Boost Converter Project

Theingi Aung, Any Pacheco, and Titus Lee

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1 Introduction

1.1 Boost Converter

A boost converter, or step-up converter, is a power electronics device that converts a low input DC voltage into a higher output DC voltage. It operates by temporarily storing energy in an inductor during the "on" phase of a switch and then releasing it to the output during the "off" phase. This process allows for a controlled increase in voltage, making boost converters essential for applications where a higher voltage is needed but only a limited input voltage is available. Common applications include powering LEDs, stepping up voltage in battery-powered devices, and renewable energy systems such as solar panels.

The key components of the boost converter are the inductor, capacitor, diode, and switching device, which together manage the energy conversion process. The switching device, typically a MOSFET, is controlled by a pulse-width modulation (PWM) signal, which regulates the on/off states of the switch. During the on-state, the inductor stores energy, and during the off-state, this energy is transferred to the load through the capacitor, which helps maintain a stable output voltage. A diode ensures unidirectional current flow, preventing backflow into the inductor and maintaining energy efficiency.

In this project, the boost converter design incorporates a 555 timer to generate the PWM signal that drives the MOSFET. This design approach combines the theoretical principles of circuit analysis with practical implementation to demonstrate how energy can be effectively transferred and regulated in power conversion systems. By synthesizing these concepts, the project aims to provide a hands-on understanding of boost converter operation, energy storage, and switching control.

1.2 Design specifications

In this project, we aim to design, simulate, and construct a functional boost converter circuit that meets specific performance criteria, including an output voltage of at least 13V ($\pm 0.3\%$) under defined load conditions. This process will involve analytical calculations, circuit simulation, and experimental validation to ensure the boost converter achieves the desired specifications. The performance of the circuit will be assessed through a combination of theoretical predictions, numerical simulations, and hands-on testing. This report breaks down into three major sections, following our engineering problem-solving approach.

- Analytical: Calculate R3, C2, and C3 values and verify inductor energy sufficiency using circuit equations.
- Computer Model: Simulate the circuit in Multisim and generate annotated plots for PWM signal and output voltage.
- Experimental: Measure the output voltage and PWM signal from the physical circuit and compare results to predictions.

2 Analysis

Derived Value for R_3

Duty cycle: between 50% and 80%
Frequency: 1 kHz

$$R_A = R_2 \quad \text{and} \quad R_B = R_3$$

$$\text{Duty cycle} = \frac{T_{\text{ON}}}{T_{\text{TOTAL}}} = \frac{R_2 + R_3}{R_2 + 2R_3}$$

- When $R_2 = 0$:
$$\text{Duty cycle} = \frac{R_3}{2R_3} = 0.5$$
- When $R_2 = 10\,\text{k}\Omega$:
$$\text{Duty cycle} = \frac{10 + R_3}{10 + 2R_3} = 0.8$$
$$8 + 1.6R_3 = 10 + R_3$$
$$1.6R_3 - R_3 = 2$$
$$0.6R_3 = 2 \implies R_3 = \frac{2}{0.6} = 3.33\,\text{k}\Omega$$

$R_3 = 3.3\,\text{k}\Omega$ from our lab kit.

Derived Value for C_2

$$f = \frac{1}{T_{\text{TOTAL}}}$$
$$T_{\text{TOTAL}} = \frac{1}{f} = \frac{1}{1000}\,\text{s}$$
$$T_{\text{TOTAL}} = T_{\text{ON}} + T_{\text{OFF}} = 0.693\,(R_2 + 2R_3)\,C_2$$
$$\frac{1}{1000} = 0.693\,(10^4 + 2 \times 3.33 \times 10^3)\,C_2$$

