ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

EE463 STATIC POWER CONVERSION I
Homework 4: DC/DC CONVERTERS

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INTRODUCTION

In this homework, Buck and Boost converters which are DC/DC converters, will be examined. The continuous current mode, power in the ideal case, and nonidealities in the real world will be examined for both converter types.

SOLUTIONS

1) Buck Converter

a)

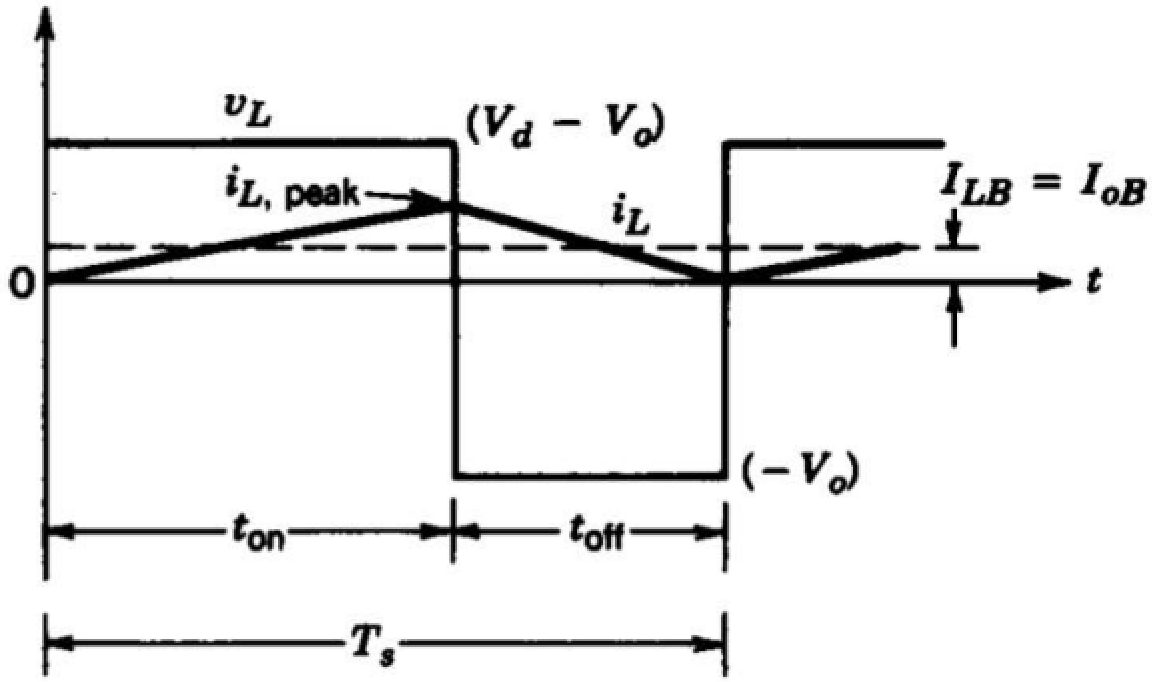

Figure 1: VL and IL graph for transition to the discontinuous current mode

In Figure 1, the boundary output current graph for DCM can be seen.

$$I_{OB} = \frac{I_{L,peak}}{2}$$

$$I_L = \frac{1}{L}\int_0^t V_L dt \; + \; i_0$$

$$I_{L,peak} = \frac{1}{L}\int_0^{t,on} V_L dt \; + \; i_0 = \frac{1}{L}(V_D - V_O)t_{on}$$

$$I_{OB} = \frac{I_{L,peak}}{2} = \frac{1}{2L}(V_D - V_O)t_{on} = \frac{1}{2L}(V_D - V_O)\frac{D}{f_s}$$

$$D = \frac{V_O}{V_D}$$

Since this boundary means the minimum current, we need to find the lower value. So the input voltage is chosen as 12V for the calculation.

$$I_{OB} = \frac{1}{2L}(V_D - V_O)\frac{V_O}{V_D}\frac{1}{f_s} = \frac{1}{2 \times 5\mu H} \times (12V - 5V) \times \frac{5V}{12V} \times \frac{1}{500kHz} = 0.583A$$

b)

The output voltage is fixed and 5V. So

$$I_O = \frac{P}{V_O} = \frac{15W}{5A} = 3A$$

$$\Delta I_L = I_{L,peak} - i_0 = \frac{1}{L}\int_0^{t,on} V_L\,dt \; + \; i_0 - i_0 = \frac{1}{L}\int_0^{t,on} V_L\,dt = \frac{1}{L}(V_D - V_O)t_{on}$$

To find maximum ripple, the maximum input voltage must be chosen.

$$\Delta I_L = \frac{1}{L}(V_D - V_O)\frac{V_O}{V_D}\frac{1}{f_s} = \frac{1}{5\mu H}(24V - 5V)\frac{5V}{24V}\frac{1}{500kHz} = 1.583A$$

$$\Delta Q_C = \frac{\Delta I_L}{2} \times \frac{T_S}{2} \times \frac{1}{2} = \frac{1.583A}{2} \times \frac{1}{500kHz \times 2} \times \frac{1}{2} = 3.9575 \times 10^{-7}C$$

$$\Delta V_O = \frac{\Delta Q_C}{C} = \frac{3.9575 \times 10^{-7}C}{10\mu F} = 0.04V$$

c)

