EE464 STATIC POWER CONVERSION II

Simulation and Magnetic Design Report

Team Members: Ozan Aktürk 2303923, Ekin Arda Çömez 2374791, Ahmet Bilgin 2231488

Deadline: 30/04/2023 23:59

Lecturer: Assoc. Prof. Ozan Keysan

Assistant: Ogün Altun

Introduction

This report is a combination of both “HW2” and “Simulation and Magnetic Design Report”. The contents include the topology selection, magnetizing inductor calculations, core selection steps, the simulation results and loss analysis. The aim of the report is to prepare a template for the hardware project circuit and face the design problems before implementation.

Topology Selection

The topology selection is done via comparing the topology types that we learnt during the lectures. The selected topologies to compare are as follows:

- Flyback
- Forward
- Push-pull
- Full Bridge
- Half Bridge

Table 1: A basic comparison between several isolated DC-DC converters

Topology Name	Optimal Power Demand	Efficiency	Number of Components	Voltage Stress	Cost
Flyback	Low (<500W)	High	4	High	Low
Half Bridge	Low (<500W)	High	7	High	Medium
Full Bridge	High (>1kW)	Medium	9	Medium	High
Push Pull	High (>1kW)	Medium	8	High	High
Forward	Low (<500W)	High	7	Medium	Low

Table 2: A more detailed analysis between the topologies

Topology Type	Advantages	Disadvantages
Flyback	Simplest and most commonly used isolated DC-DC converter	Additional snubber circuit for the leakage inductance di/dt
	Does not require a separate storage inductor	Relatively lower efficiency
Half Bridge	Higher power levels	Need to be careful with the switches not to short the input (leave dead time)
	The switching stresses are equal to the input voltage	Less suitable for high output currents
Full Bridge	Even higher power levels	Need to be careful with the switches not to short the input (leave dead time)
	Allows the power flow in both directions	Switching losses increase
Push Pull	Utilizes the core more efficiently, reaching high power levels	Switching control is a bit difficult

	Output current is regulated with the output inductor	Switching stresses are high
Forward	Can supply high output currents with less di/dt	Extra inductor at the output
	Gain equation is linear with the duty cycle	Not suitable for high output voltage

Considering the positives and the negatives, our final topology choice is the flyback converter. The most critical factor is the component number and the cost for us. The control method is also relatively easier. The flyback converter also makes same as the highest efficiency is not required and the project is a low-power project. As a disadvantage, a snubber design is required.

Flyback Converter Design

Specifications of the project are listed as follows:

- **Minimum Input Voltage**: 12 V
- **Maximum Input Voltage**: 18 V
- **Output Voltage**: 48 V
- **Output Power**: 48 W
- **Output Voltage Peak-to-Peak Ripple**: 3%
- **Line Regulation**(Deviation of percent output voltage when input voltage is changed from its minimum to maximum or vice versa): 3%
- **Load Regulation**(Deviation of percent output voltage when load current is changed from 10% to 100% or vice versa): 3%

a)

$$\frac{Vo}{Vin} = \frac{D}{1-D} * \frac{N2}{N1}$$

$$\frac{8}{3} \leq \frac{D}{1-D} * \frac{N2}{N1} \leq 4$$

Let's choose duty cycle range as

$$0.3 \leq D \leq 0.7$$

for safe operation After that, boundaries of turns ratio becomes,

$$1.15 \leq \frac{N2}{N1} \leq 9.33$$

Let's select turns ratio = N1/N2 = 1/3. After that,

$$\frac{8}{9} \leq \frac{D}{1-D} \leq \frac{4}{3}$$

Then,

$$0.47 \leq D \leq 0.58$$

when N2/N1 = 3.

b)

In order to design convenient transformer, the magnetizing inductance should be decided. Maximum, average and RMS value magnetizing current should be calculated. When the switch is on, input current is equal to magnetizing current. However, input current is equal to 0 when the switch is off.

$$Imavg = \frac{Iin}{D} = \frac{Pout}{Vin * D}$$

When the input voltage is equal to 12 V, duty cycle is equal to 0.58. Then,

$$Imavg = \frac{48}{12 * 0.58} = 6.9\ A$$

When the input voltage is equal to 18 V, duty cycle is equal to 0.47. After that,

$$Imavg = \frac{48}{18 * 0.47} = 5.67\ A$$

The ripple current formula is given below as;

$$\Delta Im = \frac{Vin * D * Ts}{Lm}$$

We assume that fs = 50 kHz because a lot of controllers work at that frequency. Moreover, we should consider the case of input voltage = 18 V and D = 0.47 because ripple current is larger for larger Vin*D values for same inductance value. In this case, the maximum ripple current would be equal to 5.67*2 = 11.34 A to stay at continous conduction mode. Hence,

$$Lm \geq \frac{18 * 0.47}{11.34 * 50 * 10^3} = 14.92\ uH$$

For the case of input voltage = 12 V, D = 0.58 and ripple current = 6.9*2 = 13.8 A;

$$Lm \geq \frac{12 * 0.58}{13.8 * 50 * 10^3} = 10.08\ uH$$

This result also verifies that Lm should be greater than 14.92 uH.

To decide the Lm current ripple we consider the 25% load case. For Vin = 18V, the minimum inductor current should not be dropping to zero. Then;

$\Delta Im = 0.25 * 5.67 * 2$ = 2.835 A

Imax = 6.9 + 2.835/2 = 8.318 A

Iavg_max = 6.9 A

Then,

$$Lm \geq \frac{18 * 0.47}{2.835 * 50 * 10^3} = 59.68\, uH$$

For the core selection, we consider magnetic flux, cross sectional area of the core and copper properties. First, we searched the ferrite cores, however, they are not suitable for flyback converter design if we do not use air gap. The reason is that they have large permeability so that they are not convenient for storing energy. Then, we look at Kool Mu cores from Magnetics from the excel table. We prepared Matlab Script that we also added it to the Github repository. We compared different cores from the Excel table that are already in the lab and will come in the May. Moreover, we have benefitted from the Magnetics Powder Core Catalog. We have specifications of;

- Minimum inductance = 59.68 uH
- The maximum current = 8.318 A (without losses)

After that, from the formula of

$$L_m = \frac{N^2}{R} = N^2 * A_l \rightarrow N = \sqrt{\frac{L_m}{A_l}}$$

we moved on the core selector charts. Then, the core 00K4022E090 satisfied the requirements of our project. Moreover, it is also available in the lab.

The inductance factor of the core is AL = 281 nH/T^2. However, it can be as ±8%. Therefore, the minimum inductance factor is calculated as 258.52 nH/T^2.

We have calculated to primary number of turns as;

$$N_{pri} = \sqrt{\frac{L_m}{A_{l-min}}} = \sqrt{\frac{59.68 * 10^{-6}}{258.52 * 10^{-9}}} = 15.1938$$

However, the number of turns should be integer number. Therefore, we have taken as

$$N_1 = 16$$

This number of turns is calculated assuming there are no change in AL. However, since AL changes with MMF, we have calculated MMF when I=$\frac{\Delta I}{2} = 1.42A$.

$$MMF = N * I = 16 * 1.42 = 22.68\, A - t$$

According to the Typical DC Bias Performance from the datasheet, and assuming it is decreasing linearly from 0 to 420 A-t,

$$Slope = \frac{281 - 150}{420} = 0.3 \rightarrow AL = 281 - 0.3 * 22.68 = 274.19$$

Since it can be as ±8%, AL = 274.19*0.92=252.26. When we recalculate the turn number with new AL value

$$N_{pri} = \sqrt{\frac{L_m}{A_{l-min}}} = \sqrt{\frac{59.68 * 10^{-6}}{252.26 * 10^{-9}}} = 15.3812$$

Hence the $N_{pri} = 16$.

Now, we have to calculate the copper losses and core losses.

