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E344 Assignment 3

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Nomenclature

Variables and functions

V_{SG}	Source-gate voltage of a P-channel MOSFET.
V_{GS}	Gate-source voltage of an N-channel MOSFET.
V_{TP}	Thresh-hold voltage of a P-channel MOSFET.
V_{TN}	Thresh-hold voltage of an N-channel MOSFET.
V_G	Gate voltage of a MOSFET.
V_S	Source voltage of a MOSFET.
V_{DS}	Drain-source voltage of an N-channel MOSFET.
V_{SD}	Source-drain voltage of a P-channel MOSFET.
$V_{Battery}$	Terminal voltage of a battery.
I_{FP}	Peak Forward Diode Current.
V_O	Output Voltage of an Op-Amp.
V_{DI}	Differential Voltage.
V_{CMR}	Common Mode Voltage.
V_{IN}	Input Voltage to an Op-Amp.
I_O	Output Current of an Op-Amp.
V_{LT}	Lower Threshhold Voltage of an Op-Amp.
V_{UT}	Upper Threshhold Voltage of an Op-Amp.

Acronyms and abbreviations

V	Voltage.
A	Ampere.
Ω	Ohm.
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor.
PMOS	P-channel MOSFET.
NMOS	N-channel MOSFET.
DC	Direct Current.
LED	Light Emitting Diode.

Chapter 1

Fuse

1.1. Literature

The purpose of a fuse is to protect circuitry when a fault in a load or a part of the circuit causes too much current to flow, thus damaging components. The time-current characteristics of a fuse determine how quickly it will respond to overcurrents. All fuses have inverse time-current characteristics. The greater the overcurrent, the quicker the fuse will blow [2].

The current carrying capacity of a fuse is also dependent on it's ambient temperature. Higher temperatures allow the fuse to respond faster to overcurrents while lower temperatures make the response to overcurrents slower [2]. When a fuse experiences an overcurrent, it will naturally increase in temperature and melt to protect the circuitry. The shelf-life of a typical fuse is a few decades since they are made out of copper or silver which does not retain moisture easily, however, fuses may trip at a lower current after excessive use or time [3].

1.2. Design

Since the fuse needs to protect from overcurrents, it is helpful to know the current that the battery will typically discharge. The proposed load for the overall system design will be five super-bright LEDs which can each have a peak forward current, $I_{FP} = 100$ mA [4]. Assuming that there will also be a micro-controller drawing current as well as an LED display and a light sensor, it is reasonable to assuming that approximately 700mA will be drawn at most.

A fault such as an accidental grounding or a component overload could cause this current to increase rapidly and since a fuse with a 1A rating will prevent such an overcurrent quickly, it is a good design choice. The 1A fuse has a voltage rating of 32VDC which means that it can safely interrupt a 1A current until 32VDC [5]. That particular voltage level is higher than any individual voltage in the circuit and so it is a safe design. Even if the fuse is used in ambient temperatures lower than room temperature (which will decrease the overcurrents it will blow at), there is enough overhead to stop any faults without impeding on the maximum current draw from the battery, by the load.

Chapter 2

Undervoltage battery protection

2.1. Overview

The under-voltage protection system seen in Figure 2.1 consists of a voltage regulator, a buffer, a Schmitt trigger, a comparator and a high-side switch. The regulator powers the components and acts as the basis for a reference voltage. The trigger determines the state of the system based on voltage threshholds and previous states. The comparator inverts the trigger output and the switch controls the discharging of the battery. An LM2940 regulator has been chosen due to the need of a 5V power supply and it's low operating input voltage.

