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E344 Assignment 2

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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 22, 2021

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Nomenclature

Variables and functions

T_j	Junction Temperature
T_{amb}	Ambient Temperature

Acronyms and abbreviations

IC	Integrated Circuit
PV	Photovoltaic
CCCV	Constant Current Constant Voltage
MOSFET	Metal Oxide Semiconductor Field Effect Transistors
OC	Open Circuit

Chapter 1

Literature

1.1. Charging lead acid batteries

Lead acid batteries are charged using the constant current constant voltage (CCCV) charge method. With this method the battery is charged as shown in figure 1.1 in 3 stages: constant current charge, topping charge and float charge. The constant current charge is where the current is kept at a constant rate and the main portion (70%) of the charging is done and the voltage rises to the peak voltage. The topping charge stage slowly decreases the current, but the voltage stays at the same level. The float charge lower the voltage to the float charge level in order to compensate for the loss caused by self-discharge. The battery is considered fully charged when the current drops below a certain set level (around 3-5% of the Ah rating), for our battery the current drawn would be around 40mA when the battery is fully charged. [1]. According to the datasheet provided by RS Pro [5] the maximum constant current rate at which our battery should be charged is 1.2A when using the constant voltage method. Our battery is fully charged at a voltage of 7.2V when the charger is still connected.

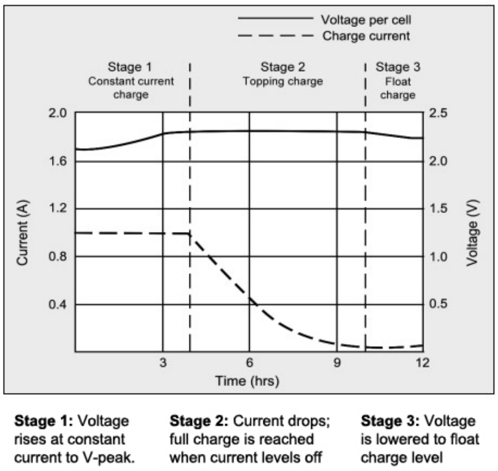

Figure 1.1: Charge States of Lead Acid Battery [1]

1.2. Voltage regulation

A voltage regulator is an integrated circuit (IC) which takes in a range of input voltages and provides a constant output voltage irrespective of a change in the load or the input voltage. Voltage regulators can be split up into two main types, linear regulators and switch-mode regulators. Linear voltage regulators work by adjusting the output voltage using a feedback loop of resistors. It compares the output voltage to a constant reference voltage and then varies the internal resistance or current in order to keep the output voltage constant [6]. Switching regulators use an op-amp and a negative feedback loop to control a transistor. The transistor is driven so that it is either fully off or fully on, this occurs at a very high frequency and thus produces a square wave as shown in figure 1.3. The output voltage is then the average value of the square wave switching voltage [3].

Linear voltage regulators are cheap, easy to use and provide a very "clean" output voltage, however, they are not very efficient as seen in figure 1.2 they are limited in efficiency by the ratio of V_{in}/V_{out}. They also dissipate excess power in the form of heat and thus very often require the use of heat sinks to keep them cool. Switch-mode regulators are much more efficient because they store excess power, however they are more expensive and are much more complicated to design and work with.

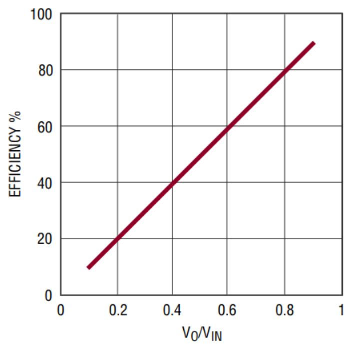

Figure 1.2: Linear Regulator Efficiency vs Vin/Vo ratio [2]

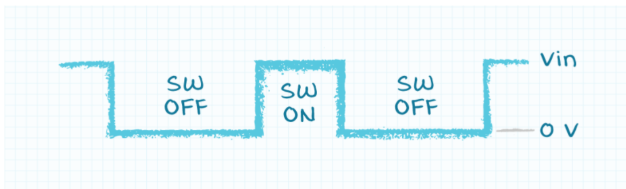

Figure 1.3: Switch Mode On/Off Switching Voltage Square Wave [3]

1.3. Switching with MOSFETs

Metal Oxide Semiconductor Field Effect Transistors (MOSFET) are a voltage controlled field effect transistor. The gate terminal is isolated from the main current carrying channel between the drain and source, as no current flows into the gate terminal [7]. Enhancement type MOSFETs requires a voltage across the gate-source terminals in order to switch the device on. Thus, the enhancement mode MOSFET acts as a normally open switch. In an NMOS (n-channel) MOSFET the device will only switch on and allow current to flow when $V_{gs} > V_{TH}$. For a PMOS (p-channel) MOSFET the opposite is true, a negative gate-source voltage will turn the transistor on, or in other words $V_{sg} > V_{TH}$.