Approximate length of cable for 1 turn is equal to 2*(F+C+2*M)=100.9 mm. Additionally since we are working with 50kHz we choose AWG-23 cable which has $A_{AWG-23} = 0.259\ mm^2$ and $R_{AWG-23} = 66.7808 * 10^{-6}\ \Omega/mm$ Hence,

$$R_{pri} = \frac{N_{pri}}{n_{pri}} * 100.9 * \ R_{AWG-23} = \frac{107.81\ m\Omega}{n_{pri}}$$

$$R_{sec} = \frac{N_{sec}}{n_{sec}} * 100.9 * \ R_{AWG-23} = \frac{323.43\ m\Omega}{n_{sec}}$$

Where n_{pri}: number of parallel cables at primary side

n_{sec}: number of parallel cables at secondary side

For core losses B=μ*H.

$$\mu\ = \frac{A_l(MMF) * l_e}{A_e} = 415.19 * A_l\left(16 * I_{\text{avg\_pri}}\right)$$

$$H = \frac{MMF}{l_e} = 162.60 * I_{\text{avg\_pri}}$$

$$B = \mu * \mathrm{H} = A_l\left(16 * I_{\text{avg\_pri}}\right) * I_{\text{avg\_pri}} * 6.75 * 10^4$$

$$P_{core} = a * B^b * f^c = B^{1.988} * 1.92 * 10^4$$

$$P_{copper} = (I_{\text{avg\_pri}} * \sqrt{D})^2 * R_{pri} + (\frac{I_{\text{avg\_pri}}}{3} * \sqrt{D})^2 * R_{sec}$$

Since both equation is related to $I_{\text{avg\_pri}}$ when $P_{out} = 48W$, we made iterative solution using MATLAB:

$$I_{\text{avg\_pri}} = 8\ A$$

$$B = 0.1205\ T$$

$$P_{core} = 6.68\ W$$

$$P_{copper} = 1.42\ W$$

$$\eta(\%) = \frac{P_{out}}{P_{out} + P_{core} + P_{copper}} * 100 = 85.56\%$$

c) Ideal Case Simulations

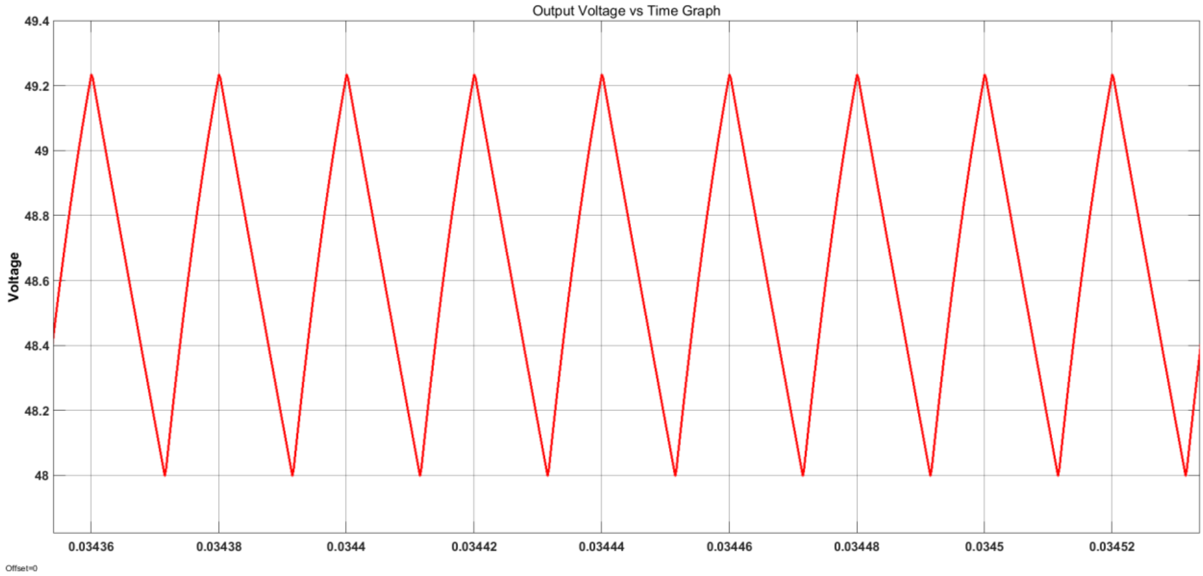

Figure 1: Output Voltage vs Time Graph For Vin = 12 V

The average output voltage is 48.64 V and the ripple voltage is 1.23. Therefore,

$$\frac{\Delta Vo}{Vo} = \frac{1.23}{48} * 100 = 2.5\%$$

Which is lower than specification.

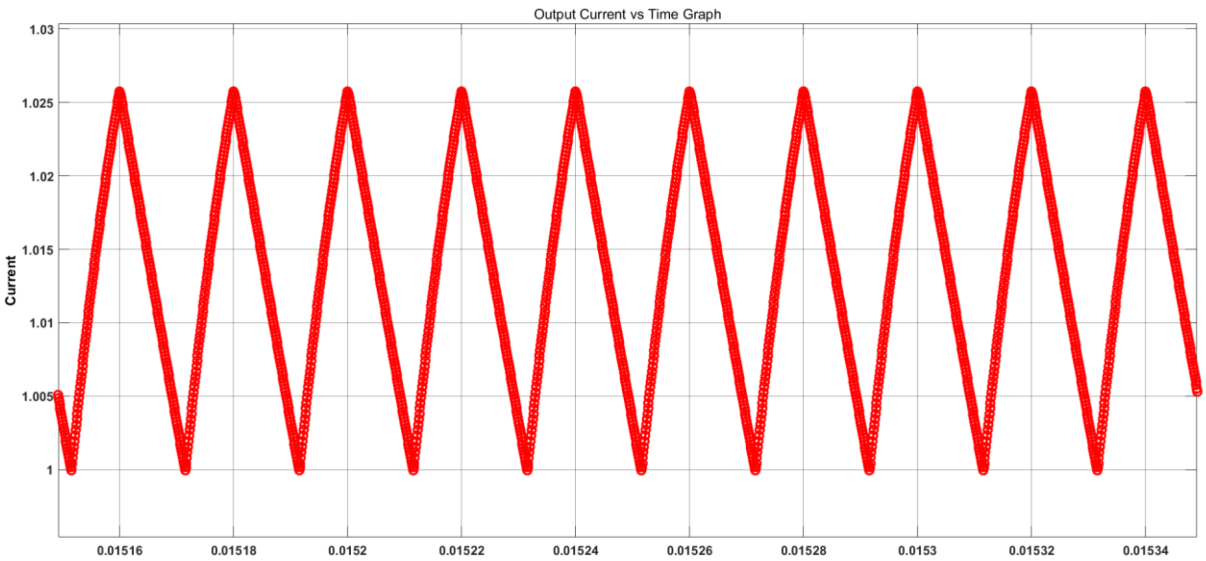

Figure 2: Output Current vs Time Graph For Vin = 12 V

The average output current is 1.01 A according to simulation.

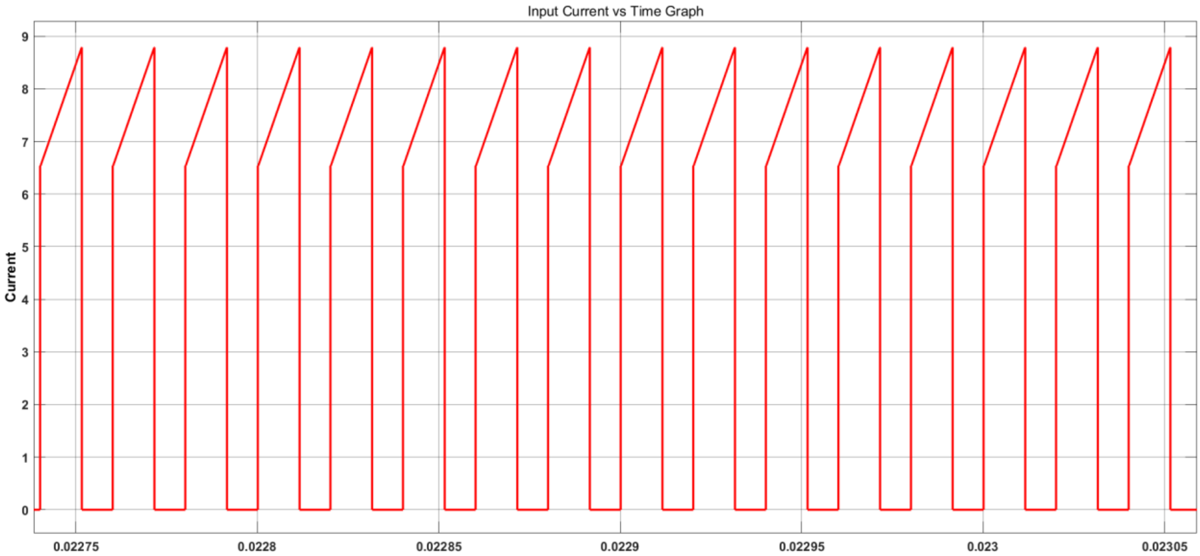

Figure 3: Input Current vs Time Graph For Vin = 12 V

The maximum input current is around 8.79 A which is similar to theoretical result.

