Experiment #3 Part 1
PV Power Electronics Laboratory

Completed By:
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Step 1:

Inductor Design:

To design the inductor, we first settled on using a switching **frequency of 100 kHz** and tried to make a design for a **13 uH inductor**. Using these parameters, we calculated that we need **4 turns**, a **wire gauge of AWG 13** and an **air gap of 1.9 mm** for a **PQ 32/20 core**. The lab has AWG 12 wire which was closest to what we needed. We started with this and found it was very difficult to twist around the core. We then decided we would use AWG 16 wire in parallel to achieve the same winding resistance as an AWG 13 wire and be able to wind it more easily. After finally getting the wire on the core, we added the air gap. This is where we had some issues. Due to a calculation error, we ended up with around 1 uH for our inductor. After a few iterations, we decreased the **air gap down to .19mm** and achieved the 13 uH goal. A simple factor of 10 must have been missed in the original calculations and caused this error.

Below is the final inductor on our buck converter:

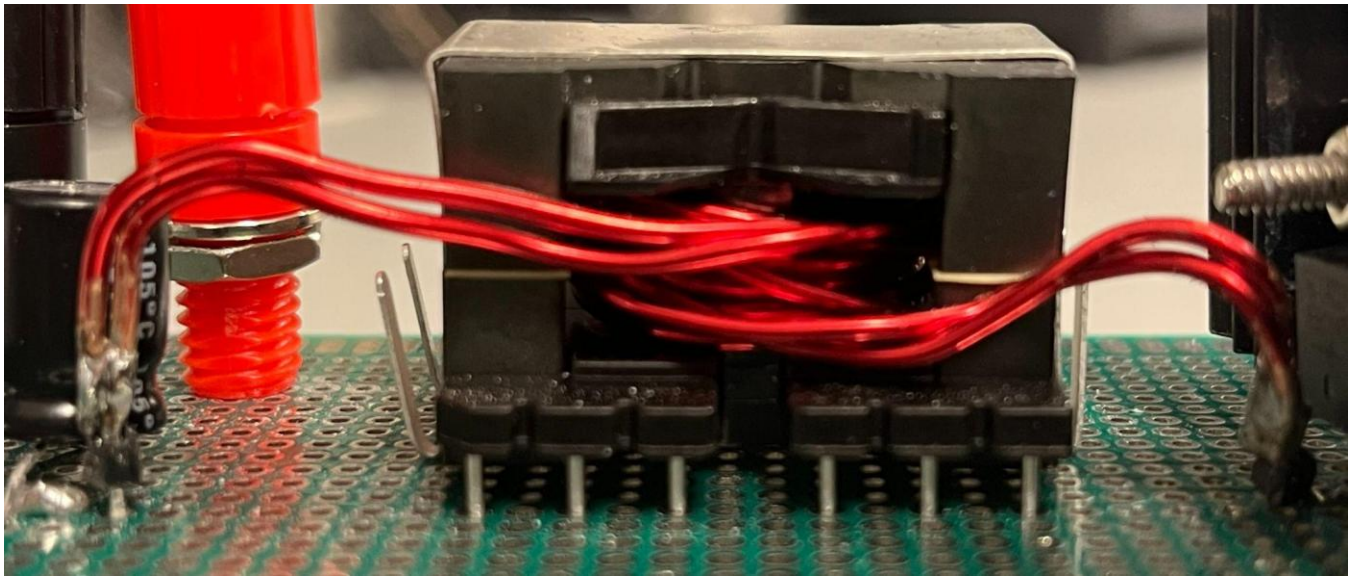


Figure 1: Final Inductor

Step 2:

Buck Converter Design:

Shown in the figure below is the schematic of the gate driver/buck converter design:

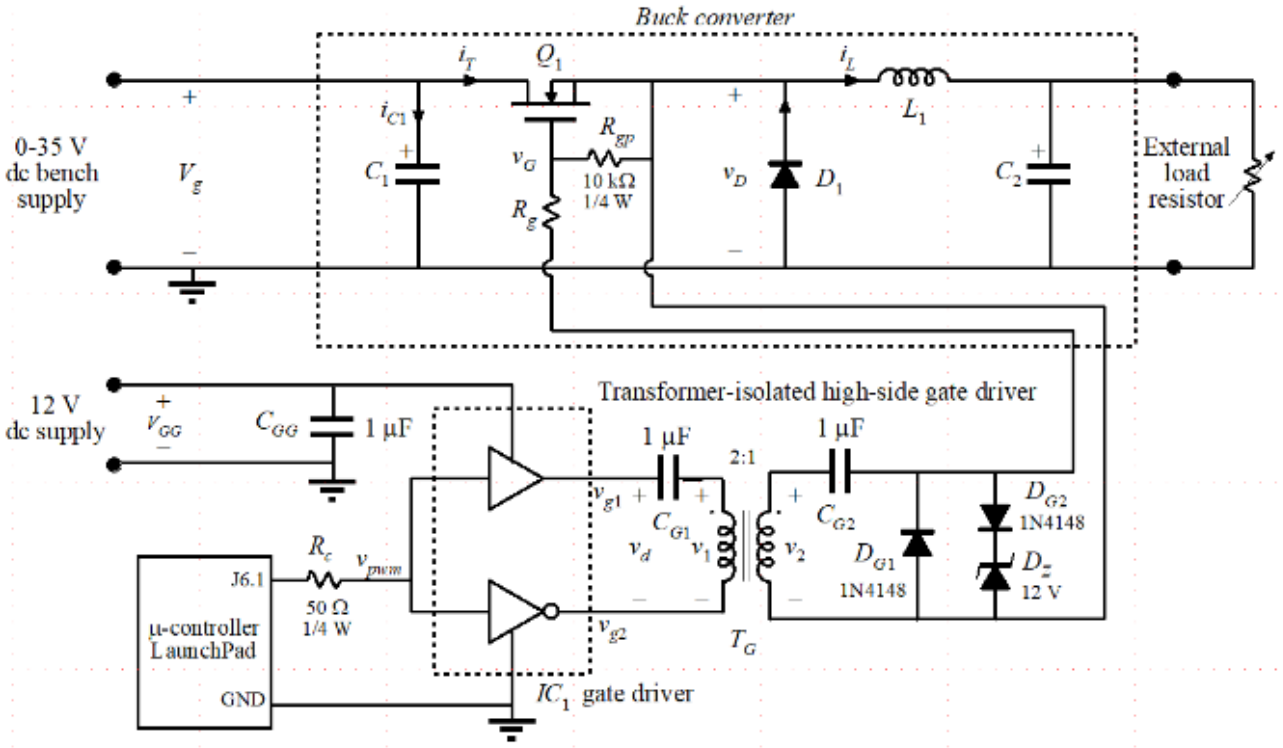


Figure 2: Buck Converter and Gate Driver Schematic

Below are pictures of the Top and Bottom of our perf board design.

