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EEE 419 – 01

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EEE 419 Homework Assignment 2 – Buck Converter

Introduction

The aim of this assignment is to design a buck converter that converts 320V to 3.3V by using the circuit shown in figure 1.

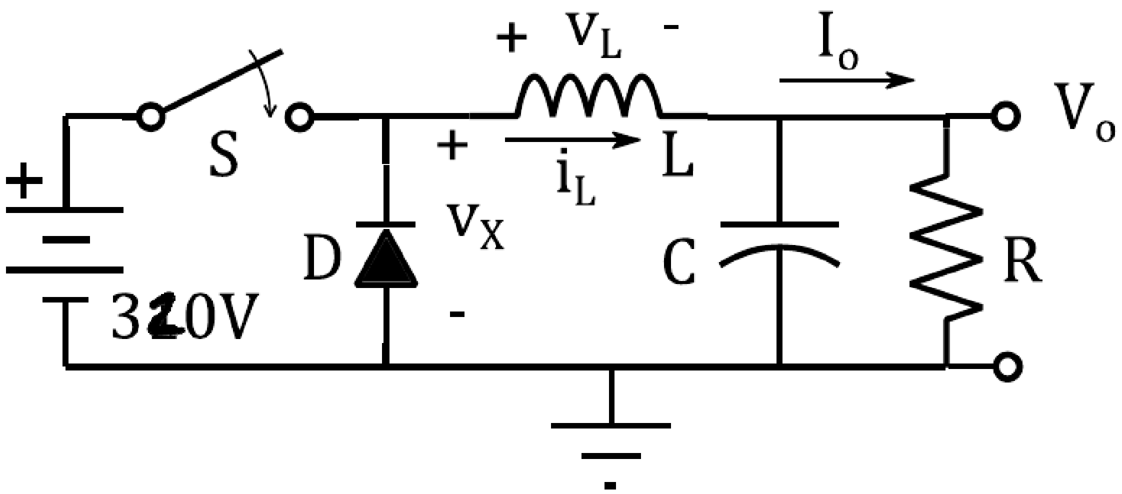

Figure 1: Buck Converter Circuit

Buck converter is a type of DC-DC power converter that steps down the input voltage to a lower output voltage while maintaining a higher current. It operates by switching on and off at high frequency, which allows energy to be stored in inductor during the "on" phase and released to the load during the "off" phase. Diode and capacitor are used to smooth and regulate the output voltage.

In this assignment, using the given formula for load resistance, R=[5+mod(BilkentID,12)/4] Ω, the value of the load resistance is found as 5.5Ω.

Measurements and Results

This part contains the answers to the related questions.

a. By using the given formula [30+5 mod(BilkentID,12)]kHz, the switching frequency is found as 40kHz. Hence the period of the buck converter T_s is 25µs.

The duty cycle D is found using formula

$$V_o = D \cdot V_d$$

where V_o is output voltage and V_d is input voltage. As given in the assignment, input voltage is 320V while input voltage is 3.3V. Hence duty cycle is

$$D \approx 0.0103 = 1.03\%$$

Duty cycle is the percentage of the "on" time of the switch to the period T_s.

b. To find the minimum value of L for continuous mode operation, assume that output current is equal to the boundary output current. Boundary output current, I_{OB}, refers to the boundary current between continuous mode and discontinuous mode.

The output current is found as

$$I_o = \frac{V_o}{R_L} = \frac{3.3\text{V}}{5.5\Omega} = 0.6A$$

And the boundary current, I_{OB}, formula is

$$I_{oB} = \frac{T_s V_d}{2L}(D - D^2)$$

By equating this formula to 0.6A, which is found output current, the minimum inductor value for continuous mode operation is found as

$$L \approx 68\mu H$$

Since it is required to choose a value twice of the found minimum value, the value of the inductor of the buck converter is 140µH.

$$L = 140\mu H$$

To plot $i_L(t)$ in PSS, $i_L(0)$ and i_{Lpeak} should be found. The formula for $i_L(0)$ is

$$i_L(0) = \frac{V_o}{R_L} - \frac{1}{2} \cdot \frac{V_d - V_o}{L} t_{ON}$$

The on time of the switch is t_{ON} and found as

$$t_{ON} = D \cdot T_S = 0.258\mu s$$

Hence

$$i_L(0) = \frac{V_o}{R_L} - \frac{1}{2} \cdot \frac{V_d - V_o}{L} t_{ON} = 0.308A$$

And peak current found as

$$i_{Lpeak} = i_L(0) + \frac{V_d - V_o}{L} t_{ON} \ = \ 0.892A$$

Hence the plot of $i_L(t)$ in periodic steady state (PSS) for the given R and L is shown in figure 2.

