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E344 Assignment 4

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Nomenclature

Variables and functions

V_{GS}	Gate-source voltage of an N-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_{OUT}	Output voltage of the TSC213.
V_{CC}	Supply voltage of the TSC213.
R_{SENSE}	Current sensing resistor.
V_{REF}	Reference voltage of the TSC213.
I_{SENSE}	Current through the current sensing resistor.
V_{pk}	Peak voltage.
V_{pk-pk}	Peak to peak voltage.
V_{BAT}	Voltage of the battery.

Acronyms and abbreviations

V	Voltage.
A	Ampere.
Ω	Ohm.
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor.
PMOS	P-channel MOSFET.
NMOS	N-channel MOSFET.
LED	Light Emitting Diode.
RC	Resistor and capacitor filter time constant.

Chapter 1

Low-side load control

A low-side switch was designed to connect/disconnect the system load (5 super bright LEDs) to/from ground. When the switch is on, the load will be grounded and current can discharge into the load, from the battery. A 5V control signal results in the NMOS $V_{GS} = 5V$ and since $V_{TN} = 0.8$ to 3V [2], we find that $V_{GS} > V_{TN}$. This turns the NMOS on and connects the load to ground since the NMOS V_{DS} is negligible for very small currents.

The load is designed to draw 100mA of current for a fully charged battery which will make the NMOS drain current: $I_D = 100$mA. In order to limit the load current to 100mA, each LED has to draw 20mA of current. This can be done by placing a 200 Ω resistor in series with each LED. $I_D = 100mA$ will not exceed the maximum drain current of the NMOS 2N7000 which is 200mA [2]. For 100mA of drain current and a $V_{GS} = 5V$, $V_{DS} \approx 0.1V$ which can be assumed to be negligible [2].

For a control signal of 0V, $V_{GS} = 0V$ and so $V_{GS} < V_{TN}$. This turns the NMOS off and disconnects the load from ground, thus preventing current flow through the load. Since a MOSFET will act as a voltage controlled switch, it requires very small amounts of current to work but it can also sink the maximum current that the load is designed to draw.

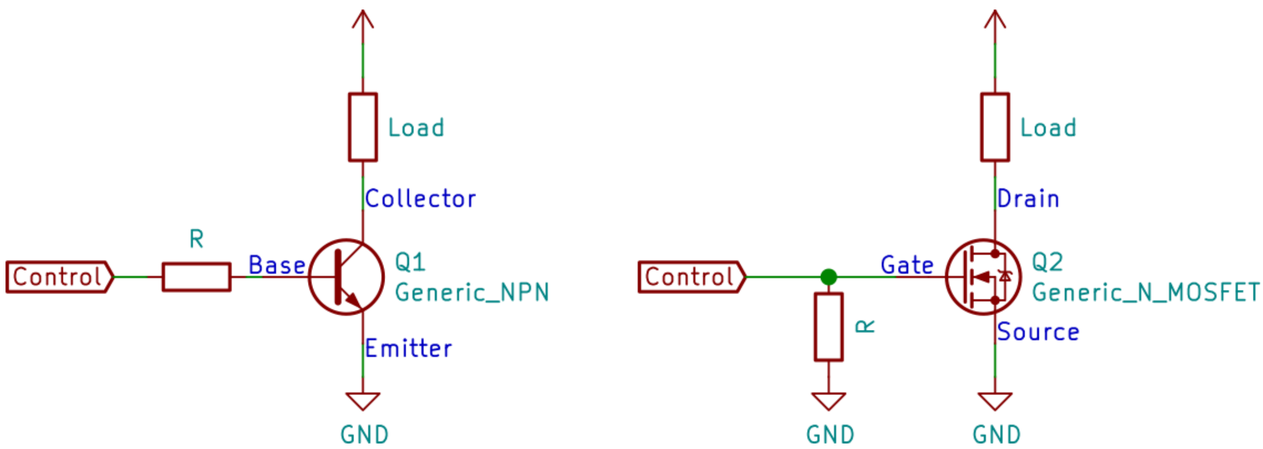


Figure 1.1: Examples of Low-side Switches [1]

Chapter 2

Bidirectional current measurement

2.1. Overview

The bi-directional current sensing system seen in Figure 2.1 consists of a current sense amplifier with a current sense resistor (which is connected to the under-voltage protection circuit and the charging circuit), a load of 5 super bright LEDs and a low-side switch . The current sense resistor creates a voltage drop when current is passed through it. This small voltage drop is amplified by the TSC213 operational amplifier and a corresponding V_{OUT} is created in order to measure the current flowing to/from the battery. The low-side switch connects/disconnects the load to/from ground to control the flow of current through the LEDs.