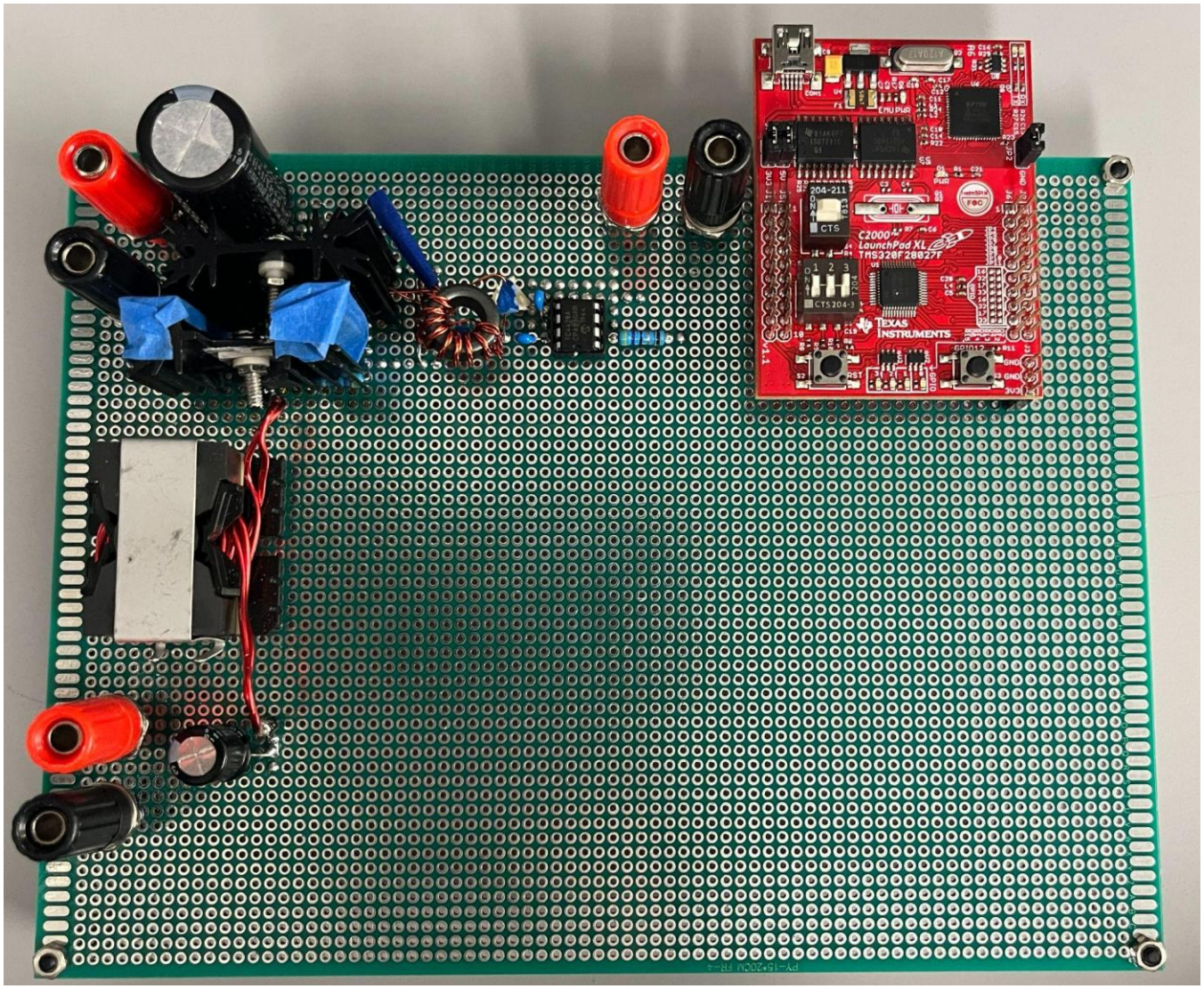


Figure 3: Buck Converter and Gate Driver Circuit Top View

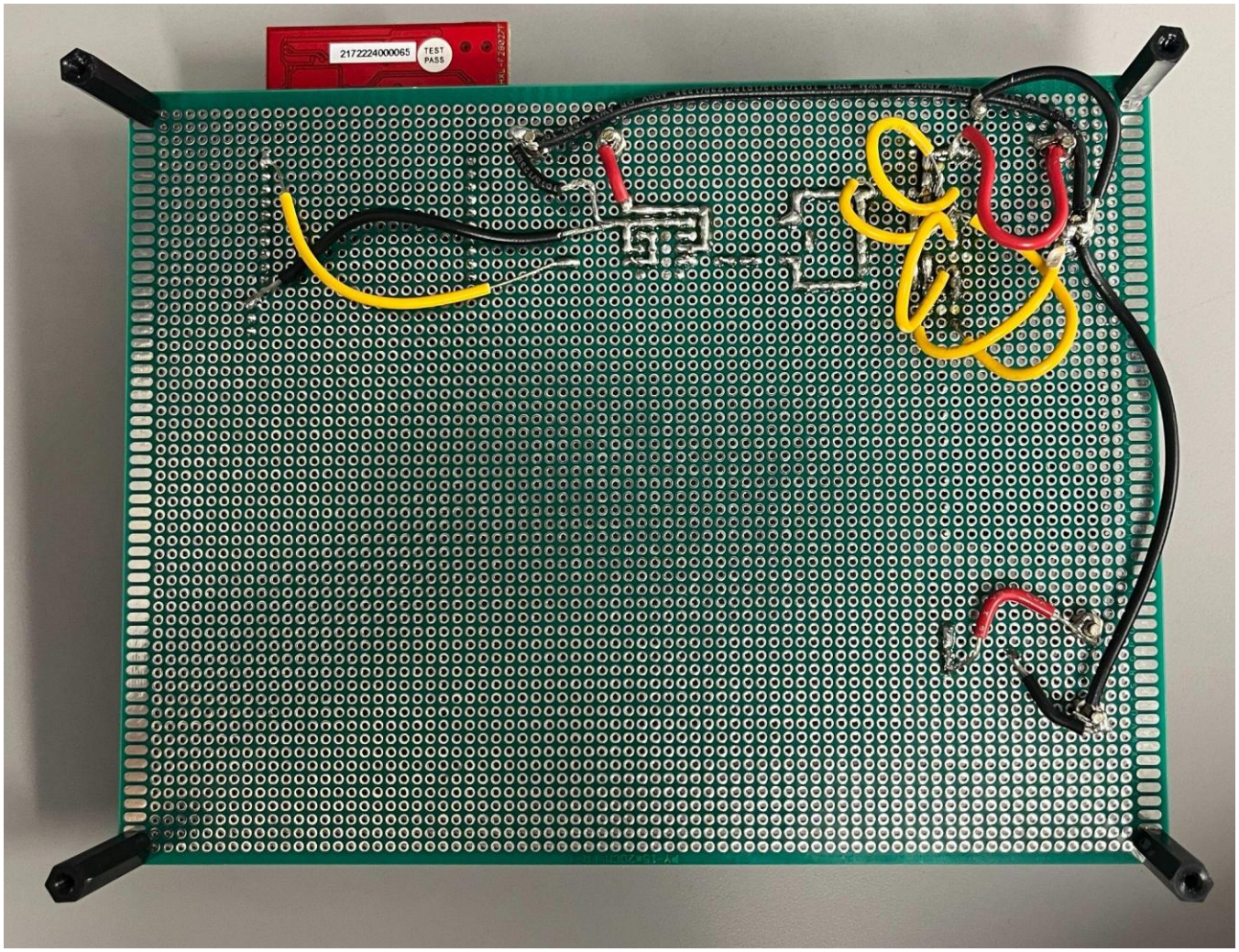


Figure 4: Buck Converter and Gate Driver Circuit Bottom View

Step 3:

Buck Power Stage Testing:

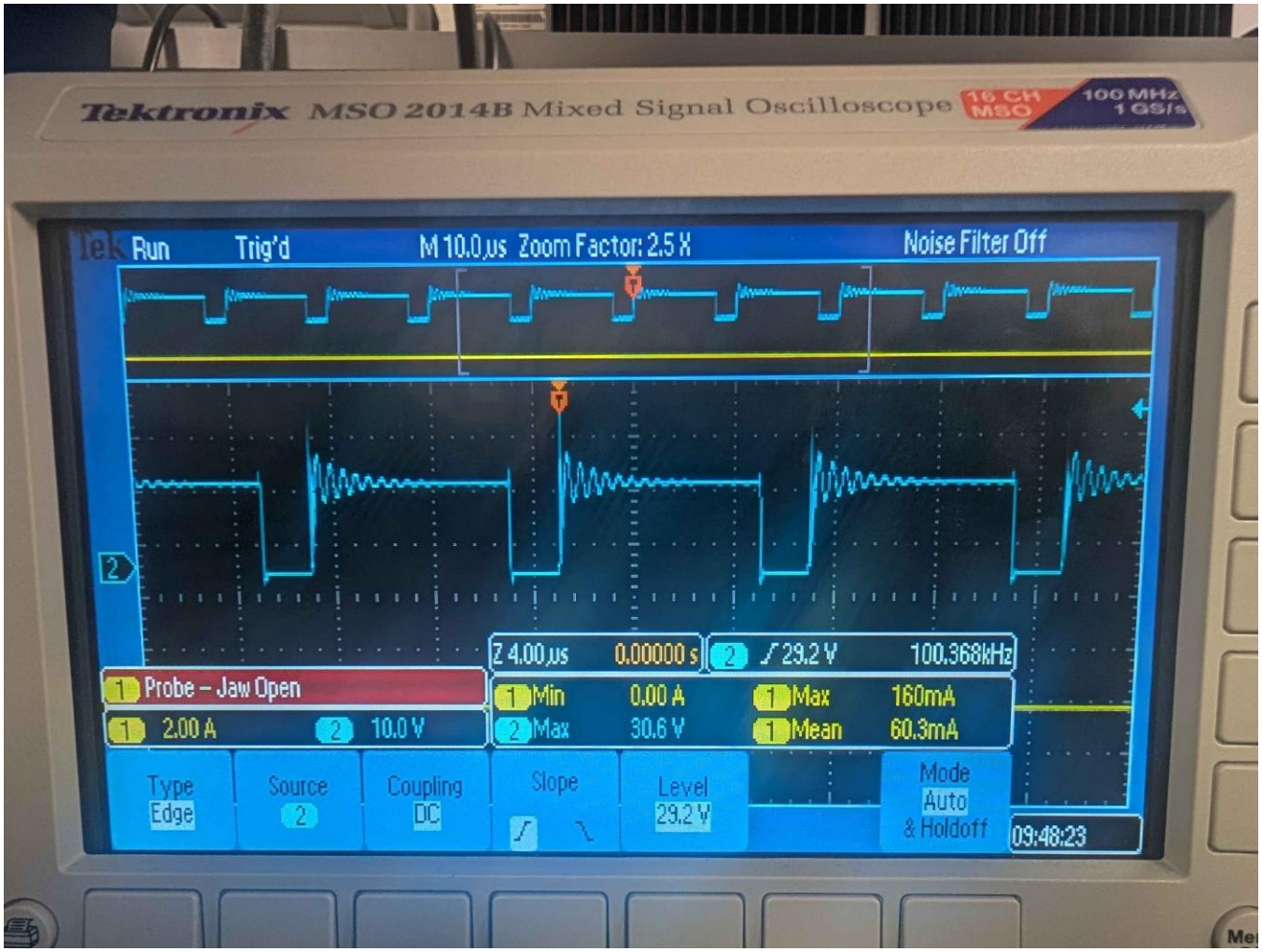


Figure 5: Diode Voltage

V_D Max = 30.6V

V_D Min = -230mV

Diode Off Time = 8.3uS

Diode On Time = 1.7uS

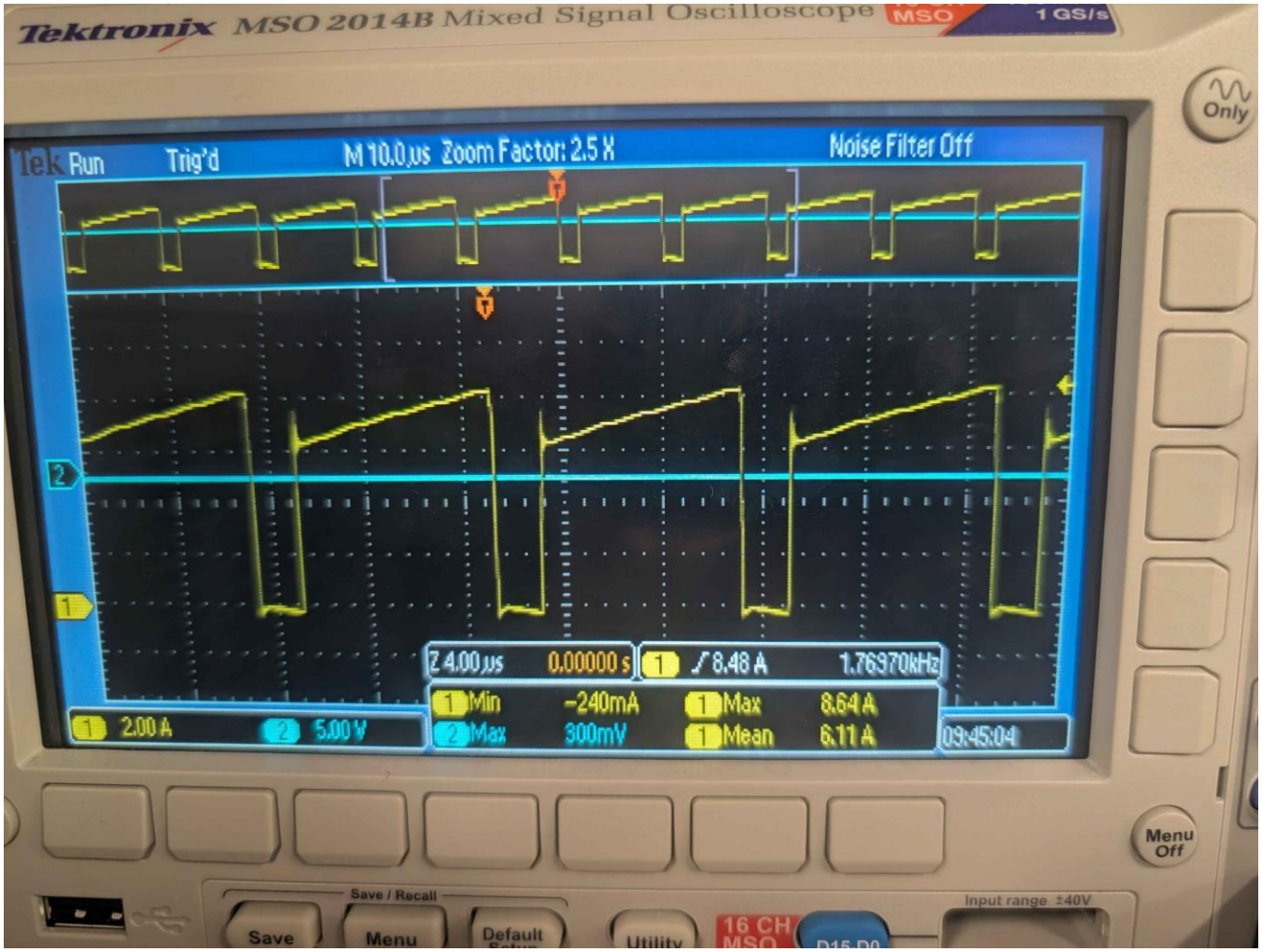


Figure 6: Transistor Current

I_T Max = 8.64A

I_T Min = -240mA

MOSFET On Time = 8.3uS

