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E344 Assignment 2

Stéphan van Biljon
22534865

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

V_{OC}	Open-circuit voltage of a PV module/cell.
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_{Supply}	Voltage of a power supply.
$V_{Battery}$	Terminal voltage of a battery.
V_F	Forward voltage of a Schottky diode.
V_O	Output voltage of the LM317T regulator.
V_{REF}	Reference voltage of the LM317T regulator
$I_{O(max)}$	Maximum load current of the LM317T regulator.
$I_{O(min)}$	Minimum load current of the LM317T regulator.
T_j	Junction temperature of the LM317T regulator.
T_{amb}	Ambient temperature of the atmosphere.
R_{thJA}	Junction to Ambient thermal resistance.
R_{thJC}	Junction to Case thermal resistance.
R_{thCS}	Case to Sink thermal resistance.
R_{thSA}	Sink to Ambient thermal resistance.
$V_{Regulator}$	Voltage developed over the LM317T regulator.
P_D	Power dissipated by the LM317T regulator.

Acronyms and abbreviations

PV	Photo-voltaic.
V	Voltage.
A	Ampere.
Ω	Ohm.
Ah	Amp-hour.
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor.
PMOS	P-channel MOSFET.
NMOS	N-channel MOSFET.
BJT	Bipolar Junction Transistor.
DC	Direct Current.
AC	Alternating Current.

Chapter 1

Literature

1.1. Charging lead acid batteries

There are 4 stages when dealing with battery charging , but the 4_{th} stage, Equalization, is optional and is recommended to be done every 3 to 6 months [4]. When a 4Ah battery is fully charged, it draws a current of less than 40mA [5]. Refer to Figure 1.1 when considering the charging stages [1].

- **Bulk Charge Mode** - The depleted battery is being charged with constant current (max of 1.2A [4]) while the battery voltage is allowed to rise linearly. This is where 80% (5.4V) of the battery capacity is returned.
- **Absorption Mode** - When 80% of the battery capacity has been returned, the battery voltage is held constant while the battery current decreases linearly until it reaches 40-80mA. This is the stage where the last 20% (1.35V) of the battery capacity is returned.
- **Float Mode** - When the battery current reduces to 40-80mA, the battery voltage is maintained at 2.25V per cell or 6.75V for a nominal 6V lead-acid battery. This is the voltage of a fully charged battery.
- **Equalization Mode** - This is an optional charging stage that is used to remove the build-up of negative chemical reactions by overcharging the battery with a very small current for a few hours until reaching 7.2 to 7.5V [4].

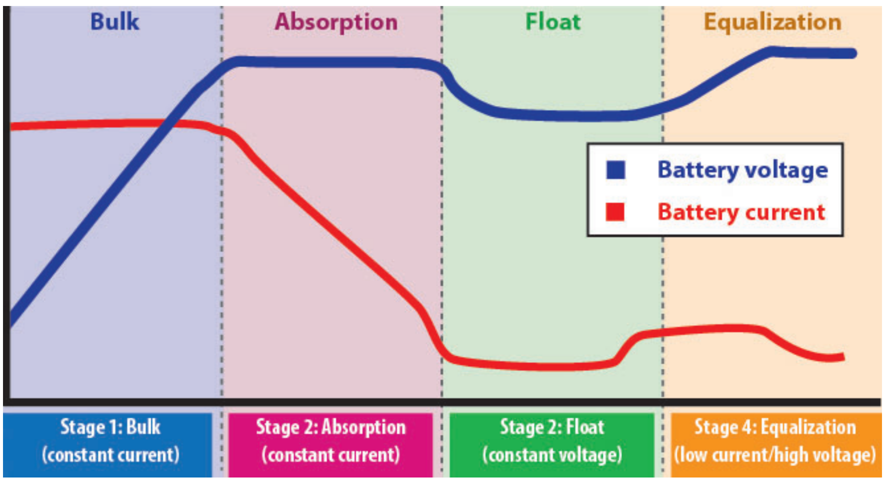


Figure 1.1: Charging stages of a battery [1]

1.2. Voltage regulation

Voltage regulation is a measure of the change of the voltage magnitude between the input and the output of a device. Since the voltage required to charge a battery can vary, we need to be able to change the voltage of a power supply to serve this purpose. We will be using an LM317T linear regulator for this purpose.

