UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

E344 Assignment 3

Michael Groenewald
22636811

Report submitted in partial fulfilment of the requirements of the module Design (E) 344 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

August 29, 2021

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

Plagiaatverklaring / *Plagiarism Declaration*

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

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

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

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

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

22636811 Studentenommer / *Student number*	Handtekening / *Signature*
A.M. Groenewald Voorletters en van / *Initials and surname*	August 29, 2021 Datum / *Date*

Contents

List of Figures

List of Tables

Nomenclature

Variables and functions

V_{DS}	Drain-Source voltage of transistor.
$V_{TH(DS)}$	Transistor turn-on threshold for Drain-Source voltage.
V_{SD}	Source-Drain voltage of transistor.
$V_{TH(SD)}$	Transistor turn-on threshold for Source-Drain voltage.
V_+	Op-amp non-inverting input voltage.
V_-	Op-amp inverting input voltage.
V_{DD}	Positive op-amp supply rail.
V_{SS}	Negative op-amp supply rail.
V_{ref}	Reference voltage, used to bias comparator circuits.
V_L	Schmitt trigger lower threshold.
V_H	Schmitt trigger upper threshold.
V_{range}	Schmitt trigger threshold differential. $(V_H - V_L)$

Acronyms and abbreviations

NMOS	N-type metal-oxide semiconductor.
PMOS	P-type metal-oxide semiconductor.
Op-amp	Operational Amplifier.

Chapter 1

Fuse

1.1. Literature

A fuse is an electrical safety device used for overcurrent protection. It is built around a conductive strip that is designed to melt and separate in the event of excessive current. It is typically enclosed in order to minimize hazards caused by electrical arcing when it blows. Fuses are primarily rated by current, however they also have a limitation on the maximum voltage they can withstand after the fuse has blown. The rated current of a fuse is for constant current, however for a shorter discharge a fuse can withstand higher currents, as high temperature is needed to blow a fuse, which directly proportionate to power dissipation and time. [1] The LittleFuse blade fuses we use are rated for a maximum voltage of 35V, which is well beyond anything our circuit is able to generate.

1.2. Design

In order to protect the battery from overcurrent under all circumstances, the fuse will be connected between the battery terminal and its interface to the circuit. From the RS-Pro lead-acid battery datasheet it can be found that the maximum recommended charging current is 1.2A. This is above the 400mA charging current we are designing for, and significantly above the expected load.

A rough estimation for the expected load can be calculated as follows. From the C503D-WAN LED datasheet (ultra bright LED), the maximum current can be found as 30mA. Assuming all 7 of our LEDs draw this current, they will draw $7 \times 30 = 210$mA. The Beetle microcontroller we are using is based on the Aruino Leonardo. The Beetle itself does not specify current in its datasheet, however from the Arduino website it can be found that the Leonardo has a fuse that limits input current to 500mA [2]. Finally, all the custom regulation circuitry built I am designing for very low current, with no single functional component drawing more than 1mA. 100mA can then be used as a very conservative (large) estimate for current draw. Altogether this results in $I_{max} = 210 + 500 + 100 = 810$mA.

With a maximum power draw of 810mA and a maximum designed charging rate of 400mA, a 1A fuse is plenty to allow all the needed current to pass, whilst staying well below the 1.2A recommended charging limit.

Chapter 2

Undervoltage battery protection

2.1. Literature

Due to design requirements, battery discharge has to resume at a higher voltage (6.2V) threshold than it should be disabled at (6V). This can be implemented with a hysteresis circuit. A standard design [3] for a non-inverting Schmitt trigger will be used. Additionally, a voltage-follower [3] is also used in the Schmitt trigger circuit for its high input-impedance, in order to prevent the trigger's feedback to V_{REF} creating noise on 5V rail.