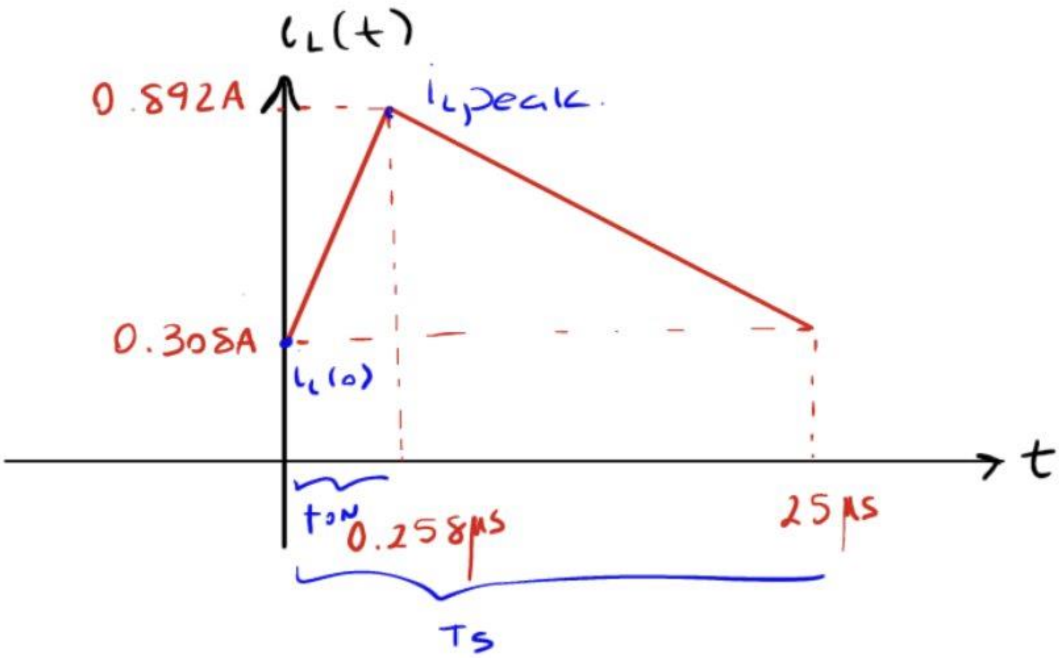

Figure 2: Plot of $i_L(t)$

c. Since the peak-to-peak ripple voltage value, ΔV_o, is 15mV and its formula is

$$\Delta V_o = \frac{1}{8C} \cdot \frac{T_s^2 V_o}{L} (1 - D)$$

Using this formula capacitor value is found as

$$C \ \approx \ 121.5\mu F$$

The ripple voltage value for this capacitor value is valid for zero ESR.

When the ESR value is 0.15Ω, the ripple voltage value is found as

$$\frac{\Delta V_o}{\Delta V_{ESR}} = \frac{T_s}{8 R_{ESR} C}$$

Hence

$$\Delta V_{ESR} \ = \ 87mV$$

This is the peak-to-peak ripple voltage value due to ESR.

d. From b), it is known that L should be at least 68μH for continuous mode operation. Hence, for discontinuous case, L should be smaller than this value. For this purpose, L value is chosen as 30μs.

To find output voltage the given formula is used:

$$V_o = \frac{D^2}{D^2 + \frac{I_o}{4I_{oB\,max}}} V_d$$

For the calculation, I_{OBMAX} value is found using the formula

$$I_{oB\,max} = \frac{T_s V_d}{8L} = 33.3A$$

Hence output voltage for discontinuous mode operation is

$$V_o = 4.948V$$

To be able to plot the inductor current graph, I_o and peak value should be calculated. For this purpose, Δ value should be found. It is the ratio of output current to the boundary current, normalized by duty cycle, and used for calculations in discontinuous mode operation. The formula is

$$\Delta = \frac{I_o}{4I_{oBmax} D} = 0.656$$

The output current in here is calculated by using new output voltage value and found as 0.9A.

Peak current value of inductor is found as

$$i_{Lpeak} = \frac{V_o \Delta T_s}{L} = 2.7A$$

Since the on-off switch time will change and there will be a time interval for both switch and diode are off, these values should be calculated as

$$t_{ON} = D \cdot T_s = 0.26\mu s$$

$$t_{OFF} = \Delta \cdot T_s = 16.4\mu s$$

The plot of $i_L(t)$ for discontinuous mode operation is shown in figure 3.

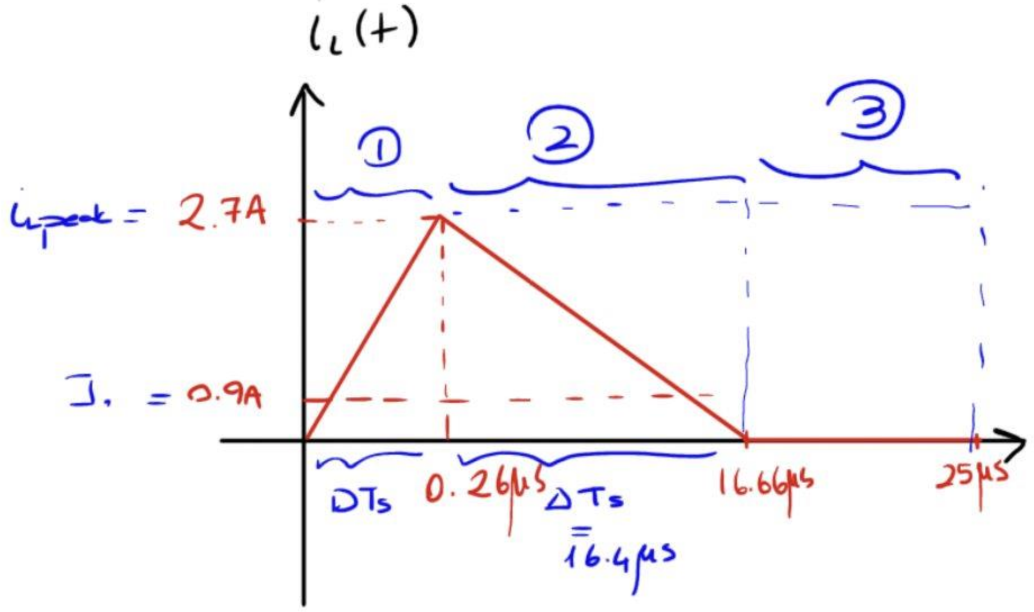

Figure 3: Plot of $i_L(t)$ for Discontinuous Operation Mode

In the first time interval, the switch is ON, and diode is OFF; in the second time interval switch is OFF and diode is ON; in the third time interval both of them is OFF.

e. By using the formula

$$V_o = \frac{D^2}{D^2 + \frac{I_o}{4I_{oB\,max}}} V_d$$

D is found as 0.685%, by keeping output voltage is 3.3V.