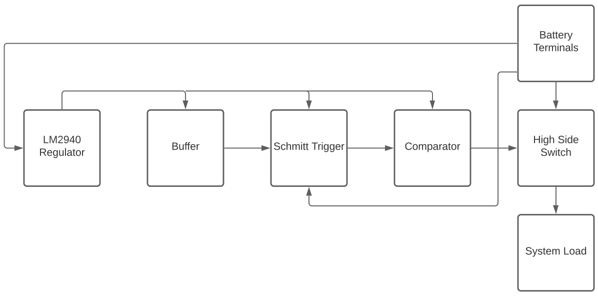


Figure 2.1: System Overview for Assignment 3

2.2. 5V rail

The regulator which has been chosen to supply power to the operational amplifiers and to act as a basis for the reference voltage is the LM2940 regulator. It was chosen because it has a lower input voltage of 6V minimum [6] while the LM7805 needs at least 7V [7]. The battery voltage will be the input voltage of the regulator and since the battery will discharge lower than 7V, the LM7805 would not be a suitable choice. The LM2940 will have a typical output voltage of 5V which is suitable for the operational amplifier and high-side switch to function.

2.3. High-side switch

A high-side switch was designed to connect the battery terminals to a load/charging circuit. A 5V comparator output results in the NMOS $V_{GS} = 5V$ and $V_{TN} = 0.8$ to 3V [8] $\therefore V_{GS} > V_{TN}$. This turns the NMOS on and pulls V_G of the PMOS to 0V since the NMOS V_{DS} is negligable for very small currents [8]. For the PMOS: since the battery terminal voltage $\geq 6V$, this results in the PMOS $V_S \geq 6V$ and the $V_{SG} = V_S$ while $|V_{TP}| = 2$ to 4V [9]. The PMOS $V_{SG} > |V_{TP}| \therefore$ the PMOS switch is on and current flows from the battery to the load.

The resistor value, R_8, can be calculated from the 5V control signal situation. Ideally, very little current should be present at the drain of the NMOS so that there is little power wastage $\therefore R_8 = 100\,\text{k}\Omega$. R_7 is a pull-down resistor that removes the charge from the NMOS V_G when a 0V comparator output occurs. This value is chosen to be $10\,\text{k}\Omega$.

A 0V comparator output results in the NMOS $V_{GS} = 0V \therefore V_{GS} < V_{TN}$ and the NMOS is off. The PMOS $V_G \geq 6V$ due to no current through R_8 and the PMOS $V_{SG} = 0$V. It can be observed that $V_{SG} < |V_{TP}| \therefore$ the PMOS is off and current won't flow from the battery.

2.4. Voltage monitoring with hysteresis design

The under-voltage protection circuit contains four stages. The Schmitt trigger, the voltage-follower (buffer), the comparator and the high-side switch. The Schmitt trigger is a comparator with memory. Hysteresis allows the inputs of the trigger to be compared with a reference and then an output is determined based on the previous output of the trigger and threshhold voltages. A successful design has to respect the limitations of the operational amplifiers. There are 5 limitations for the MCP6421 operating at a $V_{DD} = 5$V and $V_{SS} = 0V$ [10]:

- Output voltage: $-0.02V \leq V_O \leq 4.98V$ for $I_O \approx 0.5mA$.
- Differential voltage: $V_{DI} \leq 5V$.
- Common mode voltage: $-0.3V \leq V_{CMR} \leq 5.3V$.
- Input voltage: $-1V \leq V_{IN} \leq 6V$.
- Output current: $I_O = \pm 30mA$.

Refer to Figure 2.2 below during the design. We start with the battery resistive divider. From hysteresis, the positive input of the Schmitt trigger, V_{IN2+}, will be the upper threshold voltage (V_{UT} - when the output is high) and lower threshold voltage (V_{LT} - when the output is low) which will change the output of the trigger. Voltage division leads to an expression:

$$\frac{R_4}{R_3 + R_4}(V_{battery}) = V_{IN2+}$$

where $V_{battery} = 6V$ when $V_{IN2+} = V_{LT}$ and $V_{battery} = 6.2V$ when $V_{IN2+} = V_{UT}$. Choosing $R_3 = R_4 = 150\,\text{k}\Omega$ gives $V_{LT} = 3V$ and $V_{UT} = 3.1V$. Doing nodal analysis at the positive input of the Schmitt trigger, V_{IN2+}, will give us an equation for V_{LT} and V_{UT} of the hysteresis curve (which we have values for). The Schmitt trigger resistors can then be solved. The nodal analysis of V_{IN2+} leads to the equation:

$$V_{IN2+} = (V_{O1})\frac{R_6}{R_5 + R_6} + (V_{O2})\frac{R_5}{R_5 + R_6}$$

where $V_S = (V_{O1})\frac{R_6}{R_5+R_6}$ is the shift of a typical hysteresis curve shown in Figure B.1. The hysteresis dead band needs to be 0.1V since $V_{UT} - V_{LT} = 0.1V$. This difference represents a physical 0.2V change in the battery voltage from 6V to 6.2V. Since V_{UT} and V_{LT} is simply V_{IN2+} evaluated at high and low outputs of the Schmitt trigger, we can conclude that $V_{IN2+(high)} - V_{IN2+(low)} = 0.1V$ $\therefore$

$$\frac{V_{O1}R_6 + V_{O2(high)}R_5}{R_5 + R_6} - \left(\frac{V_{O1}R_6 + V_{O2(low)}R_5}{R_5 + R_6}\right) = 0.1V$$

From this equation, $R_5 = 1\,\mathrm{k\Omega}$ and $R_6 = 49\,\mathrm{k\Omega}$ when $V_{O2(high)} \approx 5V$ and $V_{O2(low)} \approx 0V$. The hysteresis curve needs to be shifted such that the origin is now in the middle of V_{LT} and V_{UT}, $\therefore$ $V_S = 3.05$V. From this, $(V_{O1})\frac{R_6}{R_5+R_6} = 3.05$ and $V_{O1} = 3.112$V. V_{O1} is the output of the voltage- follower where $V_{O1} = V_{IN1+}$. Through resistive division, we can find that:

$$\frac{R_2}{R_1 + R_2}(5V) = V_{O1}$$

where $R_1 = 34\,\mathrm{k\Omega}$ and $R_2 = 56\,\mathrm{k\Omega}$. The comparator takes in the output of the Schmitt trigger as the input to it's negative terminal. This output is then compared to the positive terminal of the comparator ($V_{IN3+} = V_{O1}$). The comparator then flips the output to the rail voltage of 5V or 0V based on this comparison. Every input of the operational amplifiers respect the common mode voltage, differential voltage and maximum input voltage limitations.