Linear regulators have linear components that are used to regulate the output (such as a resistive load) [6]. Linear regulators are quite simple in design which helps them to be cheap and have minimal noise. A drawback of linear regulators is that the input current is equal to the output current which can cause a significant wastage of power and heating up of the regulator. For the purpose of a non-commercial charging circuit where power efficiency is not the biggest concern, the linear regulator is a good choice.

In contrast to linear regulators, a switching regulator uses an internal switch to transform the input power supply into a pulsed voltage which is then smoothed with non-linear components such as inductors and capacitors [6]. This switch allows the output voltage to reach a certain level while closed, after which the switch is opened again until the output voltage drops. This is an efficient way of creating an output voltage without wasting power. Although the power efficiency can reach levels of up to 95% [7], the increased noise, cost and complicated design can be disadvantages.

1.3. Switching with MOSFETs

MOSFET transistors are semiconductor devices consisting of a gate, drain and source terminal [8]. The gate voltage determines whether current will flow between the drain and the source. for PMOS, current will flow when a gate input voltage is applied such that $V_{SG} > |V_{TP}|$. For NMOS, current flows when a gate input voltage is applied such that $V_{GS} > V_{TN}$.

One configuration for MOSFET switches that could be used is an NMOS low-side switch configuration. The biggest issue with such a configuration is that the load is connected to the supply but disconnected from ground. This means that if anything accidentally grounds the load, unintended current will flow through the load. A high-side switch is a safer configuration that doesn't make accidental connections commonplace.

A high-side switch in this application will be a PMOS transistor placed between the supply and the load. Figure B.1 is a common configuration of a PMOS high-side switch. The one limitation of a singular PMOS switch for a high-side configuration is that a control signal of 0V would not be able to make the V_{SG} small enough to turn the PMOS off [9]. $\therefore$ a driving, NMOS transistor as seen in figure B.2 has been included into the design.

Chapter 2

Design

2.1. Overview

The system built for Assignment 2 consists of the parts outlined in the block diagram present in Figure 2.1. The system consists of a DC power supply unit connected to a charging circuit (which is connected through a high-side switch) to a load which is typically a 6V battery.

For the DC power supply, a SLP005-12 PV module or a 12V DC/AC can be used as the input for the charging circuit. The charging circuit consists of a LM317T regulator which has been chosen for its ability to produce an adjustable output voltage (which is a good choice in terms of flexibility). The circuit supporting the regulator has a resistive divider which allows the output voltage to be chosen as well as an output resistor to allow low charging currents for a fully charged RS-4AH battery [10].

The high-side switch connects the charging circuit to a load (which will be the 6V battery). The switch acts as a way to disconnect the charging circuit from the battery when it's fully charged as well as connecting the battery to a charger at the issue of a control signal.

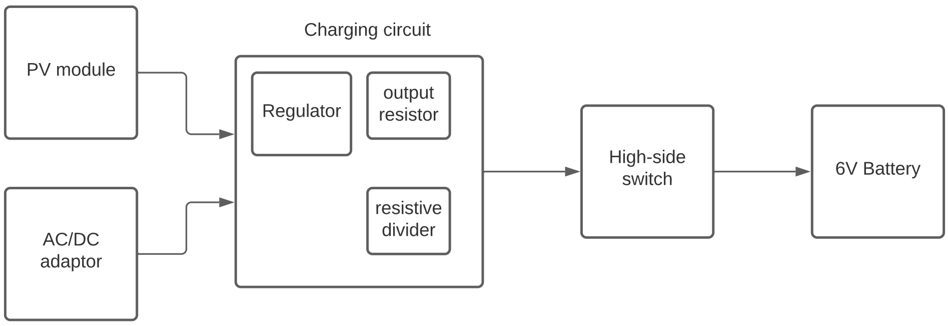


Figure 2.1: System Overview for Assignment 2

2.2. High-side switch

A high-side switch was designed to connect a charging circuit to a load (a battery). MOSFETs are more applicable to large current applications compared to BJTs [11] and the IRF9Z24NPbF PMOS can handle a drain current of up to 12A [12]. A DC supply is chosen to charge the load (battery) because an AC supply will change polarities, thus charging and then discharging a load.