2.2. Overview

The undervoltage protection circuit consists of an inverting Schmitt trigger op-amp circuit connected to a PMOS transistor acting as a high-side switch between the battery (high) and the load. A op-amp voltage follower is used as a buffer between the reference voltage divider circuit and the Schmitt trigger. All of the operational amplifiers, as well as the reference voltage, is supplied by a LM2940 5V voltage regulator. This high-side switch implementation lacks the typical NMOS driving transistor. This greatly simplifies the circuit and reduces the amount of components required. Refer to Section 2.3 for further details on the switch implementation and why it works. A simplified block diagram can be seen in appendix Figure B.1.

2.3. 5V rail

The 5V rail is implemented using a LM2940 voltage regulator down-regulating the battery's terminal voltage[1]. The LM2940 regulates to a fixed voltage of 5V, therefore the typical application circuit is used, as seen in appendix Figure B.2. This regulator has a typical drop-off voltage of 0.5V, and remains active up to a regulated output of 2V, as seen in appendix Figure B.3. This regulator was chosen above the LM7805, as it requires a lower minimum input voltage to operate (≈5.5V, as opposed to 7V for the LM7805). The LM2940 can supply less current, however the 1A it is capable of is plenty for our application.

[1]The regulator will always draw current if the battery is connected, and therefore the battery should be disconnected when idle for long periods. Automatic handling of this is beyond the scope of this project.

2.4. Voltage monitoring with hysteresis design

The behaviour that needs to be implemented is a form of hysteresis. The battery should be prevented from discharging if the terminal voltage drops below 6V and should only again be resumed when the terminal voltage increases back up to 6.2V. In order to implement this, I used a standard design for an inverting Schmitt trigger, using MCP6242 op-amps.

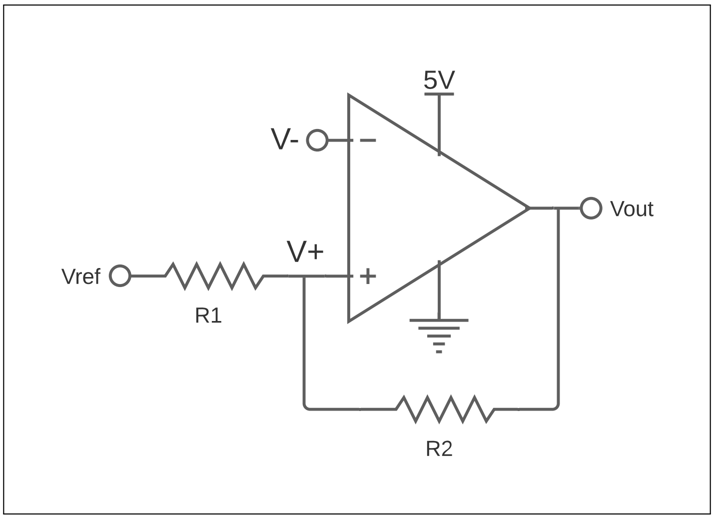


Figure 2.1: Block diagram of undervoltage protection circuit.

The output equations can be derived as follows using voltage division, neglecting input current:

$$V_+ = V_{\text{out}} + (V_{\text{ref}} - V_{\text{out}}) \times \frac{R_2}{R_1 + R_2} \tag{2.1}$$
$$= \frac{V_{\text{out}} R_1 + V_{\text{ref}} R_2}{R_1 + R_2}$$
$$= V_{\text{out}}(\frac{R_1}{R_1 + R_2}) + V_{\text{ref}}(\frac{R_2}{R_1 + R_2}) \tag{2.2}$$

The output of an op-amp is given by $V_{\text{out}} = A(V_+ - V_-)$, and the gain, A, is very large ($\approx 110_{\text{dB}}$ from the MCP6242 datasheet). As V_+ and V_- are not precisely controlled, it can be assumed that the output will be either very low or very high, and thus clip to 0V or 5V. Because a rail-to-rail op-amp is used, the clipping will happen very near the actual rail values. From this assumption, the behaviour of the op-amp can be described using two distinct states, each with their own switching conditions.