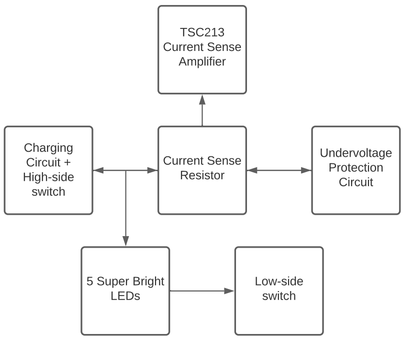


Figure 2.1: System Overview for Assignment 4

2.2. Bi-directional Current Sensor Design

The bi-directional current sensor needs to represent the current flowing through the current sensing resistor to or from the battery. For this objective, currents from -150mA (discharging) to 450mA (charging) need to be represented as an analogue output voltage by the TSC213. This results in a current range of 600mA that needs to be represented on a voltage range of 5V (0V to $V_{CC} = 5$V) [3]. When current flows through the $0.1\,\Omega$ current sensing resistor, the shunt voltage range is from -0.015V to 0.045V (assuming positive current is charging current). This voltage range is then amplified and represented on V_{OUT} by the TSC213 according to the following equation where the gain is fixed at $50\frac{V}{V}$ [3]:

$$V_{OUT} = (R_{SENSE} \times I_{SENSE}) \times Gain + V_{REF}$$

For optimal output voltage swing, you will want your voltage range (0V to V_{CC} = 5V) split in half when the current range (600mA) is also split in half. This correlates to $I_{SENSE} = 150mA$ when V_{OUT} = 2.5V. Using the equation above, the desired V_{REF} = 1.75V. This offset is required for optimal output voltage swing when we have an unbalanced input voltage (due to an unbalanced current range). For V_{REF}, it is seen that 450mA correlates to $V_{OUT} = 4V$ and -150mA correlates to $V_{OUT} = 1V$. This provides an output voltage swing of $3V_{pk-pk}$ around 2.5V. In order to provide the appropriate V_{REF} to the TSC213, voltage division from V_{CC} = 5V needs to be done:

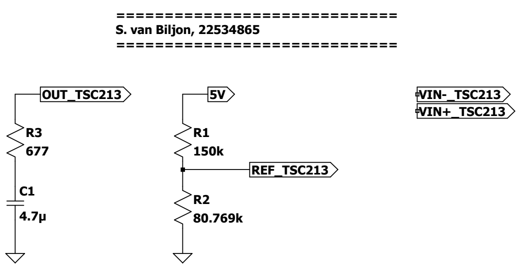
$$V_{REF} = \frac{R_2}{R_1 + R_2} \times V_{CC}$$

R_1 is chosen as $150\,\mathrm{k\Omega}$ to minimize power losses, which results in $R_2 = 80.77\,\mathrm{k\Omega}$. This V_{REF} then needs to be fed through a voltage-follower in order to ensure that the TSC213 samples the correct voltage. The final step in designing the bi-directional current sensing circuit is creating a filter to attenuate frequencies above 50Hz such that $1mV_{pk}$ noise on the 5V supply rail and $1mV_{pk}$ noise on R_{SENSE} results in less than $2mV_{pk}$ noise on V_{OUT}. This can be done using a passive, RC filter attached to the output of the TSC213. Since we want to attenuate frequencies above 50Hz, we can use the low-pass filter design equation:

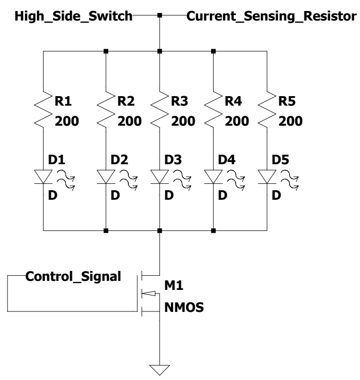
$$f_c = \frac{1}{2\pi RC}$$

Where RC is the desired time constant of the filter and $f_c = 50Hz$. A higher capacitance will result in more filtering of V_{OUT} but it will also slow down the system. In order to keep the system responsive to current changes (a current change will result in the correct V_{OUT} within 2s), the capacitance was chosen as C = $4.7\mu F$. This resulted in $R = 677\,\Omega$.