Current must not be able to flow back into the charging circuit or supply from the load. A diode only allows current to flow in one direction and so a Schottky diode has been used due to its applications for renewable energy. [13]. Refer to Figure 2.2 when considering the design calculations below.

A 5V control signal results in the NMOS $V_{GS} = 5V$ and $V_{TN} = 0.8$ to 3V [14] $\therefore V_{GS} > V_{TN}$. 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 [14]. For the PMOS: $V_S = V_{Battery} + V_F$ where $V_F = 0.45$ to 0.6V [15]. Since the battery terminal voltage is required to be 6 to 7.2V, this results in the PMOS $V_S =$ 6.45 to 7.8V and the $V_{SG} = V_S$ while $|V_{TP}| = 2$ to 4V [12]. The PMOS $V_{SG} > |V_{TP}| \therefore$ the PMOS switch is on and current flows from the charging circuit to the load.

The resistor value, R_3, can be calculated from the 5V control signal situation. Ideally, very little current should be present as the drain current of the NMOS. The reason for this is that current from the charging circuit which does not flow to the battery is wasted current which causes more power dissipation in the regulator. $\therefore R_3$ has been chosen as a large value of 116.9 kΩ. This value originates from the tolerance of a 100 kΩ resistor. R_4 is a pull-down resistor that removes the charge from the NMOS V_G when a 0V control is placed after a 5V control. This value can be chosen in the range of about 1-10 kΩ for practical purposes.

A 0V control signal results in the NMOS $V_{GS} = 0V \therefore V_{GS} < V_{TN}$ and the NMOS is off. The PMOS $V_G = 7.65$ to 7.8V due to no current through R_3 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 to the battery.

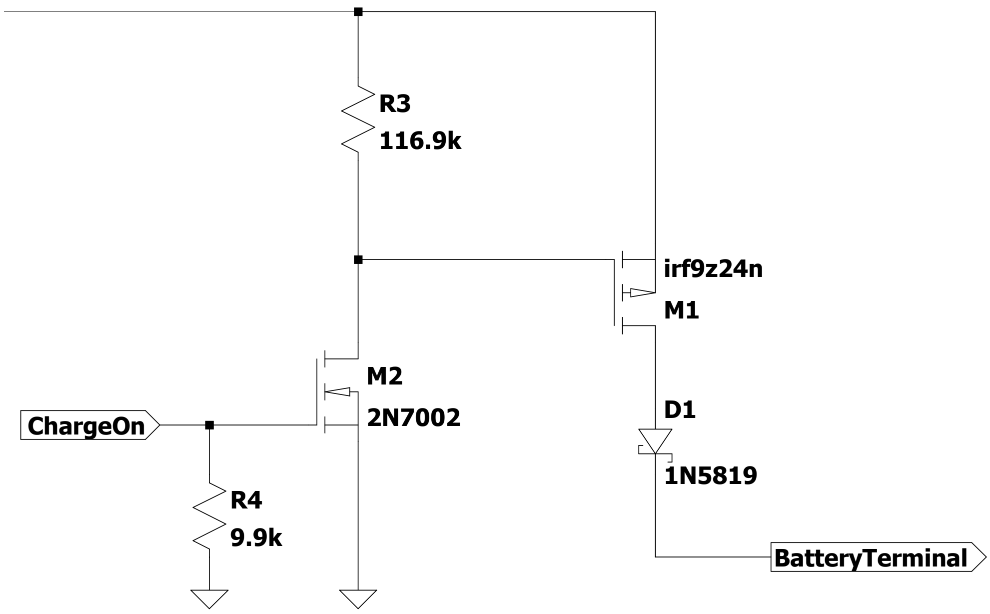


Figure 2.2: High-side PMOS switch with NMOS driver

2.3. Charging regulator

2.3.1. Voltage regulation

Since the LM317T has an adjustable output voltage of 1.2 to 37V, an input voltage range of 3 to 40V [10] is valid. This is because voltage regulators typically need an input voltage that is 2 to 3V higher than the output voltage.