$$D = \frac{V_0}{V_{in}} = 20.83\%$$

$$I_{OB} = \frac{(V_D - V_O)D}{2Lf_S} = 0.792A$$

$$\mathrm{R} = \frac{\mathrm{V_O}}{\mathrm{I_{OB}}} = 6.316\Omega$$

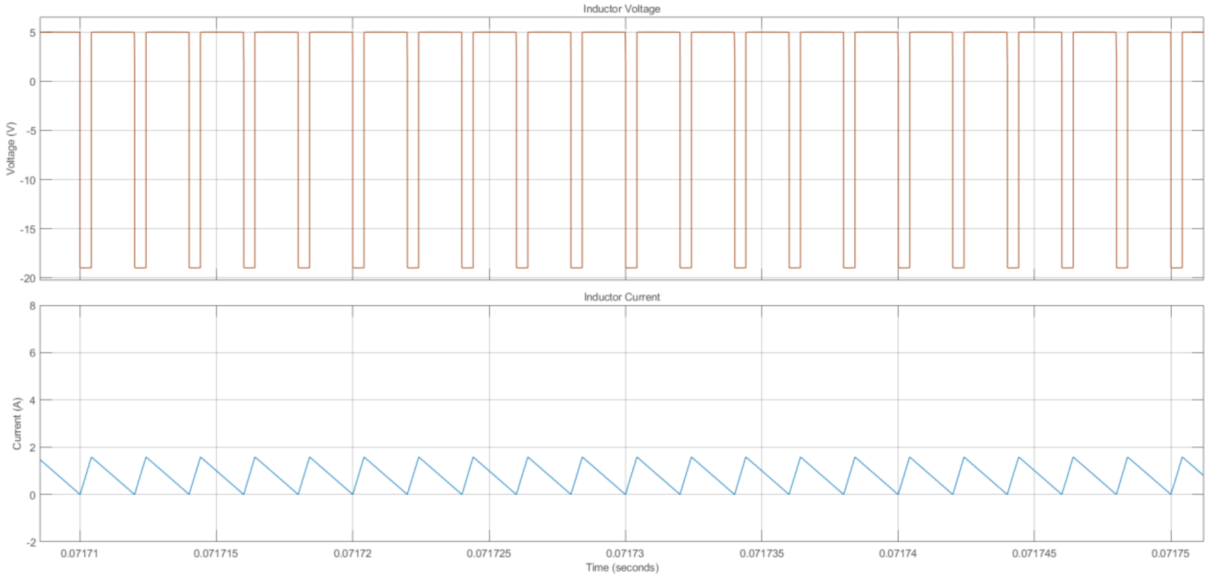

Figure 2: Inductor Voltage and Current Graph

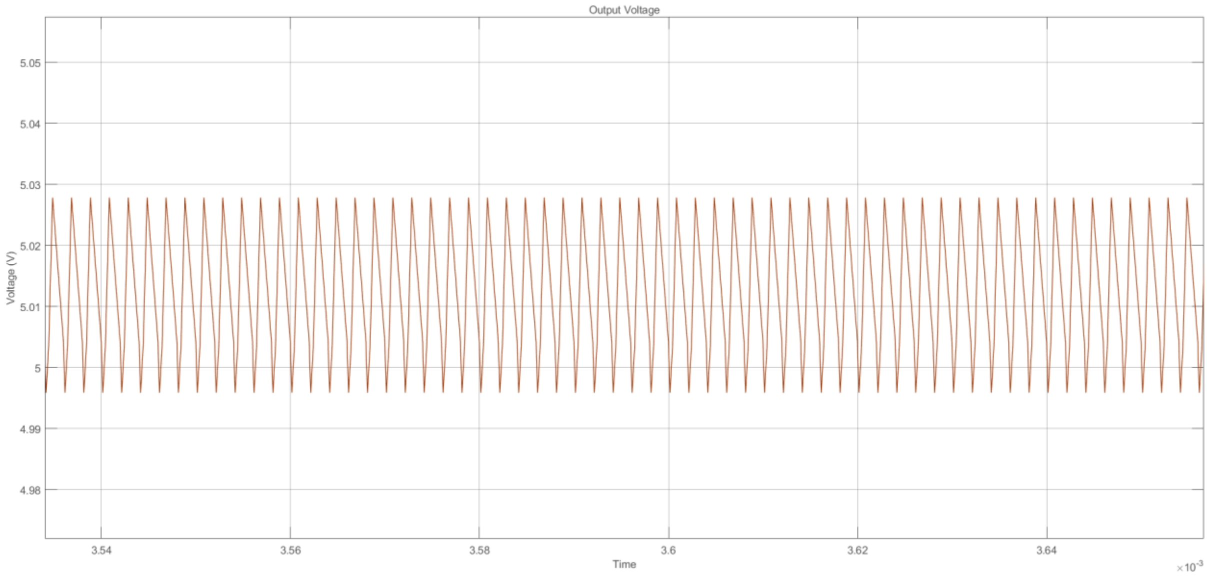

Figure 3: Output Voltage Graph

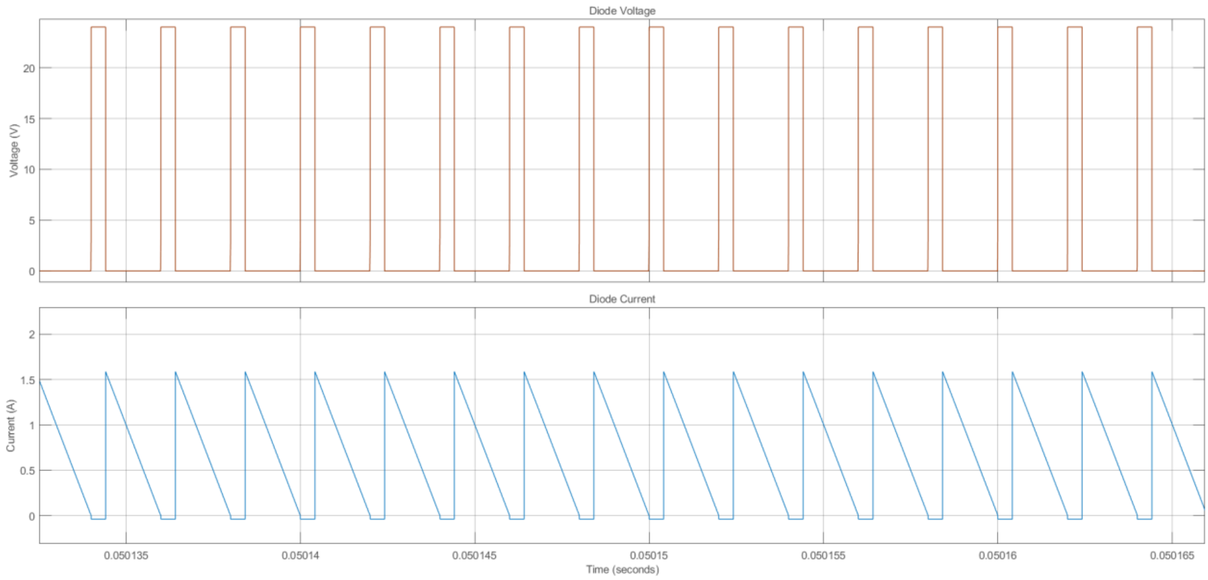

Figure 4: Diode Voltage and Current Graph

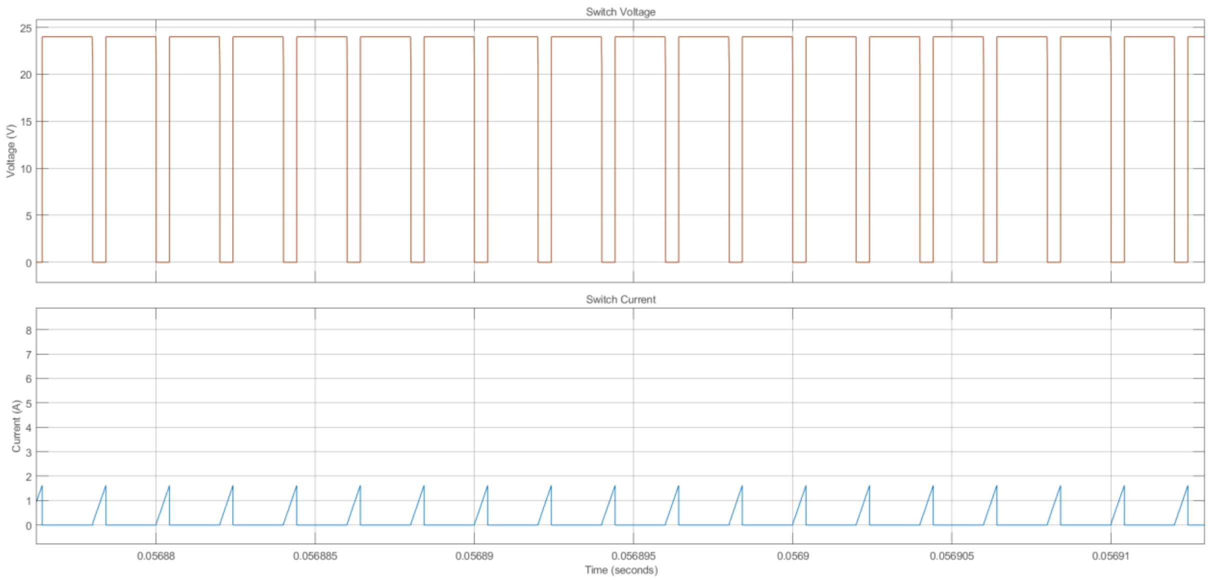

Figure 5: Switch Voltage and Current Graph

In this part, the continuous current mode of the buck converter was observed. When the inductor current graph was examined, it can be seen that the current does not remain zero; it goes down to zero and goes up.
In addition, the peak current value that guarantees CCM operation was 1.6A in part a. In this part, it can be seen that peak was 1.6A, and this is suitable for part a.

d)

$$D = \frac{V_0}{V_{in}} = 41.67\%$$

$$I_{OB} = \frac{P}{V_O} = \frac{1W}{5V} = 0.2\ A$$

$$\mathrm{R} = \frac{\mathrm{V_O}}{\mathrm{I_{OB}}} = 25\Omega$$

In the simulation, the output voltage was 7.2V with a 41.67% duty cycle. As a result, D was decreased to 24.4% to obtain a 5V output voltage.