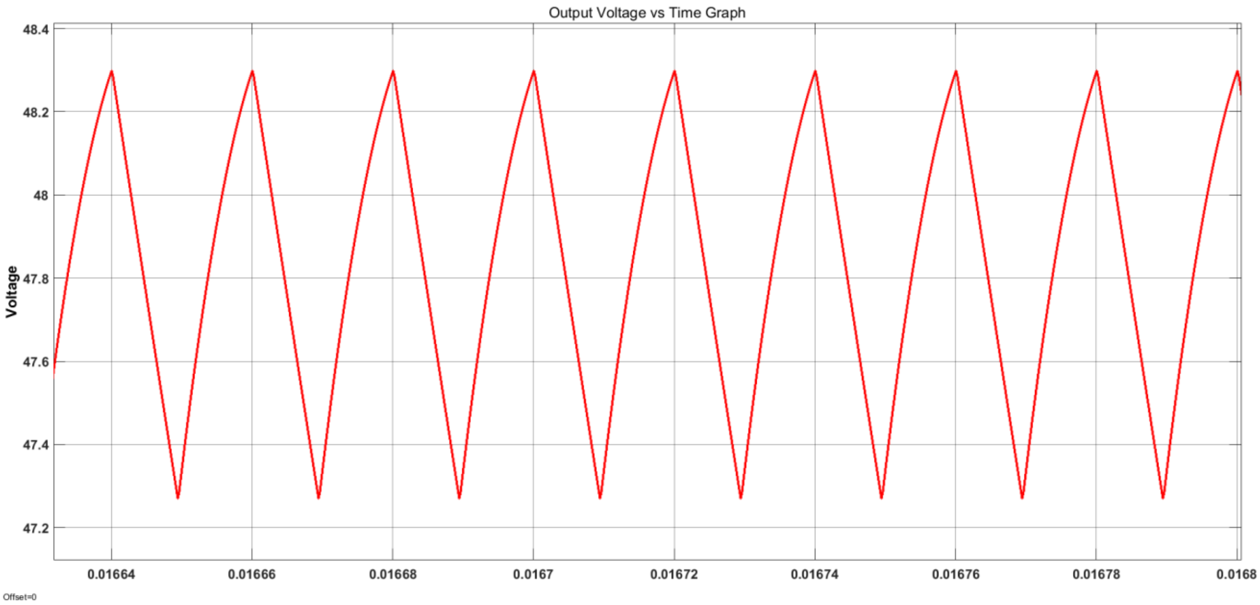

Figure 4: Output Voltage vs Time Graph For Vin= 18 V

The average output voltage is 47.84 V and the ripple voltage is 1.03. Therefore,

$$\frac{\Delta Vo}{Vo} = \frac{1.03}{47.84} * 100 = 2.15\%$$

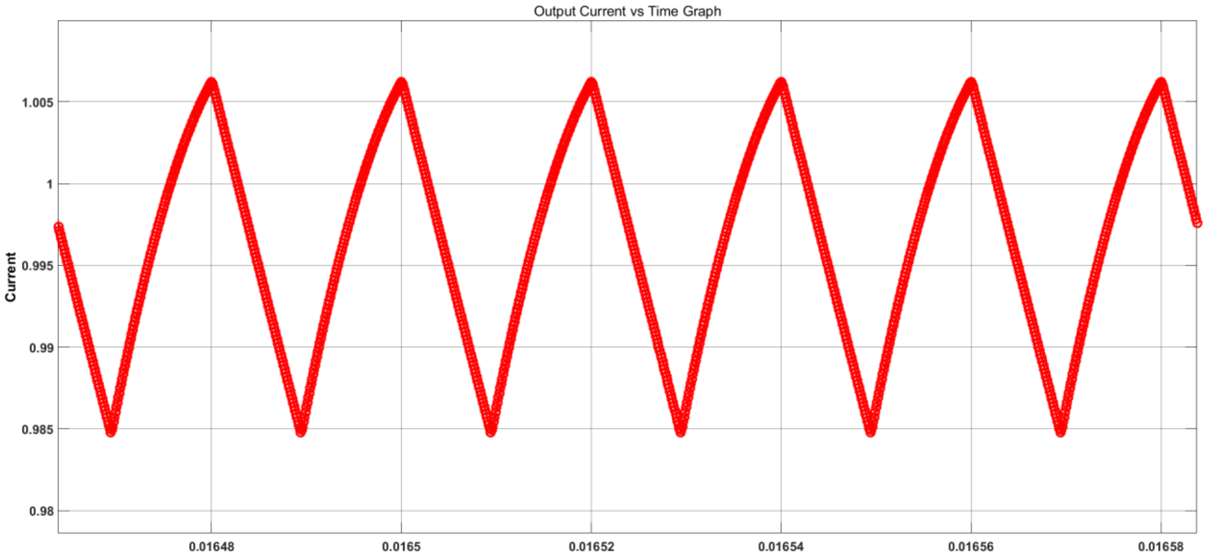

Figure 5: Output Current vs Time Graph For Vin = 18 V

The average output current is 0.996 A according to simulation.

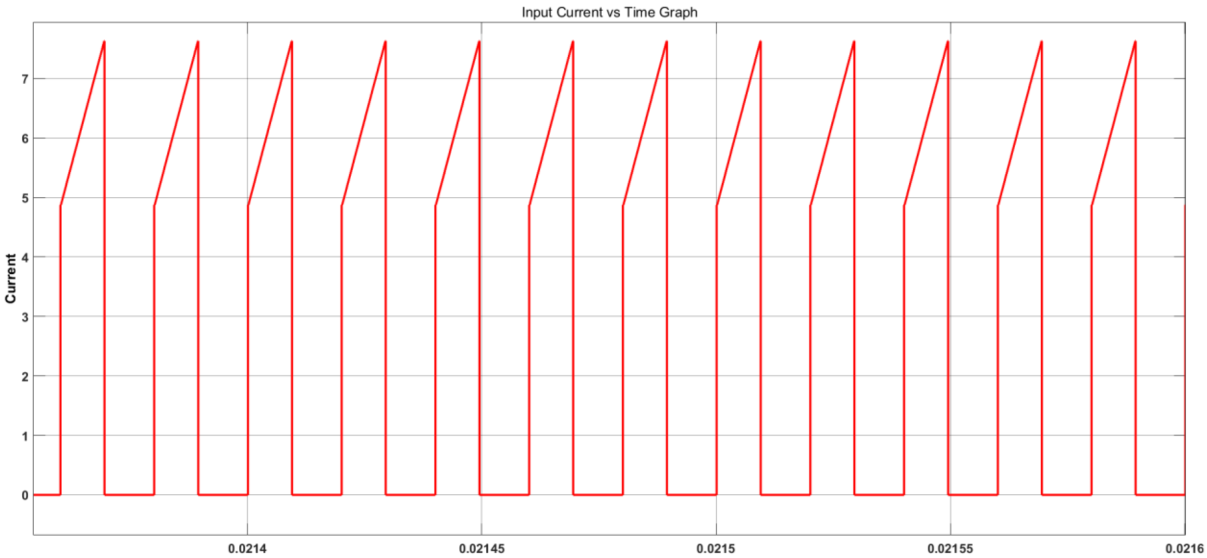

Figure 6: Input Current vs Time Graph For Vin = 18V

The maximum input current is around 7.63 A.

d) A

Lm = $16^2 * 252.26 = 64.58\ uH$

$$\Delta Im = \frac{Vin * D}{Lm * f}$$

Vin =12 V

$$\Delta Im = \frac{12 * 0.5714}{64.58 * 10^{-6} * 50 * 10^{3}} = 2.12\ A$$

$$I_{ccmavg(\min)} = 1.06A \rightarrow Load(\%) = \frac{1.06}{6.9} * 100 = 15.36\%$$

Vin = 18 V

$$\Delta Im = \frac{18 * 0.47}{64.58 * 10^{-6} * 50 * 10^{3}} = 2.62\ A$$

$$I_{ccmavg(\min)} = 1.31A \rightarrow Load(\%) = \frac{1.31}{5.67} * 100 = 23.1\%$$

The maximum average transformer current without losses is 6.9 A.

