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E344 Assignment 1

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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 12, 2021

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Nomenclature

Variables and functions

V_{OC}	Open-circuit voltage of a PV module/cell.
I_{SC}	Short-circuit current of a PV module/cell.
V_{MP}	Maximum power point voltage.
I_{MP}	Maximum power point current.
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_{DS}	Drain-source voltage of an N-channel MOSFET.
V_S	Source voltage of a MOSFET.
V_{supply}	Voltage of a power supply.
V_F	Forward voltage of a Schottky diode.
R_2	Switch circuit resistor.
I_D	Drain current of a MOSFET.

Acronyms and abbreviations

PV	Photo-voltaic.
V	Voltage.
A	Ampere.
Ω	Ohm.
IV	Current-voltage.
Ah	Amp-hour.
Wh	Watt-hour.
C	Measure of the rate at which a battery is discharged relative to its maximum capacity.
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

Solar photovoltaic cells and solar modules

A solar, photo-voltaic cell is a device, within which, the electrical characteristics vary when exposed to different levels of light. A PV cell absorbs the energy of photons and through the photovoltaic effect, creates a potential difference and induces the flow of current. This flow of current is created by the PV cell in order to be extracted through conductive metal contacts and to be used as an energy source [7].

Although PV cells and modules are used as a energy source, due to the fact that our PV modules are made of multi-crystal silicon (which allows less freedom for the electrons to move), the efficiency of solar energy to usable energy conversion is only in the range of 13-16% [8].

Two important electrical characteristics of PV modules (illustrated in Figure 1.1) includes the open circuit voltage and the short circuit current. The open circuit voltage of a solar PV module is the sum of the open circuit voltages created by each PV cell, which is the maximum voltage available from a PV cell, when the current through each cell is at a minimum (0A) [9]. The short circuit current of a solar PV module is the sum of the short circuit currents created by each PV cell, which is the maximum current available from a PV cell, when the voltage through each cell is at a minimum (0V) [10].

Polycrystalline PV cells typically have a V_{OC} of 0.6V [9] and since the SLP005-12 PV module has 36 cells, the calculated V_{OC} of 21.6V matches the datasheet value given [11]. The short circuit current of the PV module is listed as 0.34A [11].

Another important characteristic of PV modules is the maximum power point. As seen in Figure 1.1, which shows the IV relationship within a PV module, the maximum power point is the operating voltage and current, V_{MP} and I_{MP}, where the PV module gives the maximum power output [1]. The maximum/rated power that the SLP005-12 PV module can output is 5W [11].

When the values listed on the datasheet of the SLP005-12 PV module are tested for, they are tested for under Standard Test Conditions [12]. These conditions require:

- Solar radiation (light intensity) of 1 $\frac{kW}{m^2}$. This is the average energy of the sun at sea level.
- Cell temperature of 25°C.
- Air Mass = 1.5.

- No wind.

Keep in mind, however, that the current-voltage relationship in a PV module will change under non-standard test conditions. For example, Figure 1.2 shows how the curve shifts upwards for increasing light intensity. When measuring the SLP005-12 open circuit voltage and short circuit current, this changing relationship was encountered during different light intensities which are tabulated in Table 1.1. The large variance of the measured current contrasted with the small variance of the measured voltage is confirmed by the light intensity dependant IV relationship from Figure 1.2.

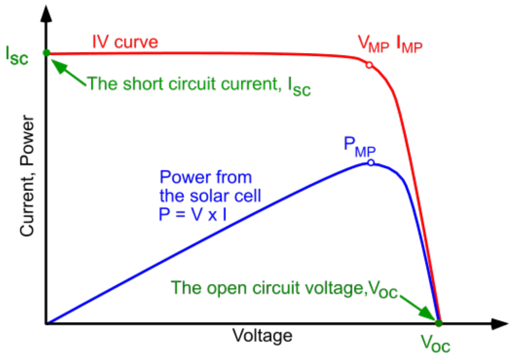

Figure 1.1: IV and Power relationship of PV module [1]

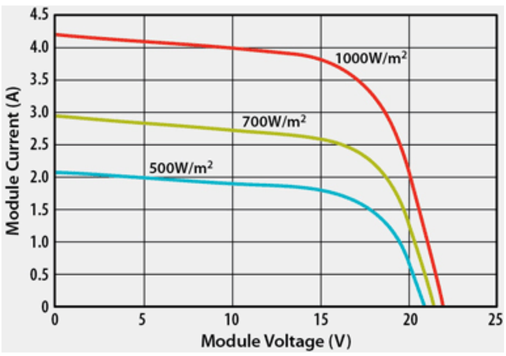

Figure 1.2: Light intensity dependent IV relationships [2]