2.3. Circuit diagram



(a) Bi-directional Current Sensing Circuit with Filter



(b) System Load with Low-side Switch (Pull-down resistor not illustrated)

Figure 2.2: Complete Assignment 4 Circuit Diagram

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2.4. Results

For the simulation results, as seen below in Figure 2.3, V_{REF} is observed as 1.75V when no current is flowing through the circuit. When 150mA is discharged from the battery, a V_{OUT} = 1V is observed after a delay of 0.675s. Finally, a V_{OUT} = 4V is observed when 450mA of current charges the battery. For $1mV_{pk}$ noise on R_{SENSE}, $V_{OUT(noise)} = 0.825mV_{pk}$. Similarly, for $49.08mV_{pk}$ noise on V_{REF} (which is attached to the 5V rail), $V_{OUT(noise)} = 0.883mV_{pk}$.

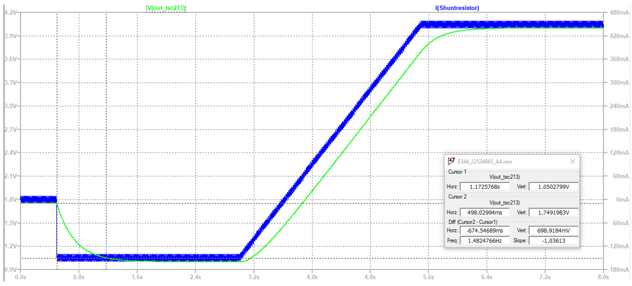
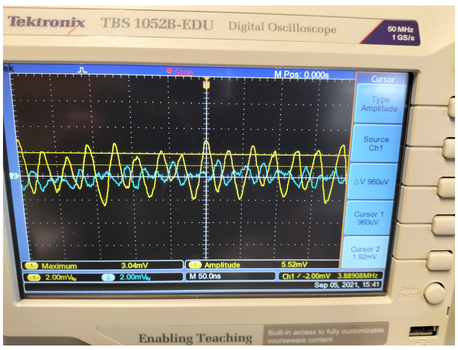


Figure 2.3: TSC213 Output Voltage vs Current through R_{SENSE}

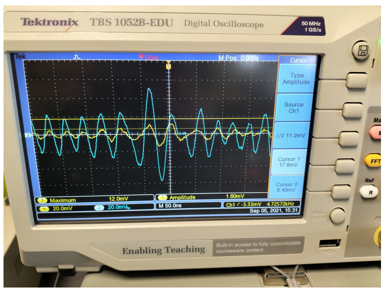
For the measured V_{OUT}, refer to Table 2.1. The results were measured for $V_{BAT} = 6.25V$ and they correspond to the simulation results for the respective voltage vs current values. The noise suppression was also measured as seen in Figure 2.4. For both the noise on the 5V rail and R_{SENSE}, the peak noise of V_{OUT} is less than or equal to double the peak noise of the 5V rail or R_{SENSE}. This confirms that the noise suppression is sufficient if the noise requirements are extrapolated for peak noise levels other than $1mV_{pk}$.

Current System Status	V_{OUT} (V)	I_{SENSE}(mA)
None	1.74	0
Charging	2.77	204
Discharging (3 LEDs)	1.52	46
Discharging (5 LEDs)	1.38	74

Table 2.1: Measured TSC213 Output Voltages and I_{SENSE} Current



(a) 5V Rail Noise (Blue) Vs V_{OUT} Noise (Yellow)



(b) I_{SENSE} Noise (Blue) Vs V_{OUT} Noise (Yellow)