The minimum average transformer current without losses is 1.06 A.

e) Component Selection and Practical Case Simulations

Mosfet:

The maximum mosfet voltage is

$$Vsw(\max) = Vd + \frac{N1}{N2} * Vo = 18 + \frac{1}{3} * 48 = 34\ V$$

On the other hand, the maximum switch current is

$$Isw(\max) = \frac{1}{1-D} * \frac{N2}{N1} * Io + \frac{N1}{N2} * \frac{(1-D) * Ts}{2 * Lm} * Vo = 2.38 * 3 * 1 + \frac{1}{3} * \frac{0.42 * \frac{1}{50000}}{2 * 59.68 * 10^{-6}} * 48$$
$$= 8.266\ A$$

We have chosen IRF 540 N Mosfet because it has a current rating of 28 A and voltage rating of 100 V. This values guarantees proper operation. Moreover, it has a drain to source resistance of 44 mohm which is quite low.

Diode:

The maximum reverse voltage of the diode is equal to output voltage when the switch is on case and it is 48 V . + 18*3 = 102 V. Moreover, maximum current on the diode is

$$\frac{8 + \frac{2.835}{2}}{3} = 3.14\ A$$

For the diode selection, we have chosen BYW29-200 Power diode which has a current rating of 8A and voltage rating of 200V. Moreover, it has a forward voltage drop 0.85 V

Output Capacitor:

The output capacitor is selected from the formula of;

$$\frac{\Delta Vo}{Vo} = \frac{D}{R * C * f}$$

$$C = \frac{D}{R * \frac{\Delta Vo}{Vo} * f} = 8\,uF$$

To guarantee proper operation, C is chosen as 10 uF.

Controller:

1. UC3845 is one of the most used DC-DC switching controller on the market. The application notes include flyback converters as shown in Figure 1. The line and load regulation values are suitable for the design requirements. Also, it can be bought easily from Özdisan. In general, UCxxxx series are looking applicable for the project.

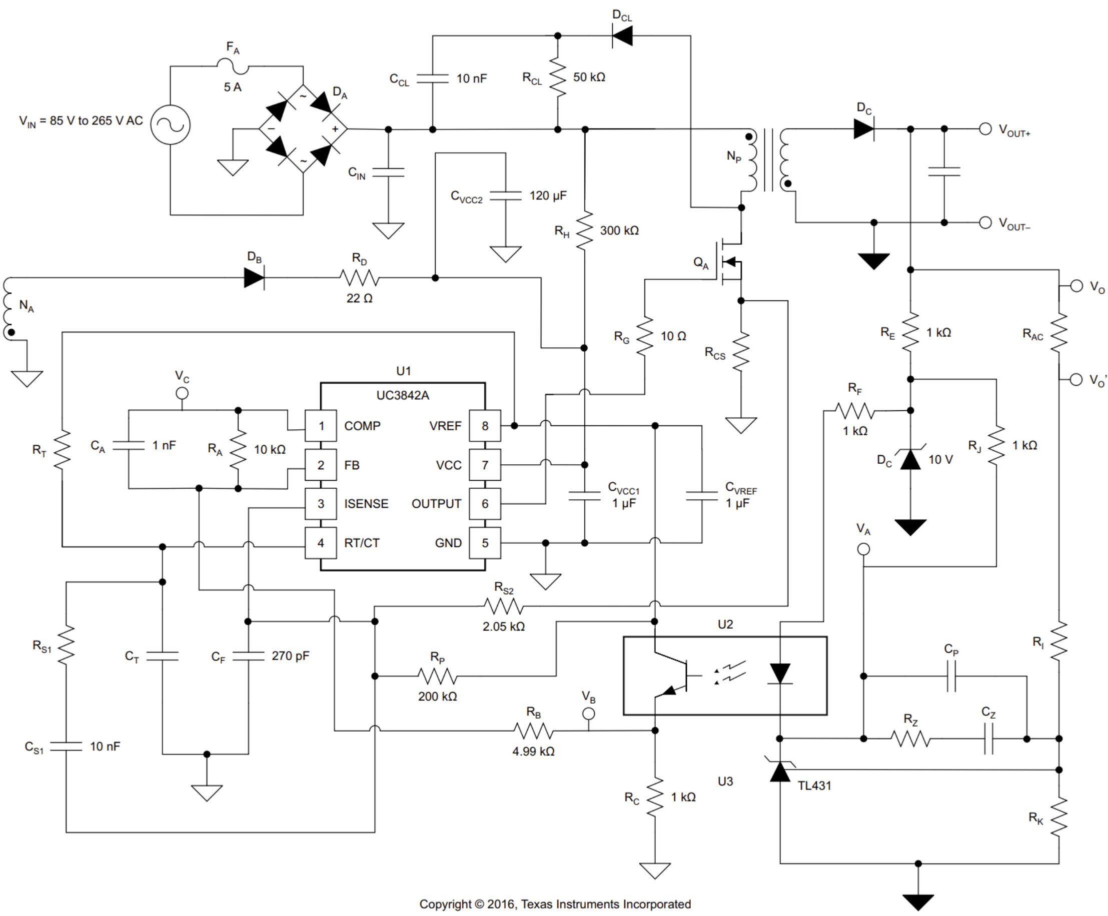

Figure 7: UC3845 Controller

[UC3842/3/4/5 Provides Low-Cost Current-Mode Control (ti.com)]

2. OB2269CAP is an alternative to UC models which can also be purchased from Özdisan. The application areas include offline flyback converters. It is also very cost-effective and easy to implement.

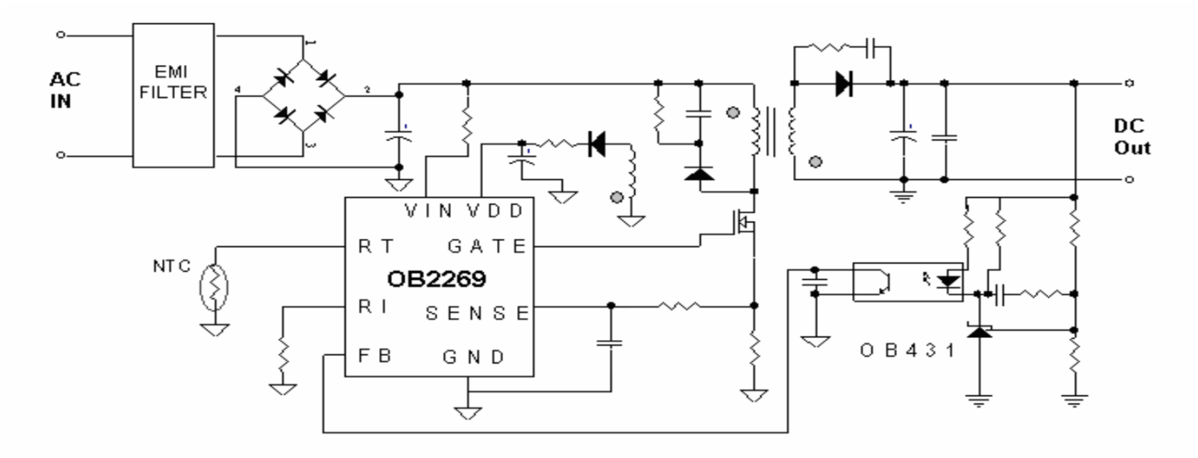

Figure 8: OB2269CAP Controller

[Microsoft Word - OB2269C_DataSheet_V31.doc (ozdisan.com)]