Table 1.1: Voltage and current measurements of the SLP005-12 PV module

	V_{OC} [V]	I_{SC} [A]
Theroretical per cell	0.6	0.094
Datasheet per module	21.6	0.34
Measured Ambient Light	11.71	0.24
Measured Dark (covered)	0	0
Measured Upside-down (sun)	15.55	0.46
Measured Oblique (sun)	19.87	0.6
Measured Perpendicular (sun)	21.6	0.66

Chapter 2

Lead acid batteries

Lead acid batteries are the most commonly used type of rechargeable battery in photo-voltaic systems due to their long lifetime and low costs. [13]. The measured open circuit voltage of the RS-4AH battery is 6.37V. This stands in contrast to the 6V nominal rating of the battery (2V per cell for 3 cells) [4]. Nominal values are approximate values that are used to classify different batteries and so measured values are the most accurate.

The advertised battery capacity is 4Ah (or 24Wh) [4] which means that if you use the battery to supply 4A of current for an hour, the battery will be depleted. Ah is a useful measurement value due to the fact that a battery is a time-variable current supply for loads in circuits. This advertised capacity is not accurate when discussing the actual, available capacity of the battery. Battery capacity is dependent on temperature (where higher temperature will increase your battery capacity at the cost of battery life and vice versa [14]) but more importantly, only 10-15% of the advertised capacity can be used to ensure battery longevity [15].

The RS-4AH battery has an internal resistance of approximately $45\,\mathrm{m}\,\Omega$. Internal resistance is the resistance of a battery or cells as opposed to the resistance of a load connected to a power source [16]. This internal resistance of the battery, illustrated in Figure 2.1 is the reason that the voltage across the terminals of the battery will drop if a load is connected [17].

Self discharge is a phenomenon that occurs when chemical reactions inside of a battery reduce the stored charge while not being connected to a load. The RS-4AH battery will self discharge 40% of its capacity at room temperature over 12 months [4].

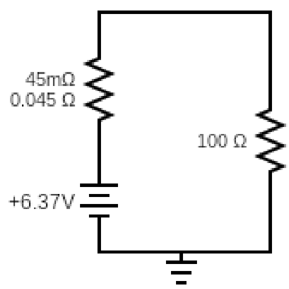

Figure 2.1: Circuit diagram of a battery with internal resistance and a $100\,\Omega$ load

2.1. Battery Charging

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 about 40-80mA [3]. Refer to Figure C.3 when considering the charging stages [3].

- **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% (5.05V) 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% (1.3V) of the battery capacity is returned.
- **Float Mode** - When the battery current reduces to 40-80mA, the battery voltage is maintained at 2.12V per cell or 6.3 to 6.4V 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.

2.2. Battery Discharging

The RS-4AH battery can discharge at a rate of up to 60A [4], although if we apply this current to Figure 2.1, the 100 Ω load (250mW rating) will heat up to the point of melting!

The RS-4AH battery is considered to be fully depleted when each cell is at a voltage of 1.8V [4] ($\therefore 5.4V$ for the battery). Only using 10-15% of the advertised capacity will ensure the longevity of this non-deep cycle, lead-acid battery [15].

Depending on the rate at which you discharge the battery, the terminal voltage of the battery will decrease at different rates. This is to say, although a current of 0.05C where C is 4Ah is 20 times smaller than 1C, the terminal voltage of the battery will not decrease 20 times slower when comparing the rate of discharge.

Refer to Figure C.4. For example, a current of 0.05C drawn for 60 minutes will not have a noticeable terminal voltage decrease [4] while a current of 1C drawn for 22 minutes will completely deplete the battery [4]. If we extrapolate this, we will find that a current draw of 0.05C will not completely deplete the battery in 20 times more time (7.33 hours). A discharge rate of 200mA used for 20 hours will fully deplete the battery and it will take 11 hours for the voltage of each cell to reach 2V [4].

Chapter 3

High-side switching circuit

3.1. Intro

MOSFET transistors are semiconductor devices consisting of a gate, drain and source terminal [18]. The gate voltage determines whether current will flow between the drain and the source. for PMOS, current will flow when a *negative* input voltage is applied and $V_{SG} > |V_{TP}|$. For NMOS, current flows when a *positive* input voltage is applied and $V_{GS} > V_{TN}$.

