EE464 HOMEWORK1

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INTRODUCTION

In this homework, different types of converters, namely Buck-Boost, Cuk and SEPIC Converters will be investigated. For each of these converters, a converter that steps 16V down to 12V (24W) will be desinged and simulated. Their differences, advantages and the disadvantages will be discussed.

1)

a)In order to have 12V output voltage with the input voltage of 16V in a buck boost converter

$$V_O = \frac{D}{1-D} \times V_D$$

$$D \cong 0.429$$

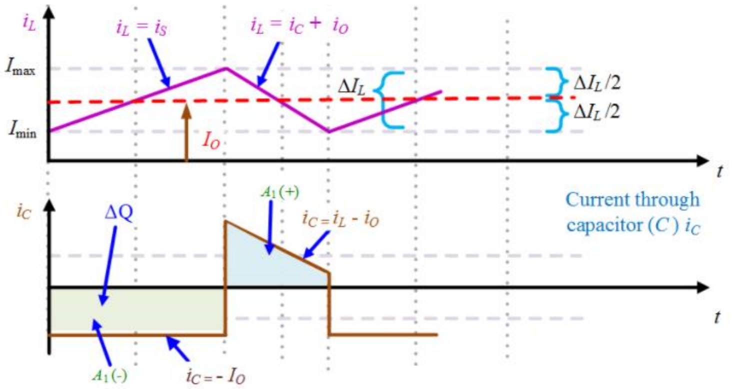

Figure 1: Buck Boost Converter Waveforms

$$\Delta I_L = \frac{1}{L}\int V_L dt = \frac{1}{L} \times V_D \times D \times T_S$$

$$\Delta I_L = I_O \times 0.1$$

The output power is 24W and the input voltage is 16V. Therefore

$$I_{in} = \frac{24W}{16V} = 1.5A \ and \ \ \Delta I_L = \frac{I_O \times 0.1}{D} = 0.35A$$

$$L = \frac{V_D \times D \times T_S}{\Delta I_L} = 0.392mH$$

b) In order to calculate voltage ripple at the output, one needs to consider charging and/or discharging operation of capacitor.

$$\Delta Q = C \times \Delta V_o$$

$$\Delta Q = D \times T_S \times I_O$$

$$\Delta V_o = V_o \times 0.02 \text{ (2\% output voltage ripple)}$$

$$\Delta Q = 0.429 \times \frac{1}{50kHz} \times 2A = 17.16\mu C$$

$$C = \frac{\Delta Q}{\Delta V_O} = \frac{17.16\mu C}{12 \times 0.02} = 71.5\mu F$$

c) Component Selection

Table 1: Selected Products with Ratings for Buck-Boost Converter

Component	Product	Voltage Rating	Current Rating	Price	Amount
L	PQ108081-471MHF	-	4.5A	$6.9000	1
C	C1608X5R1E225K080AB	25V	-	$0.19000	1
Diode	CDBA540-HF	40V	5A	$0.44000	1
MOSFET	2156-FDS5692Z-FSTR-ND	50V	5.8A	$0.99000	1
			Total Price	$8.52	

Because components ratings are the same as the Cuk Converter, we choose some components the same as Cuk Converter components. Component selection reasonings are mentioned in the Question

d)