For the charging circuit that was designed, the output voltage of the regulator-switch circuit needed to be equal to 7.2V, which is the equalization charge voltage of the battery [4]. When the battery is fully charged at 7.2V, very little current will flow through the diode attached to the battery terminals which is illustrated in Figure 2.3. This causes V_F to be small ($\approx 0.4V$ [15]). This voltage drop then results in the output of the regulator, $V_O = V_{Battery} + V_F = 7.6V$ since the voltage drop over R_5 and the PMOS V_{SD} is negligible for very small currents [12].

From this desired output voltage, the input voltage to the regulator circuit needs to be at least $10V$ and higher. For this reason, a 12V AC/DC adaptor and a PV module with a $V_{OC} = 21.6V$ [16] has been chosen as the power supplies to this charging circuit.

In order to achieve the desired output voltage of the LM317T, a resistive divider consisting of R_1 and R_2 as seen in Figure 2.3 needs to be implemented. The design equation: $V_O = V_{REF}\left(1 + \frac{R_2}{R_1}\right)$ can be used to determine the value of this resistive divider (which is done in the section below). Typically, $V_{REF} = 1.25$V for design purposes [10].

2.3.2. Current limit

The LM317T has a maximum and minimum load current that needs to be adhered to: $I_{O(max)} = 0.4A$ and $I_{O(min)} = 3.5mA$ [10] in order for it to operate. This limits how quickly the battery can charge but it is a necessary part of the regulator operation.

Since the current is very small when the battery is fully charged, only the resistive divider path can draw the current necessary to fulfil $I_{O(min)}$. Using the design equation from above and solving simultaneously with: $V_O = I_{O(min)}(R_1 + R_2)$, $R_1 \approx 360\,\Omega$ and $R_2 \approx 1.8\,\mathrm{k}\Omega$. The values seen in Figure 2.3 are as a result of resistor tolerances.

Since we know that $V_O = 7.6V$ and that when the battery is depleted (6V), the current drawn will be the largest. This large current, up to $I_{O(max)}$, will cause the diode $V_F = 0.53V$ [15]. This results in the PMOS V_S node $= V_{Battery} + V_F = 6.53V$. From this, V_{R5} and $I_{R5} \approx I_{O(max)}$ can be used to solve for $R_5 = 2.675\,\Omega$. R_S was then adjusted within SPICE to find an optimal value of $R_5 = 0.5\,\Omega$.

2.3.3. Thermal analysis

The characteristics of the LM317T regulator will change if the temperature of the device is drastically above 25° C. For example, the $I_{O(max)}$ value used above is rated for 25° C. As T_j rises, the $I_{O(max)}$ will decrease at different input-output differentials compared to $T_j = 25°$ C [10]. The reference voltage, V_{REF}, will also decrease at higher junction temperatures [10].

The maximum power dissipated within the LM317T can be calculated as: $P_{D(max)} = V_{Regulator} \times I_{O(max)}$. We know that $I_{O(max)} = 0.4$A and $V_{Regulator} = V_I - V_O$. $V_O = 7.6V$ as calculated above and $V_I = V_{Supply} - V_F$ when $I_{input} = I_{O(max)}$. $\therefore V_F = 0.53V$ [15], $V_I = 11.47V$ and $V_{Regulator} = 3.87V$. This results in the regulator $P_{D(max)} = 1.548W$ which is within the limits of the LM317T power dissipation of 20W [10].