A high-side switch in this application will be a PMOS transistor placed between the supply and the load. Figure C.1 is a common configuration of a PMOS high-side switch.The control signal of 0V would not be able to make the V_{SG} small enough to turn the PMOS off [19]. $\therefore$ a driving, NMOS transistor as seen in figure C.2 has been included into the design.

3.2. Design

A high-side switch was designed to connect a supply to a load. MOSFETs are more applicable to large current applications compared to BJTs [20] and the IRF9Z24NPbF PMOS can handle a drain current of up to 12A [21]. A DC supply of 25V 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 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. [22]. Refer to figure 3.1 when considering the design calculations below.

A 5V control signal results in the NMOS $V_{GS} = 5V$ and $V_{TN} = 0.8$ to 3V [23] $\therefore V_{GS} > V_{TN}$. This turns the NMOS on and pulls V_G of the PMOS to $V_{DS} = 0.09$ to 1.5V [23]. For the PMOS: $V_S = V_{supply} - V_F$ where $V_F = 0.45$ to 0.6V [24]. This results in the PMOS $V_S = 24.4$ to 24.55V and the $V_{SG} = 22.9$ to 24.46V while $|V_{TP}| = 2$ to 4V [21]. As can be seen from above, the PMOS $V_{SG} > |V_{TP}| \therefore$ the PMOS switch is on and current flows from the supply to the load.

The resistor value, R_2, can be calculated from the 5V control signal situation. Since the PMOS $V_G = 0.09$ to 1.5V the voltage drop over $R_2 = 23.5$ to 24.91V. The current flowing through the resistor is the drain current, I_D of the NMOS where $I_D = 50$mA for a $V_{GS} =$ 5V [23]. $\therefore R_2 = \frac{V_{supply} - V_G}{I_D} = 470$ to $498.2\,\Omega$. A resistor value of $R_2 = 470\,\Omega$ is widely available.

A 0V control signal results in the NMOS $V_{GS} = 0V \therefore V_{GS} < V_{TN}$ and the NMOS is off. The PMOS $V_G = 25V$ due to no current through R_2 and the PMOS V_{SG} = -0.6 to -0.45V. It can be observed that $V_{SG} < |V_{TP}| \therefore$ the PMOS is off and current won't flow to the load.

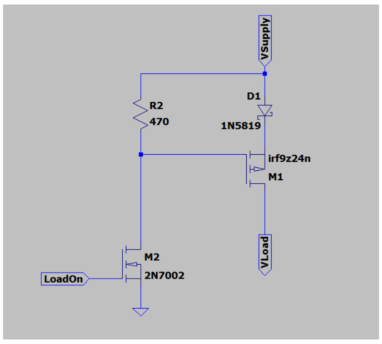

Figure 3.1: High-side PMOS switch with NMOS driver

3.3. Results

Refer to figure 3.2 and 3.1 when considering the results discussed below. At time = 0s, the supply voltage is at 25V while the control signal is at 0V, $\therefore$ the PMOS switch is open. When the control signal changes to 5V at 0.5s, the PMOS switch closes and so current flows into the capacitive load and charges it up. When the capacitor is fully charged, current stops flowing and a voltage of 25V develops over the load. The control signal going back to 0V at 1s has no effect because current already stopped flowing when the capacitor was fully charged. At 1.5s, the supply is switched to 0V, *but*, the capacitor doesn't discharge because the diode stops the flow of current back to the source. The load voltage $\therefore$ stays 25V.

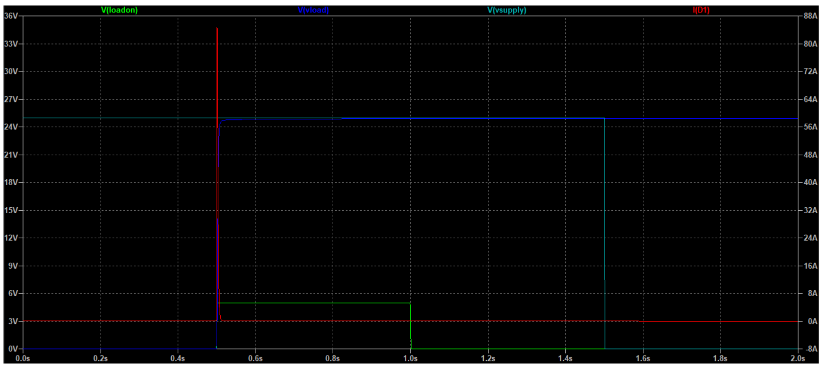

Figure 3.2: Input Control and Supply Voltage with Output Load Voltage and Load Current

3.4. Summary

The design performs as expected because the the simulation results are consistent with the theoretical calculations. The design has been made for components operating at room temperature. Mechanical shock or temperature fluctuations will change the circuit performance.