Figure 2.4: Measured Noise Suppression Results

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Bibliography

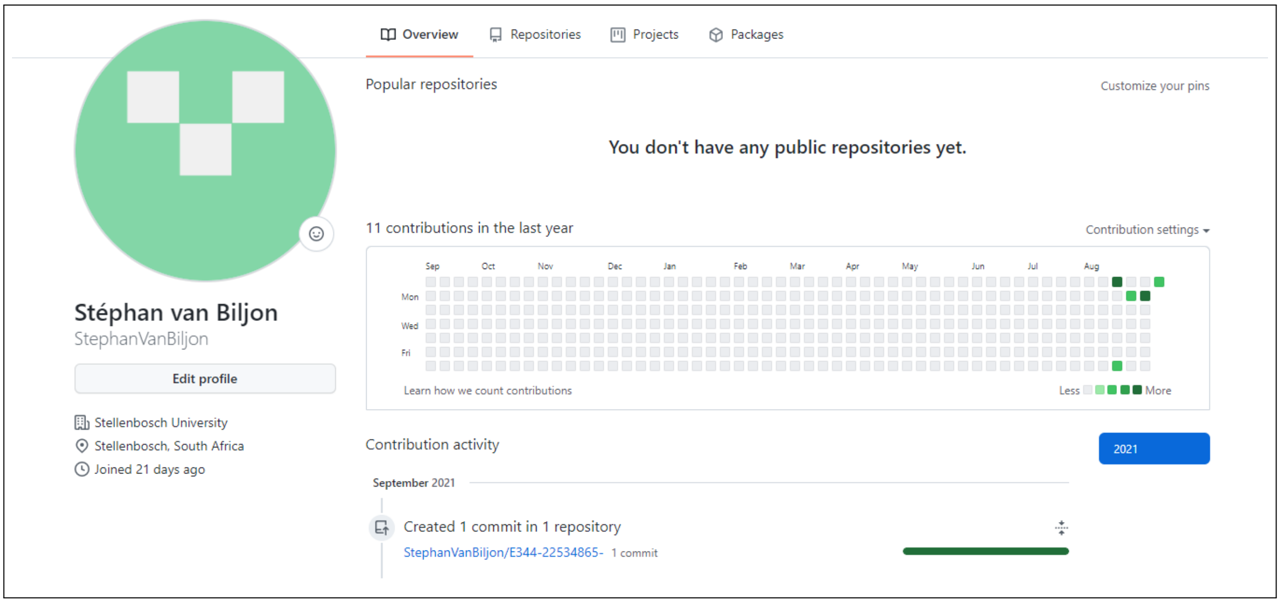
[1] James Lewis, "Low side vs. high side transistor switch," 2019. [Online]. Available: https://www.baldengineer.com/low-side-vs-high-side-transistor-switch.html

[2] ONSemiconductor, "2n7000 / 2n7002 / nds7002a n-channel enhancement mode field effect transistor." [Online]. Available: https://learn.sun.ac.za/pluginfile.php/2876543/mod_resource/content/0/2N7000.pdf

[3] STMicroelectronics, "High/low-side, bidirectional, zero-drift current sense amplifiers," 2020. [Online]. Available: https://learn.sun.ac.za/pluginfile.php/2876544/mod_resource/content/0/TSC213.pdf

Appendix A

GitHub Activity Heatmap



Appendix B

Stuff you want to include

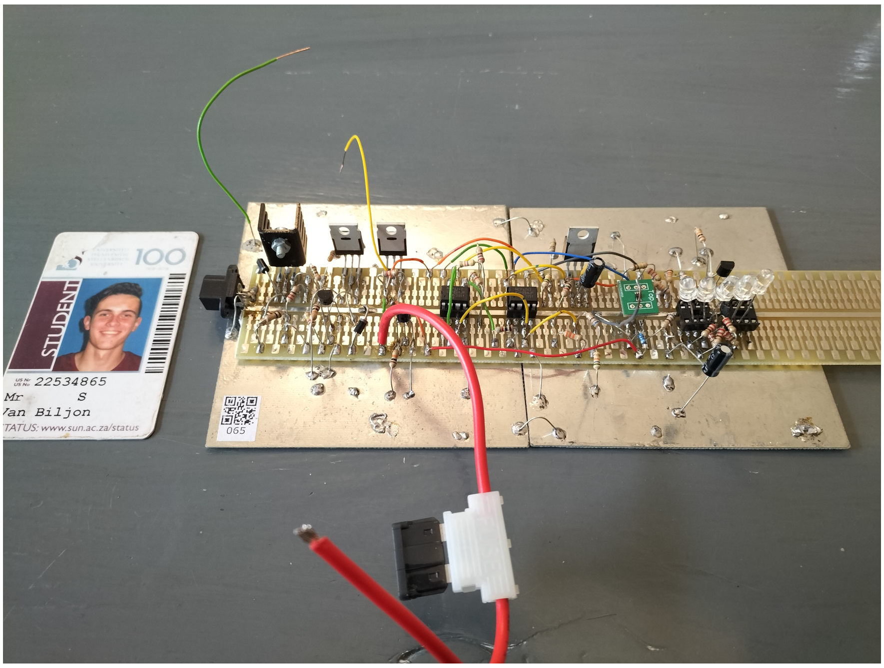


Figure B.1: PCB with Student Card