With using new duty cycle value, all the related values are recalculated as

$$\Delta = \frac{I_o}{4I_{oBmax}D} \;=\; 0.658$$

$$i_{Lpeak} = \frac{V_o \Delta T_s}{L} \;=\; 1.81A$$

$$I_o = \frac{1}{2} i_{Lpeak}(D + \Delta) \;=\; 0.601A$$

$$t_{ON} = D \cdot T_s \;=\; 0.713\mu s$$

$$t_{OFF} = \Delta \cdot T_s \;=\; 16.45\mu s$$

and the graph of inductor current is plotted as shown in figure 4.

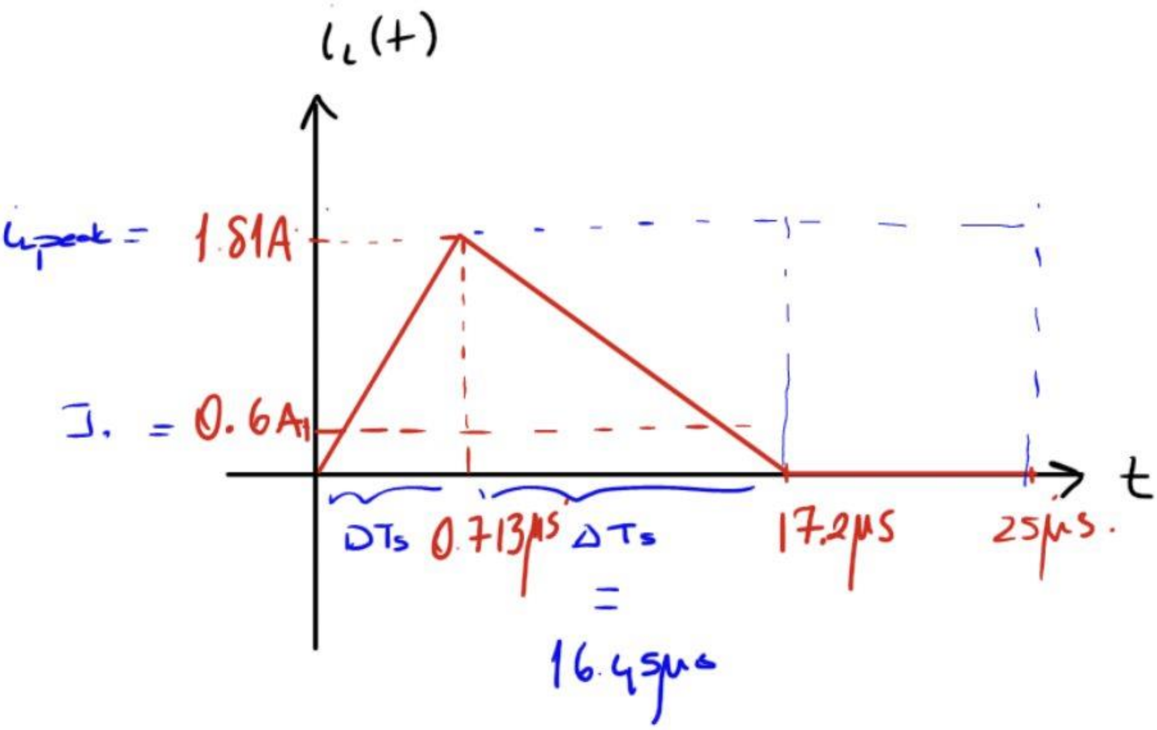

Figure 4: Plot of $i_L(t)$ for Discontinuous Operation Mode, 3.3V Output Voltage

f. To simulate the Buck Converter, the circuit is implemented on LTSPice as shown in figure 5.

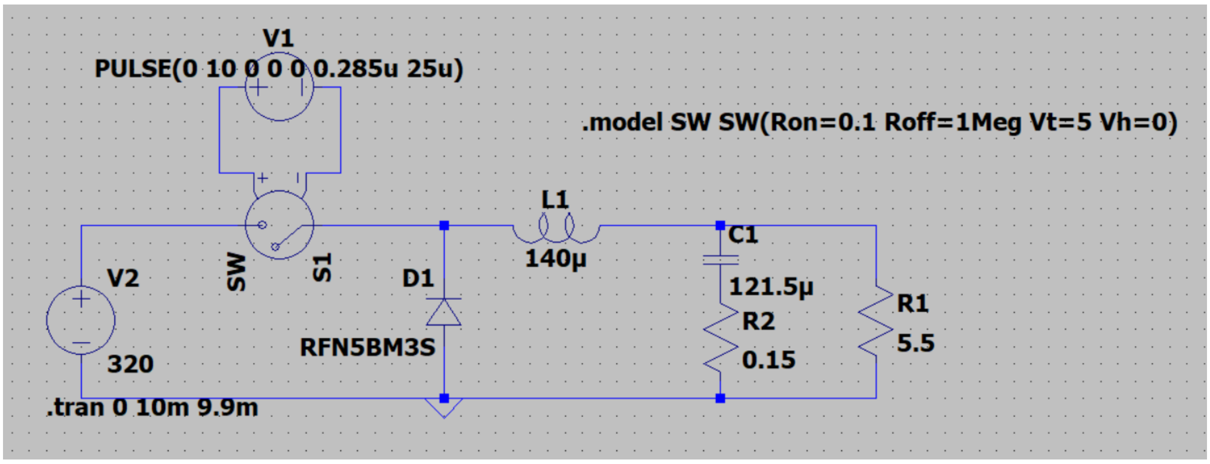

Figure 5: LTSpice Implementation of Buck Converter Circuit

The switching frequency is adjusted for desired output due to the voltage drop of the diode. This value is found by trial-and-error method.