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Appendix A

Social contract

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E-design 344 Social Contract

2021

The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and the Teaching Assistant (Kurt Coetzer) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare the assignments, to set the tests and assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

I, Stéphan van Biljon have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication online of supplementary videos on specific topics, I acknowledge that I am expected to attend the scheduled lectures to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Prof. MJ Booysen	Student number: 22534865
Signature: Digitally signed by MJ BOOYSEN Date: 2021.08.04 22:12:45 +02'00'	Signature: Stéphan van Biljon Digitally signed by Stéphan van Biljon Date: 2021.08.12 12:54:29 +02'00'
Date: 4 Aug 2021	Date: 12 August 2021

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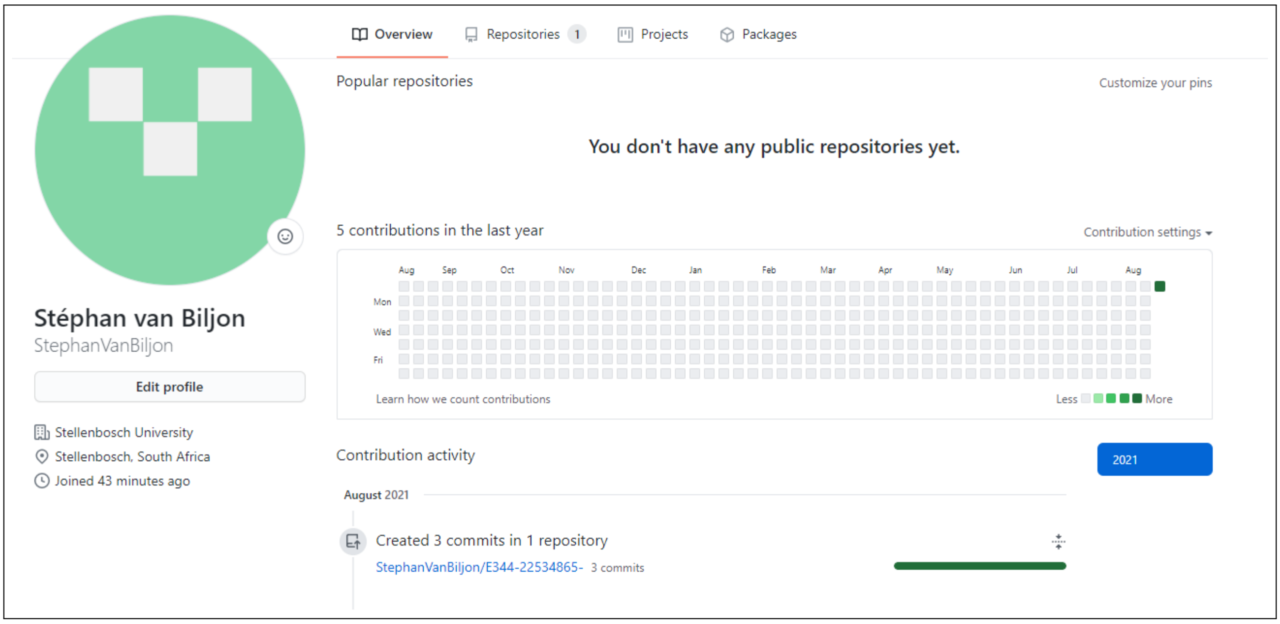
Appendix B

GitHub Activity Heatmap



Appendix C

Stuff you want to include

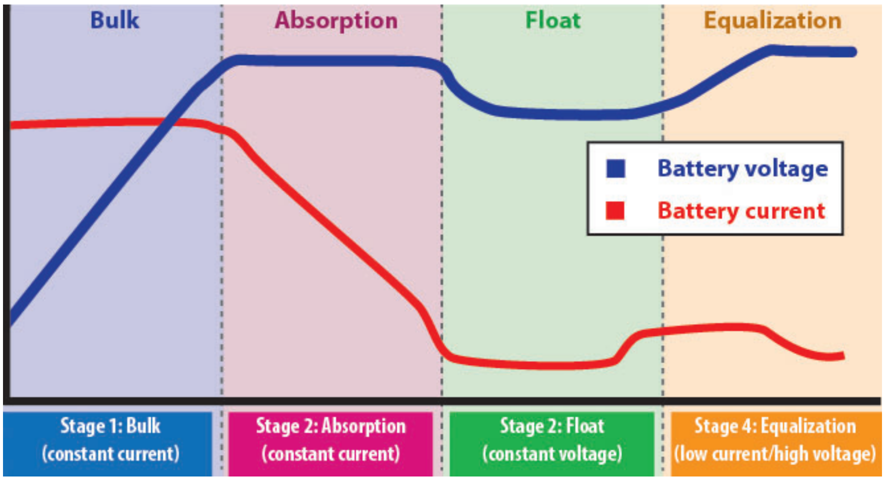


Figure C.3: Charging stages of a battery [3]