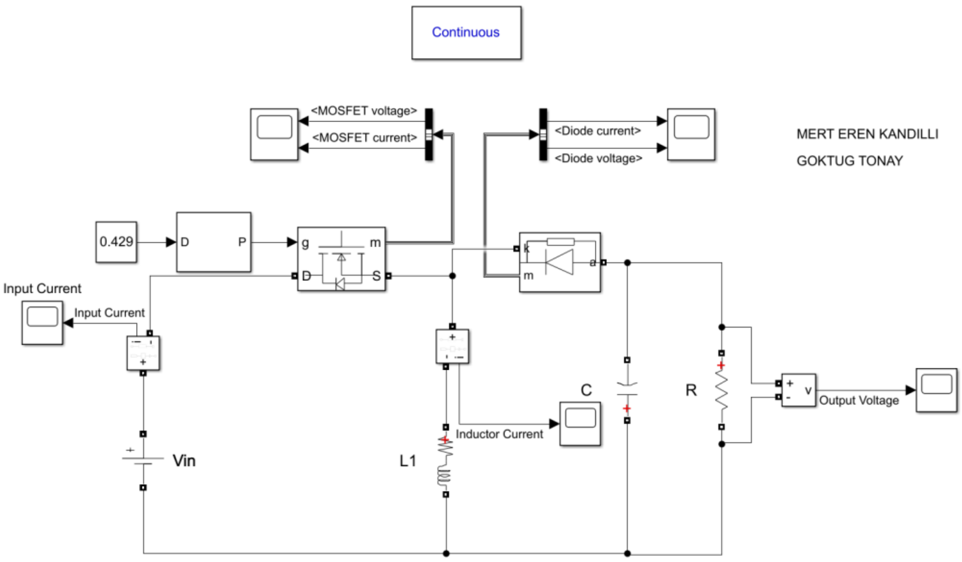

Figure 2: Circuit Schematic of Buck-Boost Converter

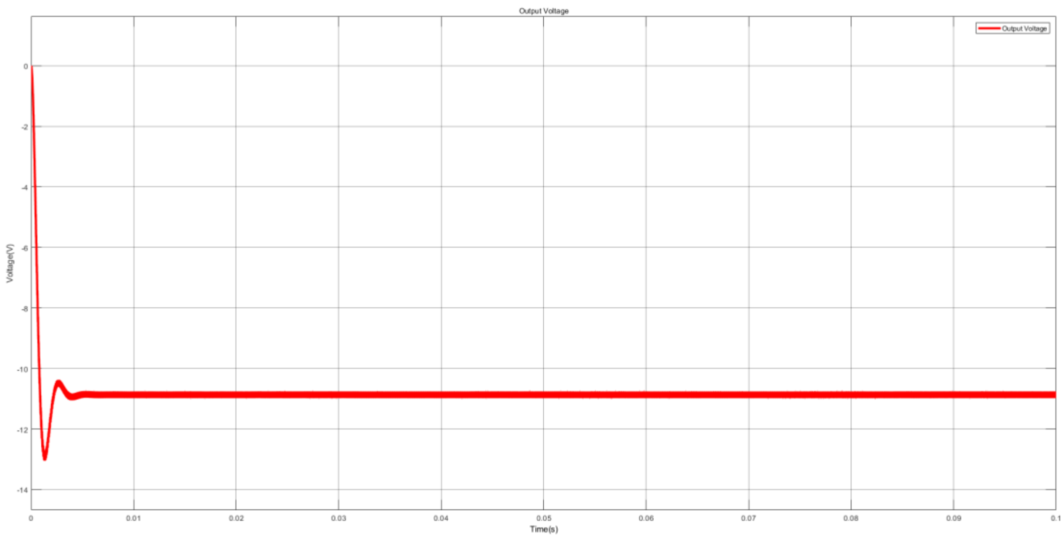

Figure 3: Output Voltage Waveform

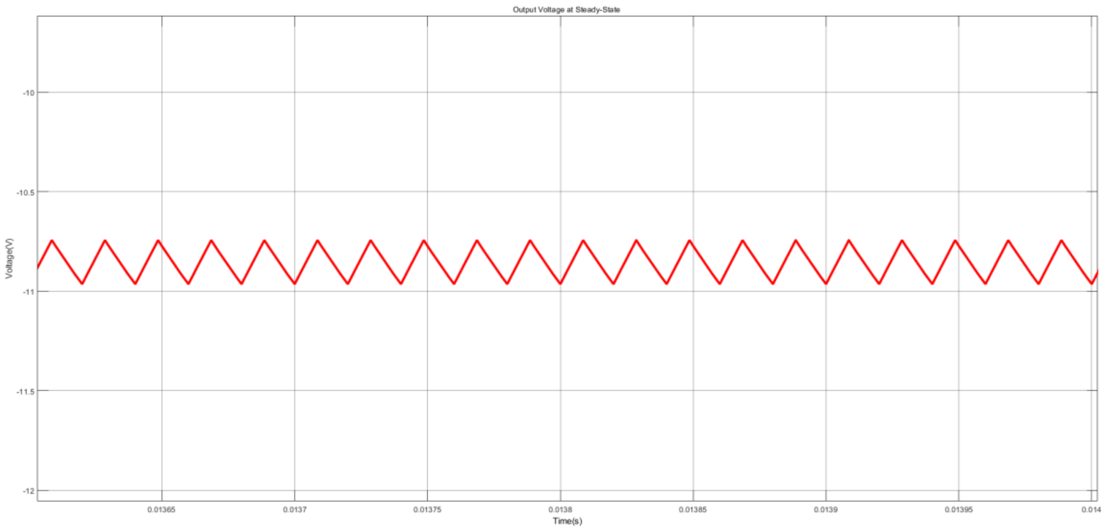

Figure 4: Output Voltage Waveform at the Steady-State

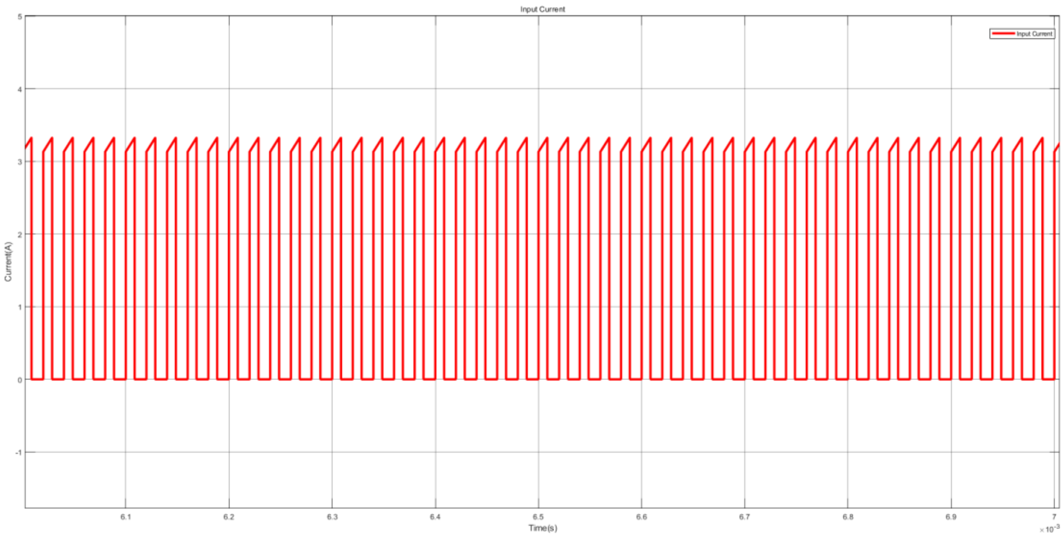

Figure 5: Input Current Waveform at the Steady-State

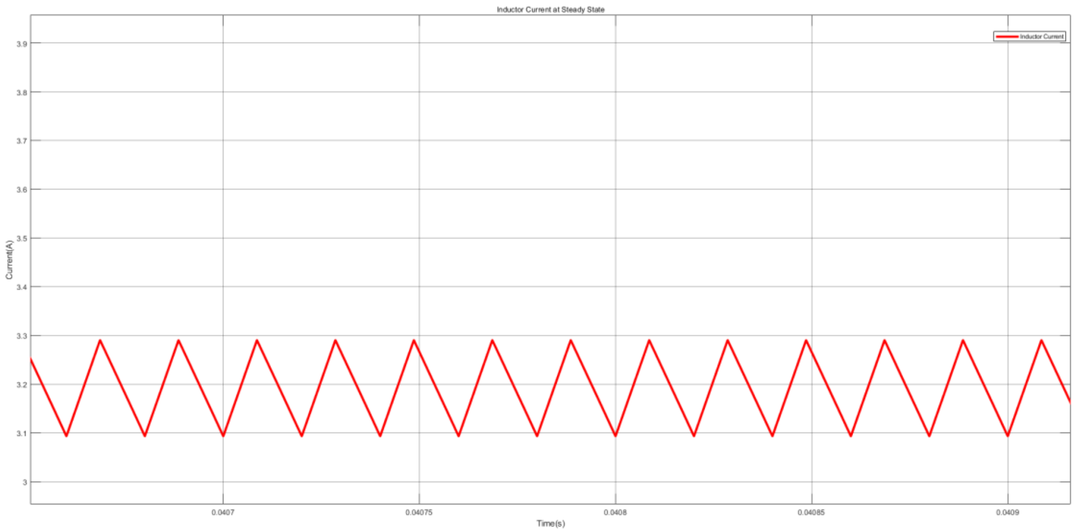

Figure 6: Inductor Current Waveform at the Steady-State

Considering the results, one can say that since there is no inductor in the input side, input current has high ripple compared to the Cuk Converter. Also, when we include the non-idealities, it is observed that the average output voltage is decreased but not significantly. It is expected because with non-idealities, there is now voltage drop on diode and switch.

2)

a) In order to have 12V output voltage with the input voltage of 16V in a buck boost converter

$$V_O = \frac{D}{1-D} \times V_D$$

$$D \cong 0.429$$

When the switch is ON L_1 charges by input source. Therefore,

$$\Delta I_L = \frac{1}{L}\int V_L dt = \frac{1}{L} \times V_D \times D \times T_S$$

$$\Delta I_{L1} = I_{L1} \times 0.1$$

$$I_{L1} = \frac{24W}{16V} = 1.5A \; and \; \Delta I_L = I_{L1} \times 0.1 = 0.15A$$

$$L_1 = \frac{V_D \times D \times T_S}{\Delta I_L} = 0.915mH$$

When the switch is OFF, voltage drop on L_2 is equal to $-V_O$. So it discharges with $-V_O$.

$$I_{L2} = \frac{24W}{12V} = 2A \; and \; \Delta I_L = I_{L1} \times 0.1 = 0.2A$$

$$L_2 = \frac{V_O \times (1-D) \times T_S}{\Delta I_{L2}} = 0.685mH$$

b)

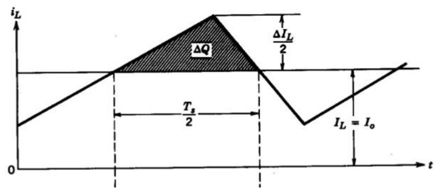

Figure 7: Capacitor Charging Graph

C_2 charges up when I_{L2} is larger than average output current. Area of ΔQ is;

$$\Delta Q = \frac{\frac{\Delta I_{L2}}{2} \times \frac{T_S}{2}}{2} = \frac{0.1 \times 10us}{2} = C\Delta V$$

$$\Delta V = 0.02 \times 12V = 0.24V$$

$$C_2 = 2.08uF$$

C_1 charges up by a constant current, therefore;

$$\Delta Q = I_{L1} \times (1-D) \times T_S = C\Delta V$$

Notice that for ΔV for C_1 is 12+16 = 28V. Therefore, using the equation above one can find C_1 as

$$C_1 = 6.12uF$$

c) Component Selection

Table 2: Selected Products with Ratings for Cuk Converter

Component	Product	Voltage Rating	Current Rating	Price	Amount
L1	CTX1000-1-52LPR	-	2.1A	$6.31860	1
L2	744375 29203681	-	4.8A	$9.16000	1
C1	C2012X5R1V685K125AC	35V	-	$0.67000	1
C2	C1608X5R1E225K080AB	25V	-	$0.19000	1
Diode	CDBA540-HF	40V	5A	$0.44000	1
MOSFET	2156-FDS5692Z-FSTR-ND	50V	5.8A	$0.99000	1
			Total Price	$17.77	

Ratings of the products are given in the Table 2.