The output voltage plot of the circuit is shown in figure 6.

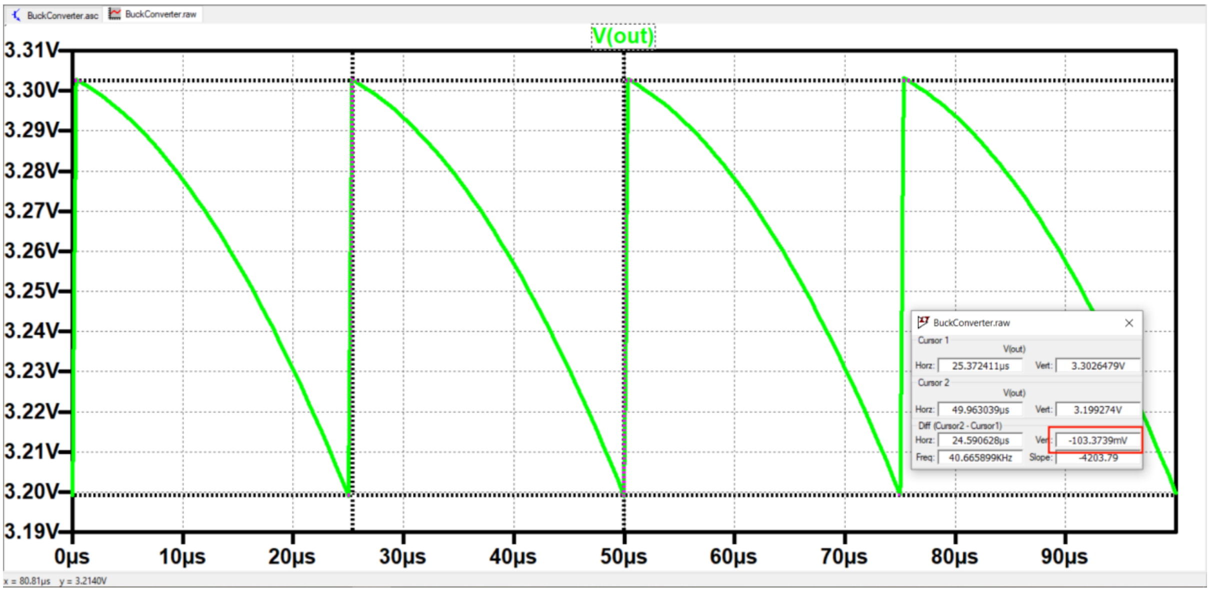

Figure 6: LTSpice Plot of $V_o(t)$

As shown in figure 6, the ripple voltage is 103.3mV, which is reasonably close to the calculated result of 87mV. Simulation result can be decreased by changing capacitor value.

Simulated inductor current plot is shown in figure 7.

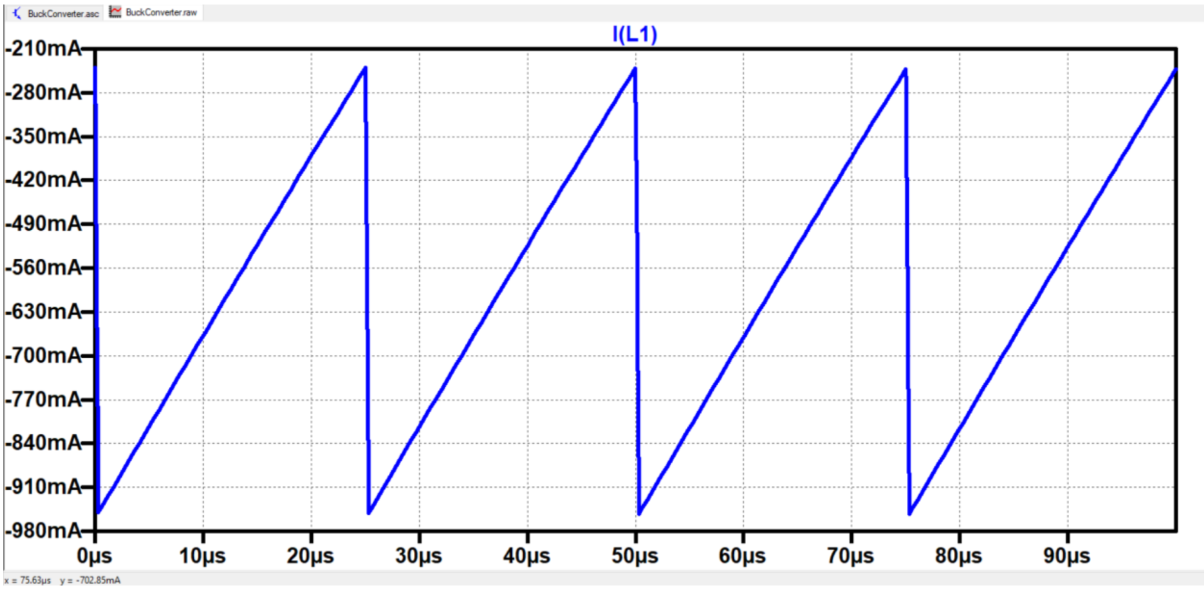

Figure 7: LTSpice Plot of $i_L(t)$

t_{ON} and T_s values of the inductor are shown in figures 8 and 9, respectively.