Case 1: $V_{\text{out}} = 0V$

$$V_- < V_+ \qquad \text{(Switching condition)}$$
$$< V_{\text{ref}}(\frac{R_2}{R_1 + R_2}) + V_{\text{out}}(\frac{R_1}{R_1 + R_2})$$
$$< V_{\text{ref}}(\frac{R_2}{R_1 + R_2}) \tag{2.3}$$

Case 2: $V_{\text{out}} = 5V$

$$
\begin{aligned}
V_- &> V_+ && \text{(Switching condition)} \\
&> V_{\text{ref}}(\frac{R_2}{R_1 + R_2}) + \frac{5 \times R_1}{R_1 + R_2} && (2.4)
\end{aligned}
$$

Let $V_L = V_{\text{ref}}(\frac{R_2}{R_1+R_2})$, $V_{\text{range}} = 5 \times (\frac{R_1}{R_1+R_2})$ and $V_H = V_L + V_{\text{range}} = V_{\text{ref}}(\frac{R_2}{R_1+R_2}) + \frac{5\times R_1}{R_1+R_2}$. The result is a circuit for which R_1 and R_2 can easily be calculated by designing for specific V_L and V_H values, as seen by equations 2.3 and 2.4.

The differential- and common-mode inputs of the MCP6242 are limited to $V_{\text{DM(abs)}} < V_{DD} - V_{SS}$ and $V_{SS} - 0.3 < V_{CM} < V_{DD} + 0.3$ respectively. By using a voltage divider with $R_a = R_a = 50\text{k}\Omega$, V_- can be set to $V_- = V_{\text{battery}} \div 2$, resulting in an inverting input limited to between ≈2.9V and 3.7V (battery terminal voltage constraints). This keeps V_{DM} and V_{CM} well within the aforementioned limits. Designing for $V_L = 3V$ and $V_H = 3.2V$ for battery thresholds 6V and 6.2V, it results in $R_1 = 49R_2$, thus $V_{\text{ref}} = 3.061V$. Choosing $R_1 = 5\text{k}\Omega$ results in $R_2 = 245\text{k}\Omega$. V_{ref} is implemented with a voltage divider where $R_a = 63.33\text{k}\Omega$ and $R_b = 100\text{k}\Omega$, that is connected through a voltage-follower to the V_{ref} node.

The shape of an inverted hysteresis curve, as produced by this circuit, can be found in appendix Figure B.4, with and upper V_{out} value of 5V.

2.5. High-side switch

The Schmitt trigger outputs an inverted output, and the NMOS of the previous design functions, in some sense, to invert the input to the switch. Rather than adding another inverter in series to compensate for the inverted trigger output, the output of the Schmitt trigger is directly connected to the gate of the PMOS, as seen in the circuit diagram in Figure 2.2. The source-gate threshold of the PMOS can be found in the datasheet as $2V < V_{\text{TH(SG)}} < 4V$. The behaviour of this setup is as follows ($V_{\text{bat}} = V_{\text{S(PMOS)}}$):

Table 2.1: PMOS behaviour for Schmitt trigger outputs (S) in [V].

Battery	S	$V_{\text{bat(min)}}$	$V_{\text{bat(max)}}$	$V_{\text{SG(min)}}$	$V_{\text{SG(max)}}$	PMOS
Full	0	6	7.4	6	7.4	ON
Depleted	5	5.9	6.2	0.9	1.2	OFF

Table 2.1 shows that the PMOS behaves as desired. A potential issue of this design would be that, would the Schmitt trigger output 0V, the PMOS would be stuck in the ON state, such as the event that the voltage regulator loses power. However, from the low-voltage characteristics of the LM2940 as seen in appendix Figure B.3, it can be seen that the regulator remains active with a small dropoff voltage for inputs as low as ≈2V, therefore the PMOS will remain OFF in the event that the battery discharges further than expected.