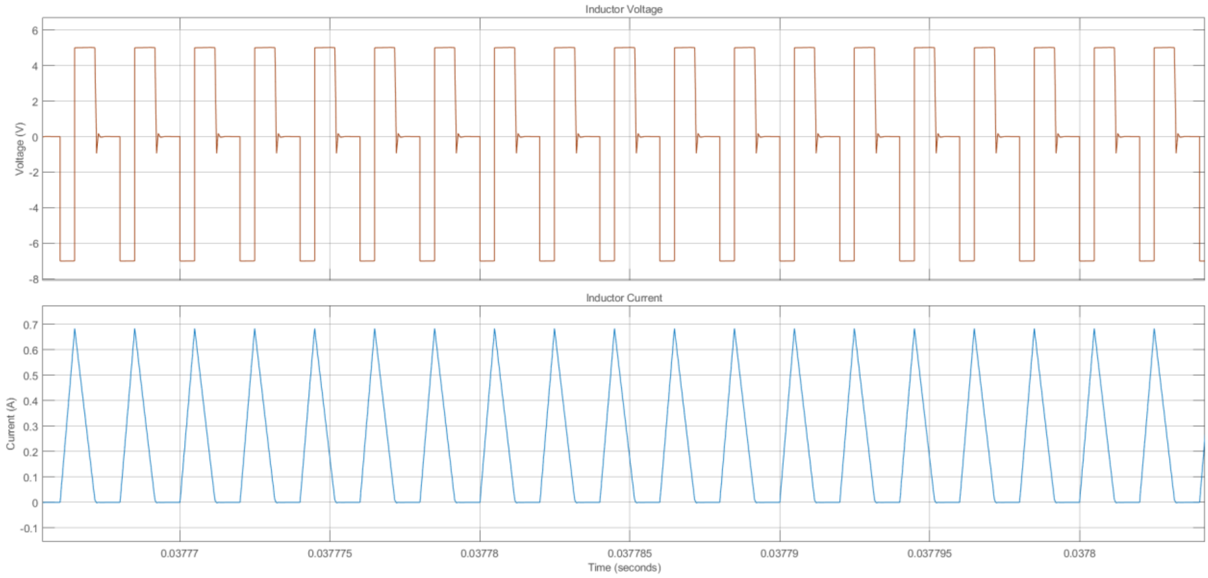

Figure 6: Inductor Voltage and Current Graph

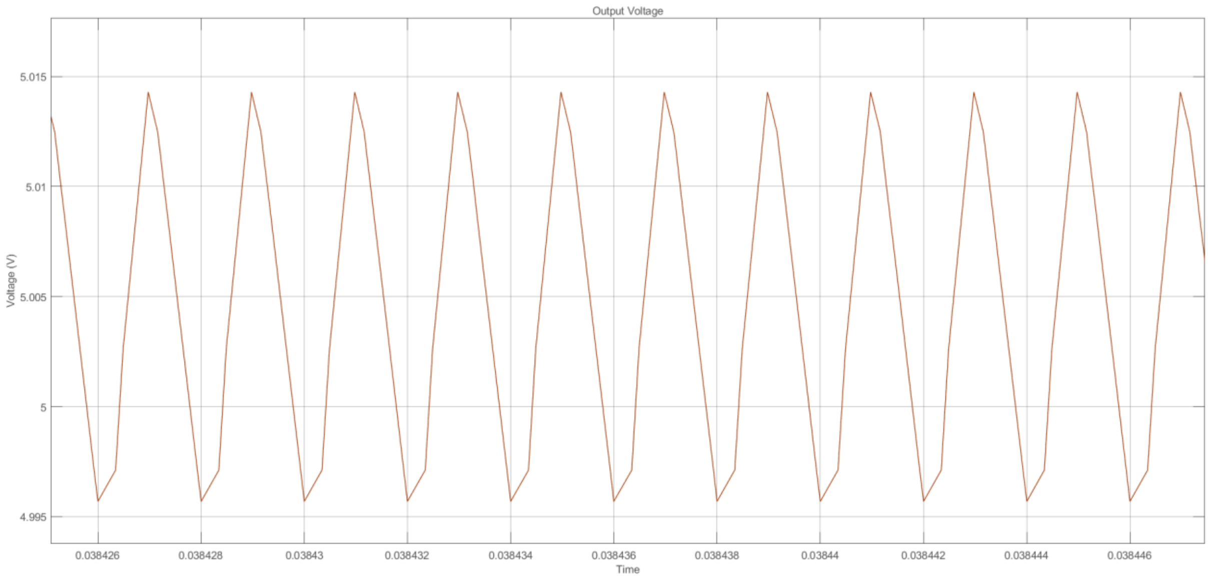

Figure 7: Output Voltage Graph

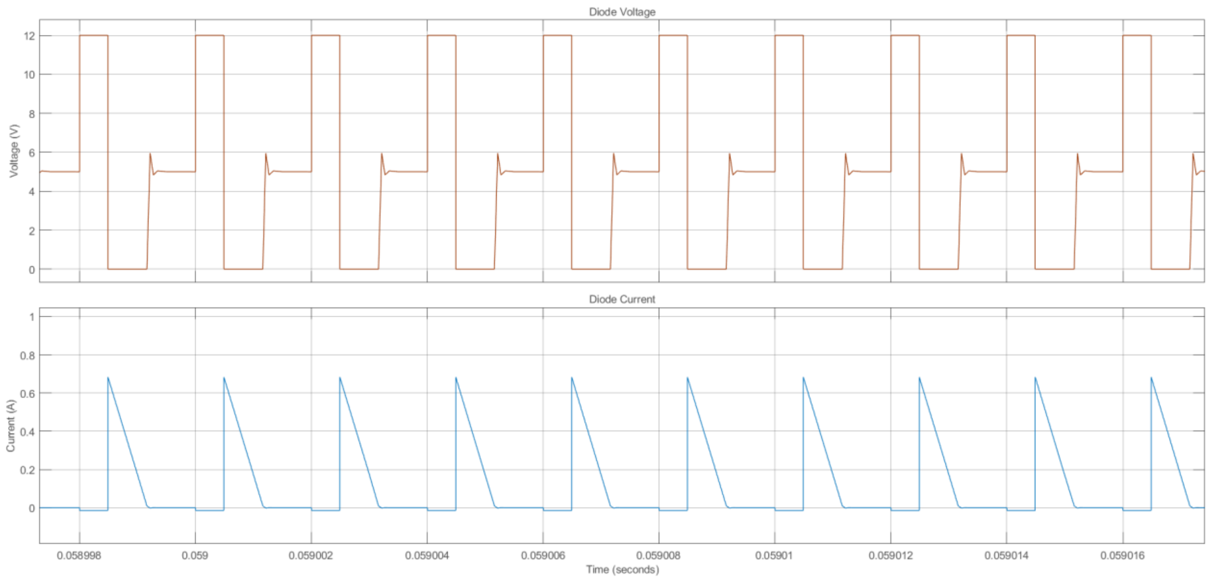

Figure 8: Diode Voltage and Current Graph

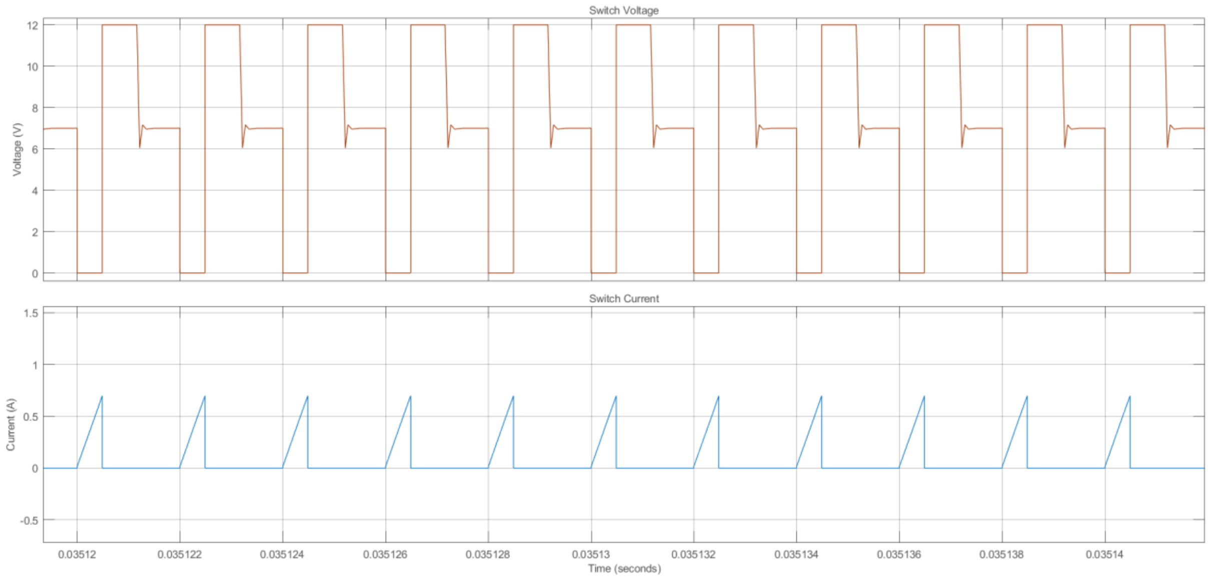

Figure 9: Switch Voltage and Current Graph

In this part, the discontinuous current mode was observed. When the inductor current graph was examined, the inductor peak current was 0.68A which is smaller than the boundary current value found in part a.

When compared with part c, it can be seen that the output voltage ripple and inductor current ripple decreased.

e)
The inrush current is the spike in the current when the supply is turned on. Since the capacitor is not charged, there is a need for a high current to charge them. It can be higher than the rated current of the component, so the components may be damaged.

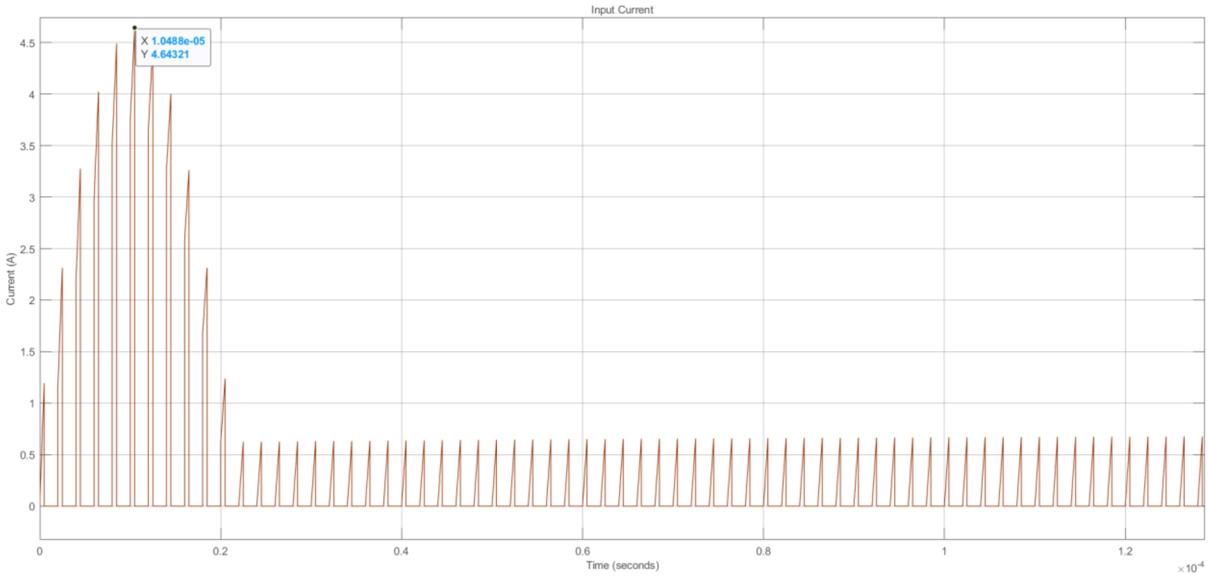

Figure 10: Input Current Graph without Applying Any Methods

It can be seen that the input current reached 4.64 A, which was approximately 6.5 times higher than the operating current.
To prevent high inrush current, soft starter can be used. With a soft starter, the duty cycle increased slowly. As a result, the current cannot reach high values.