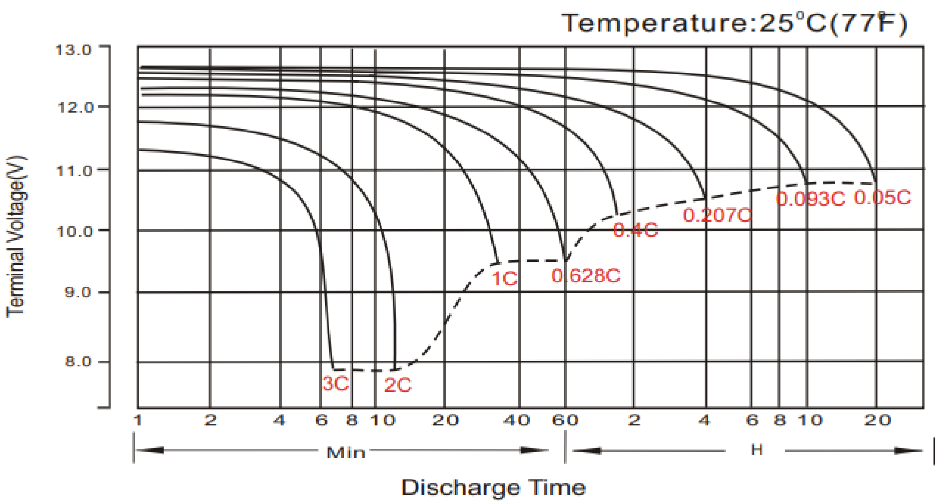


Figure C.4: RS-4AH Discharge Characteristics [4]

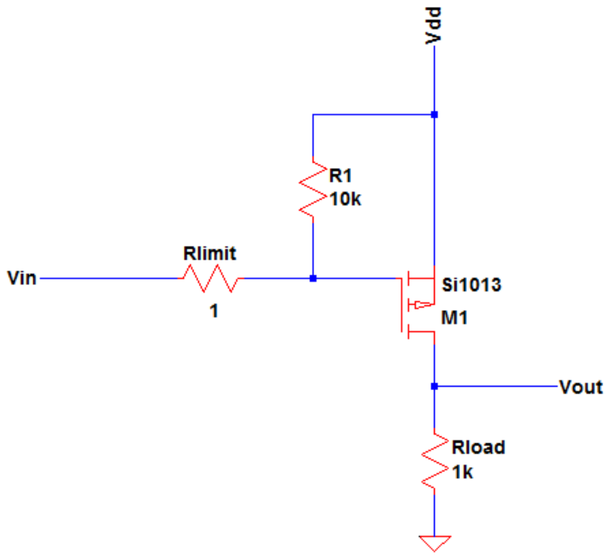


Figure C.1: High-side PMOS switch [5]

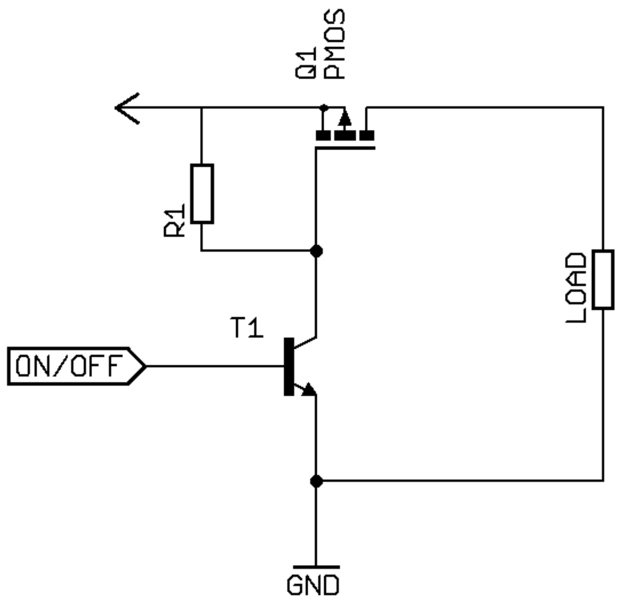


Figure C.2: High-side PMOS switch with NPN driver [6]