To choose inductor for L1, we first simulate the circuit and check the current on L1. According to the results, the max current is about 1.65A. Considering that, we choose an inductor with the current rating of 2.1A. To choose L2, again using the simulation it is seen that maximum current on L2 is about 2A. In order to satisfy the current requirement we choose the inductor L2 given in the Table 2.

For capacitors, we consider their voltage ratings. Using the simulation it is seen that voltage rating of C1 needs to be higher than both input and output voltage, which is expected. Maximum voltage on C1 is about 28V, so we choose a capacitor with the voltage rating of 35V. Also for C2 we choose a capacitor with voltage rating of 25V, since it is output filter capacitor and output voltage is about 12V, this capacitor satisfies the operation. In addition, since ceramic capacitors have lower ESR value especially at high frequencies, we choose our capacitor as ceramic capacitors.

According to the simulation results of diode and switch, they both need voltage rating of about 30V and current rating of 5A. Therefore, given products are choosen.

d)

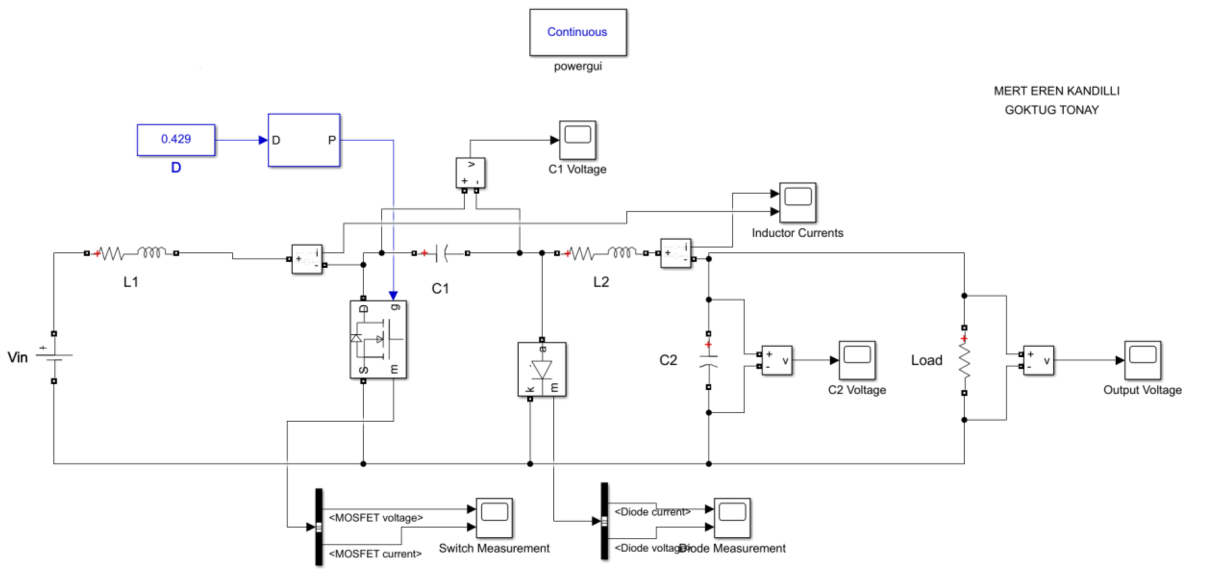

Figure 8: Circuit Schematic of Cuk Converter

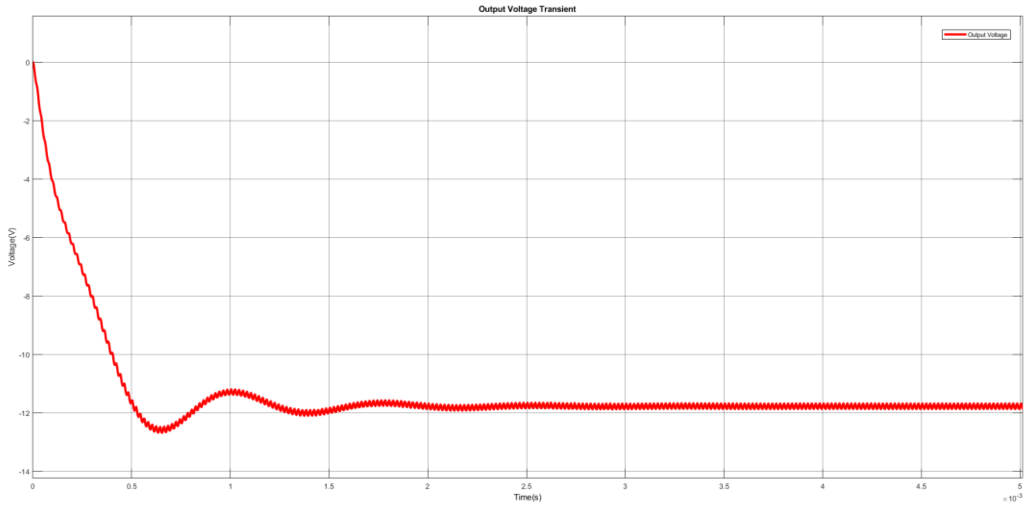

Figure 9: Output Voltage Waveform

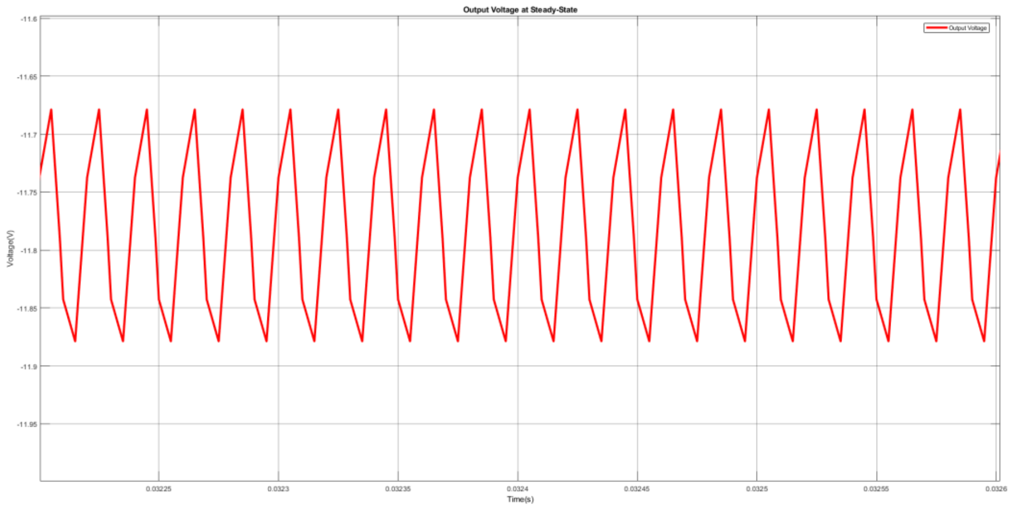

Figure 10: Output Voltage Waveform at the Steady State

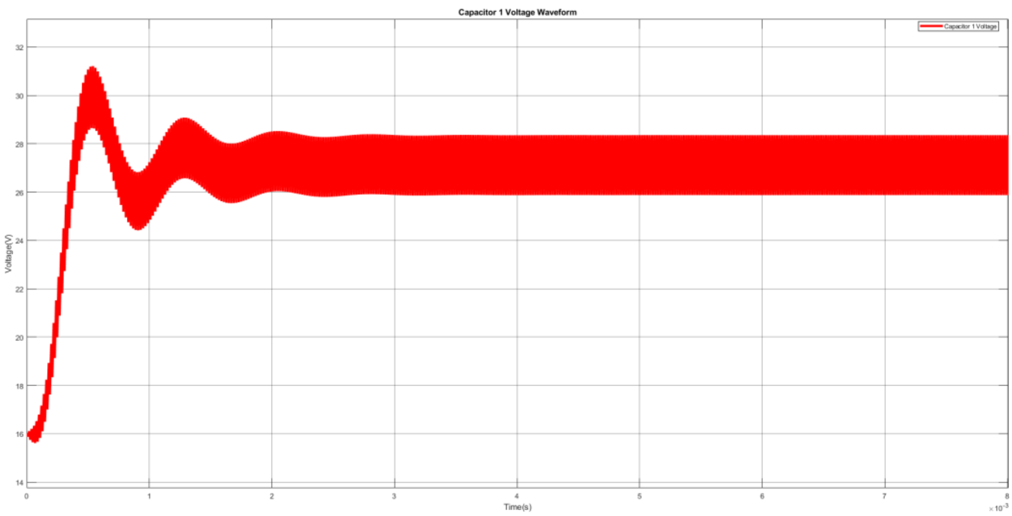

Figure 11: Capacitor Voltage Waveform

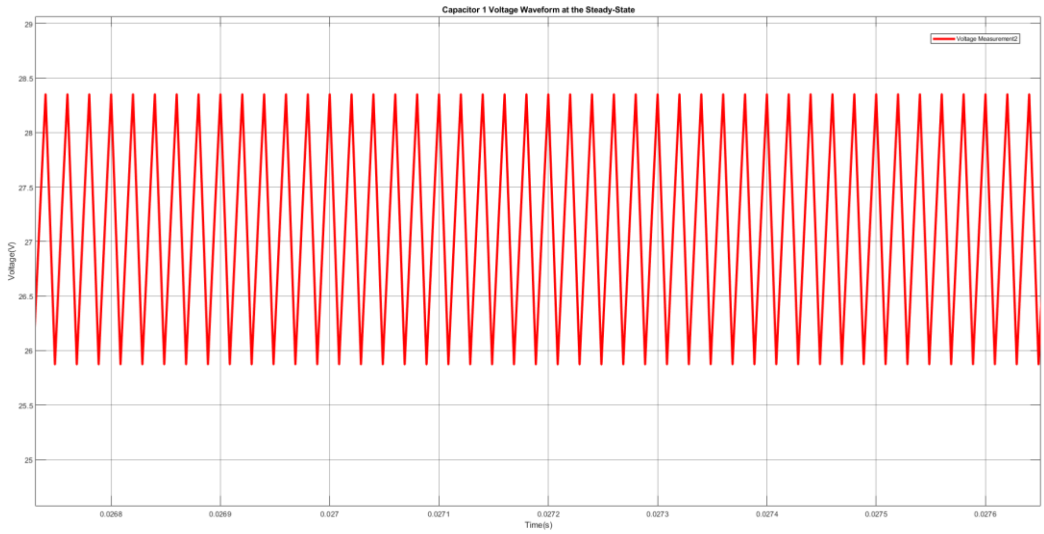

Figure 12: Capacitor Voltage Waveform at the Steady State

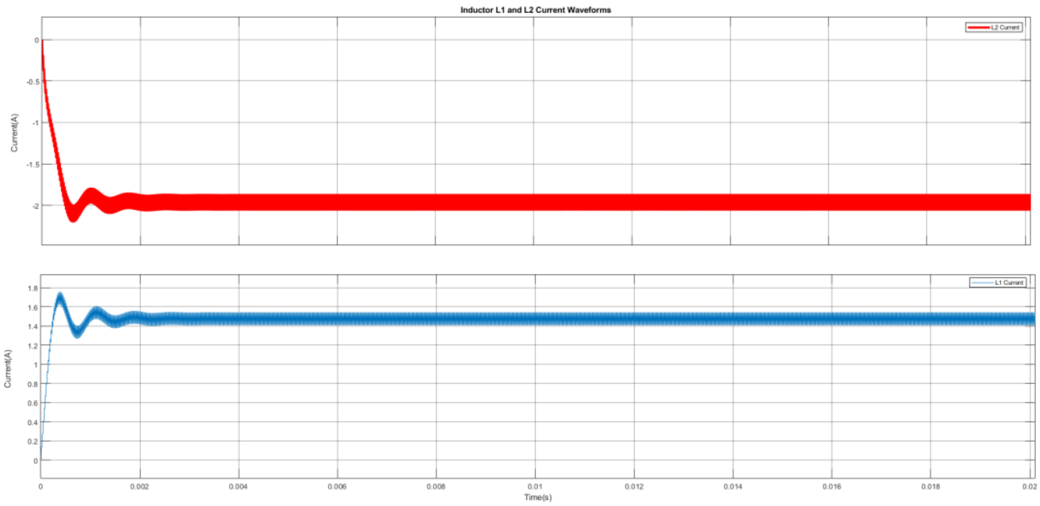

Figure 13: Inductor Current Waveforms

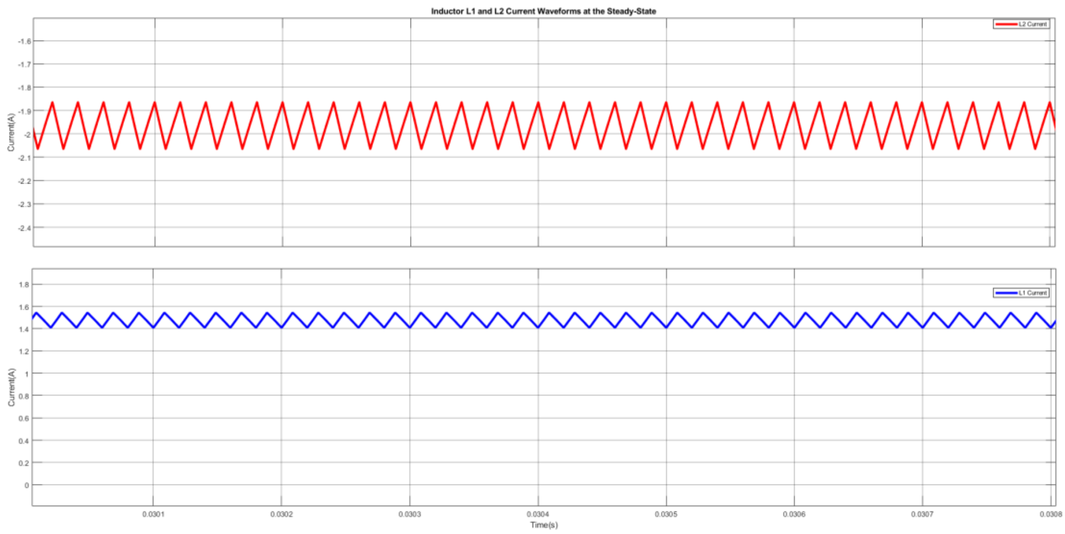

Figure 14: Inductor Current Waveforms at the Steady State

For Cuk Converter, our results (not in the homework) show that there is significant decrease in the ripple of the input current compared to the Buck-Boost Converter. It is expected because there is an inductor in the input side of the Cuk Converter. It is also seen that there is about 2.8V ripple in the capacitor voltage which satisfies the design requirements. Also, due to the nature of the Cuk Converter, a higher voltage drops on the first capacitor is observed than the input and output voltage. This phenomenon is also proved in Q2-Part (b).

