EE464 - Software Project 2
Simulation and Design of the Hardware Project Report

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1. Introduction

In this project, the initial design and its simulation for the hardware project is made by using MATLAB Simulink. As our project, we chose Forward Converter 5 topology, whose specifications are given below in Table 1. The transformer design is made and its parameters are determined. Converter is simulated with both ideal and non-ideal switches to observe voltage and current behaviours in the circuit. The efficiency of the converter is calculated for different load conditions. Moreover a controller is designed for output voltage control. Based on the simulations preliminary component selection is made.

Table 1 : Forward Converter Specifications

	$Max\ V_{in}$	$Min\ V_{in}$	V_{out}	P_{out}	Output voltage ripple	Line Regulation	Load Regulation
FOR#5	48	24	12	50	2	2	2

This report includes calculations, circuit schematics and simulation results for our forward converter design.

2. Question 1

2.1. Part A

The forward converter with the requirements given in the introduction part is designed and simulated. The proper steady-state operation of the converter is verified through the Figure 1 and Figure 2 .

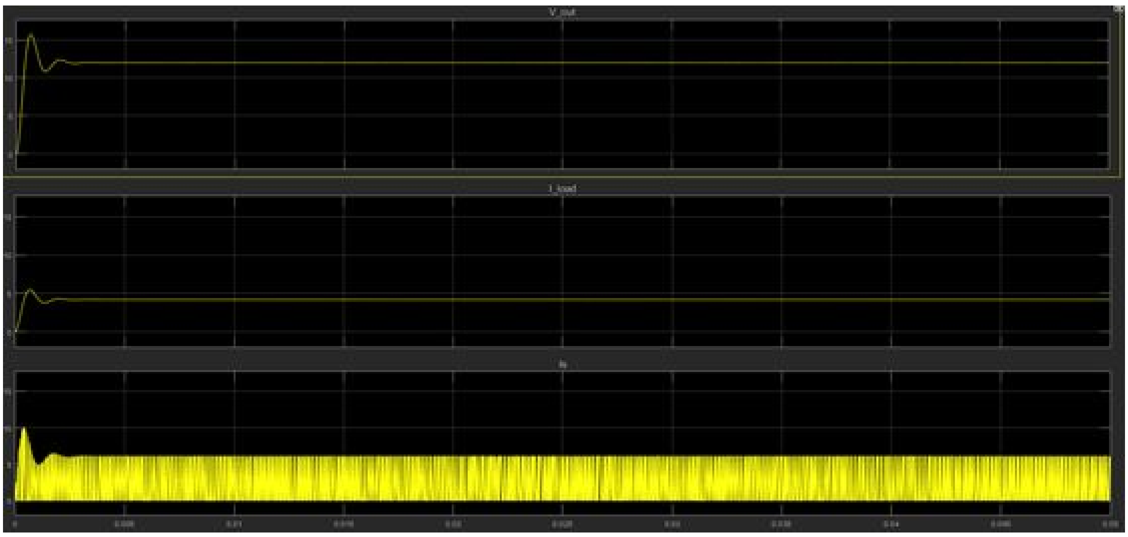


Figure 1 – Output voltage, Input and Output Current Waveforms of the forward converter.