2.6. Circuit diagram

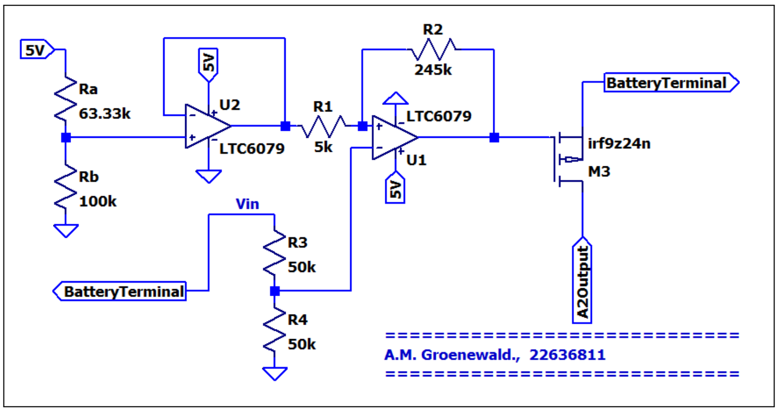


Figure 2.2: Circuit schematic in SPICE.

2.7. Results

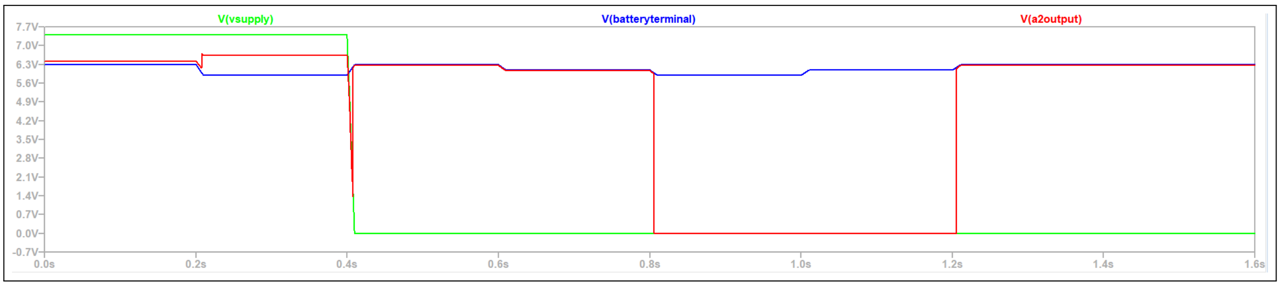
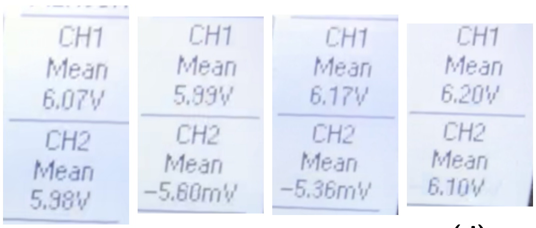


Figure 2.3: SPICE output graph.

Figure 2.3 shows that the circuit behaves as expected. Using the LTspice cursor tool the lower and upper thresholds are measured as 5.999V and 6.222V respectively, which is within margin of error of the designed 6V and 6.2V. The 5V rail is measured to consume a an average of $\approx 128\mu$A, with an instantanious spike of $\approx 770\mu$A. Switching time is measured as 195μs. SPICE confirms that the output is working as expected.

Measured results also confirm that hysteresis is working: $V_L = 6V$, $V_H = 6.19V$.



(a) (b) (c) (d)

Figure 2.4: Measured output results - V_{bat}(CH1) vs $V_{D(PMOS)}$(CH2).