Assuming that no heat-sink is present: $P_D = \frac{T_j - T_{amb}}{R_{thJA}}$ where $R_{thJA} = 50°$ C/W [10] and $T_{amb} = 25°$ C. From this, we can conclude that $T_j = 102.4°C$. This temperature will affect the regulator characteristics and needs to be decreased with a heat-sink. Now assuming the addition of a heat-sink: For the TO-220 5772 heat-sink, when $P_D = 1.548W$, $R_{thSA} = 7.8°$ C/W [17]. For a TO-220 package tightened with thermal grease, $R_{thCS} = 1°$ C/W [18]. Finally, for the LM317T regulator, $R_{thCS} = 5°$ C/W [10]. All of this combines to form the equation: $P_D = \frac{T_j - T_{amb}}{R_{thJC} + R_{thCS} + R_{thSA}}$ where you can solve for $T_j = 46.36°$ C.

Not only has the addition of the heat-sink improved the performance of the regulator, in terms of higher output currents and reference voltages, but it has also made the casing of the LM317T regulator safe to touch. This was all done by reducing T_j of the regulator.

2.4. Circuit diagram

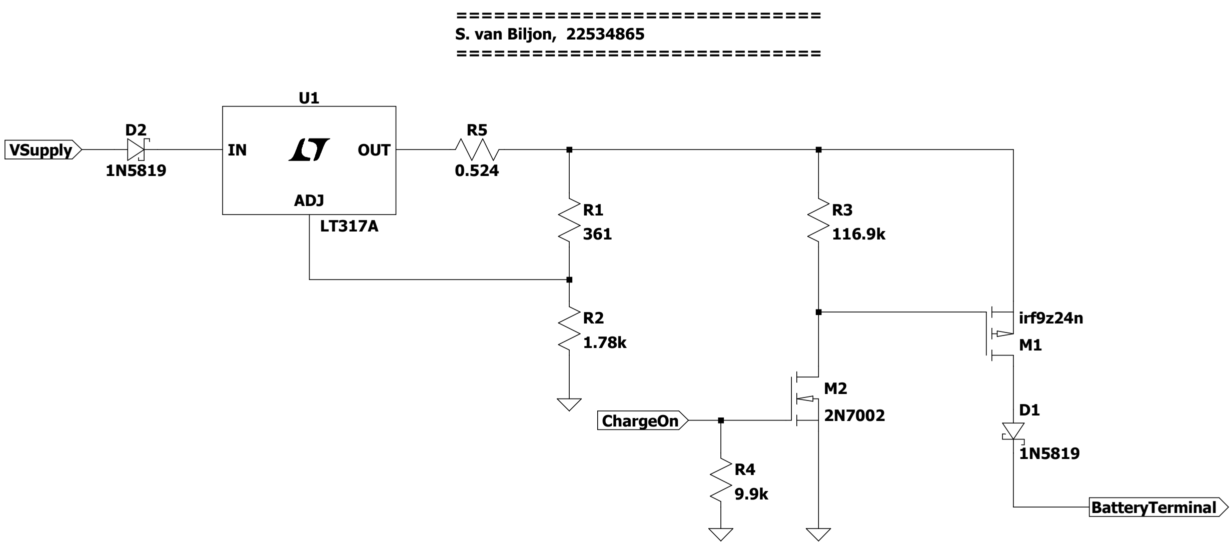


Figure 2.3: LT317A Regulator Charging Circuit with High-Side Switch

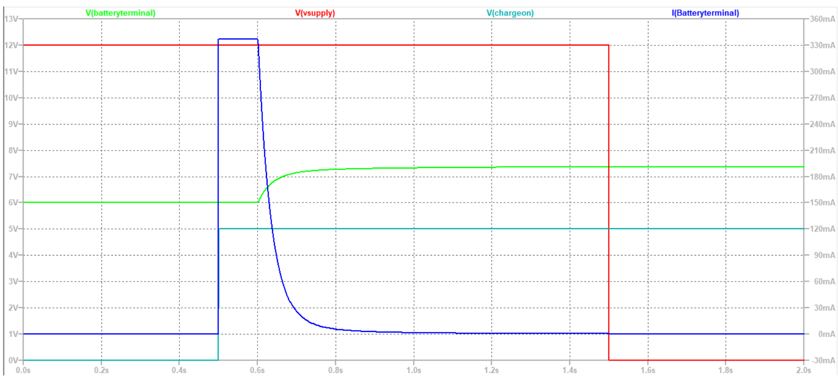
Chapter 3

Results

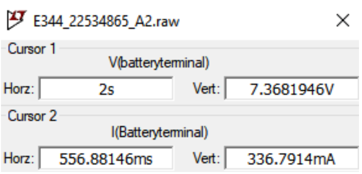
3.1. Simulation results

Refer to Figure 3.1 below when taking the simulation results into account. At time = 0, the DC power supply is 12V (high) and the control signal is 0V (low) ∴ the depleted battery level (6V) does not charge. When the control signal goes high at t = 0.5s while the supply is still high, the depleted battery starts to charge after 0.1s. As seen in Figure 3.1a, the battery level starts to rise while the charging current decreases from a limit of 337mA. 300 to 400mA is the range which can be provided by the PV module power supply.