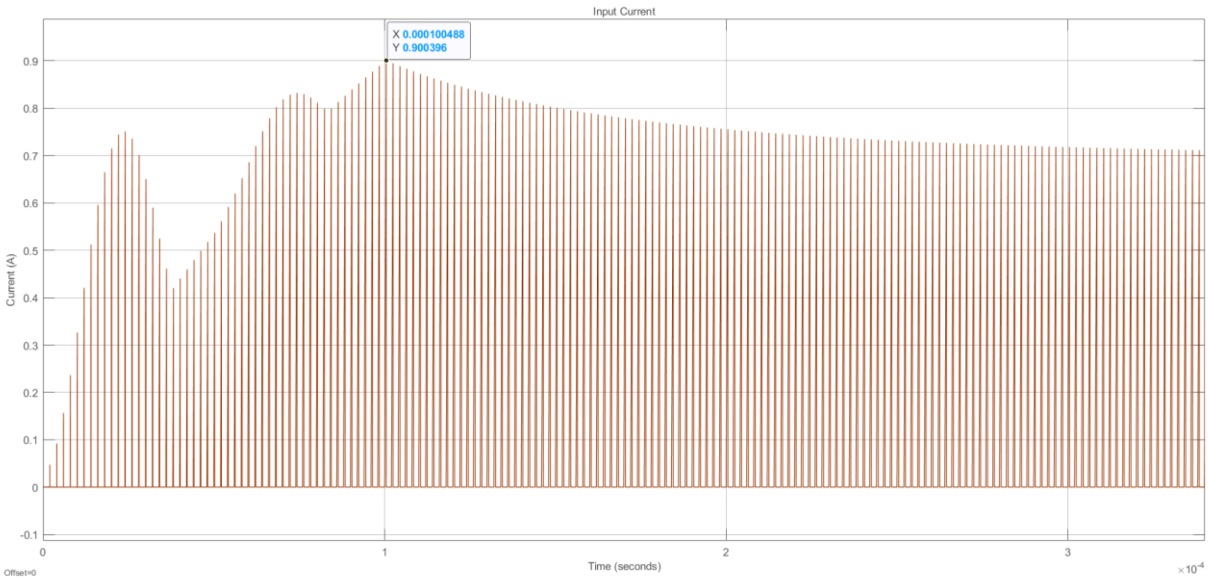

Figure 11: Input Current Graph When Soft Starter is Used

f)

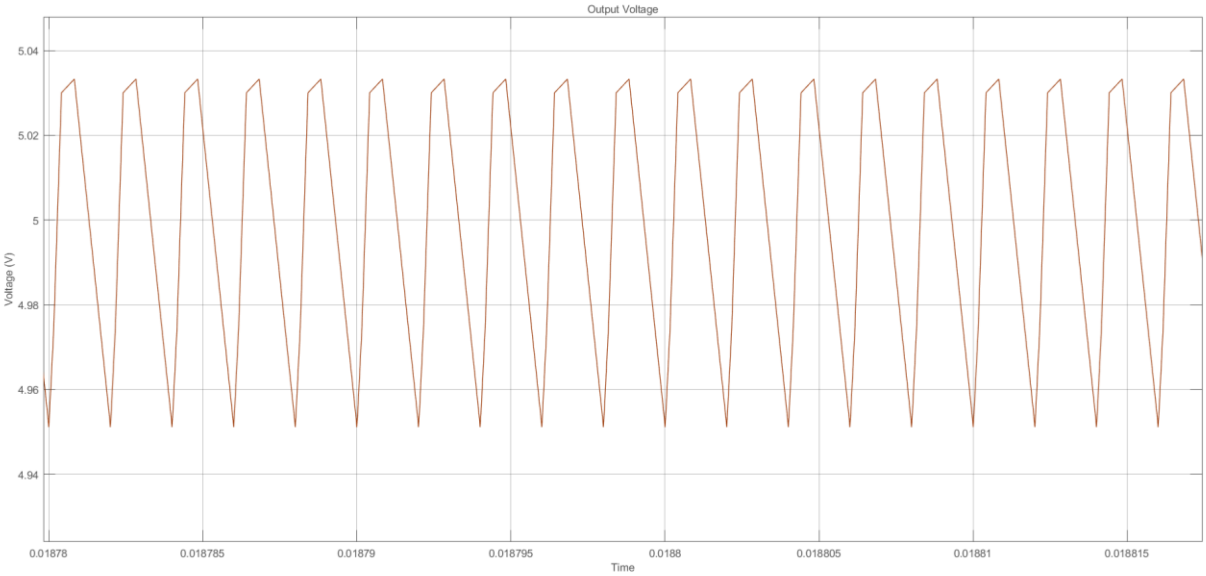

Figure 12: Output Voltage Graph When the Input is 24V, and there is ESR

ESR affected output voltage ripple. The output ripple voltage was 82.24 mV which was 1.64% of the average output voltage in this case. In part c, it was 31.98 mV which was 0.64% of the average output voltage. To decrease ripple voltage, a smaller ESR is needed. To do that, capacitors can be connected in parallel.

2) Boost Converter

$$Input\ Voltage\ Range\ (V_d) = \ 5 - \ 12\ V$$

$$Output\ Voltage\ (V_o) = 16V$$

$$Switching\ Frequency\ (f_s) = \ 300kHz$$

$$Rated\ Output\ Power\ (P_o) = \ 16\ W$$

a)

According to given values, duty cycle (D) range is 0.25 - 0.6875. This range is found using the equation AA. The converter should be operating in CCM operation between this duty range.

$$\frac{V_o}{V_d} = \frac{1}{1 - D}$$

Equation 1

And using the given constant output voltage and rated output power in equation BB, the output current I_o is found to be 1 A.

$$I_o * V_o = P_o$$

Equation 2

In order to find **minimum** inductance that would keep de converter operating in CCM operation, the output current should be equal to output boundary current value (*Equation 3*). It cannot directly found from the maximum boundary current value (*Equation 4*) since all values in D range (0.25 – 0.6875) should be ensured but in equation X2, D = 1/3.

$$I_{OB} = \frac{V_O * D * (1-D)^2}{2 * L * f_s}$$

Equation 3

$$I_{OB,max} = \frac{V_O * 0.074}{L * f_s}$$

Equation 4

The possible L range with respect to found data is 1.79 – 3.95 µH. If 1.79 µH (i.e. minimum value of the possible inductor range) is chosen, the converter cannot operate in CCM operation mode when duty cycle is below 0.6875. In order to converter operate in CCM operation mode under given all circumstances, **L should be chosen as 3.9** µH, considering all the values in D range**.**

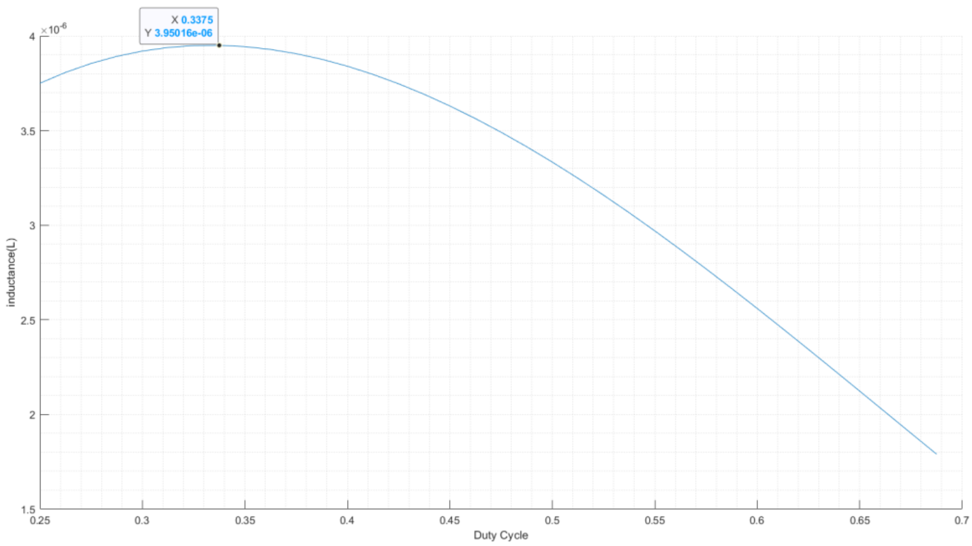

Figure 13:Duty cycle vs Inductance

b)

Output capacitance for peak-to-peak voltage ripple less than 2% can be calculated by using the equation *Equation 1* where $V_{ripple} = 0.02 * V_O = 0.32V$ and $R_O = 16\Omega$.

$$V_{ripple} = \frac{V_o * D}{R_o * C * f_s}$$

Equation 5

The connection between duty cycle and output capacitance can be observed in figure X. Output capacitance should be chosen as 7.16146 µF for voltage ripple smaller than 2% for all values of duty cycle.

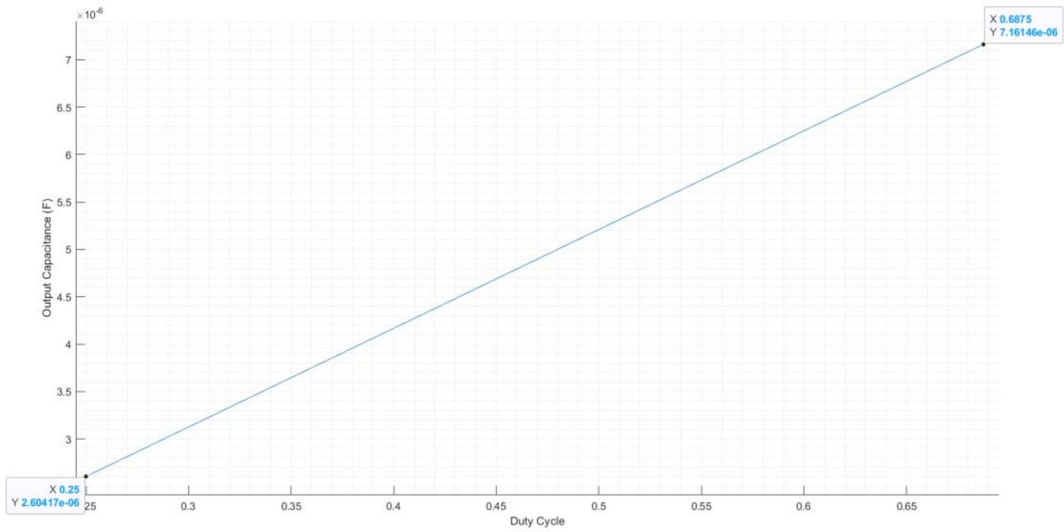

Figure 14:Duty Cycle vs Output Capacitance

c)