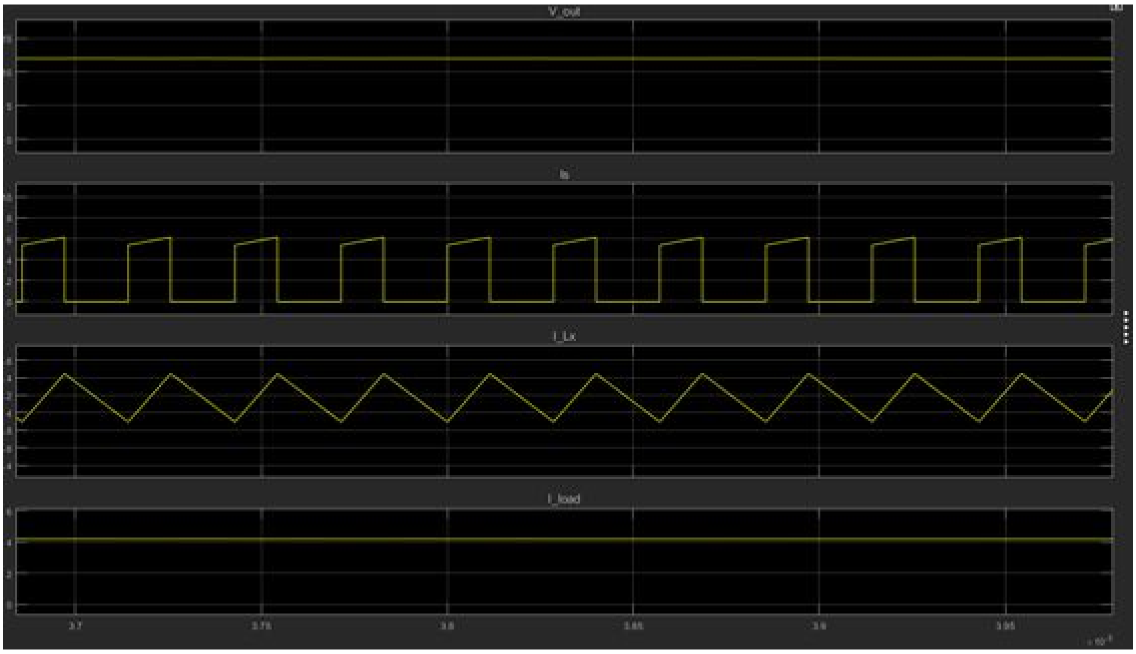


Figure 2 – Output voltage, Input, Output and Inductor current waveforms of the forward converter.

2.2. Part B

The Forward Converter topology is selected for our design. It is wanted to obtain 12 V at the output when voltages between 24-48 V given from the input.

There will also a third winding in order to provide a path for magnetizing current when the switch is open. The time passed while demagnetization, t_m, should be shorter than the off time for full demagnetization. Hence the maximum duty cycle of the operation becomes,

$$D_{max} = \frac{1}{1 + \frac{N_3}{N1}}$$

N3 is chosen equal to N1, which yields a Dmax of 0.5. We have chosen our duty cycle as 0.4 in order to give a margin. From the relation between the input and output of the forward converter,

$$\frac{V\,out}{V\,in} = \frac{N_2}{N1} \times D$$

$$\frac{12}{24} = \frac{N_2}{N1} \times 0.4$$

$\frac{N_2}{N1}$ is founded as 30/24 and we chose 32/24=4/3 as our winding ratio. As the core, 0P43434EC is chosen. Datasheet can be found at [this link].

Firstly the primary winding turn number is found by the following formula [1],

$$N_{p,\,min} = \frac{V_{DC,\,min} \times D_{max}}{A_e \times f_s \times \Delta B}$$

$A_e = 97.11\ mm^2$ for our selected core, which is obtained from the datasheet.

Operating frequency, fs is chosen as $35\ kHz$

Flux density at this operating point is approximately $0.2\ T$ at 35kHz, which is obtained from the graph below in Figure 3.

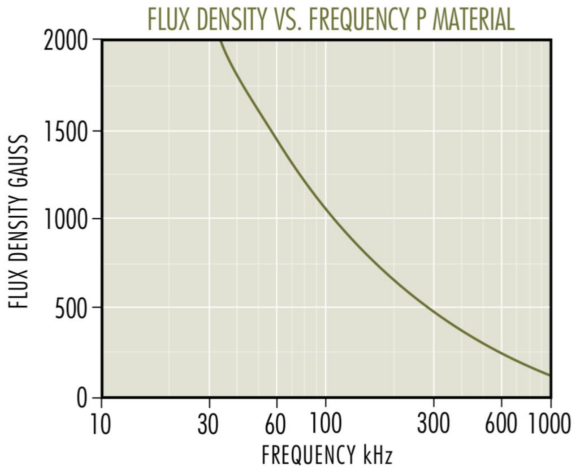


Figure 3 – Flux density vs Frequency characteristics of core material [2]

We found $N_{p,\,min} = 14.12$, hence 15 is chosen as the primary turn number. From the turns ratio, secondary winding turn number can also be found.

$$N_p = 15$$

$$N_s = \frac{N_2}{N_1} = 20$$

After founding the turn number, magnetizing inductance can be found with the following formula [1],

$$L_m = A_L \times N_p^2 \times 10^{-9} = 0.66\ mH$$

Reset and secondary currents can also be calculated by the below formulas[1].

$$I_{reset} = \frac{V_{DC,\,min} \times D_{max}}{L_m \times f_s} \times \sqrt{\frac{D_{max}}{3}} = 0.15\ A = 150\ mA$$

$$I_{secondary} = I_o \times \sqrt{\left(3 + K_{RF}^2\right) \times \frac{D_{max}}{3}} = 2.16\ A$$

K_{RF} is taken as 0.1 for practical design purposes[1].