3)

a) We know that average current through C_2 at steady state is zero.

$V_O = 12V, P_O = 24W \rightarrow \quad I_O = 2A$ and $R_O = 6\Omega$
$V_{in} = 16V, P_{in} = 24W$ (100% efficiency assumed) → $I_{in} = I_{L1,mean} = 1.5A$

We know that $V_O = V_{in}\frac{D}{1-D}$, then for our values
$12 = 16\frac{D}{1-D} \quad , D = \frac{3}{7}$

We also know that our switching frequency is equal to 50Khz, this means that our period is equal to 20µS. Since we know that while the switch in conduction, capacitor supplies power to the load. This means that for $t = DT = \frac{60}{7}\mu s$ capacitor is discharging.

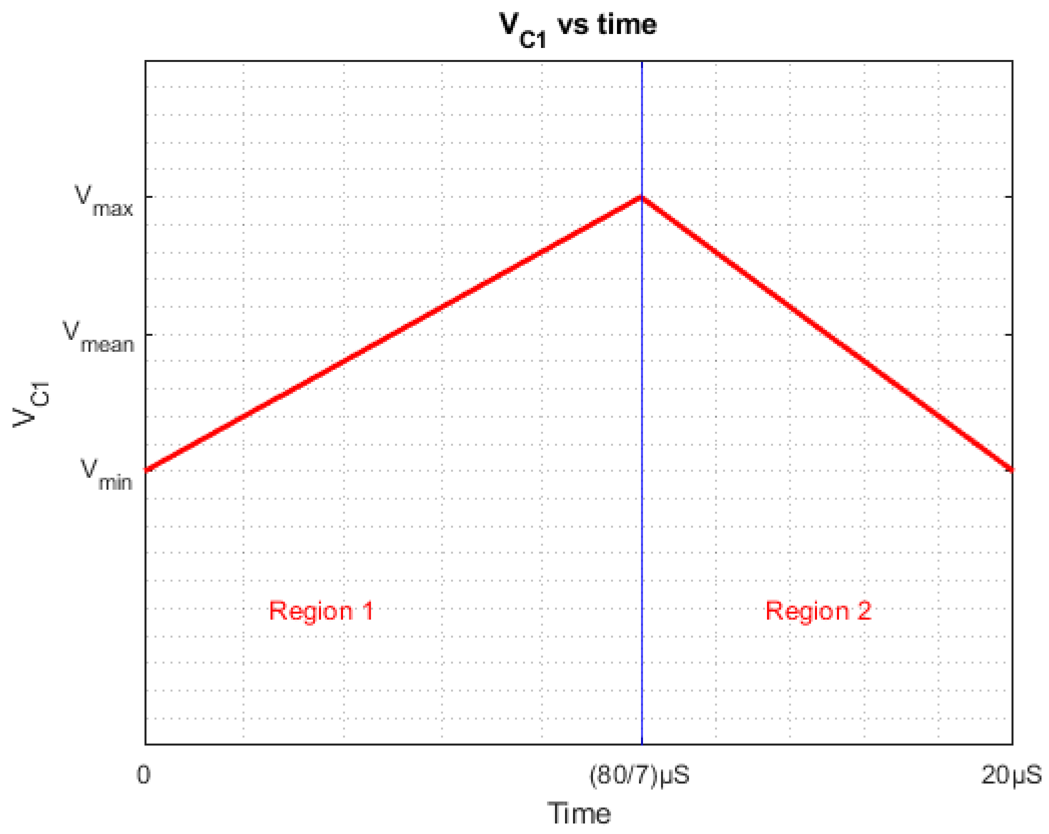

Figure 15: Capacitor voltage vs time graph

Figure 15 shows the capacitor voltage in one period of switching, we know that mean capacitor voltage is equal to 12V.

We also know that in region 1, switch is not in conduction and capacitor is charging. Moreover, in region 2, switch is in conduction and supplies power to the load.

For the 2% voltage ripple, $\Delta v = 0.24V$. This means that $v_{\min} = 11.88V$ and $v_{\max} = 12.12V$

Since this is first homework, we will make this calculation, first assuming that capacitor is discharging with constant current, then by assuming that current is not constant but converter is loaded with constant R load.

If we assume constant discharge current of 2A then

$$v_c(t) = v_c(t=0) + \frac{1}{C}\int_0^t i(\tau)\,d\tau$$

$$11.88V = 12.12V + \frac{1}{C}\int_0^{t=\frac{60}{7}\mu S} -2A\,d\tau$$

Solving this equation yields, C = 71.43µF.

If we assume constant R load

$$I_c = c\frac{dv_c}{dt}$$

$$V_C - V_R = 0$$
$$V_C + I_C R = 0$$
$$V_C + c\frac{dv_c}{dt}R = 0$$
$$\frac{1}{CR}V_C + dV_C = 0$$

Solving this differential equation, $V_C(t) = K * e^{\frac{-t}{RC}}$

If we check for t=0, we can find that K=12.12V, then to satisfy the 0.24V voltage drop in 60/7µs our capacitor must be equal to 71.42µF. This means that constant current method is a good method. For the inductors, I will assume that while charging or charging inductor voltage is constant.

For L_1, we know that mean current is equal to mean input current which is 1.5A, if we assume 10% current ripple, this means that inductor current must fluctuate between 1.425A and 1.575A. Since it is clearly seen that while the switch is in conduction, the inductor current rises with the power of supply voltage, we can easily calculate the required inductance.

$$v_L = L\frac{di}{dt}$$
$$16V = L\frac{0.15A}{\frac{60}{7}\mu S}$$
$$L_1 = 914.3\mu H$$

For the calculation of L_2, if we assume that C_1 and C_2 is large enough to keep the voltage constant, then we can say that mean current through L_2 is equal to mean output current. Moreover, it is clearly seen that while the switch is in conduction, inductor charges with the power of V_{C1}. If we assume that $V_{C1} = V_{in}$. We can calculate the required inductance for L_2.

$$16V = L\frac{0.2A}{\frac{60}{7}\,\mu S}$$

$$L_2 = 685uH$$

B) Since we know the mean current through L_2, by assuming constant discharge current on C_1. We can calculate the required capacitance for 10% ripple voltage. We know that mean voltage is equal to the input voltage, then for 10% ripple voltage change is equal to 1.6V.

$$-1.6V = +\frac{1}{C}\int_{0}^{t=\frac{60}{7}\mu S} -2A\,d\tau$$

$$C_1 = 10.71\mu F$$

C) Since the required capacitance value for C_2 is high for using all ceramic capacitor (it is not an economical solution), I will select an electrolytic capacitor and use it parallel with a ceramic capacitor. This will also help our electrolytic capacitor to handle high ripple current.

I will select an 68µF electrolytic capacitor and add ceramic capacitors for the complete it to 71.43µF. We know that capacitance of ceramic capacitors highly depends on the voltage across it. So, the exact required capacitance for the ceramic capacitors will depend on the selected series (given capacitance value is generally at 0V).