$$C_2 = \frac{1}{0.693\,(10^4 + 2 \times 3.33 \times 10^3)\,10^3}$$

$$C_2 = \frac{1}{0.693\,(10^4 + 6.66 \times 10^3)\,10^3}$$

$$C_2 = \frac{1}{0.693\,(1.666 \times 10^4)\,10^3}$$

$$C_2 = 1.08225 \times 10^{-7}\,\mathrm{F}$$

$$C_2 = 0.108225\,\mu\mathrm{F}$$

$$C_2 \approx 0.1\,\mu\mathrm{F}\,(\text{ceramic capacitor})$$

Resistance of potentiometer to get 1kHz frequency using value of R3

$$R_3 = 3.3\,\mathrm{k\Omega}$$

$$T = \frac{1}{f} = 0.001\,\mathrm{s}$$

Calculating R_A at New Capacitor Value ($C = 0.1\,\mu$F):

$$0.001 = 0.693\,(R_A + 2(3.3\,\mathrm{k\Omega}))(0.1\,\mu\mathrm{F})$$

$$R_A = R_2 = 7.83\,\mathrm{k\Omega}$$

Derived value for C_3

$$\Delta V_{\text{led}} = 2\,\mathrm{V}$$
$$\Delta V_R = 11\,\mathrm{V}$$
$$R = 2.2\,\mathrm{k\Omega}$$

Using Ohm's law:

$$V = IR \implies I = \frac{V}{R} = \frac{11\,\mathrm{V}}{2.2\,\mathrm{k\Omega}} = 5\,\mathrm{mA}$$

The capacitance C is given by:

$$C = \frac{q}{V}$$

Charge q is calculated as:

$$\Delta t \times I = q$$
$$q = 0.5 \times 10^{-3}\,\text{s} \times 5 \times 10^{-3}\,\text{A}$$
$$q = 2.5\,\mu\text{C}$$

Substituting into the equation for C:

$$C_3 = \frac{q}{V} = \frac{2.5 \times 10^{-6}\,\text{C}}{0.039\,\text{V}}$$
$$C_3 = 64.1026 \times 10^{-6}\,\text{F}$$
$$C_3 = 64.1026\,\mu\text{F}$$

Therefore, a C_3 value of $100\,\mu$F (radial electrolyte capacitor) is chosen.

Amount of Current

Maintaining 13 V and 2 V Drop Across LED at $T_{\mathbf{ON}}$:

Using KVL:

$$13\,\text{V} - 2\,\text{V} - V = 0$$
$$I_R = \frac{11\,\text{V}}{2.2\,\text{k}\Omega} = 5\,\text{mA}, \quad I_{\text{LED}} = 5\,\text{mA}$$

$$I_{\text{load}} = 5\,\text{mA}$$

Since I_R, I_{LED}, and C_3 are in series, they have the same current:

$$I_{\text{current}} = 5\,\text{mA}$$

Amount of Power

$$P_{\text{load}} = IV \implies P_{\text{load}} = 5\,\text{mA} \cdot 13\,\text{V} = 65\,\text{mW}$$

$$P_{\text{load}} = 65\,\text{mW}$$

Final Energy Calculation

Given:

$$V_{\text{CC}} = \text{Supply voltage (5V)}, \quad V_{\text{DS}} = \text{Drain-source voltage}, \quad R_L = \text{Inductor resistance},$$

$\text{V}_T = 1.824\,\text{V}$ (Threshold voltage)

We measured:

$$R_L = 50.2\,\Omega$$

Equation for $V_{\mathbf{DS}}$:

$$V_{\text{DS}} = (V_{\text{GS}} - V_T) + \frac{1}{R_D K_n} + \sqrt{\left(V_{\text{GS}} - V_T + \frac{1}{R_D K_n}\right)^2 - \frac{2V_{\text{DD}}}{R_D K_n}}$$

Substituting values:

$$V_{\text{DS}} = (5 - 1.824) + \frac{1}{(50.2)(0.1233)} + \sqrt{\left(5 - 1.824 + \frac{1}{(50.2)(0.1233)}\right)^2 - \frac{2(5)}{(50.2)(0.1233)}}$$

Simplification:

$$V_{\text{DS}} = 3.34 + 3.086 = [0.254, 6.426]$$

Conclusion:

We chose 0.254 V (which is less than the source voltage, 5V).