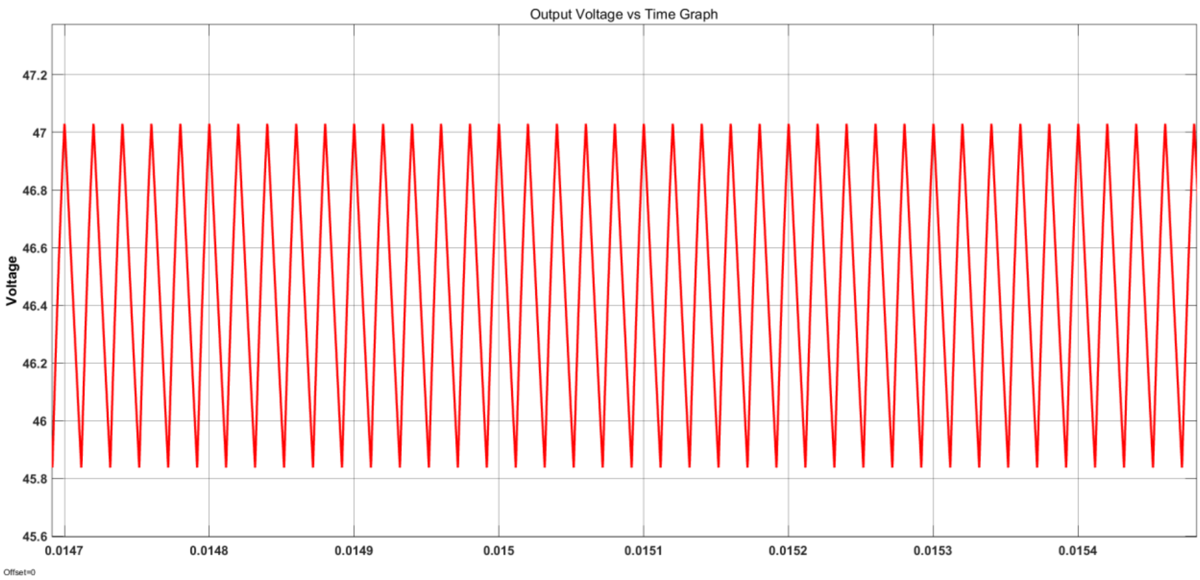

Figure 9: Output Voltage vs Time Graph For Vin = 12 V

The average output voltage is 46.46 V and the ripple voltage is 1.19. Therefore,

$$\frac{\Delta Vo}{Vo} = \frac{1.19}{46.46} * 100 = 2.56\%$$

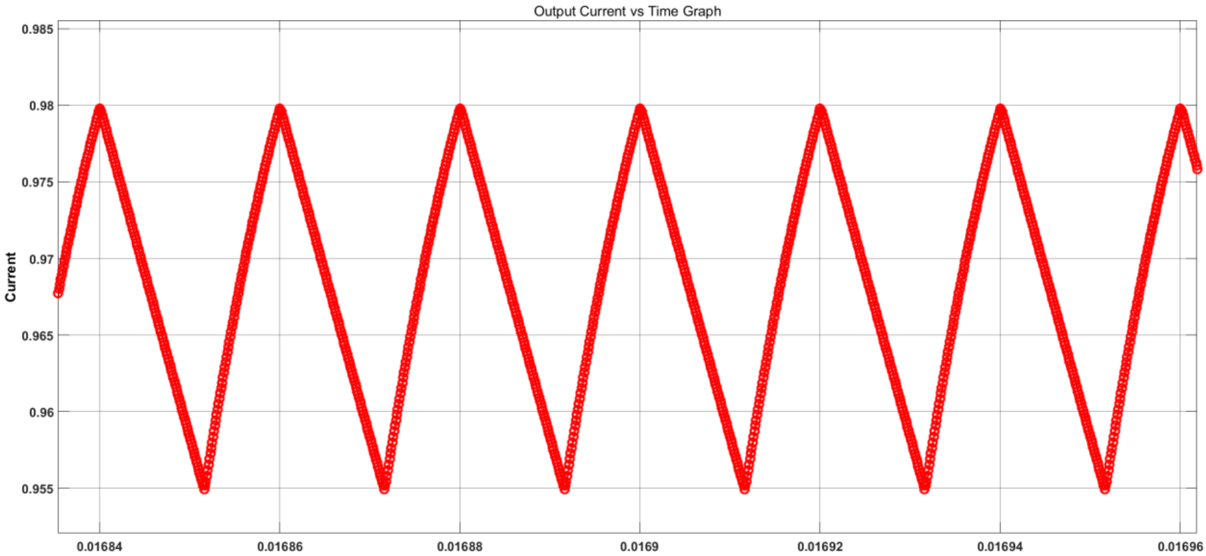

Figure 10: Output Current vs Time Graph For Vin = 12 V

The average output current is 0.968 A according to simulation.

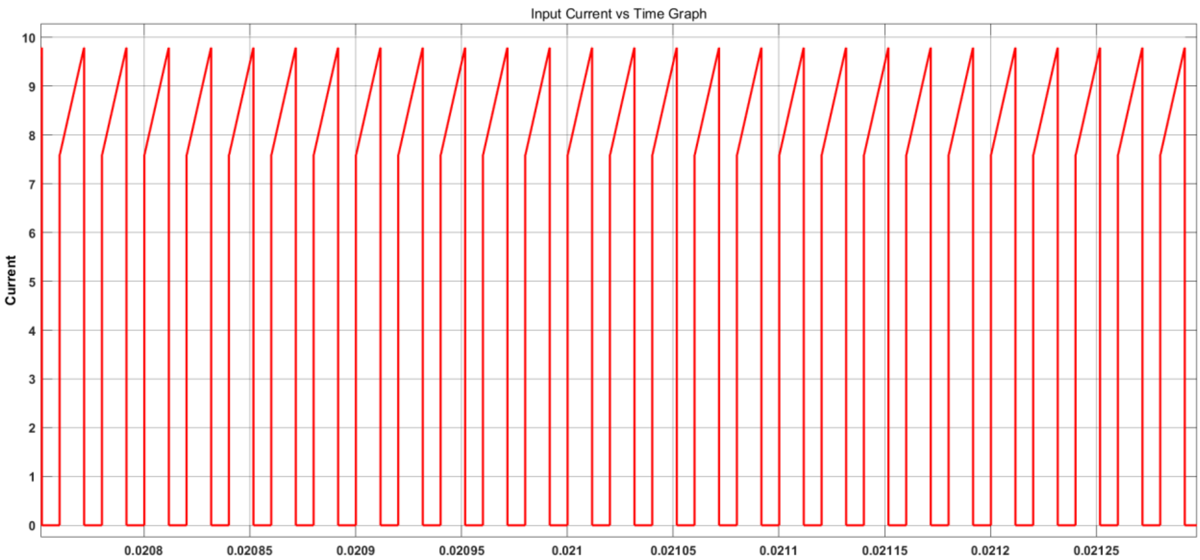

Figure 11: Input Current vs Time Graph For Vin = 12 V

The maximum input current is around 9.79 A.

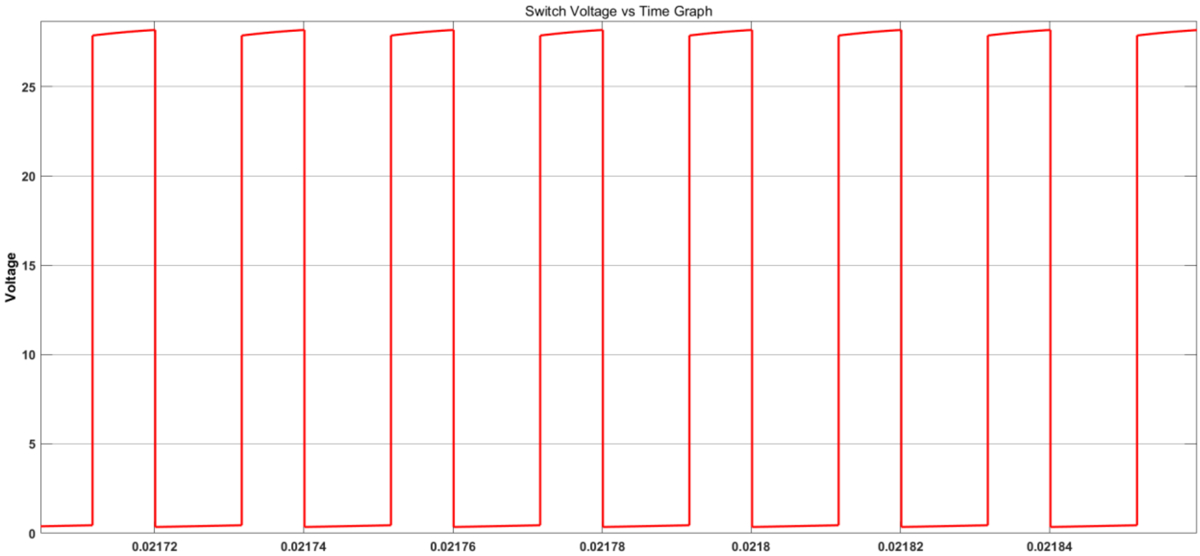

Figure 12: Switch Voltage vs Time Graph For Vin = 12V

The maximum switch voltage is 28.18 V according to simulation.

