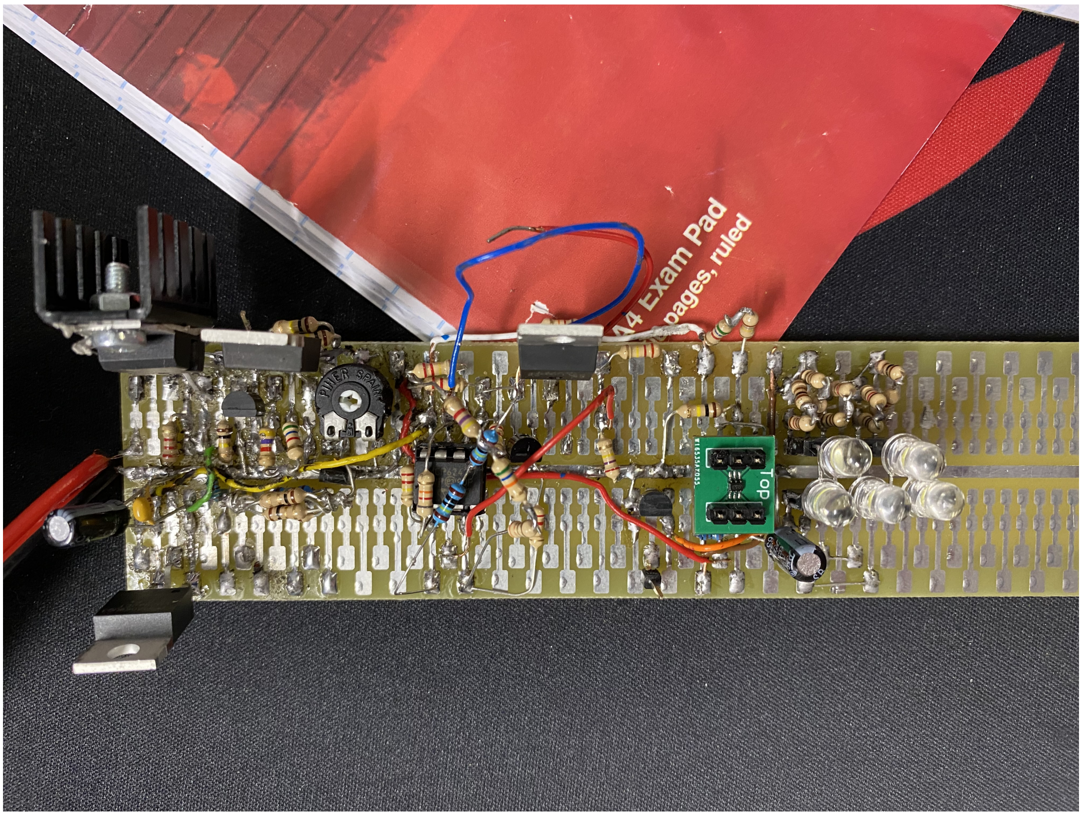
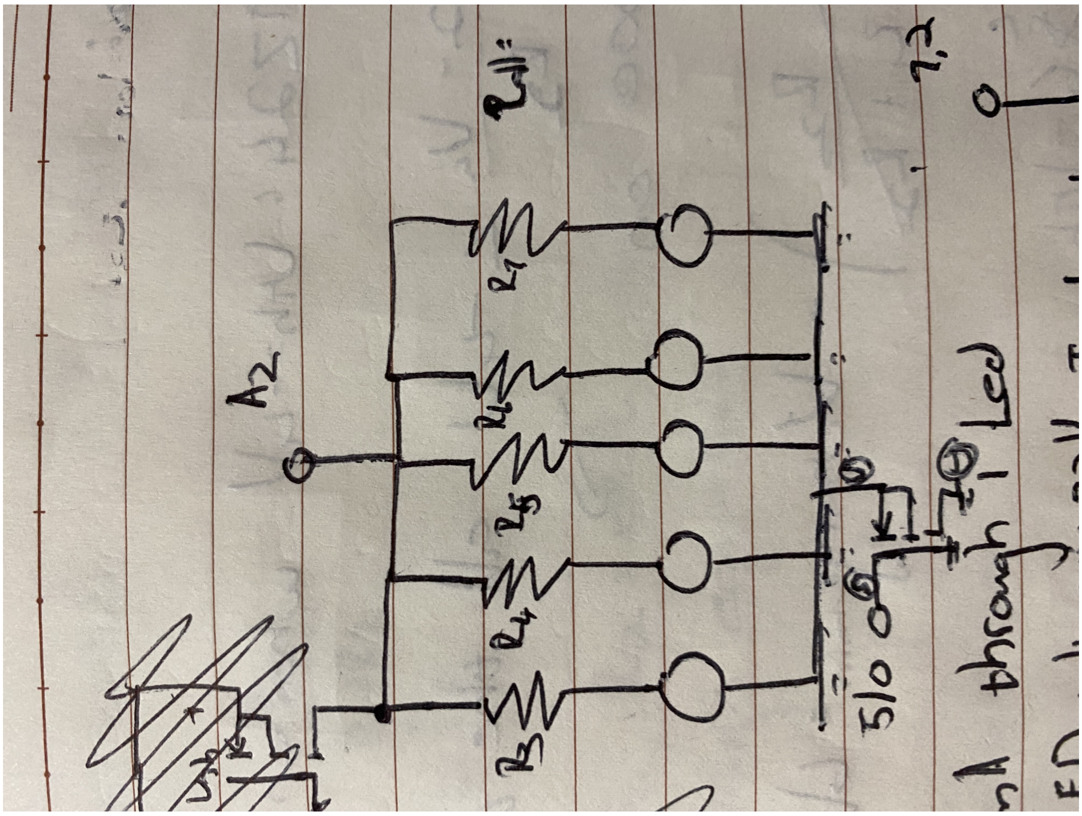


Figure 3.9: Low side switch circuit design



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Appendix A

GitHub Activity Heatmap

Take a screenshot of your github version control activity heatmap and insert here.