Chapter 2

Design

2.1. Overview

The charging circuit consists of two main parts, the high-side switch and the voltage regulator. As shown in figure B.1 in appendix B the voltage regulator will receive it's input from either an AC/DC power adapter or from a solar PV module. The voltage regulator will take an input and regulate it down to around 7.4-7.8V. The output from the voltage regulator will be used as the input to the high-side switch which is used to turn the charging circuit on/off. This design will ensure that the output voltage at the battery terminals is 7.2V after all the voltage drops have been taken into account.

2.2. High-side switch

In order to design a high-side switch that uses logic level voltages (0-5V or 0-3.3V) we need to make use of a complementary pair of PMOS and NMOS MOSFETs.Pullup resistor R3 is added to keep to p-channel MOSFET off in unkown floating voltage states. Similarly a pulldown resistor R4 is added to the gate of the n-channel MOSFET to keep it off in unknown states. Resistor R3 in figure 2.1 is also used to limit the amount of current that flows through the n-channel MOSFET. If the control voltage LoadOn is at a high of 5V the n-channel MOSFET will be turned on, thus pulling the gate of the p-channel MOSFET to ground and turning it on. According to the 2N7000 n-channel MOSFET datasheet the maximum current that can flow through the drain-source channel is 200mA, thus the minimum resistor value for R3 can be calculated as:

$$R3_{min} = \frac{7.8V}{200mA}$$
$$R3_{min} = 39\Omega$$

This value was designed for extremities and would most likely not work in the physcial circuit as it is a very small resistor and it is the minimum resistance value that R3 can be, I chose a value of $100k\Omega$ as a design choice.

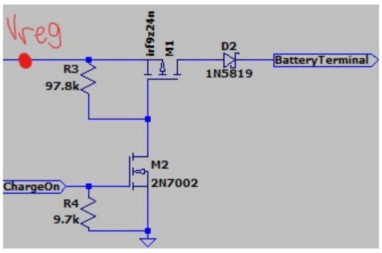

Figure 2.1: Circuit Diagram of High-Side Switch (Vreg is the voltage coming from the regulator)

2.3. Charging regulator

2.3.1. Voltage regulation

We will make use of the LM317 adjustable voltage regulator in this project in order to regulate the voltage to the required 7.2V at the battery terminals. Thus we can look at our datasheet for the LM317 and we can find a battery charging circuit as shown in figure 2.2. In order to set the output voltage level, voltage dividing resistors R_1 and R_2 are used and in order to limit the current resistor R_s is used. We can calculate the value of these resistors as follows: *(for the calculation of Vout the voltage drop Vds and VRs was ignored as they are quite small.)

$$V_{out} = V_{batteryterminal} + V_{diode}$$
$$V_{out} = 7.8V$$

Picking a value for R1 as 240Ω we can then solve for R2.

$$V_{out} = 1.25(1 + \frac{R_2}{R_1})$$
$$\therefore R_2 = 1247.6\Omega$$

Solving for Rs using If as 0.4A:

$$I_f = \frac{V_{out} - 1.25(1 + \frac{R_2}{R_1})}{-R_s(1 + \frac{R_2}{R_1})}$$
$$\therefore R_s = 0.72\Omega$$

These resistor values were further fine tuned in LTSpice and then the nearest physically available resistor was chosen or a series/parallel combination for the physical circuit as shown in figure 2.1.

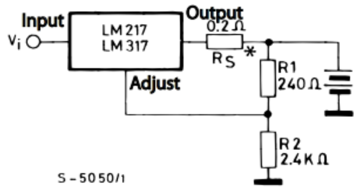

Figure 2.2: Voltage Regulator Battery Charger [4]

2.3.2. Current limit

If the battery is charged at too high a current it will cause decomposition of the water in the electrolyte and cause premature battery aging and may even permanently damage the battery. According to the RS components battery datasheet [5] the charging rate limit for our charging method is 0.1C, which in our case is $0.1(4Ah) = 400mA$. This current limit will be implemented with the use of Resistor R_s shown in figure 2.2. See section 2.3.1 for the calculation of the value of R_s.

2.3.3. Thermal analysis

According to the LM317 datasheet [4] the maximum junction temperature is $T_j = 125°C$. This means that without a heatsink on an average day at an ambient temperature of 25° Celsius and using the 12 DC power supply the maximum power that the regulator can dissipate is:

$$P_{max} = \frac{(T_j - T_{amb})}{\theta_{j-a}} \quad with\ \theta_{j-a} = 50°C/W$$
$$P_{max} = 2W$$

When adding a small TO-220 package heatsink the maximum power dissipated becomes:

$$\theta_{j-c} = 5°C/W;\ \theta_{c-s} = 1.64°C/W;\ \theta_{s-a} = 24.4°C/W$$
$$P_{max} = \frac{(T_j - T_{amb})}{\theta_{j-c} + \theta_{c-s} + \theta_{s-a}}$$
$$P_{max} = 3.22W$$

Thus we can see that adding a heatsink we can dissipate an extra 1.22W of power.