2.5. Circuit diagram

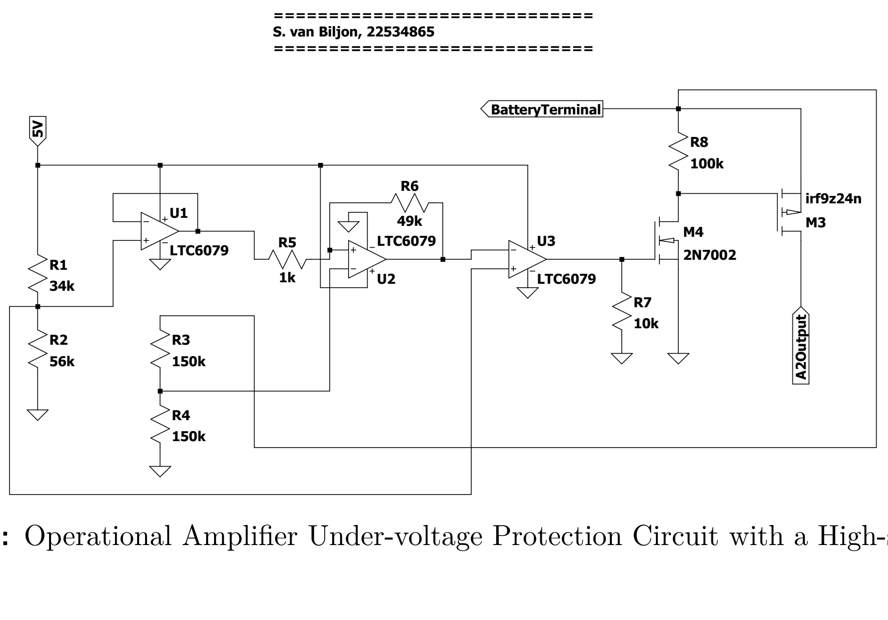
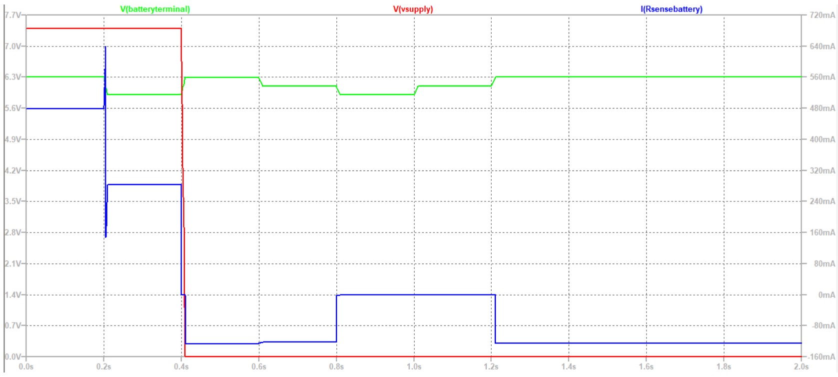


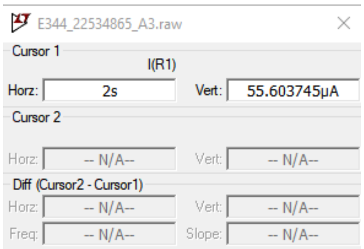
Figure 2.2: Operational Amplifier Under-voltage Protection Circuit with a High-side Switch

2.6. Results

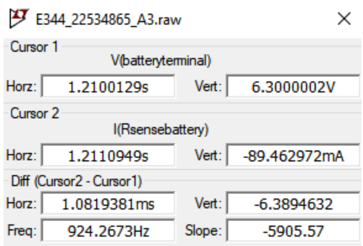
As seen below in Figure 2.3b, the 5V rail will only draw 0.056 mA of current which is below the required 10mA. From Figure 2.3c, the PMOS will also switch between an On/Off state within 1.082 ms of a voltage threshhold being reached. Looking at Figure 2.3, it can be seen that initially, the battery will charge because the charging circuit is on. When the charging circuit goes off , any battery voltage above 6V will allow the battery to discharge. After the battery terminals drop below 6V, the battery will stop discharging. This state is switched to at approximately 6V. After this low voltage stage has been reached, the battery will start to discharge again after rising to approximately 6.2V.



(a) Simulation Battery Voltage and Current, Supply Voltage



(b) Simulation 5V Rail Current



(c) Simulation Switching times

Figure 2.3: Simulation Output and Values

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The current draw of the 5V rail was measured to be 0.14 mA, which is seen in Figure B.2 and is below the required current draw of 10mA. For the measured results, a 10 kΩ resistor simulated the battery load. The same behaviour as the simulated results was observed, where the battery would discharge above 6.2V, stop discharging below 6V and then start discharging again at 6.2V. The state of the battery current remained constant during the hysteresis dead-band (as it was designed to do). The exact switching voltages of the battery is observed in Table 2.1.