$I_o = \frac{50}{12} = 4.16\ A$

Transformer Wire Selection and Resistance Calculations

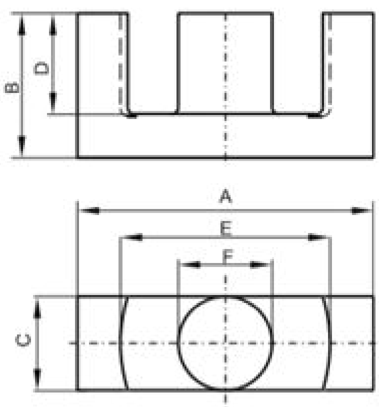
First of all, the skin effect should be calculated at the switching frequency of our design.

$$\delta = \sqrt{\frac{2 * \rho}{\mu * w}}$$

$$= \sqrt{\frac{2 * 1.72 * 10^{-8}}{2 * \pi * 35000 * 1.256629 * 10^{-6}}} = 0.353\ mm$$

The diameter of the wire should be chosen regarding the skin effect on the current capability of the wire. When the AWG table is examined, **AWG-21** is found suitable for the wire of the transformer which has a diameter of 0.723 mm.

Both the primary and the secondary windings are winded on the middle of the E- Core. From the datasheet of the chosen magnetic core, the following figure, which illustrates the dimensions of the core, is obtained.



(mm)	Nominal:	Tol. min.:	Tol. max.:
A	35.0	-1.6	0.0
B	17.3	-0.2	+ 0.2
C	11.1	-0.6	0.0
D	11.8	0.0	+ 0.6
E	25.6	0.0	+ 1.4
F	11.1	-0.6	0.0
Eff. Parameters			
Ae mm ^{2}	Amin mm ^{2}	le mm	Ve mm ^{3}
97.1	91.6	78.6	7640

Figure 4 – The dimensions of the E – Core 0P43434EC.

Considering that the primary winding is winded first on the middle part of the E – Core, the circumference of the part F must be calculated first.

The circumference is equal to : π * R , where R = 11.1 mm as highlighted in Figure 4.

= 34.87 mm.

For the primary winding, N_p = 15. Thus, the total wire length at the primary winding is equal to 15 * 34.87 = 0.523 m. At the AWG table, the resistance/length constant is given as 42 mΩ/m . Resistance of the wire in the primary winding is calculated as :

R_p = 0.523 * 42 * = 0.0219 Ω.

The secondary winding will be winded on the primary winding which increases the circumference of the surface. New circumference can be found as :

= π * R , where R = 11.1 + 0.723*2 = 12.54 mm

= 39.41 mm.

For the secondary winding, N_s = 20. Thus, the total wire length at the secondary winding is equal to 20 * 39.41 = 0.788 m. At the AWG table, the resistance/length constant is given as 42 mΩ/m . Resistance of the wire in the secondary winding is calculated as :

R_s = 0.788 * 42 * = 0.033 Ω.

2.3. Part C

The forward converter is simulated with the transformer designed in part b with ideal switches. The input voltage is 24 V DC. Simulation results can be seen in Figure 5 below.