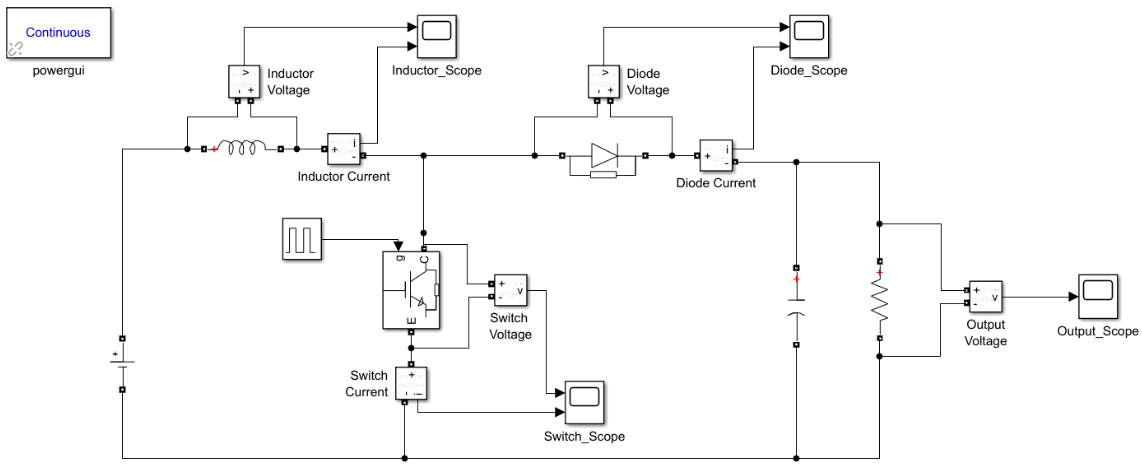

Figure 15:Boost Converter Circuit Design for Part 2.c

Considering the constant output and varying input voltage, a duty cycle range is calculated using the equation 1. The results can be seen in figure 16.

Vin (V)	5	6	7	8	9	10	11	12
Calculated Duty Cycle(D)	0,6875	0,625	0,5625	0,5	0,4375	0,375	0,3125	0,25

Figure 16:Varying Input Voltages and Respective Duty Cycles

But those calculations are made under the assumption that components are ideal. Even though simulation is designed to converge to ideal, there are still some non-idealities that causes approximately 5% duty cycle deflection (they should be increased approximately 5% to get Vo = 16V).

In order to analyze the waveforms properly they first observed on a large scale then small scale. There are high fluctuations in the beginning of the simulations, which can be explained by capacitor not being pre-charged.