MOSFET Off Time = 1.7uS

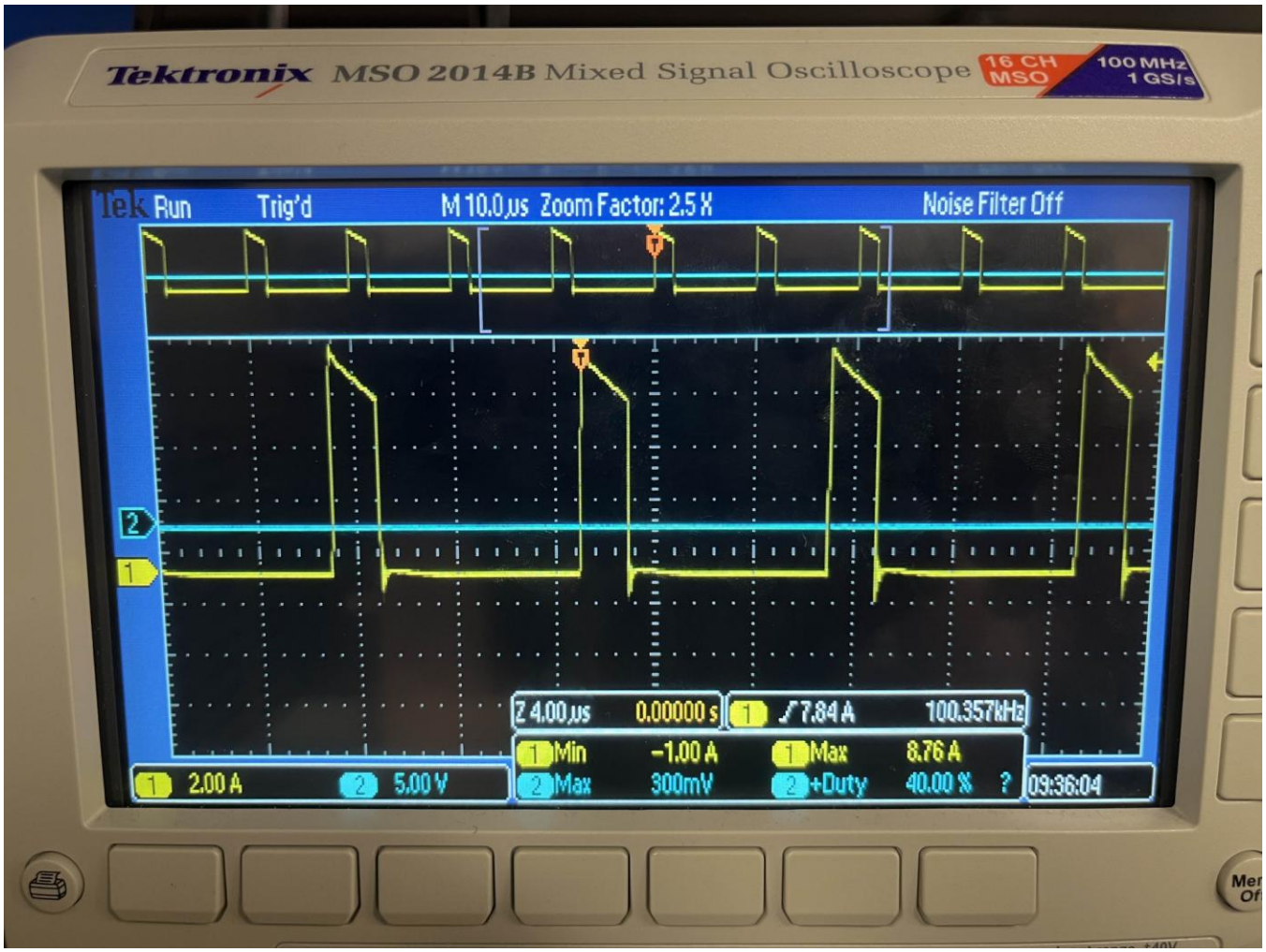


Figure 7: Diode Current

I_D Max = 8.76A

I_D Min = -1A

Diode On Time = 1.7uS

Diode Off Time = 8.3uS

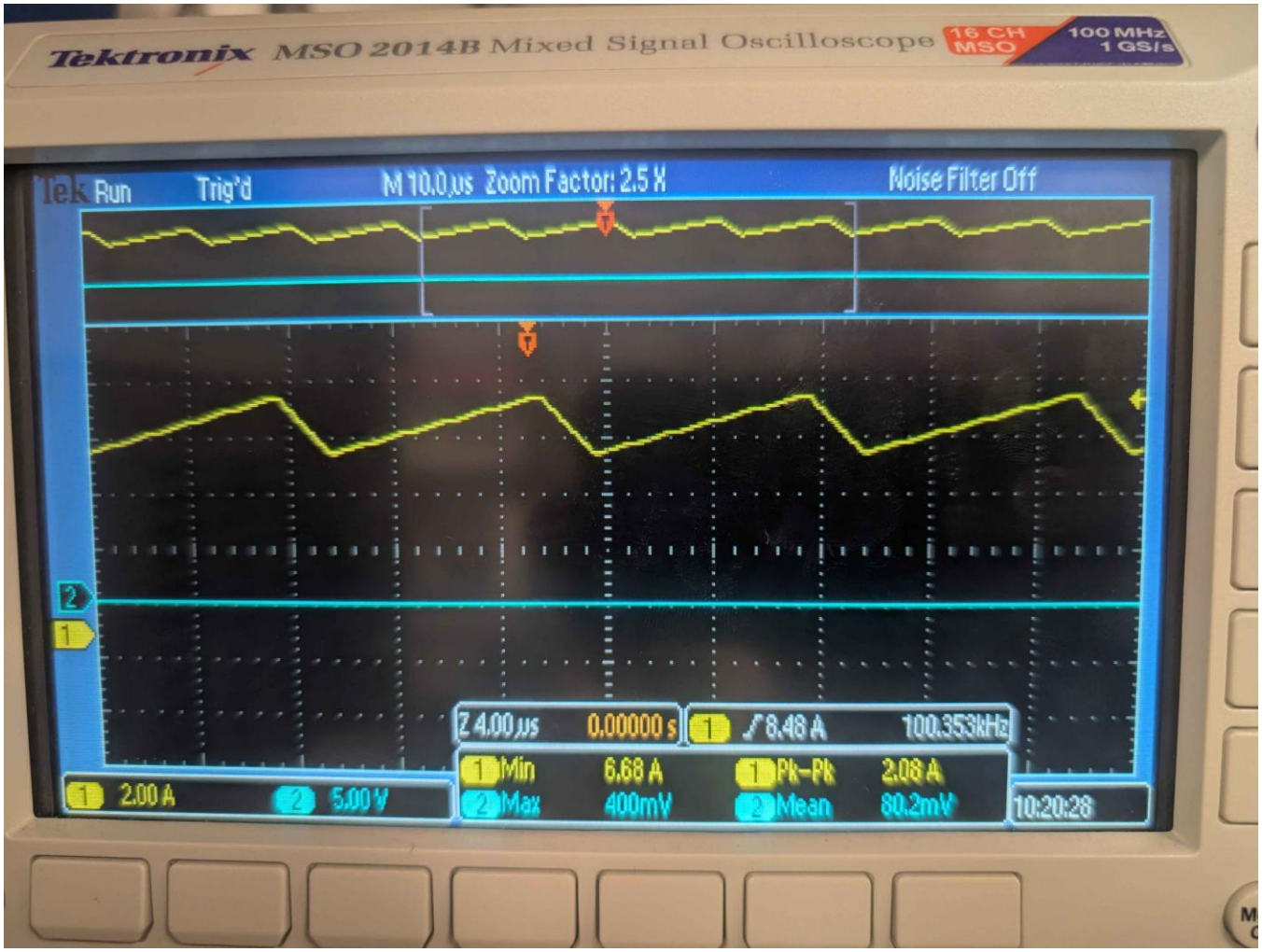


Figure 8: Inductor Current

I_L Max = 8.76A
I_L Min = 6.68A
Calculated Δi_L = 1.36A
Measured Δi_L = 2.08A
Period = 10uS

There is a fairly large difference between the calculated and the measured values in Δi_L. This is likely due to the fact that we had the wrong output wattage set so we had a much larger current through our buck converter than what we were supposed to have.