Calculations

By KVL

$$-V_{CC} + v_L + iR_L + v_{DS} = 0$$

$$v_L = L\frac{di}{dt}$$

$$L\frac{di}{R_L dt} + i(t) = \frac{V_{CC} - v_{DS}}{R_L}$$

Time Constant:

$$\tau = \frac{L}{R_L} = \frac{33\,\text{mH}}{50.2\,\Omega} = \frac{33 \times 10^{-3}}{50.2} = 0.657 \times 10^{-3}$$

Current $i(t)$:

$$i(t) = i(\infty) + [i(0) - i(\infty)]\, e^{-t/\tau}$$

Substitute the values:

$$i(t) = \frac{V_{\text{CC}} - V_{\text{DS}}}{R_L} + \left[0 - \frac{V_{\text{CC}} - V_{\text{DS}}}{R_L}\right] e^{-t/\tau}$$

$$\frac{V_{\text{CC}} - V_{\text{DS}}}{R_L} = \frac{5 - 0.254}{50.2} = 0.0945$$

Final Expression for $i(t)$:

$$i(t) = 0.0945 + [-0.0945]\, e^{-t/\tau}$$

At $t = 7.71 \times 10^{-4}\,\text{s}$ and $\tau = 0.657 \times 10^{-3}$:

$$i(t) = 0.0945 + [-0.0945]\, e^{-7.71\times10^{-4}/0.657\times10^{-3}}$$

$$i(t) = 0.06512\,\text{A}$$

Energy Stored in the Inductor:

$$E_L = \frac{1}{2} L i(t)^2$$

$$E_L = \frac{1}{2} \times 33 \times 10^{-3} \times (0.06512)^2$$

$$E_L = 69.96\,\mu\text{J}$$

3 Numerical

The numerical verification involves simulating the boost converter in Multisim to confirm its performance. A plot of the PWM signal at 1 kHz, with a time scale in milliseconds, illustrates the total period and duty cycle. Additionally, a plot of the output voltage, with a time scale in seconds, demonstrates the converter's ability to achieve and maintain the desired 13V output. These simulations validate the theoretical design and serve as a reference for experimental testing.