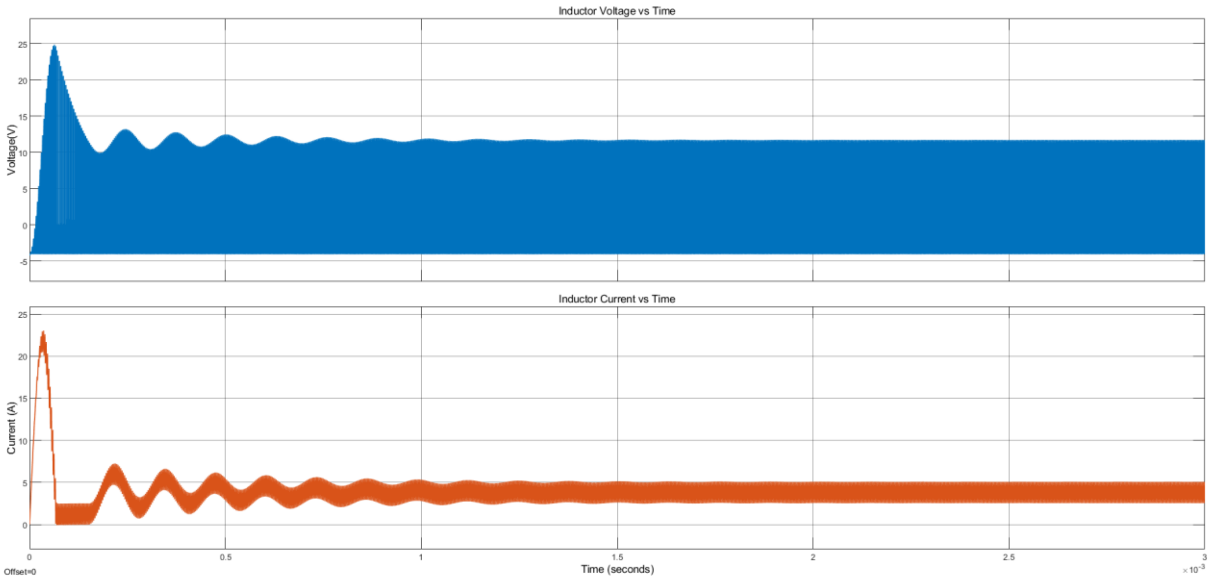

Figure 17:Inductor Voltage & Current vs Time for Input Voltage = 5V and D = 74%

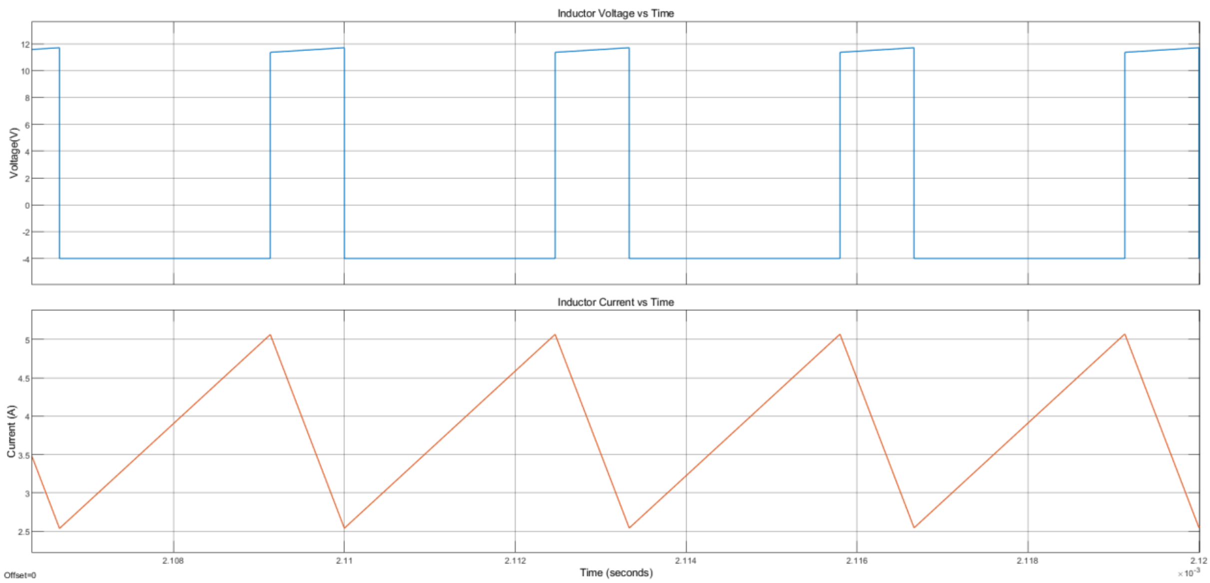

Figure 18:Inductor Voltage & Current vs Time for Input Voltage = 5V and D = 74%

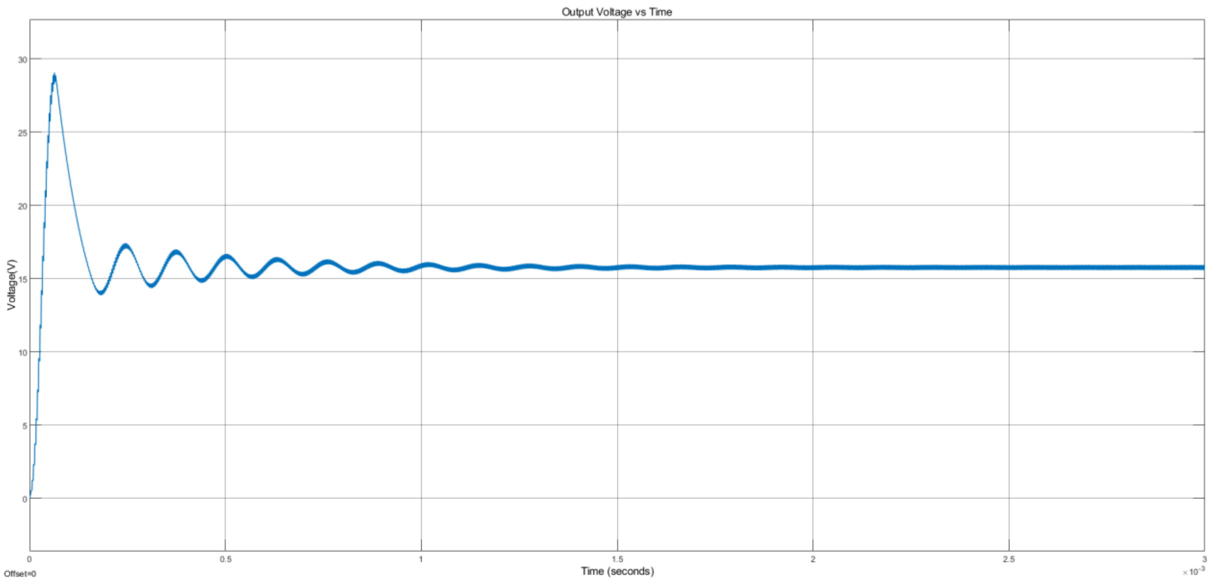

Figure 19: Output Voltage vs Time for Input Voltage = 5V and D = 74%

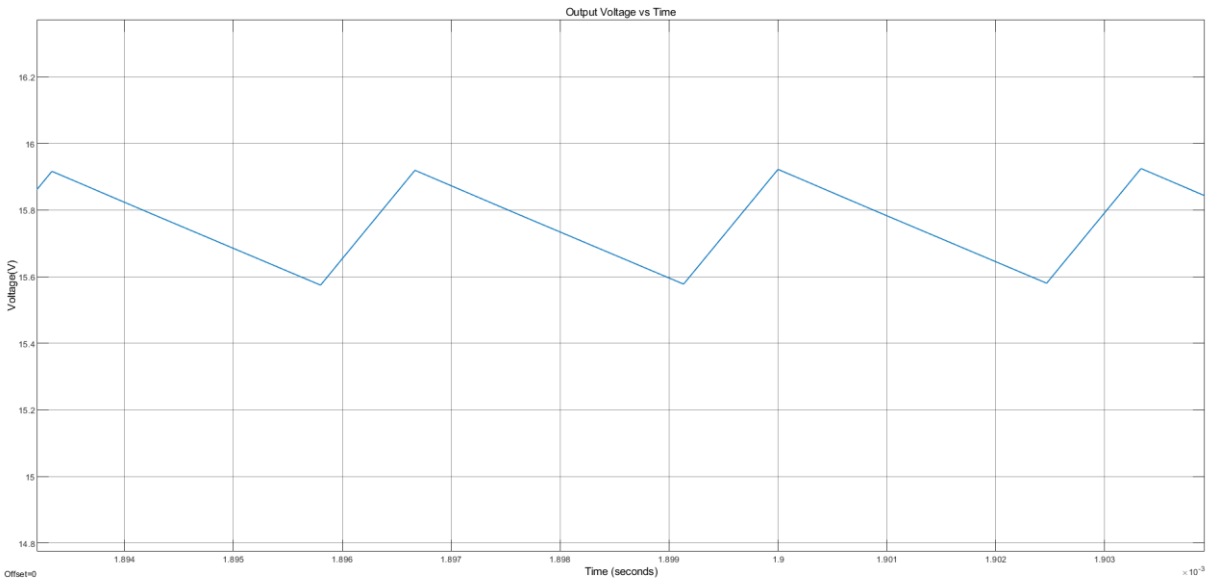

Figure 20:Output Voltage vs Time for Input Voltage = 5V and D = 74%

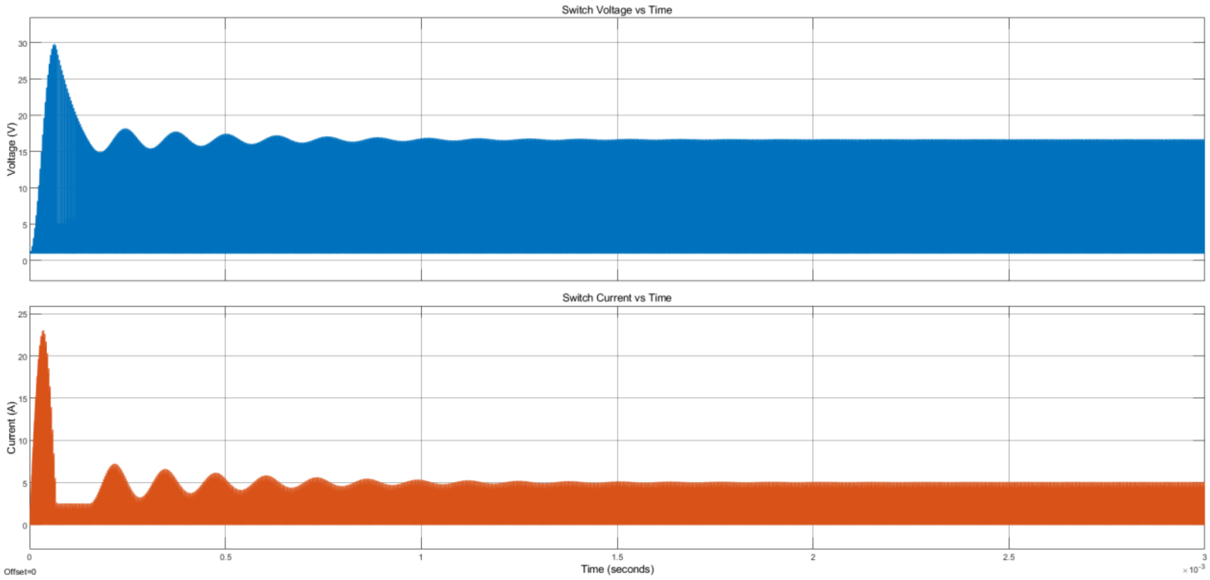

Figure 21:Switch Voltage & Current vs Time for Input Voltage = 5V and D = 74%

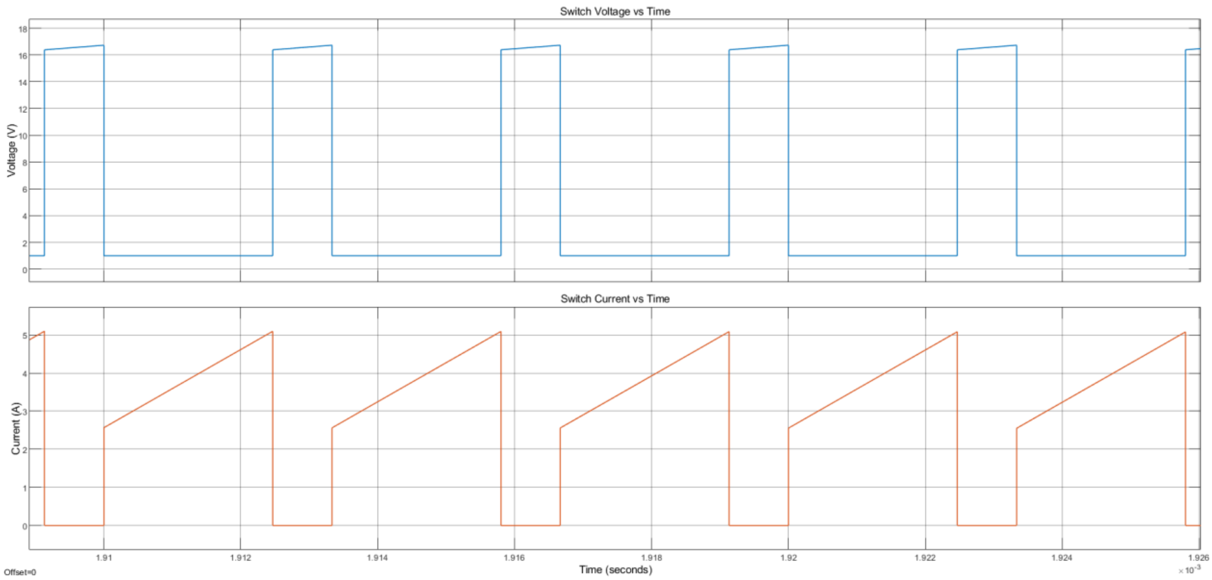

Figure 22: Switch Voltage & Current vs Time for Input Voltage = 5V and D = 74%

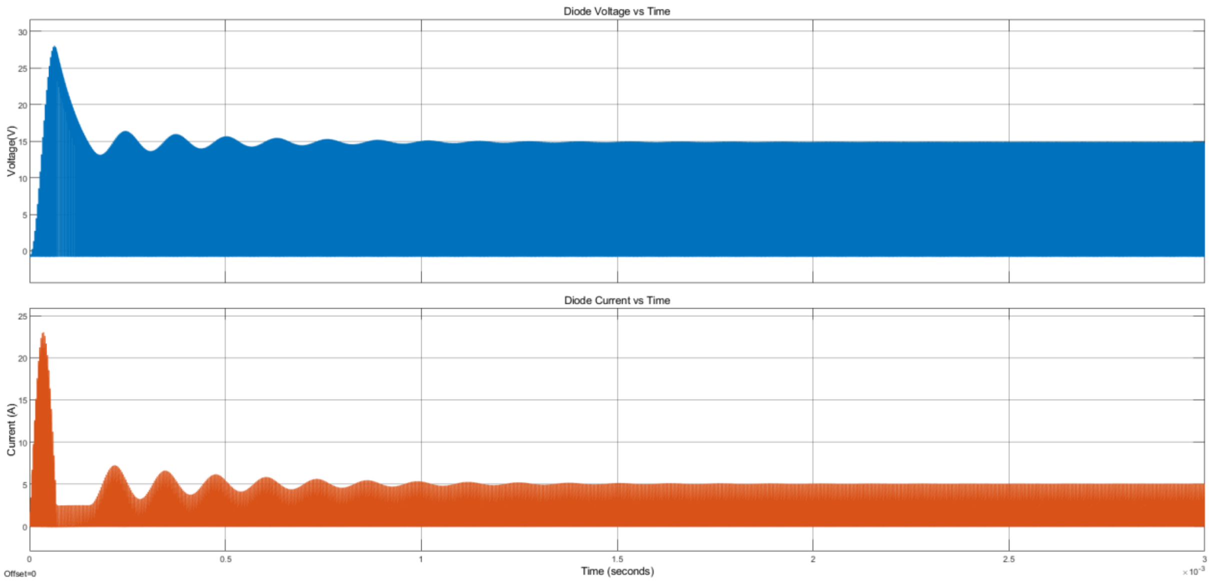

Figure 23:Diode Voltage & Current vs Time for Input Voltage = 5V and D = 74%

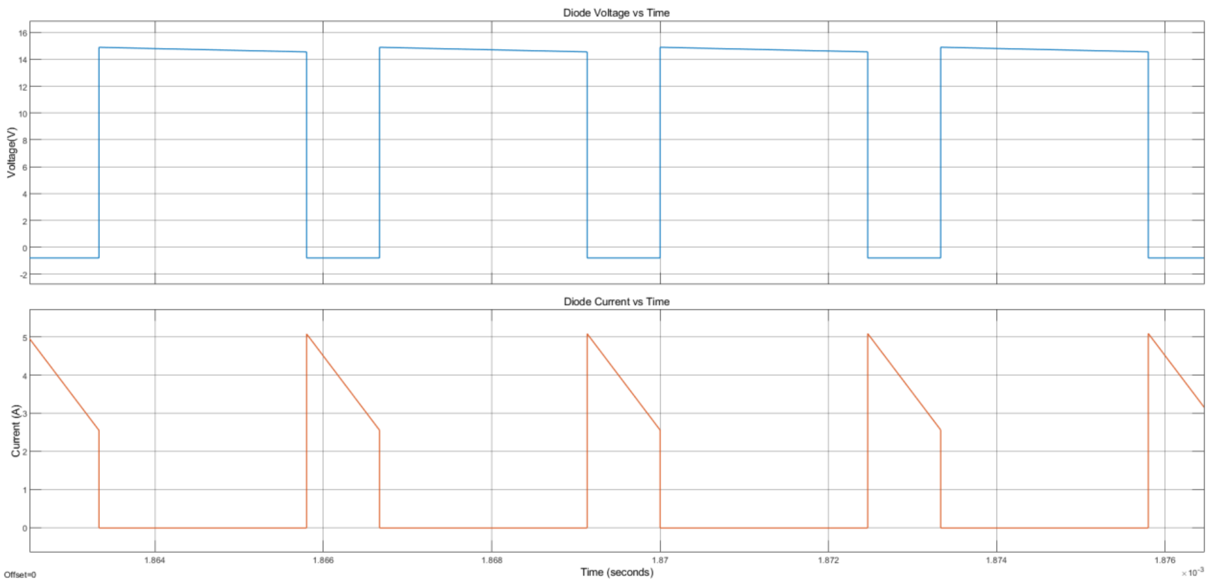

Figure 24:Diode Voltage & Current vs Time for Input Voltage = 5V and D = 74%

d)