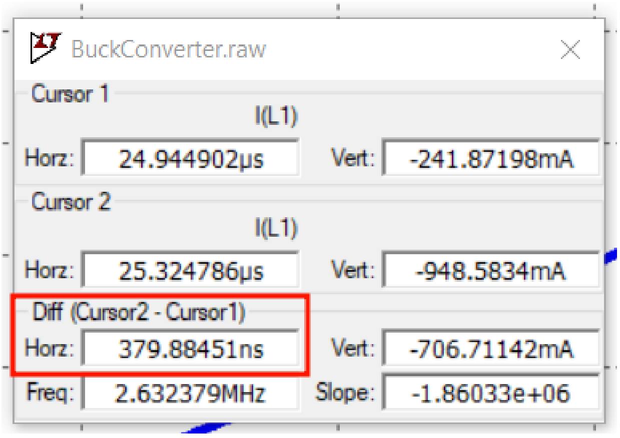

Figure 8: Simulation value of t_{ON}

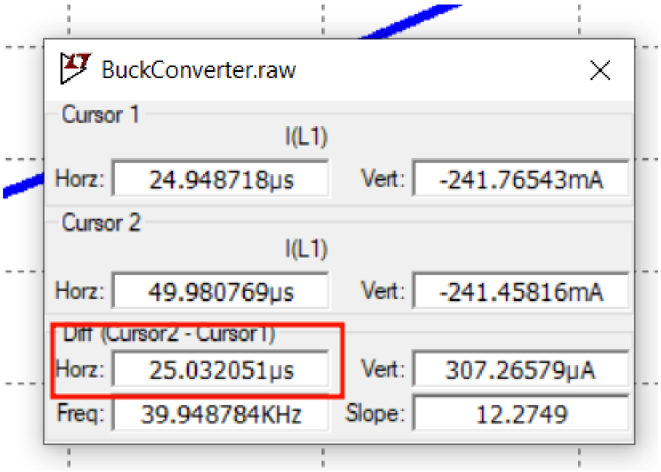

Figure 9: Simulation Result of T_S

The simulation results are quite close to the calculated values even though the duty cycle is adjusted for required output voltage.

The duty cycle is 1.52% for this simulation.

g. The inductor value is changed to 30µH, and the output voltage of the converter is shown in figure 10.

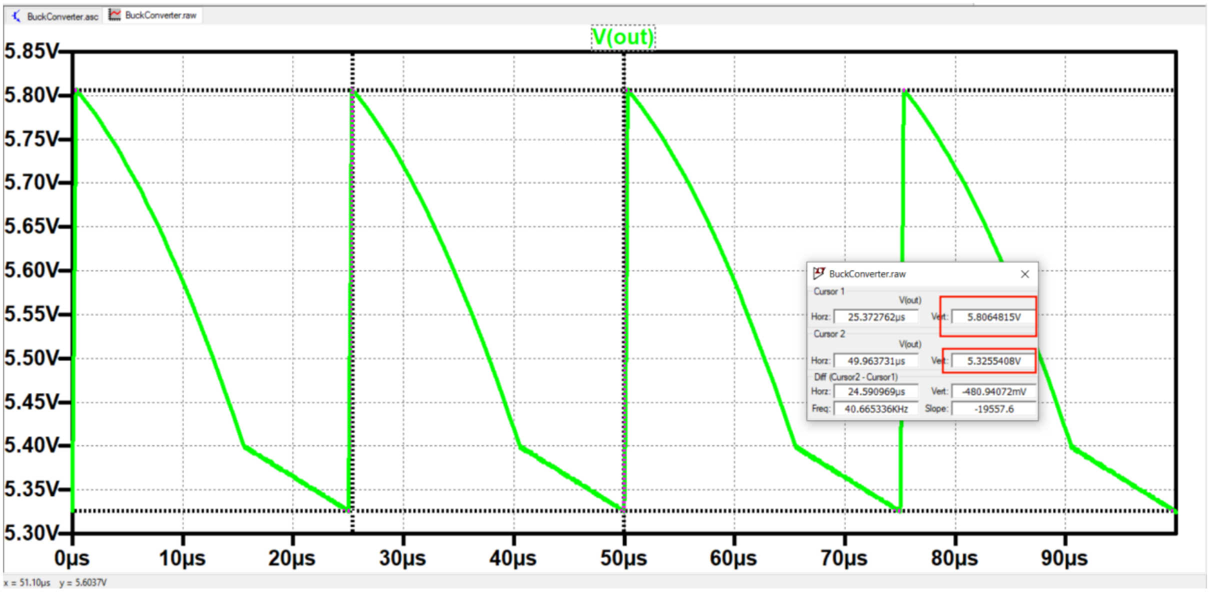

Figure 10: Simulated Output Voltage in Discontinuous Operation Mode

The simulation result of inductor current is shown in figure 11.