Discharge Cutoff (V)	Discharge Resumption (V)
6.05V	6.23V

Table 2.1: Measured Discharge Threshold Voltages

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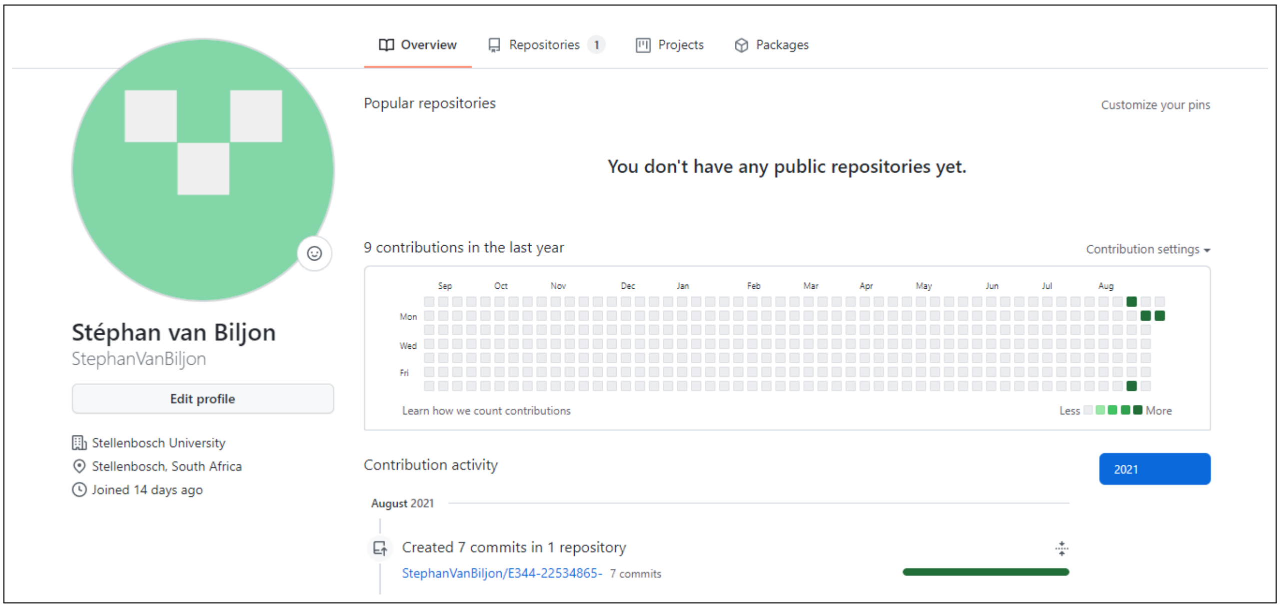
Appendix A

GitHub Activity Heatmap



Appendix B

Stuff you want to include

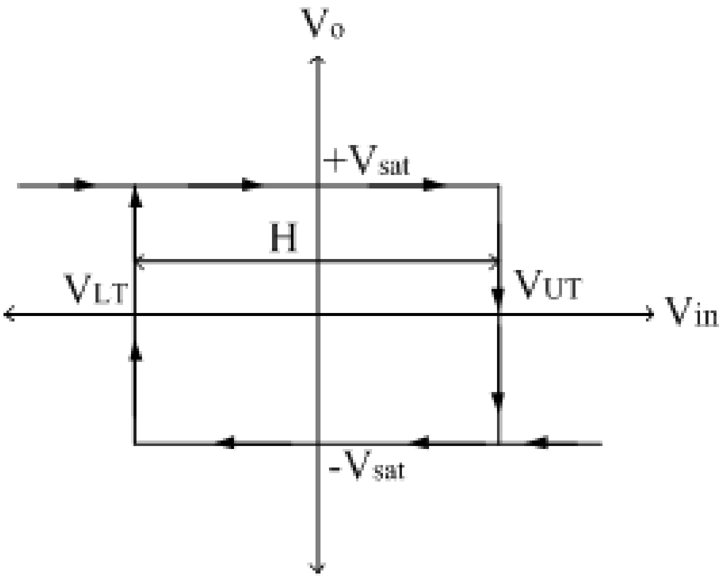


Figure B.1: Hysteresis Curve of an Inverting Schmitt Trigger with $V_{REF} = 0V$ [1]

Figure B.2: Current Draw of the 5V Rail (B) with a Voltage Over the Load (A)