When the battery becomes fully charged at 7.37V (which is in the range of equalization charge), the current that the battery draws drops close to 0mA. The resistive divider draws enough current to keep the regulator functioning. Due to the placement of Schottky diodes in the circuit, the battery does not discharge when the switch is on and the power supply drops to 0V (low). The power dissipation of the regulator can be calculated as 1.45W. The output voltage of the charging and switch circuit, as well as the current that the battery draws, and the regulator power dissipation are within acceptable ranges ∴ the circuit works as expected.



(a) Simulation Battery Voltage and Current, Supply Voltage and Control Voltage



(b) Simulation Battery Voltage and Current Values

Figure 3.1: Simulation Output and Values

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3.2. Measured results

The successful operation of the switch was confirmed through measured voltages as seen below in Table 3.1. For a control signal of 0V, both the V_{GS} of the NMOS and the V_{SG} of the PMOS were measured to be 0V, which indicates that neither the NMOS nor the PMOS were on and so the switch is open. For a control signal of 5V, the V_{GS} of the NMOS was 5.05V and so the NMOS is confirmed to be on. The V_{SG} of the PMOS was 7.43V and so the PMOS is also confirmed to be on which indicates that the switch is closed.

Control Signal (V)	Vgs (V)	Vsg (V)
0	0	0
5	5.05	7.43

Table 3.1: Measured Switch Terminal Voltages

Found in Table 3.2, the charging voltage of the circuit was also measured under no load, $1\,\mathrm{k}\Omega$ and $10\,\mathrm{k}\Omega$ conditions. Under a no load condition, the charging voltage measures higher than the load conditions. The lower the value of load resistance, the more current is drawn from the regulator, and consequently the more voltage drop takes place inside the regulator. This causes the terminal voltage (charging voltage) to decrease [19]. The diode V_F measured at a peak of 0.2V under the $1\,\mathrm{k}\Omega$ load which indicates that the diode is active and will stop the discharging of a battery if the supply drops to 0V.