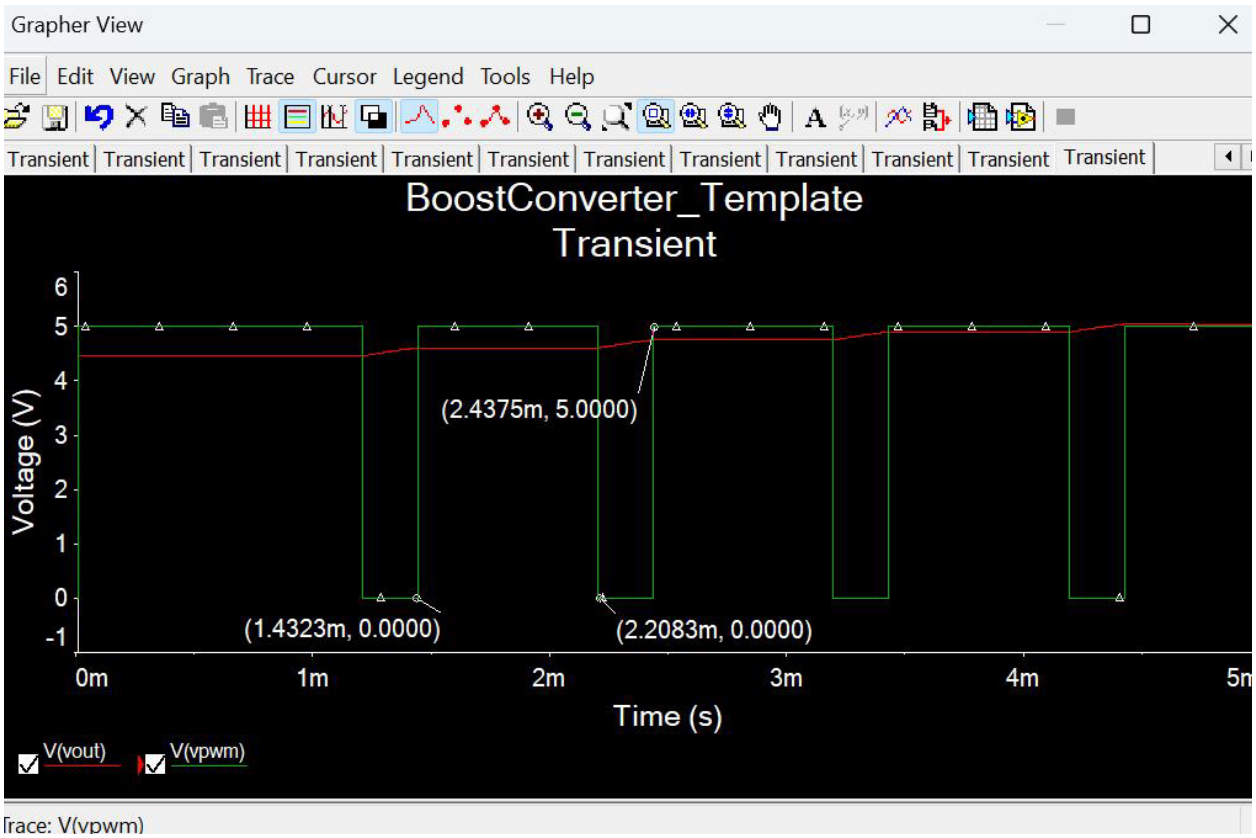

Figure 1: Annotated plot of PWM signal at 1 kHz

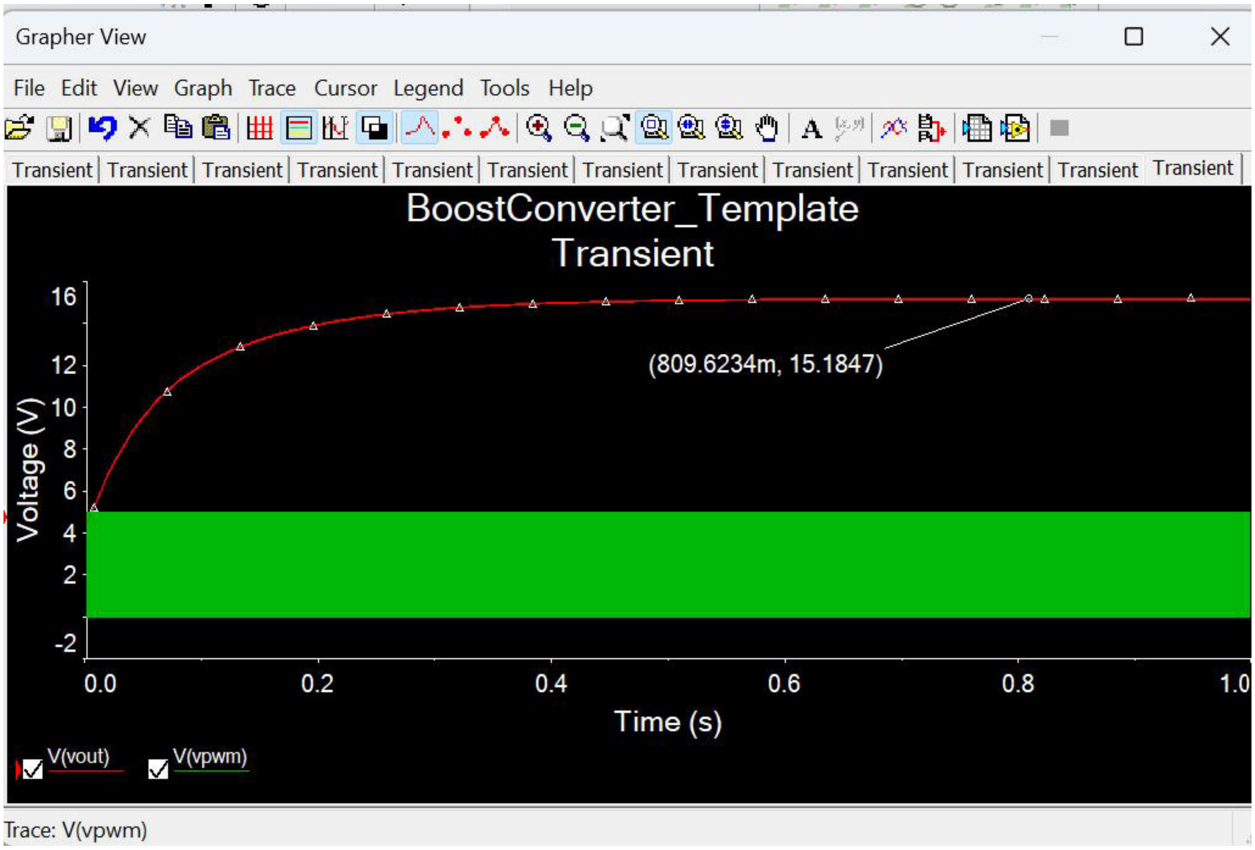

Figure 2: Annotated plot of output voltage with PWM signal at 1 kHz

Figure 3: Plot of PWM Signal at 1 kHz

PWM Signal Analysis

Determining T_{on} and T_{off}

From the annotated PWM signal plot, the following timestamps are observed:

- The signal rises to 5 V at 1.4323 ms and drops to 0 V at 2.2083 ms.
- The duration for which the signal is high is:

$$T_{on} = 2.2083\,\text{ms} - 1.4323\,\text{ms} = 0.776\,\text{ms}$$

- The signal stays low from 2.2083 ms to 2.4375 ms.
- The duration for which the signal is low is:

$$T_{off} = 2.4375\,\text{ms} - 2.2083\,\text{ms} = 0.2292\,\text{ms}$$

Duty Cycle Calculation

The formula for the duty cycle is:

$$\text{Duty Cycle} = \frac{\mathrm{T_{on}}}{\mathrm{T_{on}} + \mathrm{T_{off}}} \times 100$$

Given:

$$\mathrm{T_{on}} = 0.776\,\text{ms}, \quad \mathrm{T_{off}} = 0.2292\,\text{ms}$$

The total period (T) is:

$$T = \mathrm{T_{on}} + \mathrm{T_{off}} = 0.776\,\text{ms} + 0.2292\,\text{ms} = 1.0052\,\text{ms}$$

Substituting into the formula:

$$\text{Duty Cycle} = \frac{0.776}{1.0052} \times 100 = 77.2 \approx 77\%$$

Conclusion

The high time ($\mathrm{T_{on}}$) is 0.776 ms, the low time ($\mathrm{T_{off}}$) is 0.2292 ms, and the duty cycle of the PWM signal is approximately:

$$\boxed{77\%}$$

4 Experimental

4.1 Procedure

To validate the theoretical and numerical results obtained for our boost converter circuit, we designed and built PCB circuit (Printed Circuit Board) which we would then use to solder in place key components for the boost converter. First, using KiCad, the schematic of the boost converter was imported to create the PCB layout. Then component placements were then strategically placed to create a compact design and reduce noise After running and sent to freedfm.com to verify our design could be manufactured. After finalizing that our PCB design met all requirements we began fabrication, which involved soldering each component from our lab kit onto the PCB.