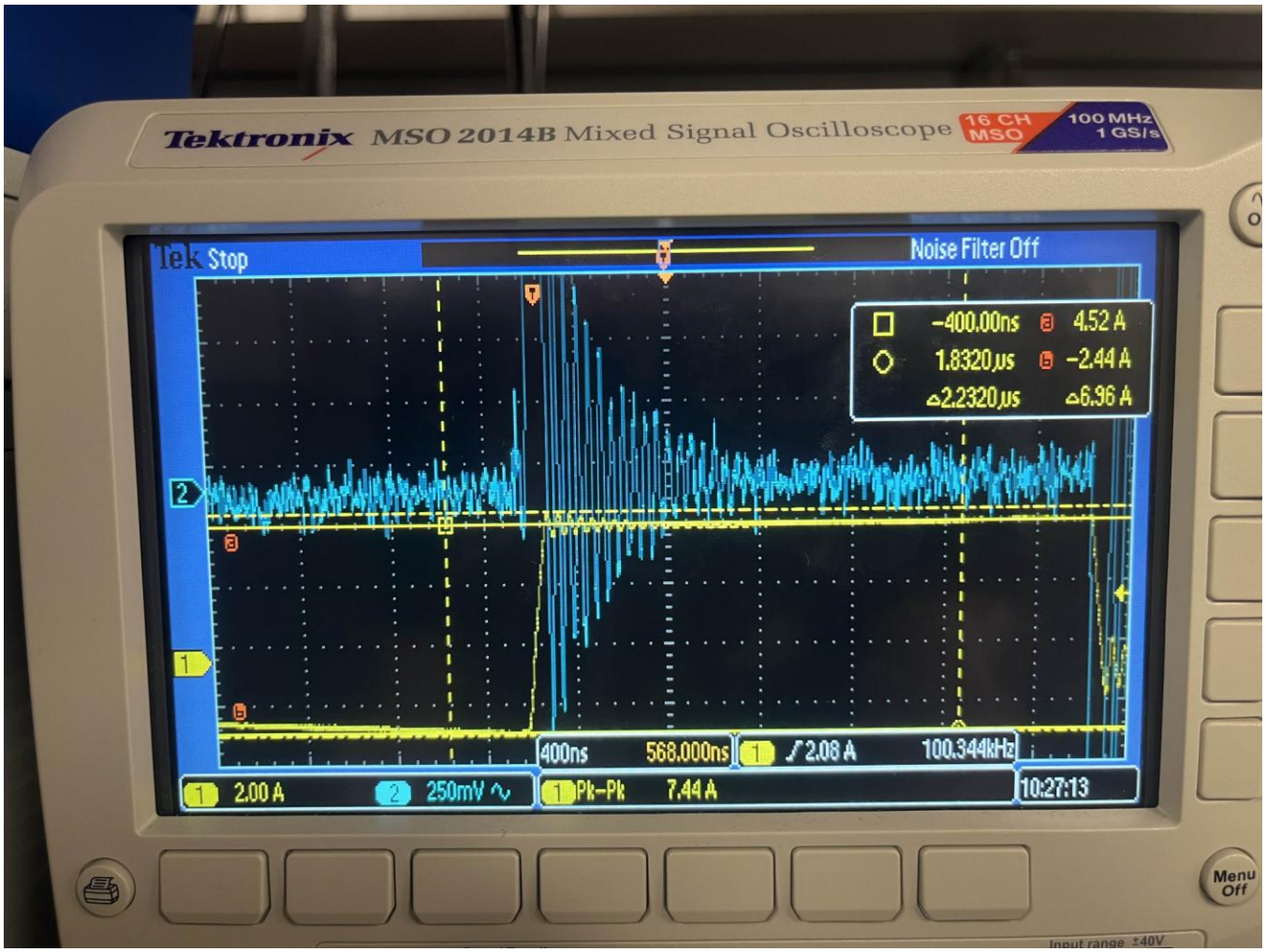


Figure 9: Capacitor Current

I_{C1} Max = 11A

I_{C1} Min = -5.8A

ΔI_C = 6.96A

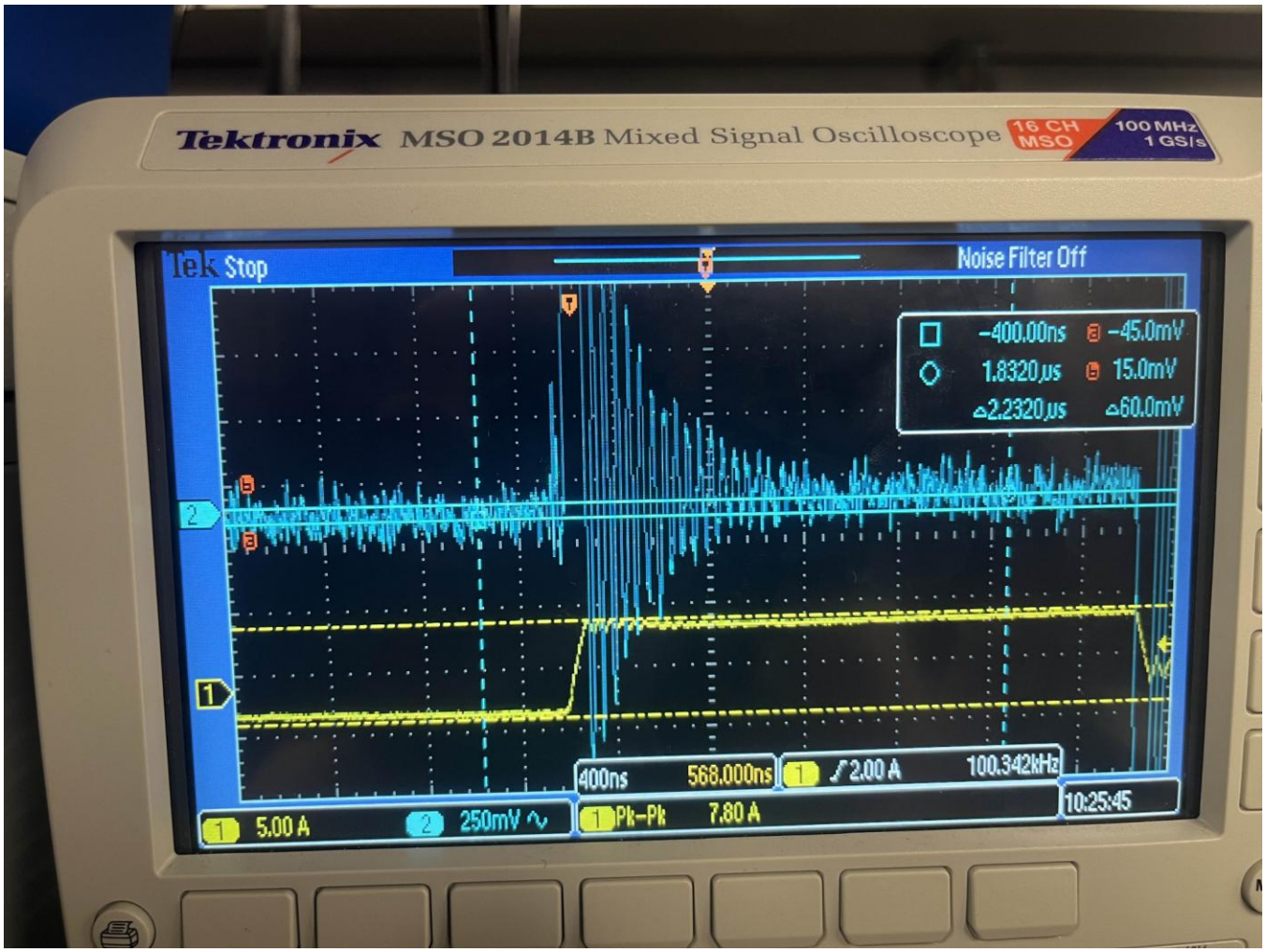


Figure 10: Capacitor Voltage

V_{C1} Max = 18.2V
V_{C1} Min = 15.7V
ΔV_C = 60mV

Measured Input and Output Power (Efficiency):

After realizing our mistake in the input power, we adjusted it and measured the efficiency for 85W output.:

V_{in} = 17.2V
I_{in} = 5.2A
P_{in} = 89.44W

V_{out} = 13.2V
I_{out} = 6.44A
P_{out} = 85.008W

η = 95.04%

ESR Calculation for Capacitor C1:

$\Delta V_C = 60mV$
$\Delta I_C = 6.96A$

ESR = $\Delta V_C/\Delta I_C$ = 8.62mΩ

Power Loss on Capacitor:

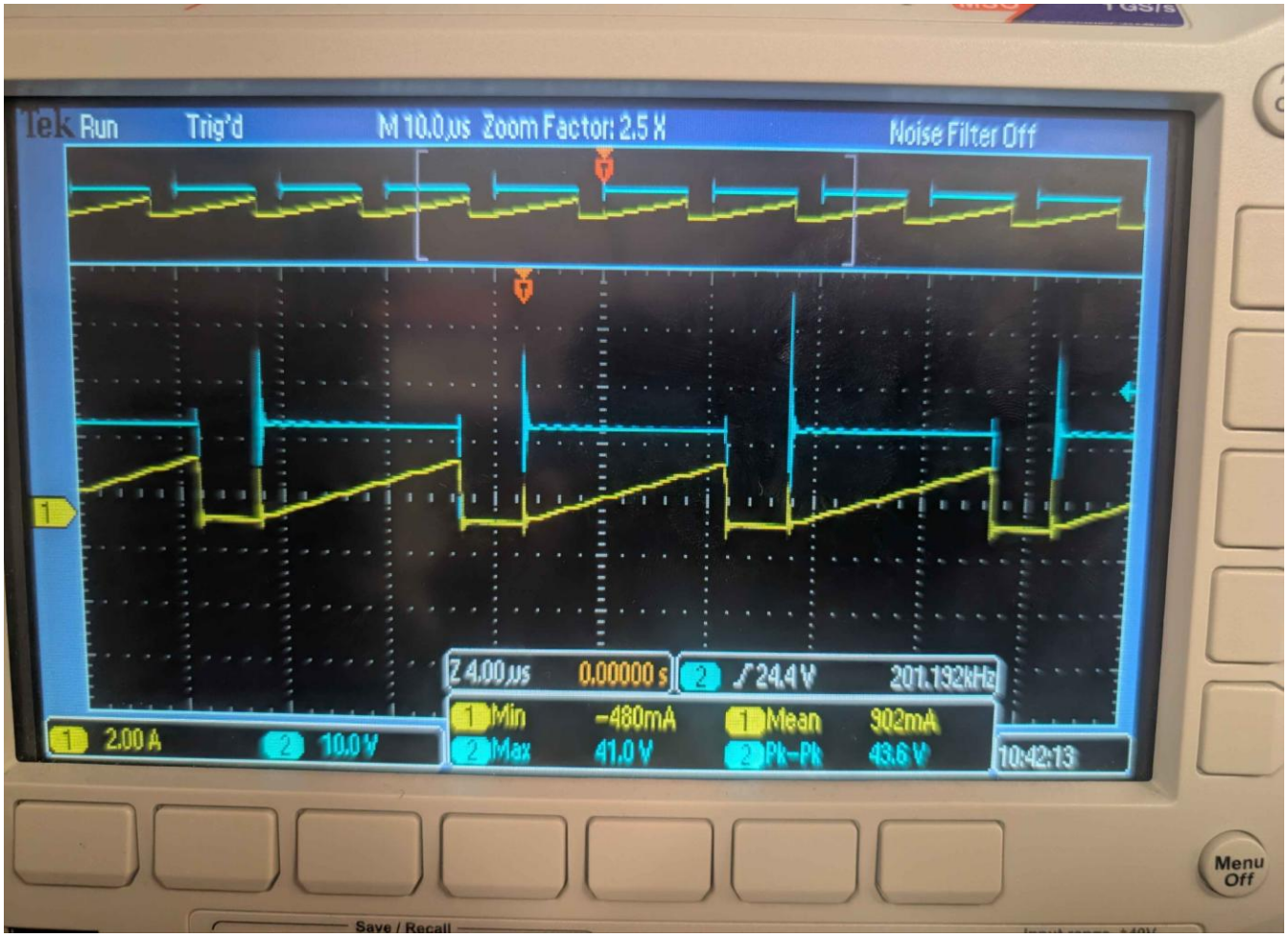
$P_c = I_{rms}^2 * ESR = 3.914^2 * 0.00862$

P_c = 0.132W

Rated RMS = 4.08A. This is very close to the measured RMS current.

Load Test Results:

Our load test with a 15W output required an input voltage of 17.2V and had an output voltage of 13V. The output current was 1.15A and the duty cycle was 76.2%



$i_T(t)$ [Yellow] and $v_D(t)$ [Blue] Waveforms at 15W Output

For the load test at 15W it was not necessary to significantly change the duty cycle. During the buck power stage testing of our experiment we were using a duty cycle of 82% for MPPT and for this step we adjusted it to 76.2%. This is because our converter was operating close to normal load conditions. The inductor was still carrying significant current and the converter remained in CCM indicating the inductor never dropped to zero and there was a reasonable amount of power transfer still occurring.

For the 1W load test our input voltage was 17.2V and our output voltage was 3.6V. The output current was 290mA and the duty cycle needed to be decreased down to 10.8%.

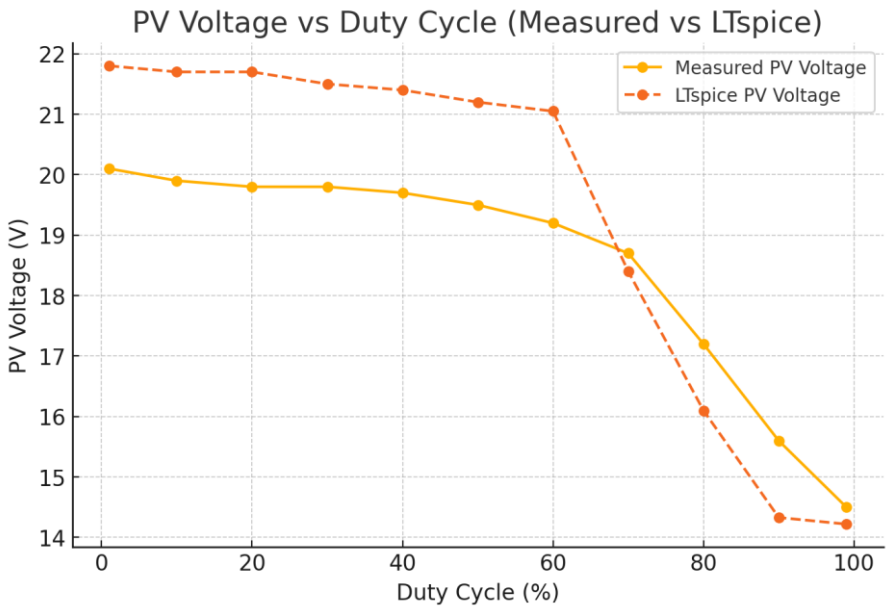
$i_T(t)$ [Yellow] and $v_D(t)$ [Blue] Waveforms at 1W Output