For 68uF electrolytic capacitor, I am selecting 25ZLJ68M5X11 from Rubycon. Specifications of it for 50Khz can be seen in the table below.

Table 3: Selected electrolytic capacitor

Capacitance	68µF
Voltage rating	25V
Impedance at ~50Khz	0.4Ω
Rated ripple current ~50Khz	450mA

For the ceramic capacitors Taiyo Yuden is selected as manufacturer, it is known that capacitance value will reduce with increased voltage. Even though we know that we will lose most of capacitance if we select 25V rated capacitor, for simplicity I am directly selecting an 25V voltage and by looking the DC bias characteristics I am selecting a 10uF 25V rated 0805 package capacitor coded as MSAST21GBB5106MTNA01 (previously TMK212BBJ106MG-T) its DC bias characteristics can be seen below.

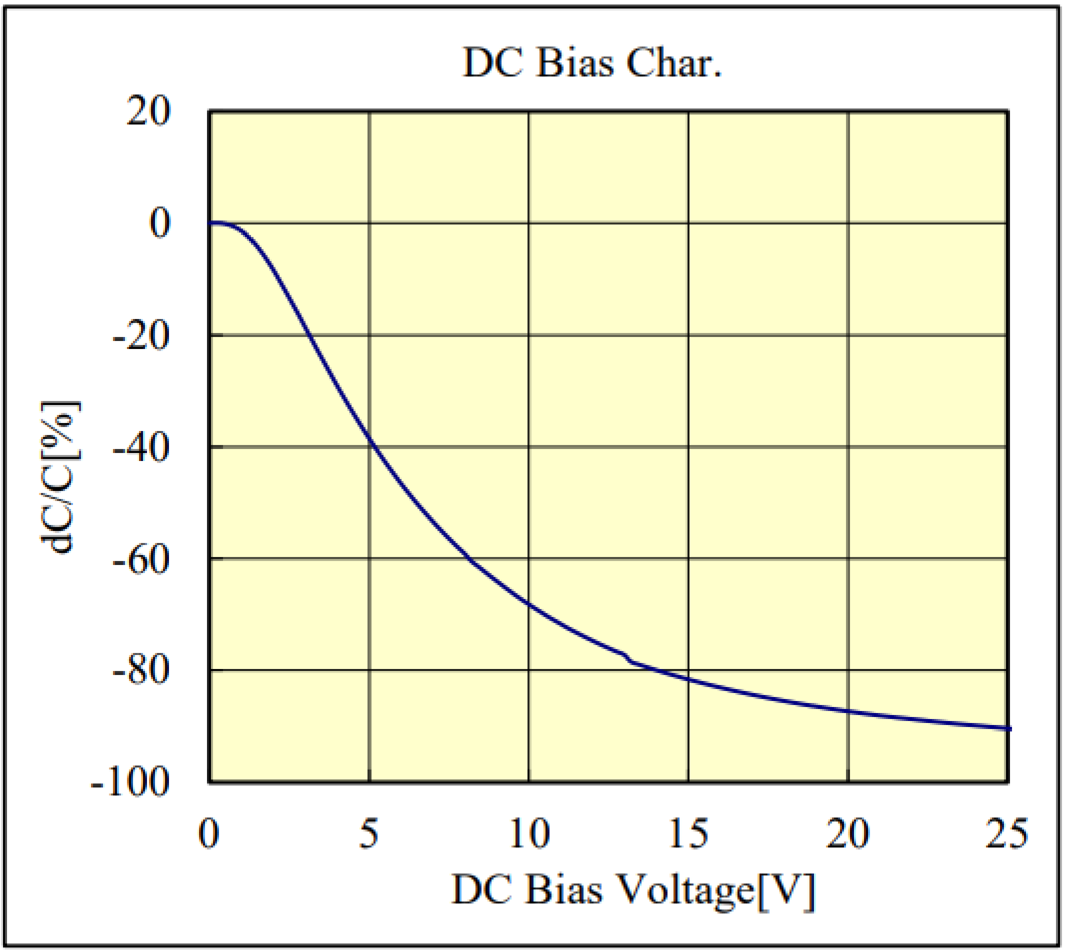

Figure 16: DC bias characteristics for selected ceramic capacitor

Dc bias value for every voltage value can be seen from the manufacturer's web site, for 12V bias loss in capacitance is equal to -74.73% this means that our capacitance at steady state will equal to 2.527µF.
Then by simplicity we can use two of them in parallel.

Final $C_2 = 68\mu F(\text{electrolytic capacitor}) + 2 * 2.52\mu\text{F}(\text{ceramic capacitor}) = 73\mu F$

For the C_1, required capacitance value can be satisfied by using only ceramic capacitors, but it will require a lot of them in parallel. Since we don't have a restrictions about it, I will do it. So if we use the same ceramic capacitor at 16V, capacitance value will be equal to 1.69µF, we can use it by paralleling seven of them.

Final $C_1 = 7 * 1.69\mu F = 11.83\mu F$. Using the same capacitor again better for mass production.

I will continue with the selection of inductors and start with the L1. Required minimum inductance value is 914µH and I will ignore the saturation effect on this part and look for inductors which have higher saturation current than 1.575A

For the L1, AIRD-03-102K from Abracon LLC, satisfies those conditions. It has 1mH inductance value and 2A saturation current.

After repeating the same procedure for L2, DC1050R-824K from API Delevan Inc., can be used for L2. It has 820µH inductance and 2.5A saturation current.

Since our currents are quite low for a discrete mosfet, I will directly search for a mosfet. RQ3G100GNTB from Rohm Semiconductor. It has the enough voltage and current ratings for our converter.

Our last component is diode, SS5P4-M3/86A from Vishay General Semiconductor - Diodes Division selected.

Table 4: Selected Products for SEPIC Converter

Component	Product	Price	Amount
L1	**AIRD-03-102K**	**$6.07**	**1**
L2	**DC1050R-824K**	**$7.37**	**1**
C1	**MSAST21GBB5106MTNA01**	**$0.21**	**7**
C2 ceramic	**MSAST21GBB5106MTNA01**	**$0.21**	**2**
C2 electrolytic	**25ZLJ68M5X11**	**$0.28**	**1**
MOSFET	**RQ3G100GNTB**	**$0.49**	**1**
Diode	**SS5P4-M3/86A**	**$0.67**	**1**
		Total Price	$16.77

D)