Without a heatsink:

$$P_{dissipated} = (V_{in} - V_{out})I_{out}$$
$$\therefore T_j = P_{dissipated}(\theta_{j-a} + T_{amb})$$

Using the 12V DC supply:

$$P_{dissipated} = 1.68W$$
$$T_j = 109°C$$

Using the Solar PV Module (21.6V):

$$P_{dissipated} = 5.52W$$
$$T_j = 301°C$$

With a heatsink:

Using the 12V DC supply:

$$P_{dissipated} = 1.68W$$
$$\therefore T_j = P_{dissipated}(\theta_{j-c} + \theta_{c-s} + \theta_{s-a}) + T_{amb}$$
$$T_j = 77.14°C$$

Using the Solar PV Module (21.6V):

$$P_{dissipated} = 5.52W$$
$$T_j = 196.34°C$$

Thus we can see that adding a heatsink greatly improves the performance of the voltage regulator and keeps the juntion temperature cool when using the 12 DC supply. However if we were to use the solar PV module the voltage regulator would still burn out, so we would need to implement some overvoltage protection in order to limit the amount of voltage the solar PV module can provide.

2.4. Circuit diagram

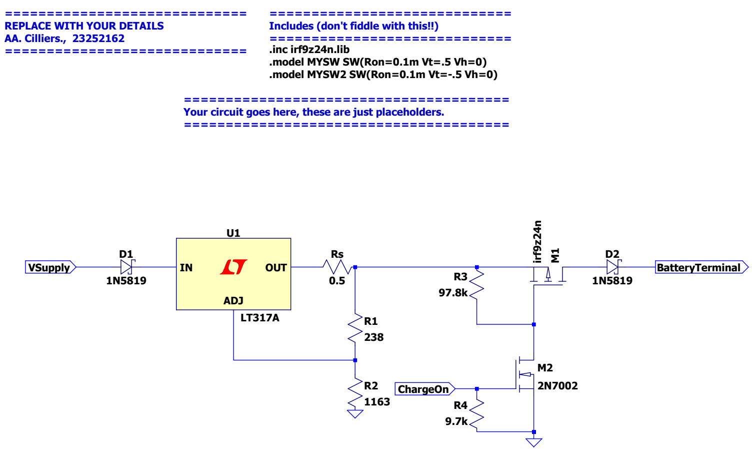

Figure 2.3: Full Circuit Diagram of Voltage Regulator and High-Side Switch

Chapter 3

Results

3.1. Simulation results

Figure 3.1 shows the output of the simulated circuit where V(batteryterminal) is the voltage at the battery terminals and I(Rsensebattery) is the output current through the battery terminal. The charging circuit only switches on when the $5V$ logic control signal (Vchargeon) is set high and the battery does not discharge when V_{supply} is switched off. The current requirement of less than $400mA$ when the battery is flat(at $6V$) is fulfilled since the circuit only pulls $326.82mA$. The final voltage when the battery is fully charged is $7.28V$, thus also meeting the required design specfication of $7.2V$ (with a 5% tolerance). Thus this design is working as intended and meets all the requirements during the simulation.

Figure 3.1: Output Graphs of LTSpice Simulation

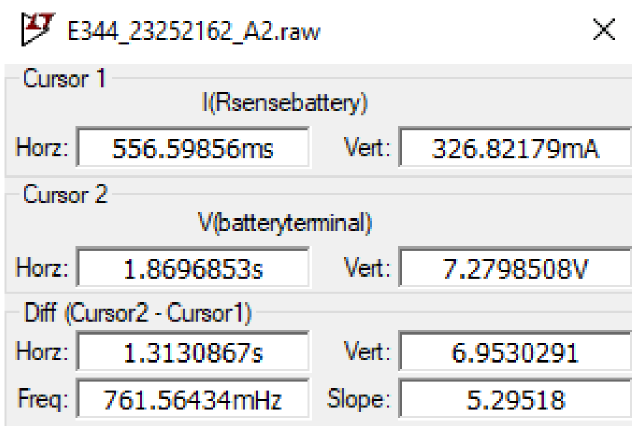

Figure 3.2: Cursor Measurements of the Output Current through Battery and the Battery Terminal Voltage

3.2. Measured results

Figures 3.3 to 3.5 show the measured results of the OC voltage, the voltage over a 1k load and over a 10k load. Figure 3.6

Figure 3.3: Multimeter measurement of the Open Circuit Voltage at the Battery Terminal