Figure 13: Diode Voltage vs Time Graph For Vin = 12 V

The maximum reverse voltage of the diode is 82 V.

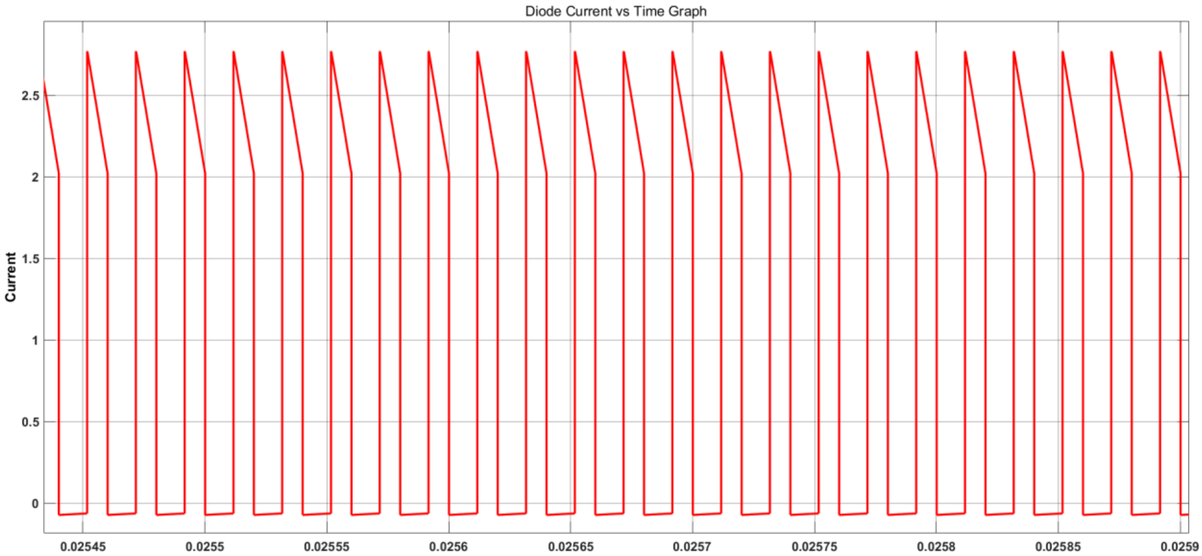

Figure 14: Diode Current vs Time Graph,

The maximum diode current is 2.77 A.

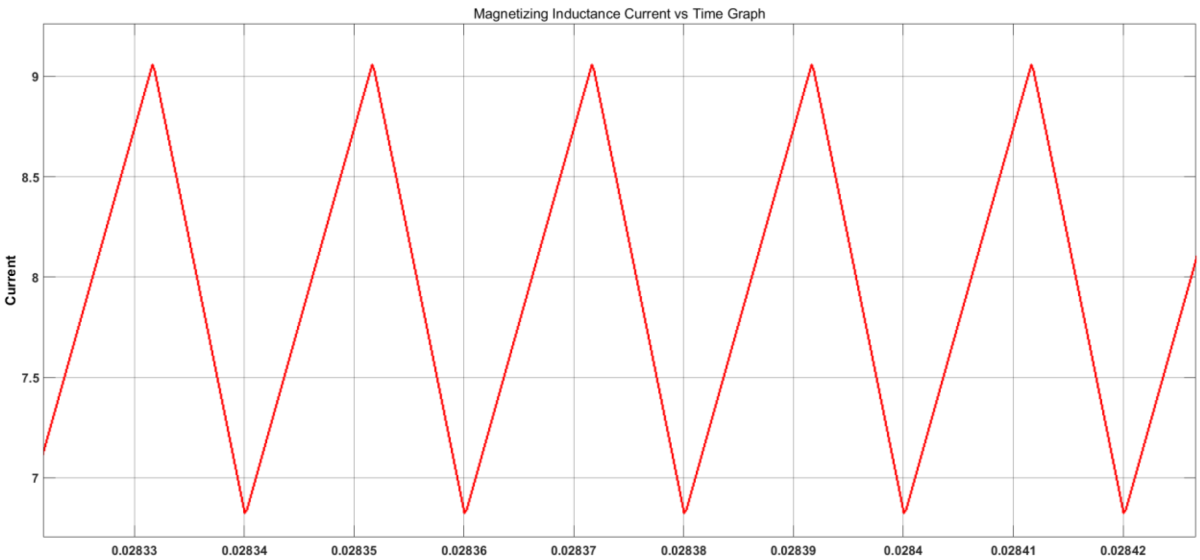

Figure 15: Magnetizing Inductance Current For Vin = 12 V

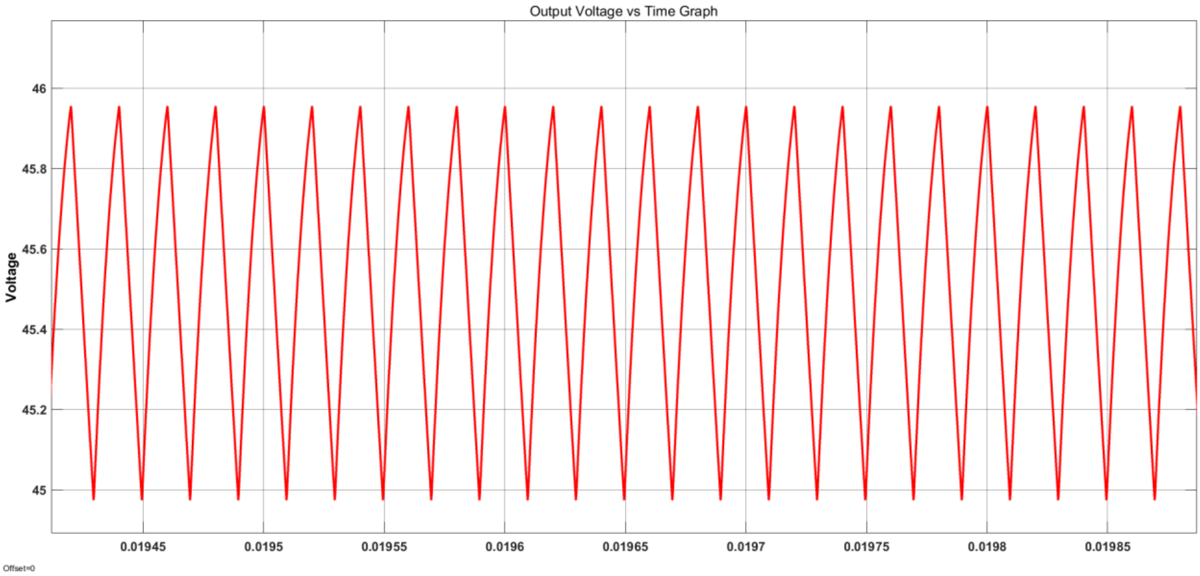

Figure 16: : Output Voltage vs Time Graph For Vin = 18 V

The average output voltage is 45.51 V and the ripple voltage is 0.98. Therefore,

$$\frac{\Delta Vo}{Vo} = \frac{0.98}{45.51} * 100 = 2.15\%$$

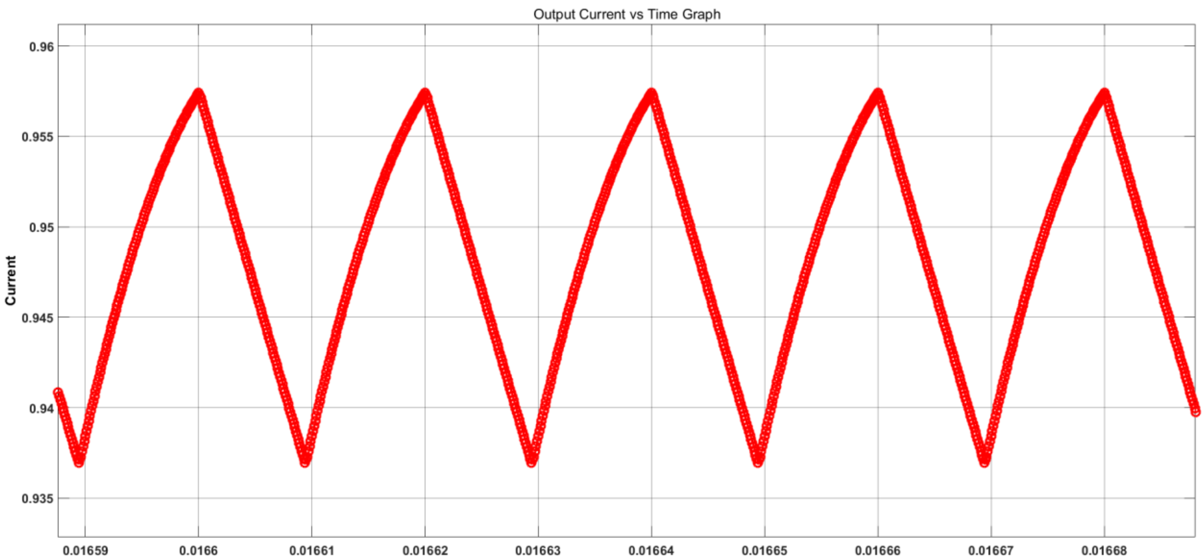

Figure 17: Output Current vs Time Graph For Vin = 18V

The average output current is 0.948 A according to simulation.