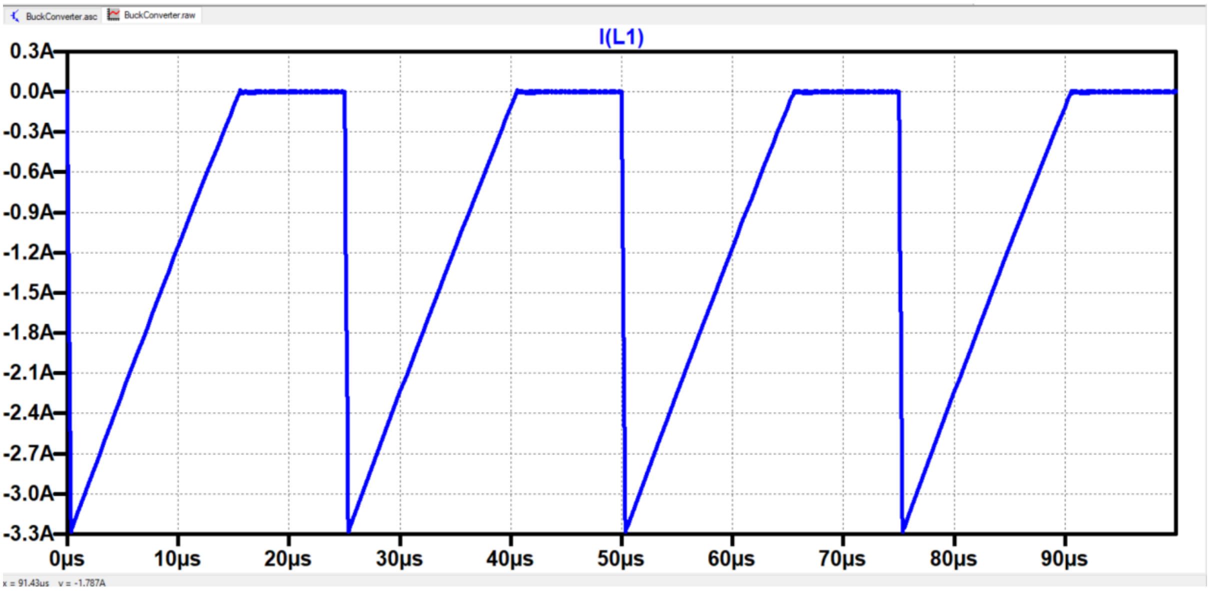

Figure 11: Simulated Inductor Current in Discontinuous Operation Mode

The t_{ON} value is shown in figure 12. Period of the switch is not changed; hence T_S is about 25µs.

The duration of the switch OFF diode OFF situation is given in figure 13.

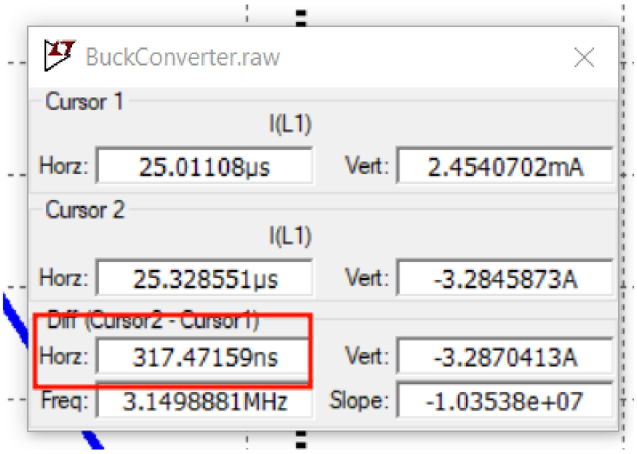

Figure 12: Simulation value of t_{ON}, DCM

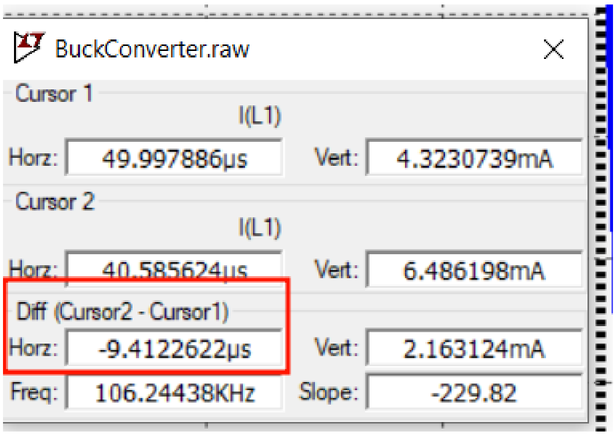

Figure 13: Simulation Value for Both Diode and Switch are OFF

The duty cycle of this simulation is 1.27%. Since the duty cycle is adapted to diode voltage drop, the result is reasonably close to the calculated duty cycle 1.03%.

h. To get the desired output voltage 3.3V, the switching frequency is changed, and the output voltage is simulated as shown in figure 14. Even though the output voltage is about 3.3V, ripple voltage is around 300mV, which is relatively high.

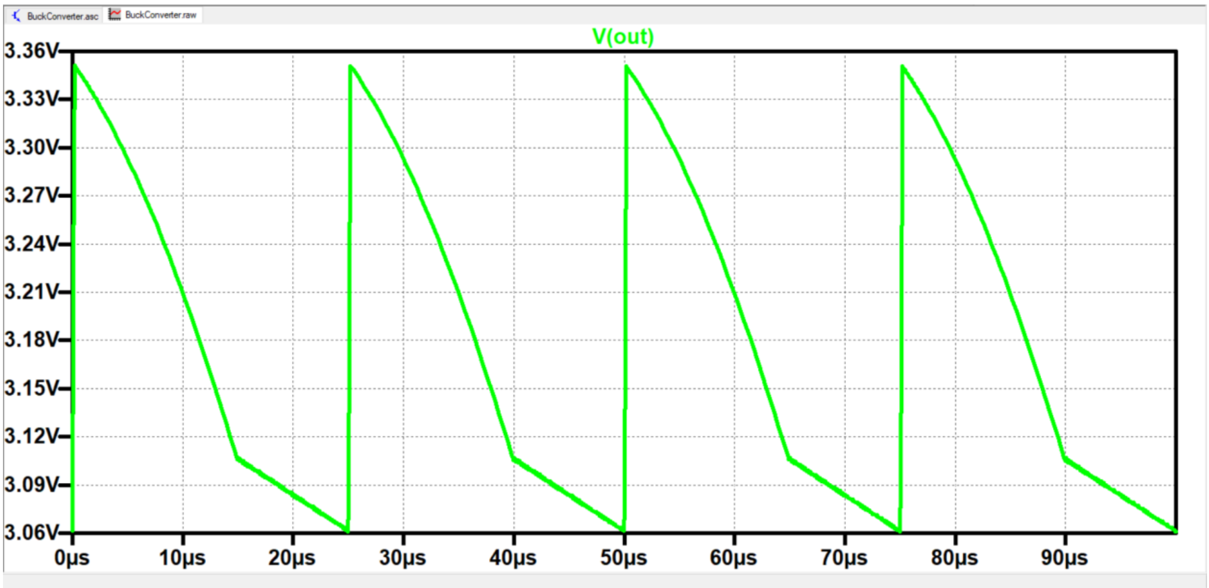

Figure 14: Output Voltage for 30µH Inductor

The inductor current plot is given in figure 15.