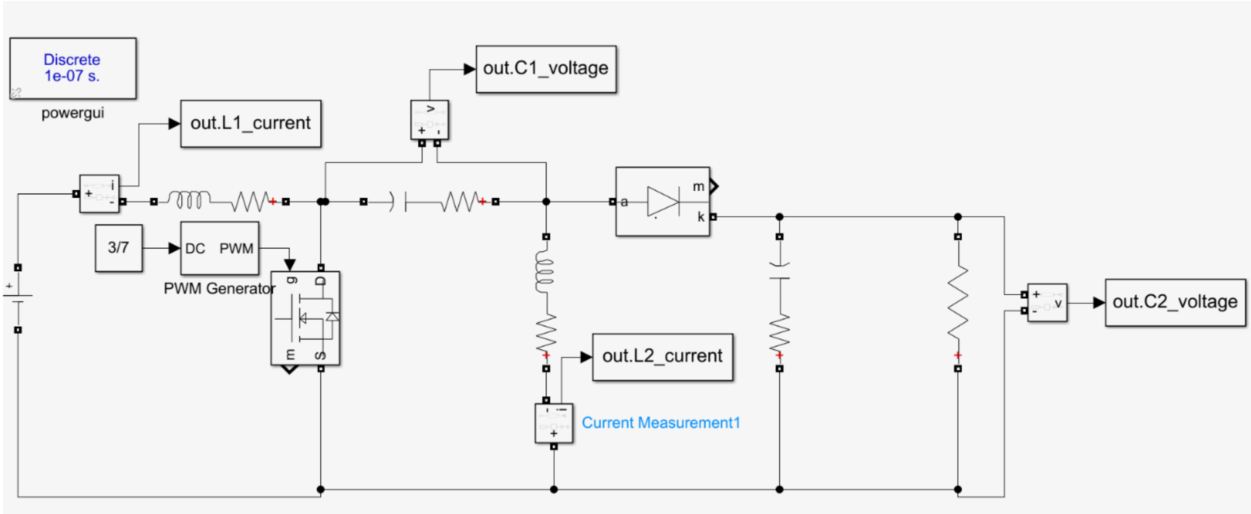

Figure 17: Simulation model for SEPIC converter

Firstly, while calculating our duty cycle we didn't include voltage drop due to diode. Moreover, we neglect the resistance of the inductors, ESR of capacitors. Due to those differences, our results will be different than our idealized solutions.