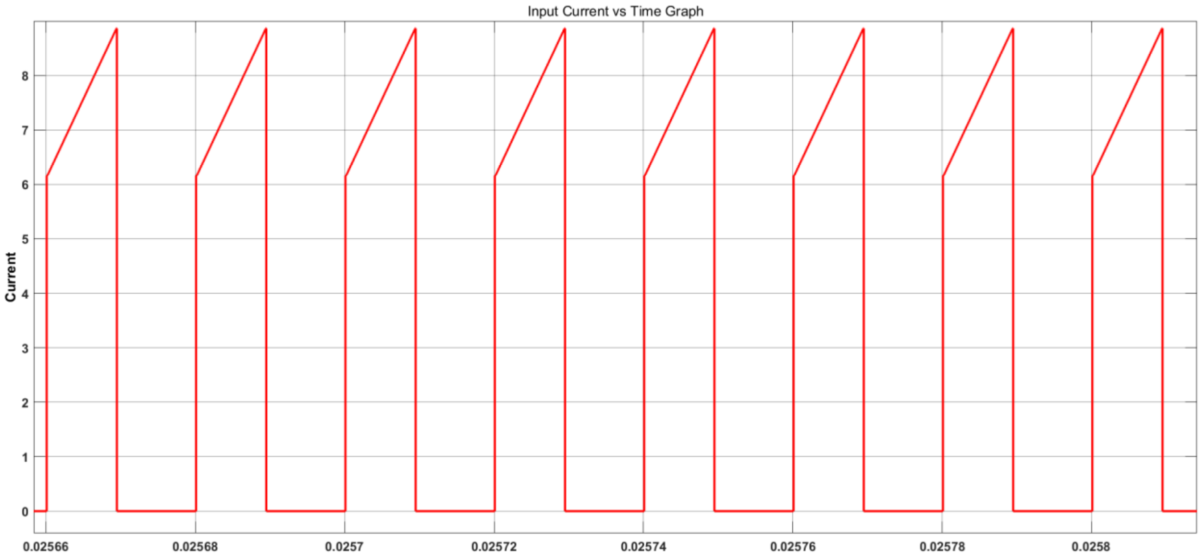

Figure 18: Input Current vs Time Graph For Vin = 18V

The maximum input current is 8.86 A according to simulation.

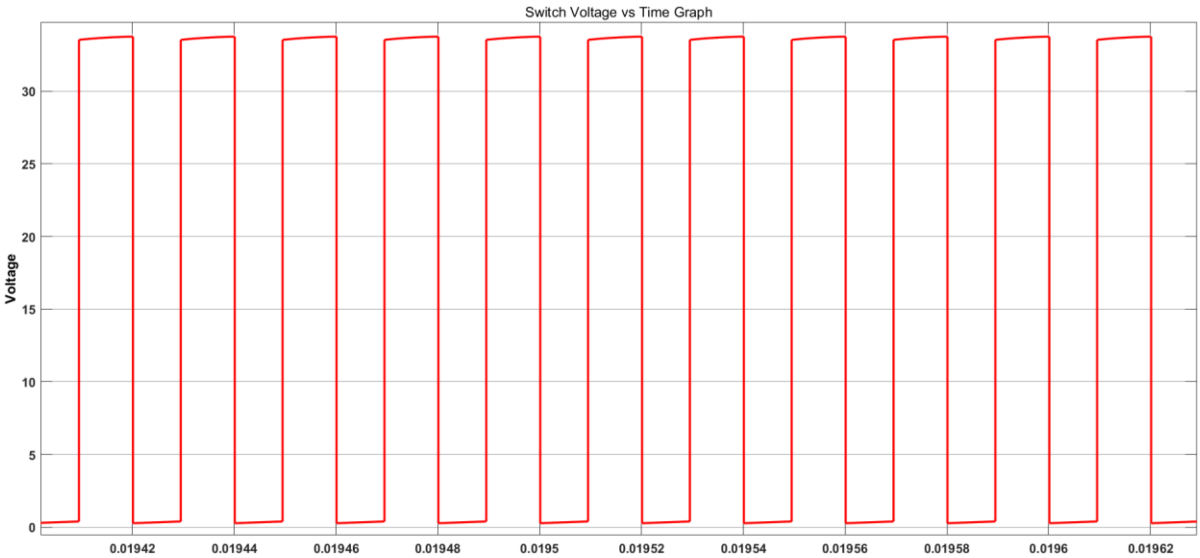

Figure 19: Switch Voltage vs Time Graph For Vin = 18V

The maximum switch voltage is 33.75 V according to simulation.

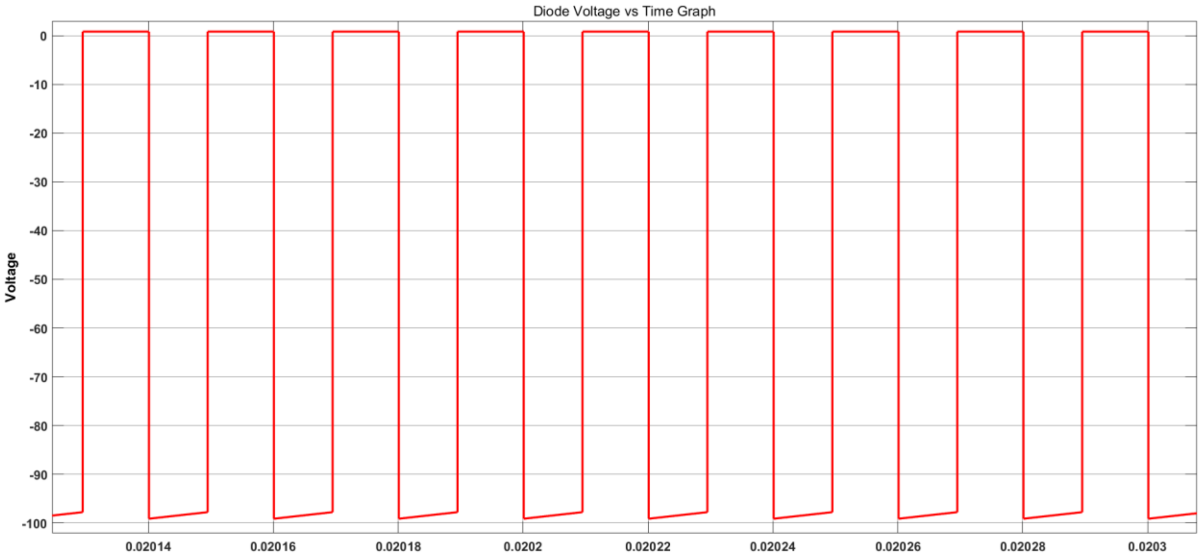

Figure 20: Diode Voltage vs Time Graph For Vin = 18V

The maximum reverse voltage of the diode is 80.22 V.