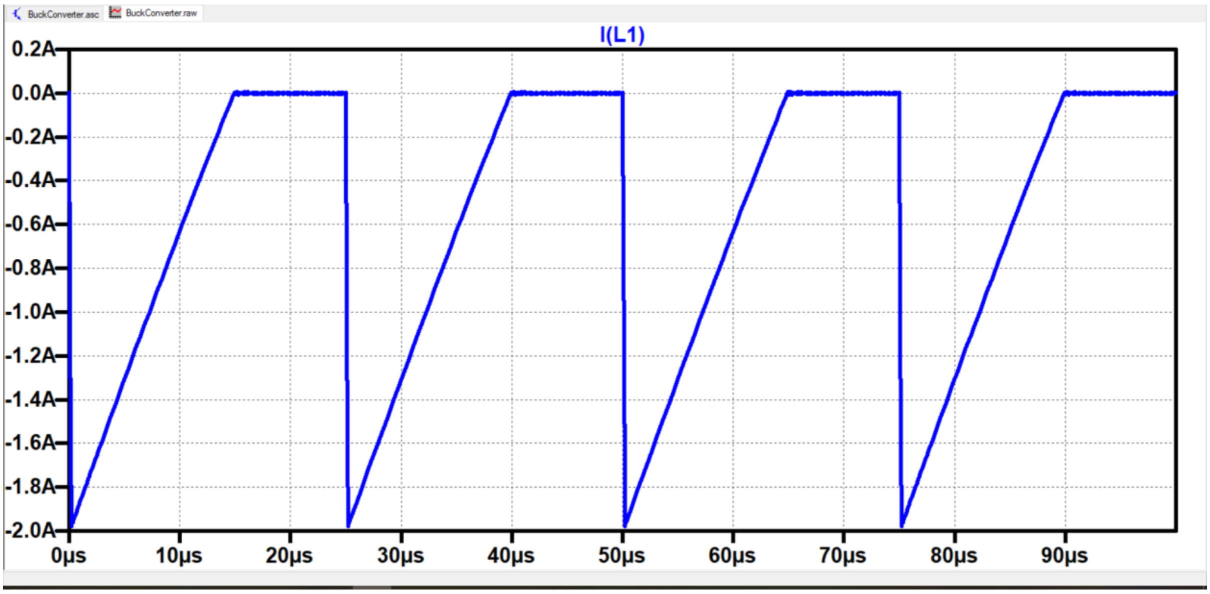

Figure 15: Simulated Inductor Current with Adapted Duty Cycle

t_{ON} value is shown in figure 16, and T_S is shown in figure 17.

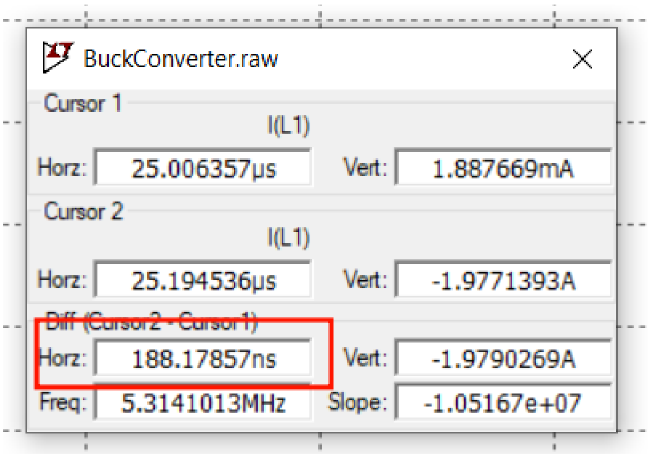

Figure 16: t_{ON}

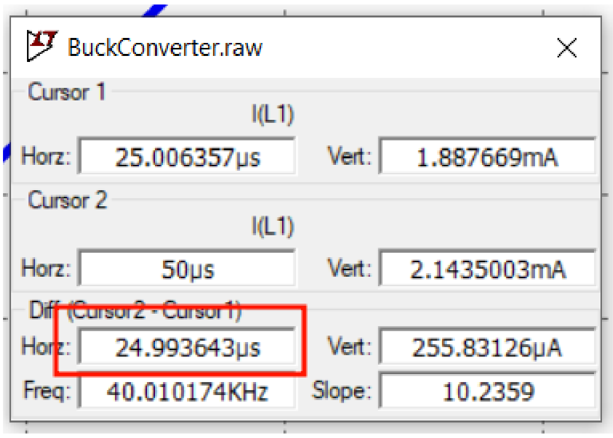

Figure 17: T_S

Hence the duty cycle is 0.75%. This value is very close to the calculated value 0.69% in e).

i. In the simulation, $v_x(t)$ graph is shown in figure 18, while both switch and diode are OFF.