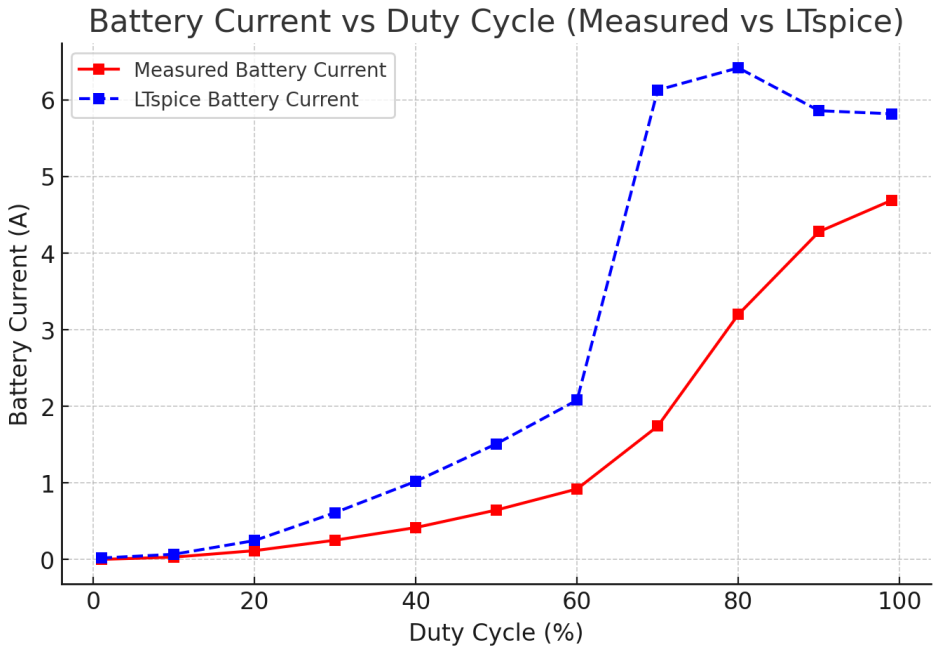
For the load test at 1W it was necessary to significantly reduce our duty cycle. Because our output voltage was 3.6V we had to reduce the ON time of the converter to prevent excessive voltage from being transferred. At lower power, switching losses also become more dominant, in addition to parasitic losses.

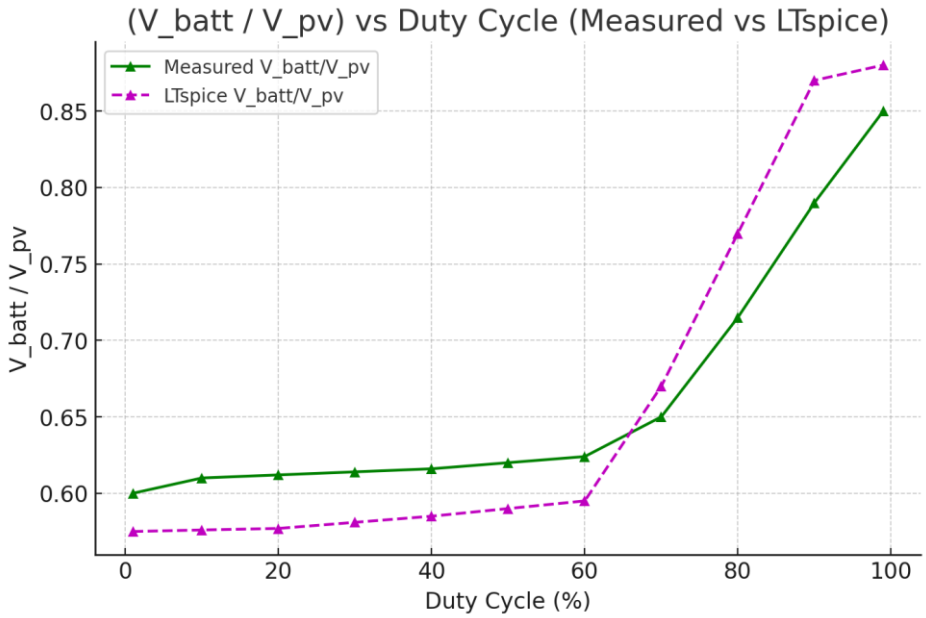
Open Look Behavior and Interpretation:

Below is a table of our open loop outdoor measurements followed by our plots of our measured data plotted with the simulated LTSpice data:

Duty Cycle %	V_{PV}	V_{batt}	I_{batt}
1	20.1	12.14	0
10	19.9	12.14	40mA
20	19.8	12.14	150mA
30	19.8	12.15	300mA
40	19.7	12.16	490mA
50	19.5	12.17	730mA
60	19.3	12.19	1.02
70	18.7	12.23	1.9
80	17.2	12.3	3.2
90	15.6	12.34	3.8
99	14.5	12.35	4







In our measured data, looking at the PV voltage plot it is shown that at low duty cycle the PV voltage is near its open-circuit voltage because the MOSFET is mostly off. As duty cycle increases the converter loads the PV panel which draws more current and lowers the PV voltage over time. Looking at the battery current, it can be seen that a higher duty cycle allows a greater energy transfer to the battery which is reflected by the increasing current. At very high duty cycle the PV voltage drops significantly, reducing the power and limiting the current. Recall that, ideally $V_{batt} = D * V_{PV}$ so that as D increases, more of the panel voltage is transferred to the battery.

Plot Comparisons:

Our measured plots do exhibit the expected behavior but on average it is shown that our measured voltages and currents were consistently lower than the simulated values. This shows that our physical system exhibits much more loss than what is simulated. This is most likely in the form of conduction losses in the MOSFET and diode as well as switching losses in the MOSFET alone. Inductor core and copper losses could also play a role as well as inductance in our traces creating unwanted noise and limiting the performance of our system.

Optimum Duty Cycle (Measured):

According to our measured data, our best power transfer occurred at 90% duty cycle and output 59.3W. More likely our MPPT will occur between a duty cycle of 80-90%.

Direct Energy Transfer vs. MPPT Battery Charging Power:

Using MPPT we can currently maximize our power transfer to 59.3W. If we did not use MPPT and just relied on direct energy transfer the PV panel would be forced to match the battery voltage which would significantly reduce our output power. If we can improve our losses we should be able to transfer around 78W with our calculations from experiment 2 and charge the battery much faster than if we were to use direct energy transfer methods.