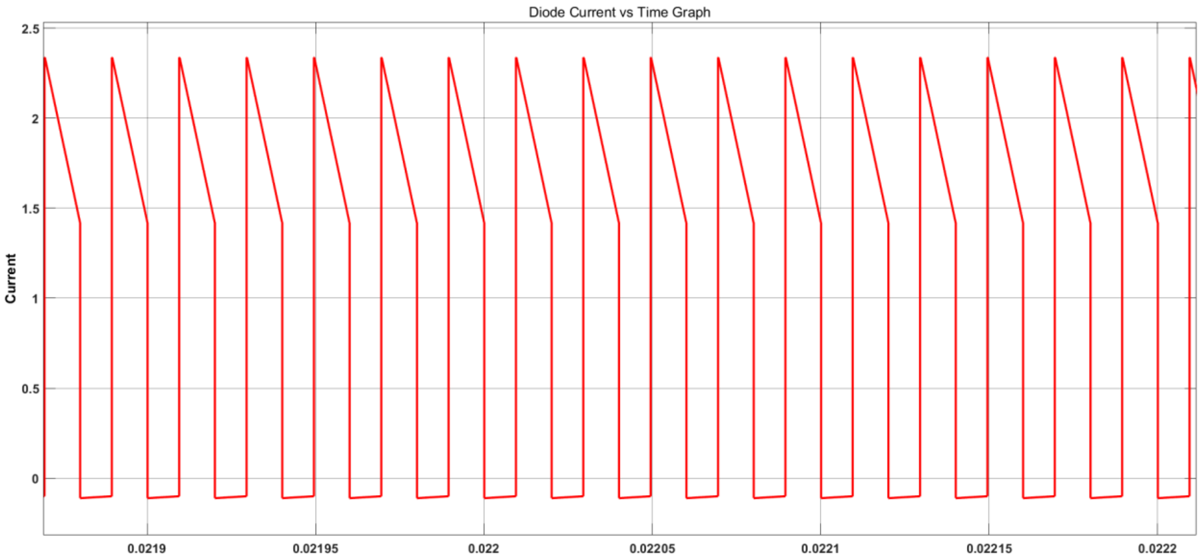

Figure 21: Diode Current vs Time Graph For Vin = 18V

The maximum diode current is around 2.34 A.

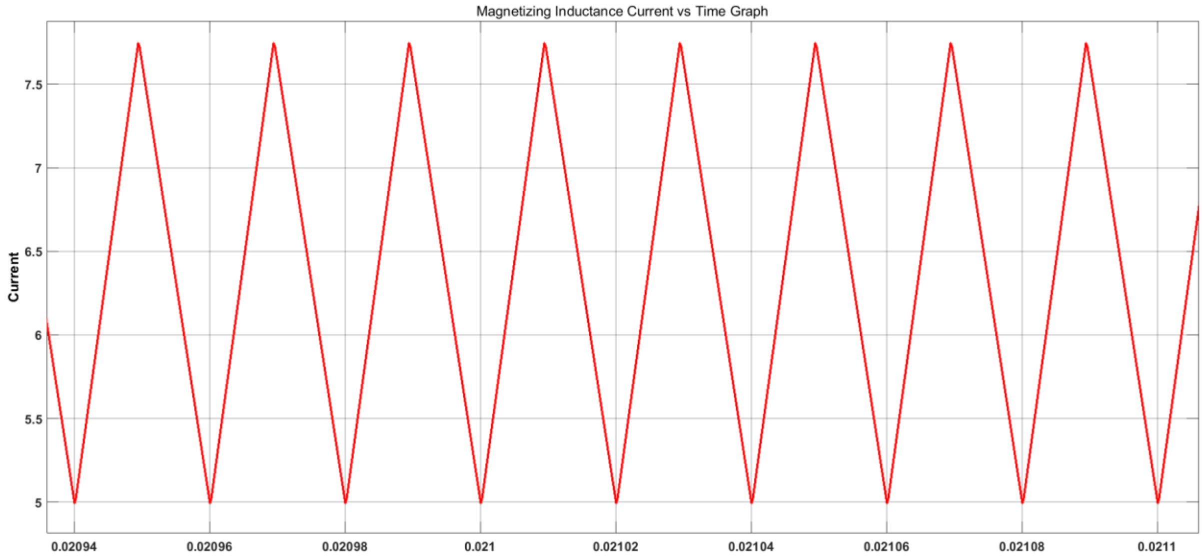

Figure 22: Magnetizing Inductance Current For Vin = 18 V

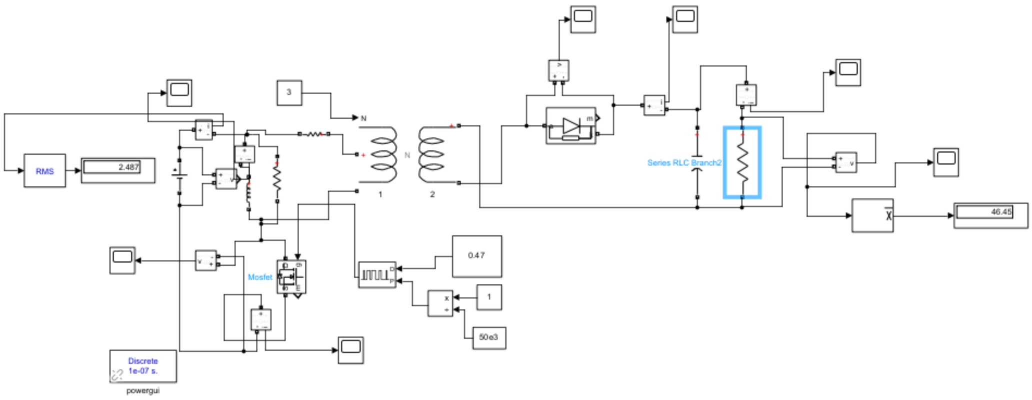

Figure 23: Simulation Block Diagram

f) Efficiency Calculation For Different Loads

Vin = 12 V

100% Load:

Pin = 79.6 W, Pout = 44.95 W that yields 56.47% efficiency.

75% Load:

Pin= 64.5 W, Pout = 44.95 W that yields 53.4% efficiency.

50% Load:

Pin= 49.09 W, Pout = 23.46 W that yields 47.79% efficiency.

25% Load:

Pin= 33.44 W, Pout = 12 W that yields 35.89 % efficiency.

Vin = 18 V

100% Load:

Pin = 93.15 W, Pout = 44.95 W that yields 46.32% efficiency.

75% Load:

Pin= 77.15 W, Pout = 32.79 W that yields 42.5% efficiency.

50% Load:

Pin= 61 W, Pout = 22.16 W that yields 36.33% efficiency.

25% Load:

Pin= 44.77 W, Pout = 11.24 W that yields 25.11 % efficiency.

However, we calculated efficiency theoretically also. As we can sen in part b the core loss and the copper losses are 6.64W and 1.43W. And the efficiency is around 85% without semiconductor losses with full load. It is higher when the load decreases because both copper losses and core loss decreases exponentially. The reason why the efficiency decreases when the load decreases is we assumed Rcu is constant. The efficiency is directly taken from the simulations. When we calculate the conduction loss of mosfet it is equal to 1.93W maximum, switching losses of mosfet equal to 0.39W and diode loss is equal to 1.88W.

Maximum Total Loss = 12.27 W theoretically at full load case and that yields 79.64% efficiency.

Conclusions

There are different isolated DC-DC converter topologies where basically a trade-off is made. The most used isolated step-up converter is the flyback converter. After deciding on the flyback, there came a lot of different factors when determining the duty cycle and the turns ratio, turn numbers and selecting a proper core. The datasheets do not include sufficient information to be used at the loss calculations, so the catalogs are searched instead. The Steinmetz's equation is used to check with the core characteristics included in the core catalogs. The copper losses are also calculated by hand using the AWG cable catalog, core dimensions and turn numbers. The simulation is run repeatedly with different selections until the desired outcome occurs. The semiconductor losses are not to be ignored as they decrease the overall efficiency significantly. A more proper component and controller selection must be made until the presentation as this iteration of the flyback converter is quite fragile. A snubber design is also strongly suggested for flyback converters, which we also aim to do in the following weeks.

References

Switch Mode Power Supply Topologies: A Comparison (we-online.com)

The comparisons of DC DC converters | Download Table (researchgate.net)

DC DC Switching Controllers | Power Management (PMIC) | Electronic Components Distributor DigiKey

DC-DC Switching Voltage Controllers - Hundreds of thousands of electronic components at ozdisan.com with same day shipping advantages. Add to basket with best prices, buy original parts from stock | Özdisan Electronics

American Wire Gauge Chart and AWG Electrical Current Load Limits table with ampacities, wire sizes, skin depth frequencies and wire breaking strength (powerstream.com)

Magnetics - Kool Mu Cores Manufacturer (mag-inc.com)