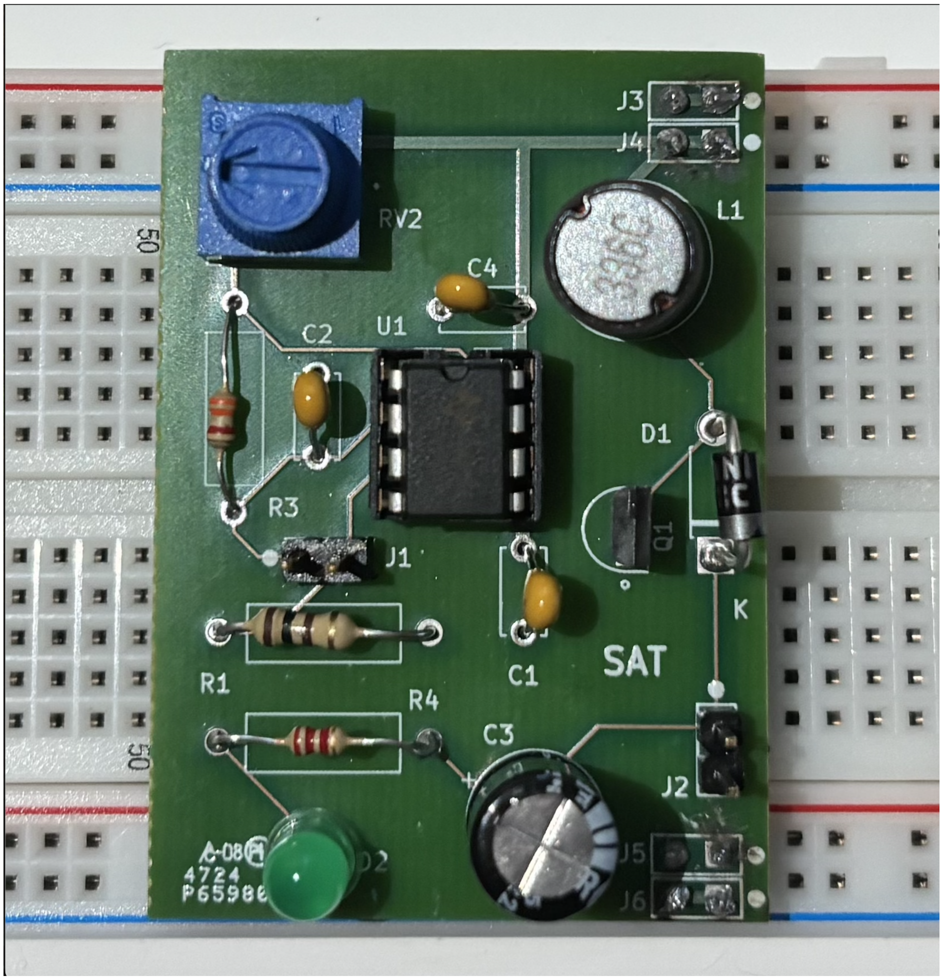

Figure 4: Assembled Boost Converter PCB

. Once we had an Assembled PCB, we could begin experimental verification of our Boost converter circuit and validate our theoretical and numerical results. By connecting our PCB to a breadboard attached to a AD2, we used waveform to provide power supplies and measure the targeted values. This procedure would then allow us to confirm whether our PWM signal is at 1kHz and the output voltage.

4.2 Results

This section presents the experimental outcomes of the boost converter circuit. The first plot shows the output voltage when the PWM signal is set to 1 kHz, demonstrating that the circuit meets the design requirements. The second plot displays the PWM signal itself at 1 kHz, confirming that the frequency aligns with the expected value.