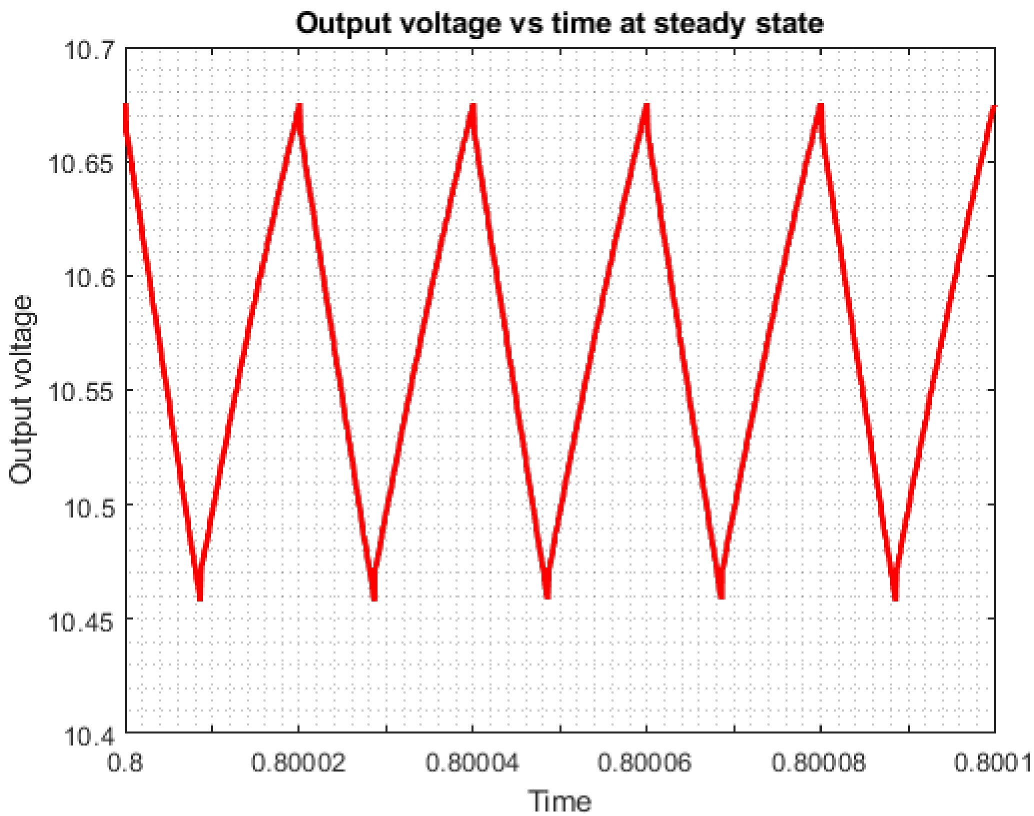

Figure 18: Output voltage vs Time

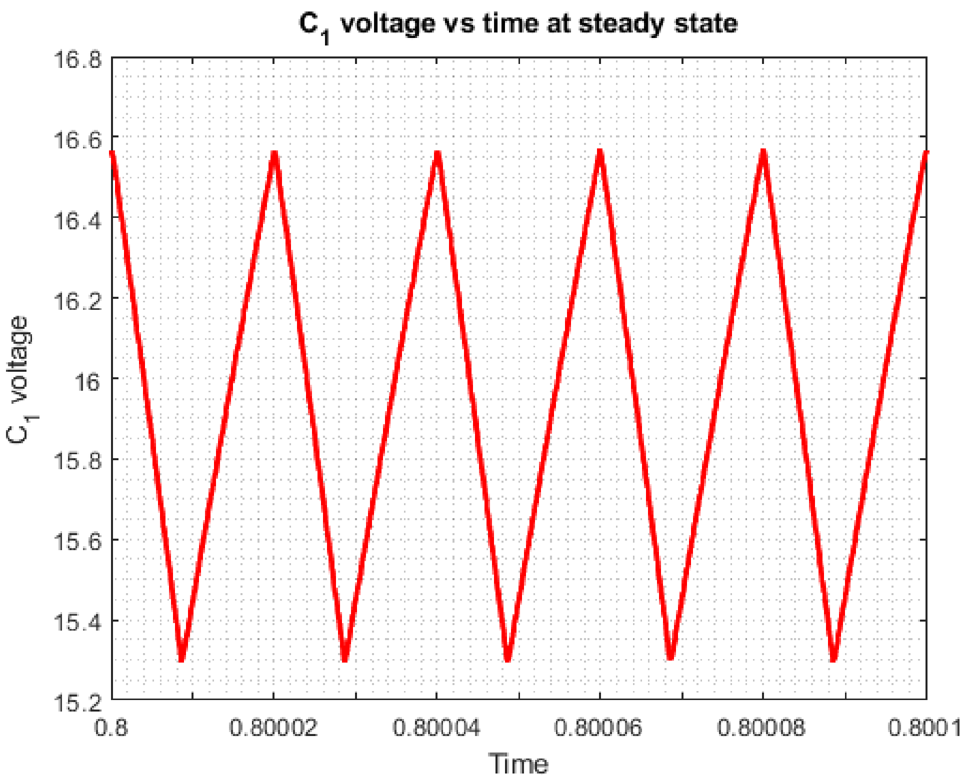

Figure 19: C1 voltage vs time

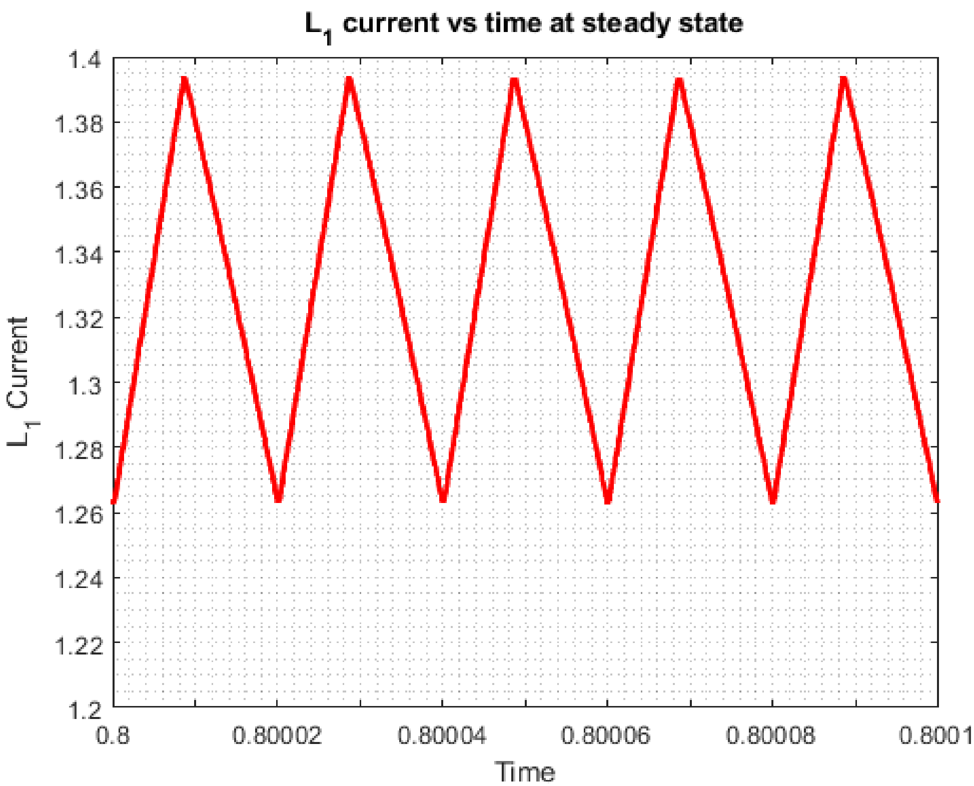

Figure 20: L1 current vs time

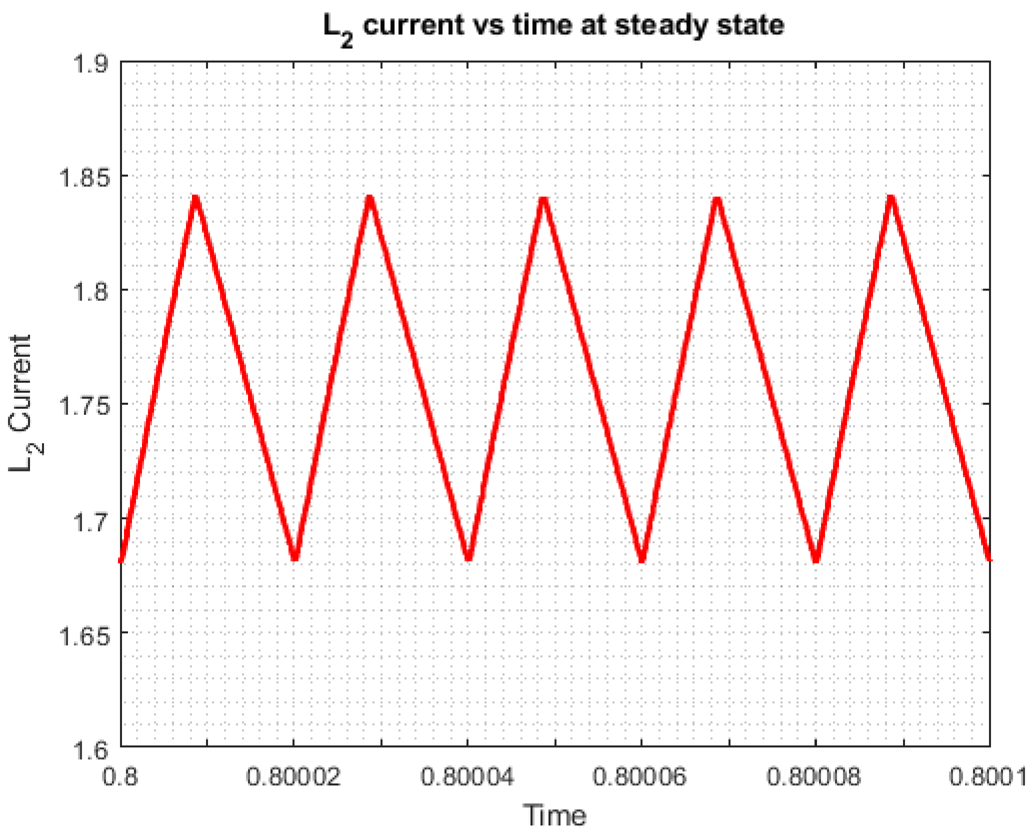

Figure 21: L2 current vs time

Figure 18, 19, 20, 21 shows the required plots. It is clear that output voltage is less than required, however this can be fixed easily with closed loop control. Moreover, output voltage ripple value is required is less than 2%, for the 12V output this is equal to 0.24V ripple, this is satisfied, however our output voltage is different and for the current value the ripple value 0.21V with mean voltage of 10.57V, this means that our ripple value is at the limit. The assumptions for the C1, L1 and L2 is satisfied.

4)

A) Cost of each design in table represented in their relevant sections, for the detailed costs Table 1,2 and 3 can be analyzed. Summary of the costs can be seen table below.

Table 5: Summary of cost of designs

Topology	**Cost**
Buck-Boost	$8.52
Cuk	$17.77
SEPIC	$16.77

B) Input current waveforms are also mentioned in advantage/disadvantage section however, for the SEPIC and CUK converter it is much better than buck-boost converter, main reason of this difference is the inductor at the input current path of CUK and SEPIC converter.

Advantages of Buck Boost converter can be summarized as follows:

- Required inductance is smaller than other converters
- Switch current is smaller
- Number of required components are less, smaller design could be achieved
- If negative voltage is required, it can be created quite easily with that topology

Disadvantages of Buck Boost converter can be summarized as follows :

- Output is inverted, this could create problematic cases if we need to communicate with a circuit which is referenced the sources ground, to solve it we need additional components, this will increase the price of system
- Input current ripple is higher, there will be problems about EMC, more filtering is required at the input compared to other converters
- Switch is in high side, so more complex or expensive drive circuitry(maybe integrated with control circuitry) required

Advantages of CUK converter can be summarized as follows:

- Better input current waveform compared to buck-boost converter
- Switch is in low side, simpler driver circuit than buck-boost converter
- Small capacitances are needed
- If negative voltage is required, it can be created quite easily with that topology

Disadvantages of CUK converter can be summarized as follows :

- Output is inverted, this could create problematic cases if we need to communicate with a circuit which is referenced the sources ground, to solve it we need additional components, this will increase the price of system
- Require more components compared to buck-boost converter, it is more expensive
- High current ripple on capacitor

Advantages of SEPIC converter can be summarized as follows:

- Better input current waveform compared to buck-boost converter
- Switch is in low side, simpler driver circuit than buck-boost converter
- Positive output voltage

Disadvantages of SEPIC converter can be summarized as follows :

- It has more components compared to buck-boost topology, due to our switching frequency capacitances and inductances are quite high.
- Require more components compared to buck-boost converter, it is more expensive
- High ripple current on capacitors

C)

First of all, I think that our switching frequency for CUK and SEPIC converter is quite low, for the buck-boost converter it could be in a usable range. Due to our low switching frequency, required inductances and capacitances are quite big.

If I must choose one of them, I will certainly choose SEPIC converter due to positive output voltage. It will have a lot of advantage in terms of feedback and communication-based things. However, I will certainly increase my switching frequency to more than 200kHz. Main reason of my chose is positive output voltage.

For the CUK and buck-boost converter, negative output voltage could be quite useful in Display power supplies, if filtered correctly in symmetrical supply cases. However CUK converter has advantage in terms of EMC (input and output has inductors) , due to that reason if there is no problem space or price related, then I will chose CUK converter. Buck-boost will be my last choice.