Figure 3.4: Multimeter Measurement of the Voltage over a 1k Load

Figure 3.5: Multimeter Measurement of the Voltage over a 10k Load

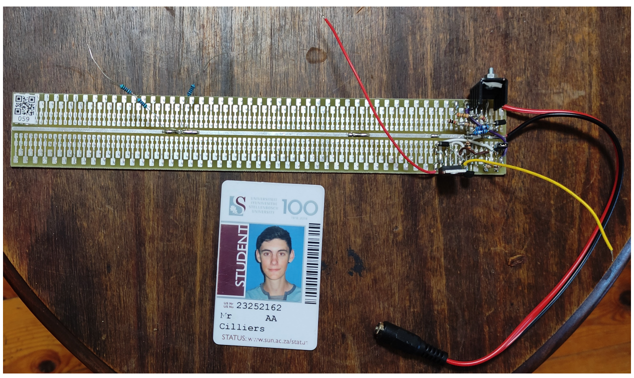

Figure 3.6: Physical Circuit

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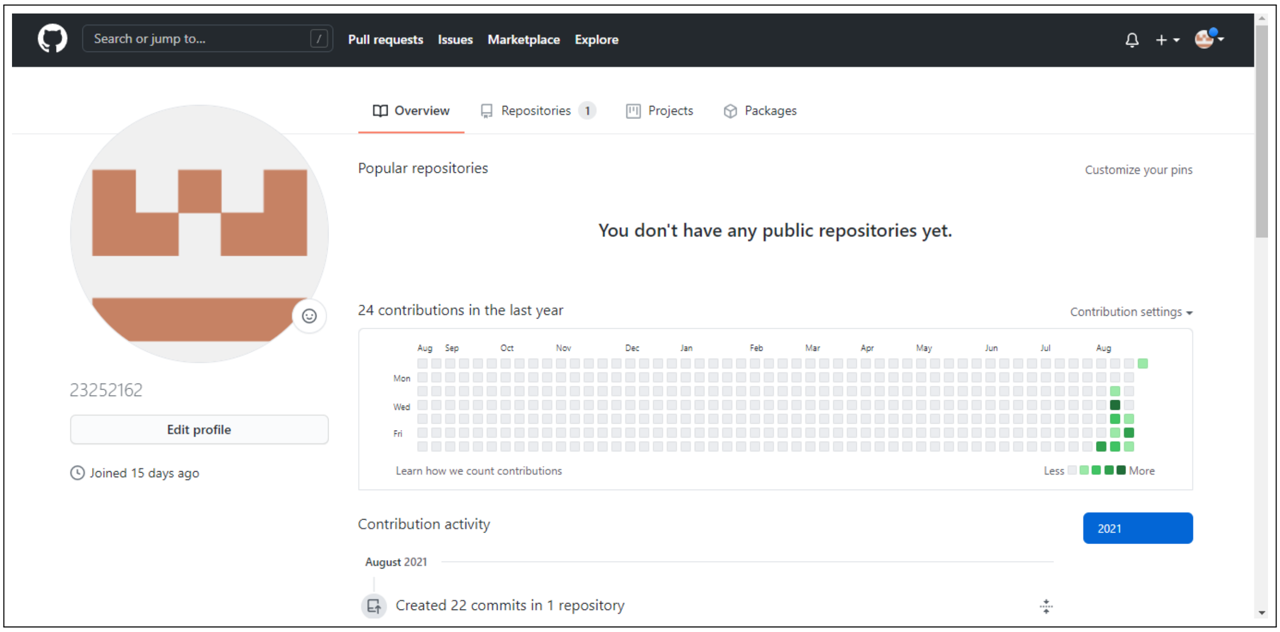
Appendix A

GitHub Activity Heatmap



Appendix B

Stuff you want to include

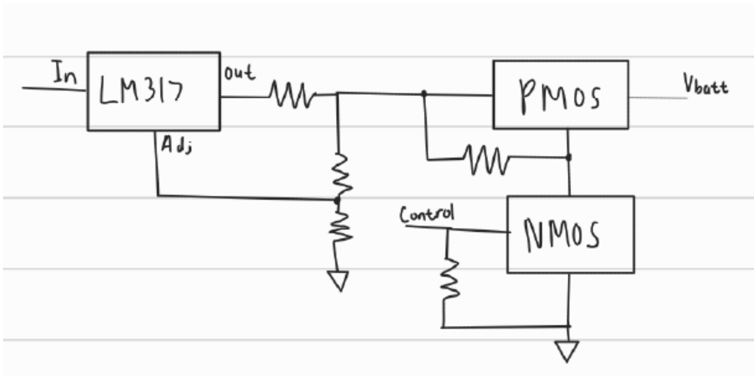


Figure B.1: Conceptual Block Diagram Of Charging Circuit