without ESR (at steady state):

$$V_L = D * V_{in} + (1 - D) * (V_{in} - V_o)$$

$$V_{in} = (1 - D) * V_o$$

Equation 6

$$D = 1 - \frac{Vin}{Vo}$$

$$\boldsymbol{VoltageGainwithoutESR} = \frac{\boldsymbol{Vo}}{\boldsymbol{Vin}} = \frac{\mathbf{1}}{\mathbf{1} - \boldsymbol{D}}$$

Equation 7

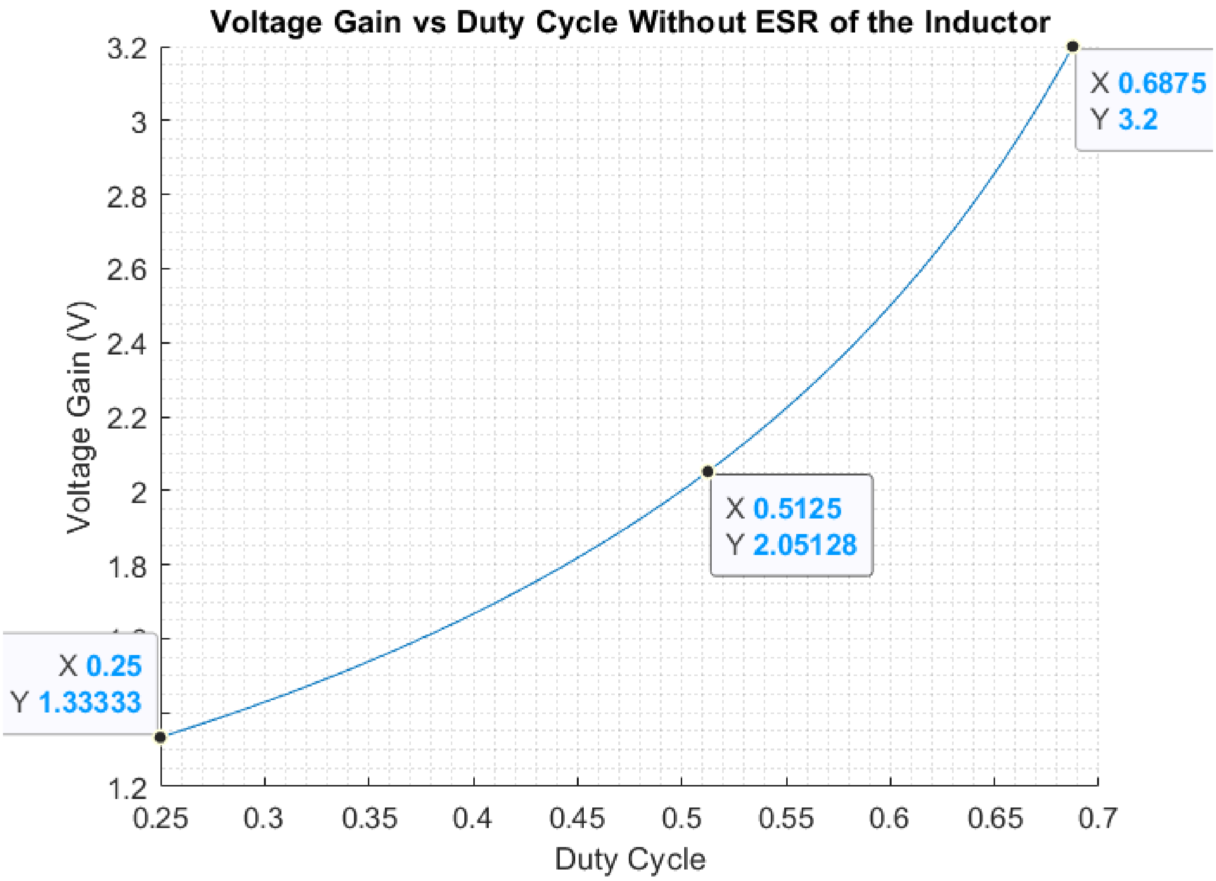

Figure 25:Voltage Gain vs Duty Cycle Without ESR of the Inductor

$$V_{in} * I_L = V_o * I_O = \frac{V_O^2}{R_O}$$

$$I_L = \frac{V_O}{(1 - D) * R_O}$$

Equation 8

With ESR = 0.03Ω;

$$V_L = D * (V_{in} - I_L * ESR) + (1 - D) * (V_{in} - V_o - I_L * ESR)$$

$$V_{in} = (1 - D)V_o + I_L * ESR$$

Using the inductor current found in *Equation 8*:

$$V_{in} = (1-D)V_o + \frac{V_O}{(1-D)*R_O} * ESR = V_O * ((1-D) + \frac{1}{(1-D)*R_O} * ESR)$$

Equation 9

$$VoltageGainwithESR = \frac{Vo}{Vin} = \frac{V_O}{V_O * ((1-D) + \frac{1}{(1-D)*R_O} * ESR)}$$

$$\boldsymbol{VoltageGainwithESR = \frac{1}{((1-D) + \frac{1}{(1-D)*R_O} * ESR)}}$$