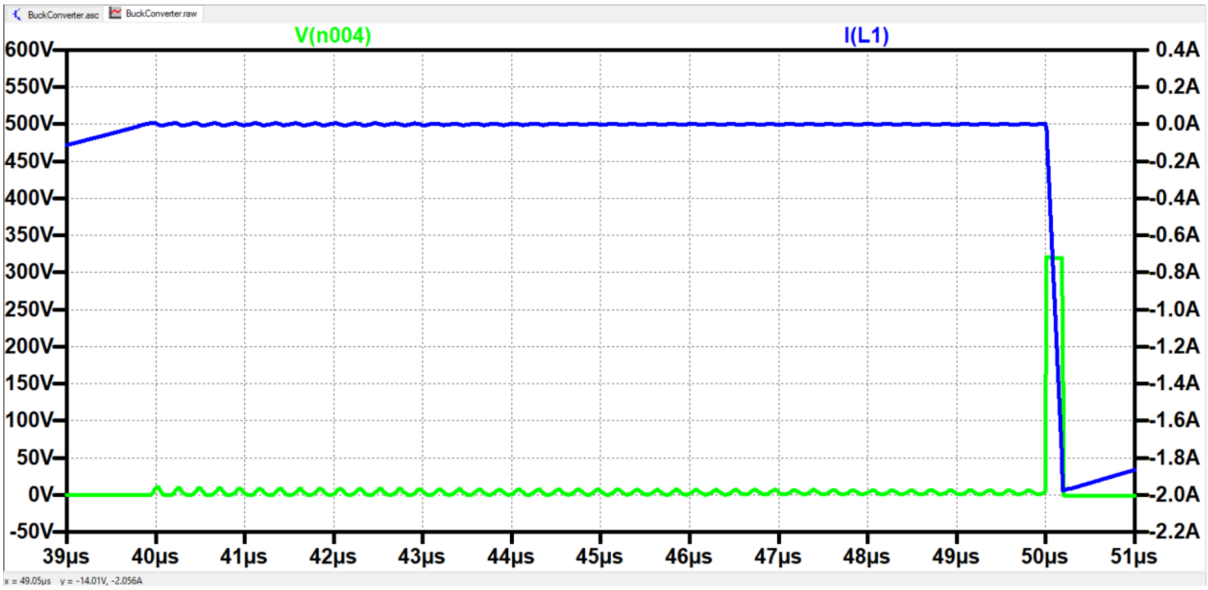

Figure 18: $v_x(t)$ and $i_L(t)$ Plots

The period of the sinusoidal signal in $v_X(t)$ is shown in figure 19.

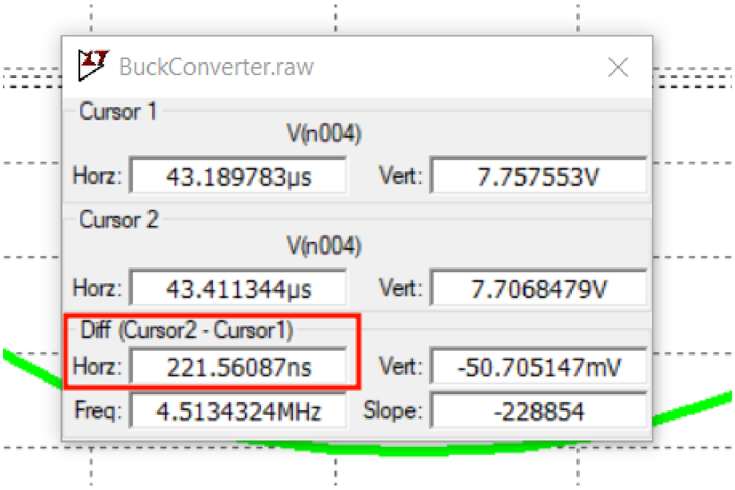

Figure 19: Period of Sinusoidal Signal

Using the formula

$$f = \frac{1}{2\pi\sqrt{L \cdot \mathrm{C}}}$$

The reverse bias capacitance of the diode is found as 41.4pF.

j. Average input power of the circuit is shown in figure 20

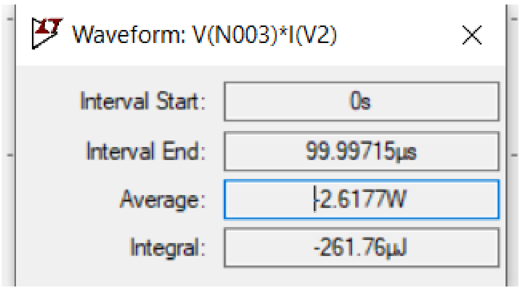

Figure 20: Average Input Power

Average output power of the circuit is shown in figure 21.

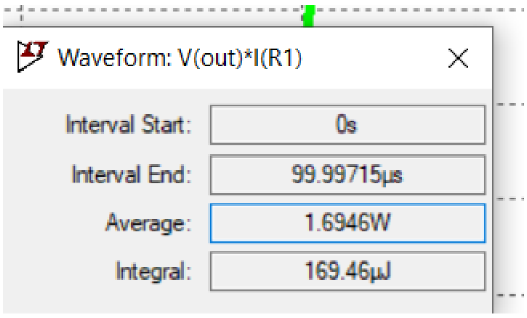

Figure 21: Average Output Power

Using the efficiency formula

$$\frac{P_{out}}{P_{in}} \times 100$$

The efficiency found as 64.74%.

Conclusion

In this assignment, a buck converter was designed and analyzed to convert 320V to 3.3V under continuous and discontinuous conduction modes. Key parameters such as duty cycle, inductance, and capacitance were calculated and verified through simulation. The effect of ESR on the output voltage ripple was examined, and the impact of changing the inductance value on the output voltage and current was evaluated. Additionally, the frequency of the sinusoidal signal during the switch-off period was used to estimate the reverse bias capacitance of the diode. The results were confirmed using LTSpice simulations, showing good agreement with theoretical calculations. Through these exercises, the behavior of the buck converter under different conditions was thoroughly explored, providing insights into both practical design considerations and the performance of the converter.