Bibliography

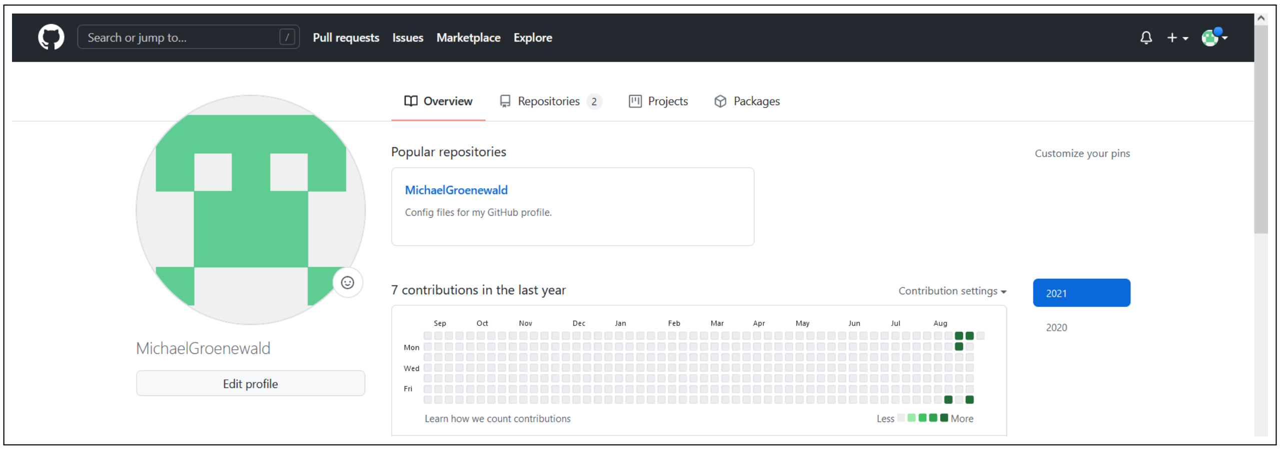
[1] T. Kuphaldt, "Fuses," 1996. [Online]. Available: https://www.allaboutcircuits.com/textbook/direct-current/chpt-12/fuses/

[2] [Online]. Available: https://www.arduino.cc/en/Main/Arduino_BoardLeonardo

[3] "Operational amplifiers - electronics tutorials," 2015. [Online]. Available: https://www.electronics-tutorials.ws/opamp

Appendix A

GitHub Activity Heatmap



Appendix B

Additional Resources

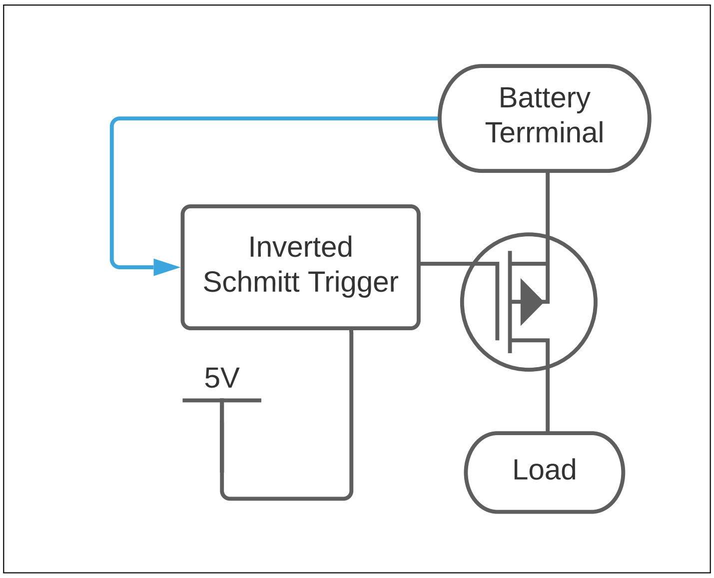


Figure B.1: Block diagram of undervoltage protection circuit.