Equation 10

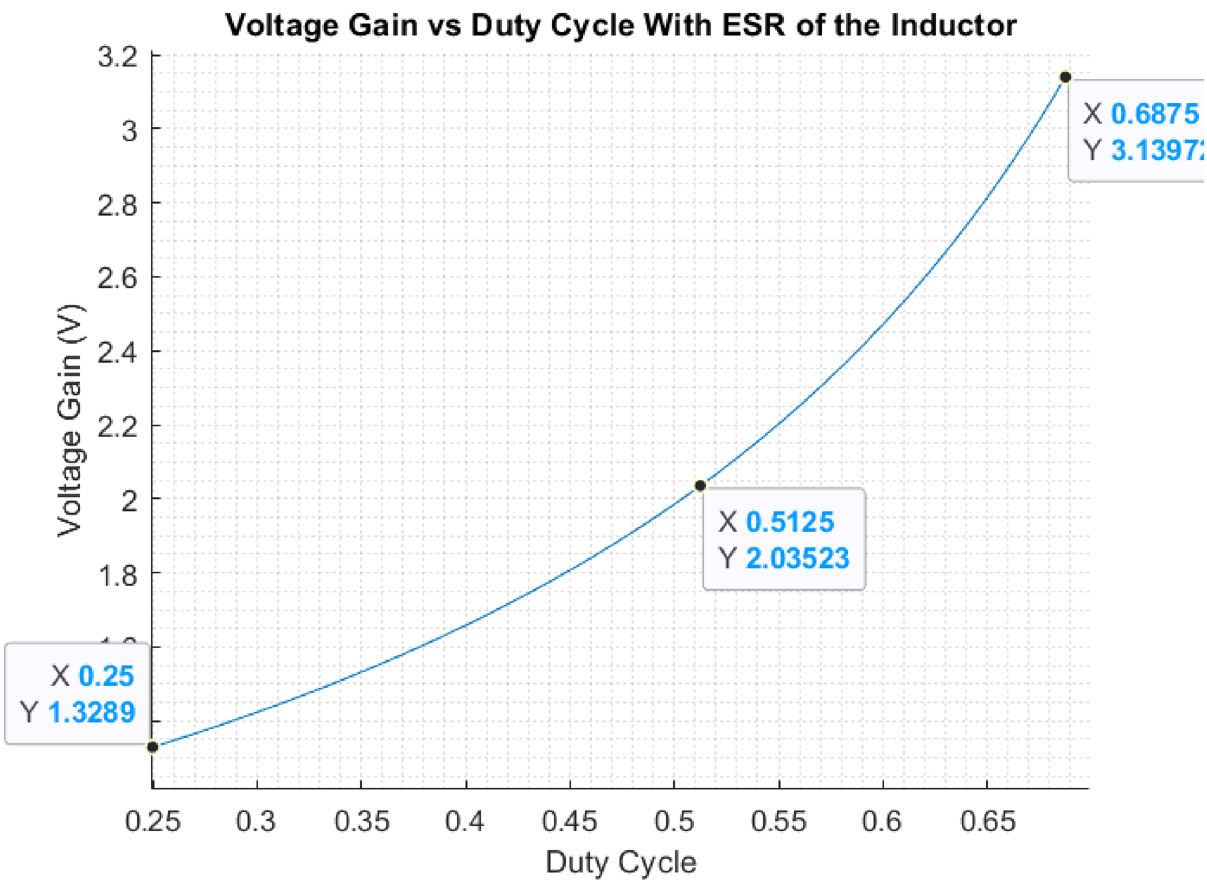

Figure 26:Voltage Gain vs Duty Cycle With ESR of the Inductor

As it can be observed from the plots, there is a slight decrease in voltage gain when the equivalent series resistance of the inductance is also considered. The importance of decrease depends on the ESR: sincec ESR is only 0.04Ω for this question, decrease is not very much.

e)

$$Efficiency = \frac{P_o}{Pin} = \frac{V_o}{V_{in}} * \frac{I_O}{I_{in}}$$

$$\frac{I_o}{I_{in}} = 1 - D$$

Equation 11

Using equation *Equation 11 and Equation 7:*

$$Efficiency = \frac{V_O}{(1-D) * V_O}$$

$$\boldsymbol{EfficiencywithoutESR = 1}$$

Using equation *Equation 9 and Equation 11:*

$$EfficiencywithESR = \frac{Vo}{Vin} = \frac{1}{((1-D) + \frac{1}{(1-D) * R_O} * ESR)} * (1-D)$$

$$\boldsymbol{EfficiencywithESR = \frac{1-D}{((1-D) + \frac{1}{(1-D) * R_O} * ESR)}}$$

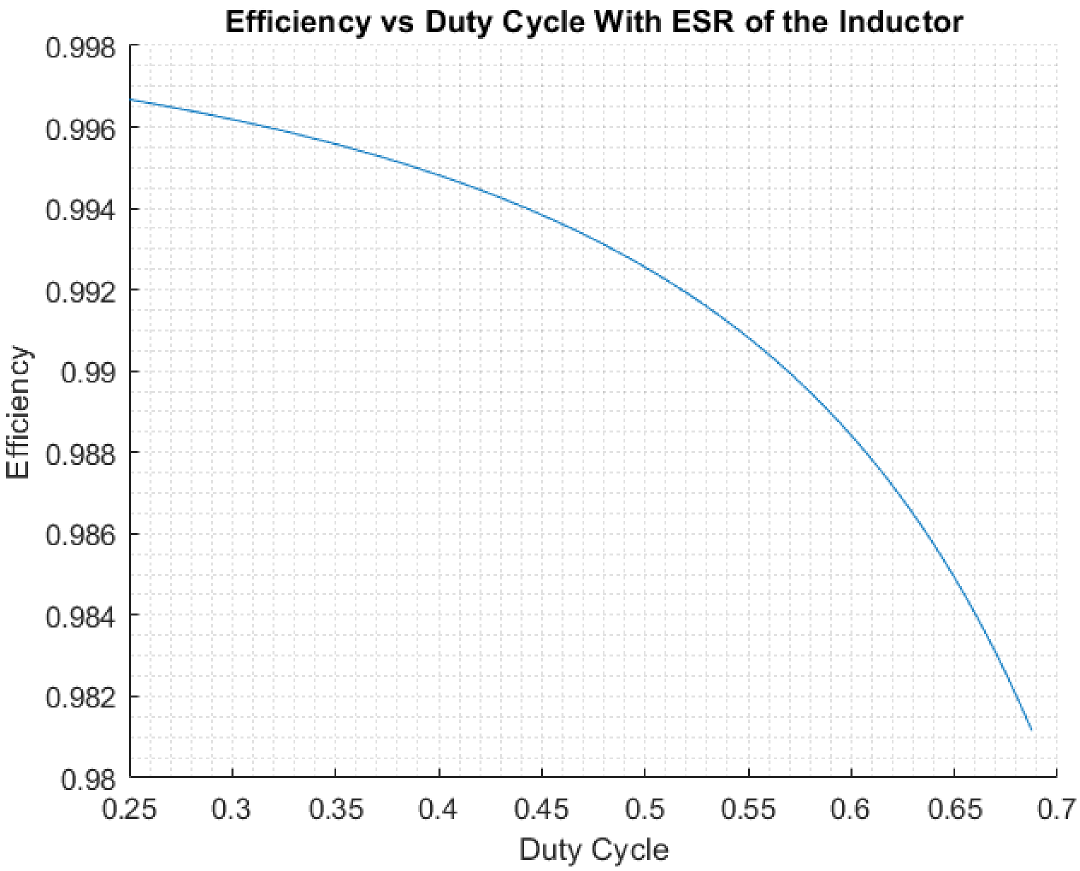

Figure 27:Efficiency vs Duty Cycle With ESR of the Inductor

The efficiency of the converter decreased when the ESR is considered. The reasons are same with the change in voltage drop (part 2.d). So efficiency decreases with increasing ESR.

f)

SB520 Shotthy Rectifier diode and Si3469DV P channel MOSFET are chosen.

MOSFET parameters:

- $R_{DS(on)} = 24\ m\Omega\ (typical)$
- $t_r = 12\ ns\ (typical)$
- $t_f = 35\ ns\ (typical)$

Diode parameters:

- $V_F = 0.55\ V\ (typical)$

For input voltage to be 12V, D=0,25. Then:

$$I_L = \frac{V_O}{(1-D)*R_O} = \frac{16}{(1-0{,}25)*16} = 1.333\ A$$

Losses:

MOSFET:

$$P_{MOSFET} = P_{conduction} + P_{switch}$$

$$P_{conduction} = I_d^2 * R_{DS(on)} * D$$

$$P_{switch} = I_L * V_{max} * fs * \left(t_r + t_f\right)$$

$$P_{conduction} = 1.333^2 * 0.024 * 0.25 = 10.66\, mW$$

$$P_{switch} = 1.333 * 16 * 300000 * (12 + 35) * 10^{-9} = 300.72\, mW$$

$$P_{MOSFET} = 10.66 + 300.72 = 311.38 mW$$

DIODE:

$$P_{Diode} = I_L * V_F * (1 - D)$$

$$P_{Diode} = 1.333 * 0.55 * (1 - 0.25) = 549.86\, mW$$

Duty cycle is proportional to diode loss and MOSFET conduction loss. Even though diode loss has significant effect, MOSFET conduction loss is insignificant compared to MOSFET switching loss at this frequency.

g)

- $T_{Ambient} = 25^{o}C$

MOSFET

- $R_{Thj} = 90^{o}C/W$

$$T_{MOSFET} = T_{Ambient} + P_{MOSFET} * R_{Thj}$$

$$T_{MOSFET} = 25 + 311.38 * 10^{-3} * 90 = 53.02^{o}C$$

Diode

- $R_{ThJA} = 25^{o}C/W$

$$T_{Diode} = T_{Ambient} + P_{Diode} * R_{ThJA}$$
$$T_{Diode} = 25 + 549.86 * 10^{-3} * 25 = 38.75^{o}C$$

Considering the found temperature datas are between 0°C − 70°C which is temperature standart of commercial, there is no need for any heatsink.

CONCLUSION

In this homework assignment, buck and boost converters were examined. In a buck converter, continuous and discontinuous current modes were investigated. The boundary current that ensures CCM operation was found by analytical calculation. In simulations, it can be seen that the converter that has a lower output current than the boundary current sometimes has zero inductor current. In addition, in DCM operation, when the duty cycle was calculated, it could not be found by using Vo/Vin formula because there is zero output current time in DCM operation. The inrush current was observed in the output current. This caused due to the capacitor is not charged. By adding a soft starter, the duty cycle was increased slowly, and the inrush did not occur. Also, the effect of ESR was observed. ESR increased the output voltage ripple, and a lower ESR was needed for a more stable output voltage. To do that, capacitors with lower ratings can be connected in parallel. As a result, the same capacitance value capacitor with lower ESR can be obtained. Moreover, in a boost converter, continuous and discontinuous current modes were investigated. The minimum inductance that would keep the converter operating in continuous conduction mode is calculated. It is found that in order to inductance to be minimum, the rated current should be eeual to boundary value. Then the output capacitance for a specific voltage ripple is calculated. Both capacitance and inductance are chosen considering the duty cycle range which the converter should work with. After that steady state behavior of the converter is plotted and examined. There happens to be an in rush current due to capacitor not being initially charged. Furthermore, effect of the ESR of the inductor is examined. The voltage gain and efficiency of the converter with and without inductor ESR observed and compared. Finally, proper components with respect to done calculations are selected and then the losses of the system are calculated. Using the selected components parameters and the found losses, a thermal calculation is done and it is decided that the converter does not need a heatsink.

References

- https://www.onsemi.com/pdf/datasheet/sb580-d.pdf
- https://www.vishay.com/docs/72676/si3469dv.pdf