Load (kΩ)	Charging Voltage (V)
0	7.41
1	7.15
10	7.24

Table 3.2: Measured Charging Voltage of the Charging Circuit

Figure 3.2: Image of the Charging Circuit and Switch

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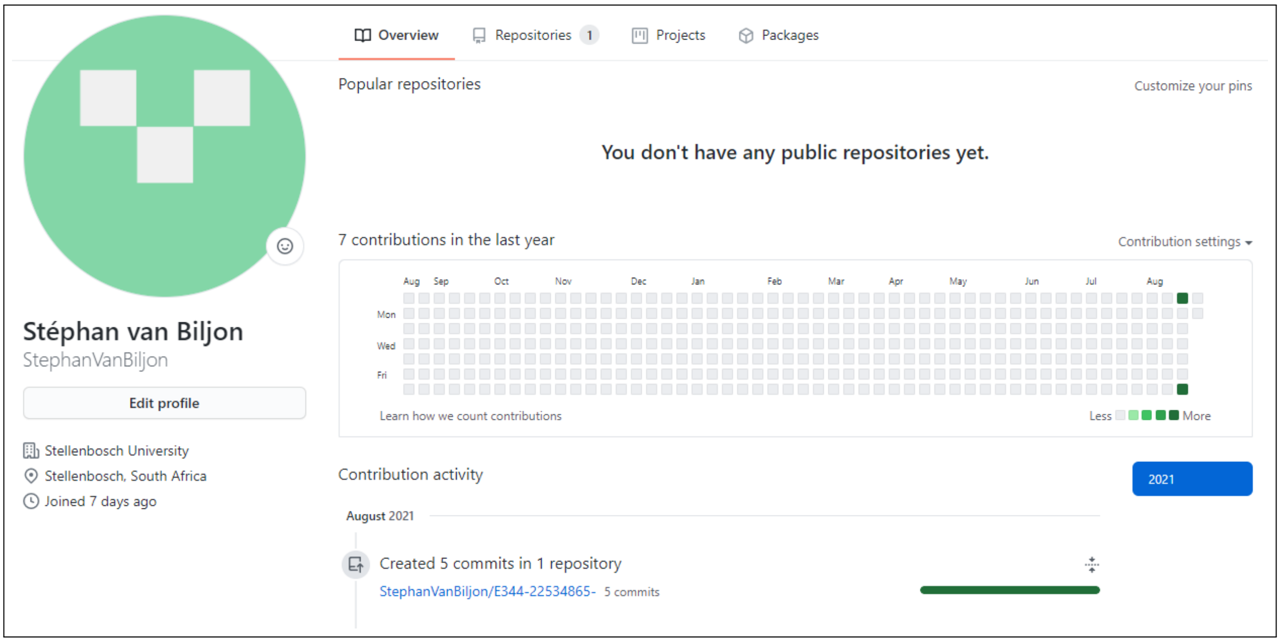
Appendix A

GitHub Activity Heatmap



Appendix B

Stuff you want to include

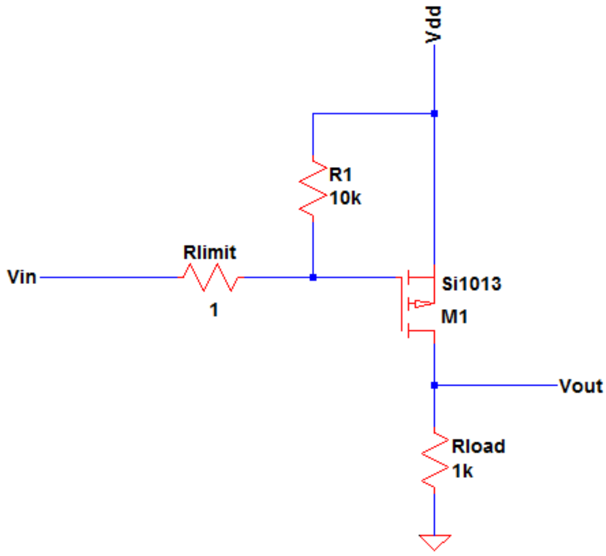


Figure B.1: High-side PMOS switch [2]

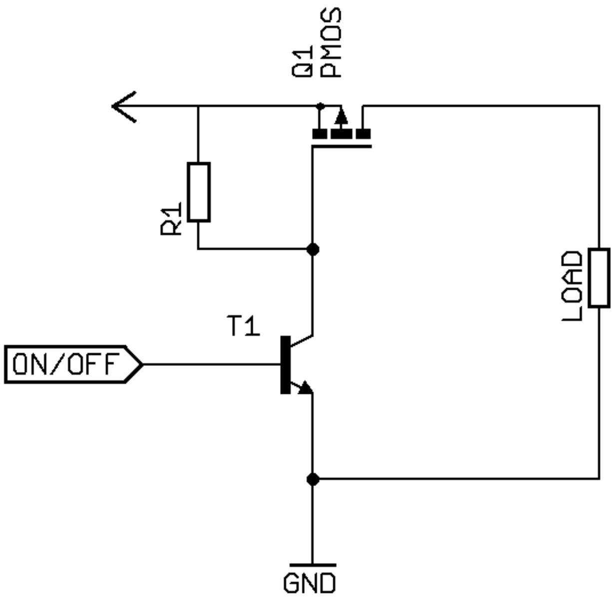


Figure B.2: High-side PMOS switch with NPN driver [3]