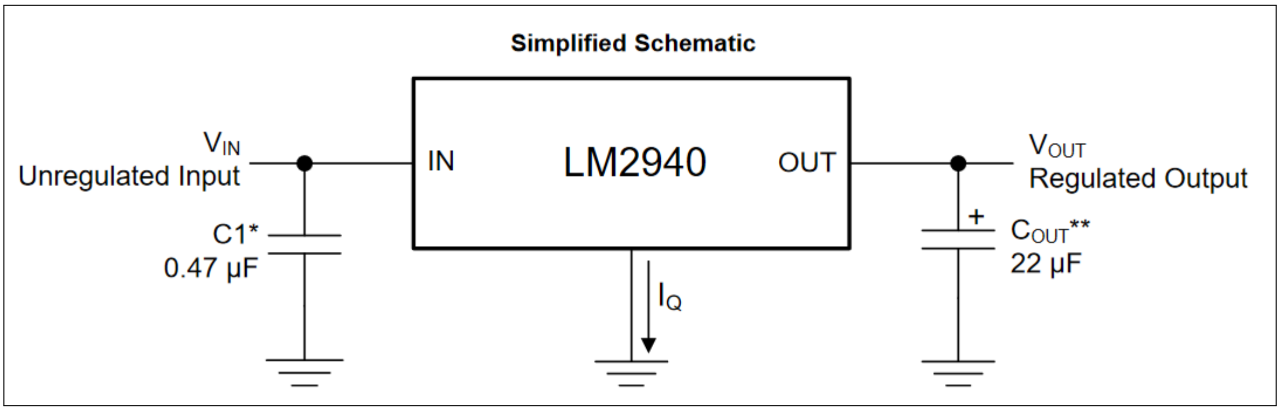


Figure B.2: LM2940 typical application circuit as found in datasheet.

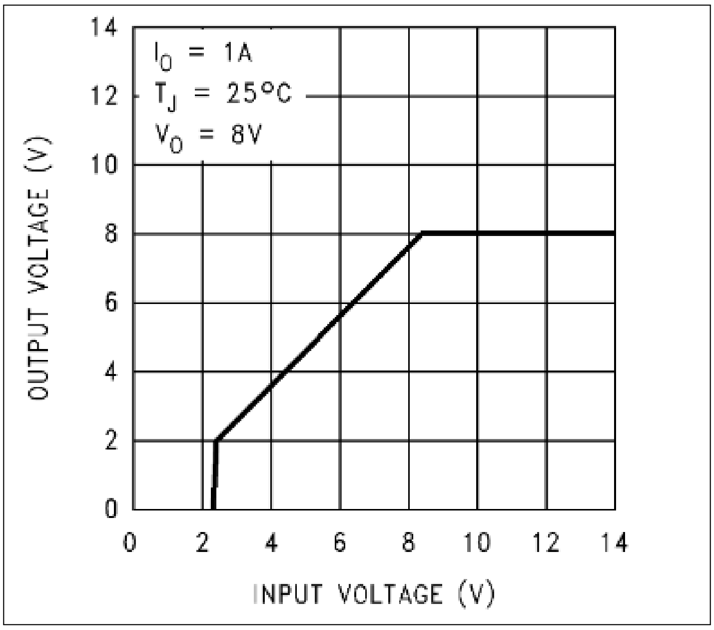


Figure B.3: LM2940 Low Voltage Behaviour as found in datasheet.

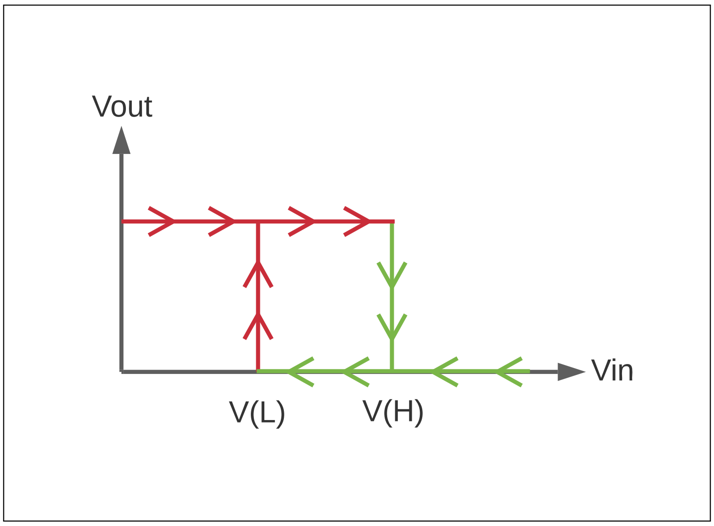


Figure B.4: Inverted hysteresis behaviour.