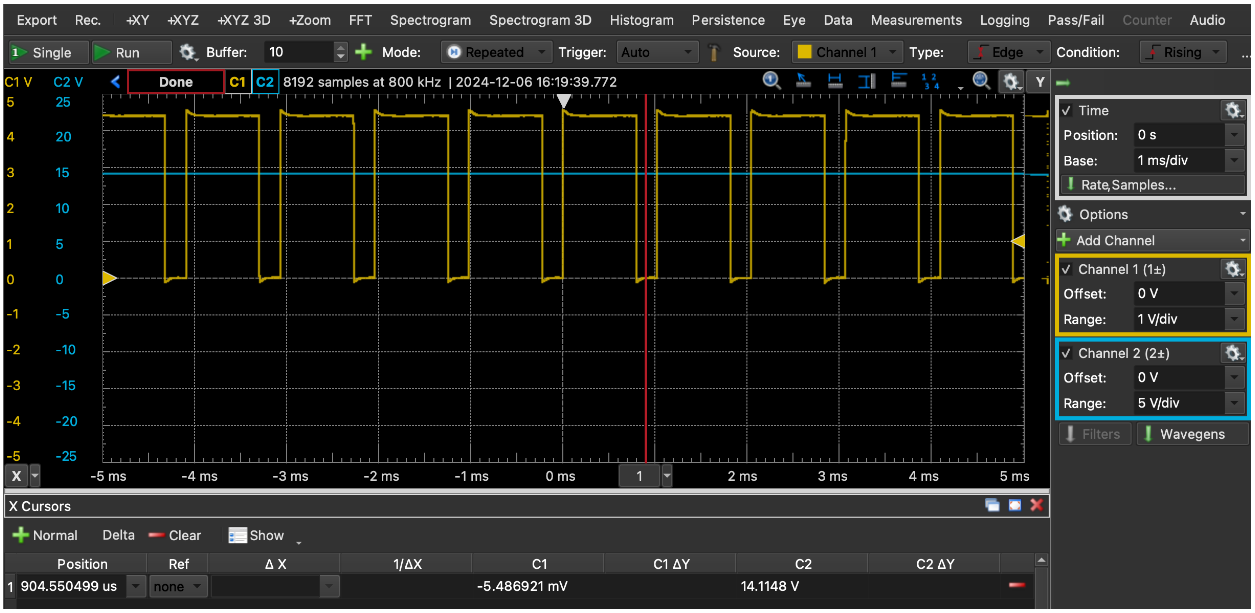

Figure 5: Output voltage with PWM signal at 1kHz

This figure indicates the output voltage to 14.11 V.

Figure 6: PWM signal itself at 1kHz

This figure is annotated to indicate the period of the signal and the duty cycle. It can be seen it the figure above that the total period is 1.09ms and time on is 789.47µs. This can can then be used to determine the duty cycle:

$$\text{Duty Cycle} = \frac{T_{on}}{T_{total}} = \frac{789.47\mu s}{1016.76\mu s} = 0.776 = 77.6\% = 78\%$$

5 Conclusions

5.1 Lab Results

For this lab, we were presented with design specifications for a boost converter the PWM signal should produce a duty cycle between 50% and 80% when tested at 1 kHz and be designed to provide 13V minimum (within 0.3%) across a load consisting of an LED in series with a 2.2k ohm resistor. Therefore, by applying circuit analysis theories, we calculated values of key boost converter components needed to accurately set the frequency of the PWM signal and to maintain a minimum of 13V for each PWM cycle. After following our experimental procedure, we obtained results from our booster converted which demonstrated our design met these specifications as the measured values agreed with our calculated values. The design specification required the output voltage to be within 13V $\pm$ 0.3%, which translates to a range of 12.961V to 13.039V. While the experimental result of 14.11V exceeds this range. Despite this, the output voltage was still close to the design goal, indicating that the boost converter's performance was generally consistent with the expected results.The duty cycle of the PWM signal was measured to be 78%, which is within the specified range of 50% to 80%. This confirms that the PWM signal was operating as expected, maintaining a duty cycle that is capable of driving the boost converter to produce the required output voltage.

5.2 Sources of Error

Potential sources of error and discrepancies in the data stem from both simulation assumptions and practical challenges in the experimental setup. In simulations, idealized models may not account for real-world effects such as parasitic resistances and component tolerances. Experimentally, one of the primary issues was the soldering process. Poor soldering quality, including loose connections, and solder leakage into the breadboard introduced unexpected resistance and possible short circuits, impacting circuit performance. Additionally, small errors in setting the PWM signal frequency and duty cycle could have compounded these discrepancies. These factors emphasize the importance of precise soldering, clean assembly, and careful calibration to minimize deviations in results.

5.3 Constructive Feedback

The lab was helpful in understanding the boost converter design, with experimental results closely matching the specifications. However, the procedure for measuring the duty cycle and output voltage could be clearer,. There could be more guidance on verifying the PWM signal and understanding discrepancies that could occur through notes or lectures.

6 Collaboration Statement

Contributions of each team member for the team SAT

Theingi Aung: Performed Analytical and Numerical and wrote analytical section of the lab report.

Any Pacheco: Performed experimental measurements and wrote Experimental section of the lab report and the Conclusion. Did final formatting and editing of lab report.

Titus Lee: Wrote Intro and Numerical sections of the lab. Also determined potential sources of error and discrepancies.