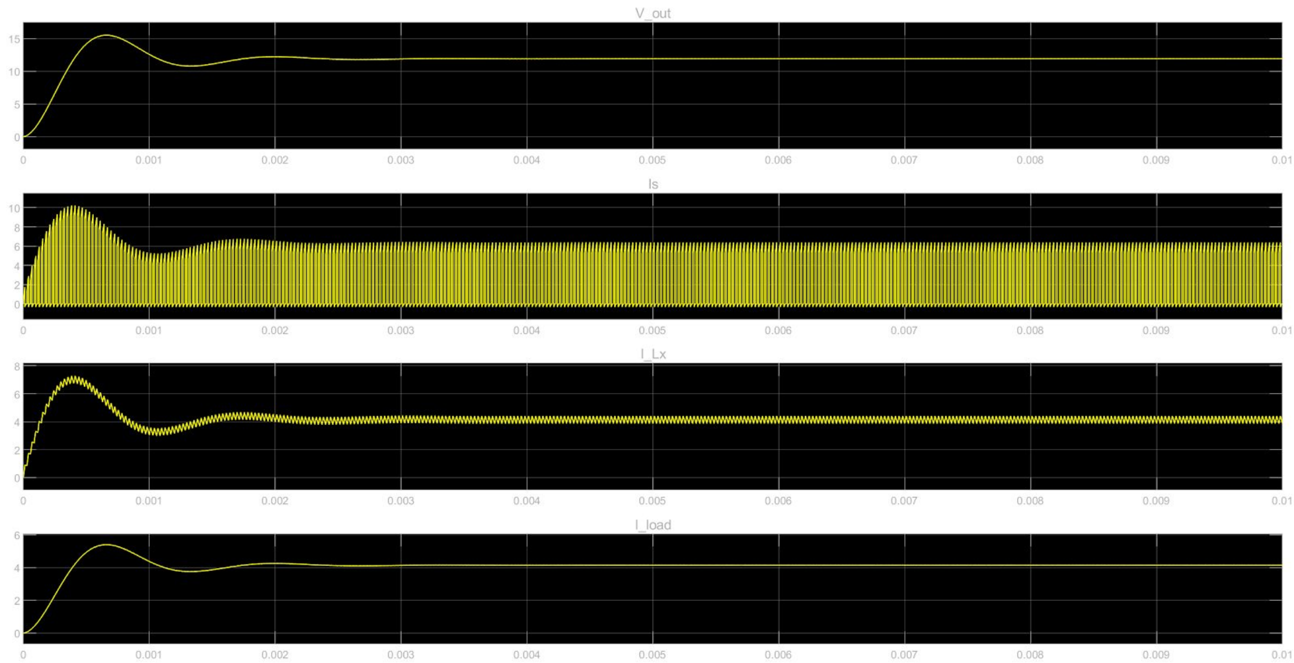


Figure 5 – Output voltage, Input, Output and Inductor current waveforms of the ideal forward converter.

Output voltage and output voltage ripple can be seen in Figure 6 and Figure 7 respectively.

As one can see, ripple is approximately 0.019 V which is more than enough for the 2% ripple constraint.

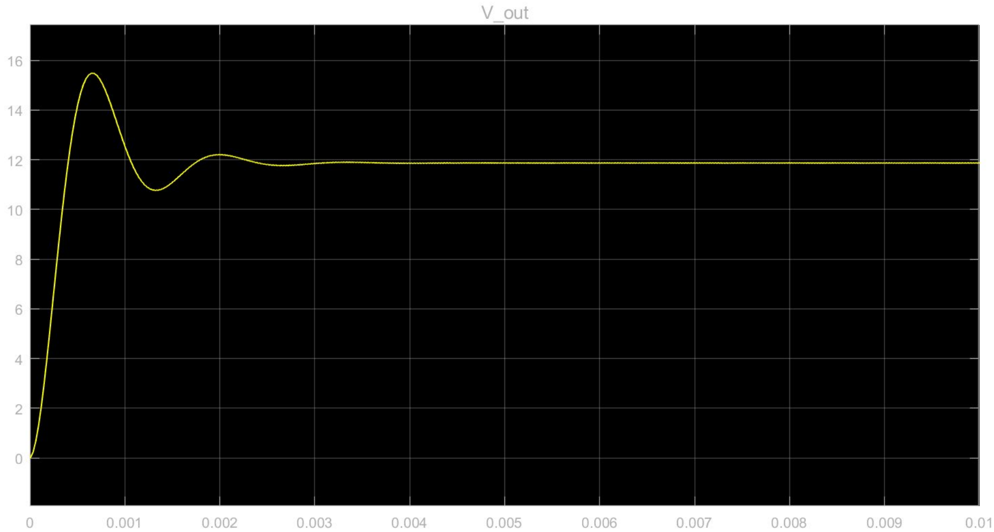


Figure 6 – Output voltage waveform of the ideal forward converter

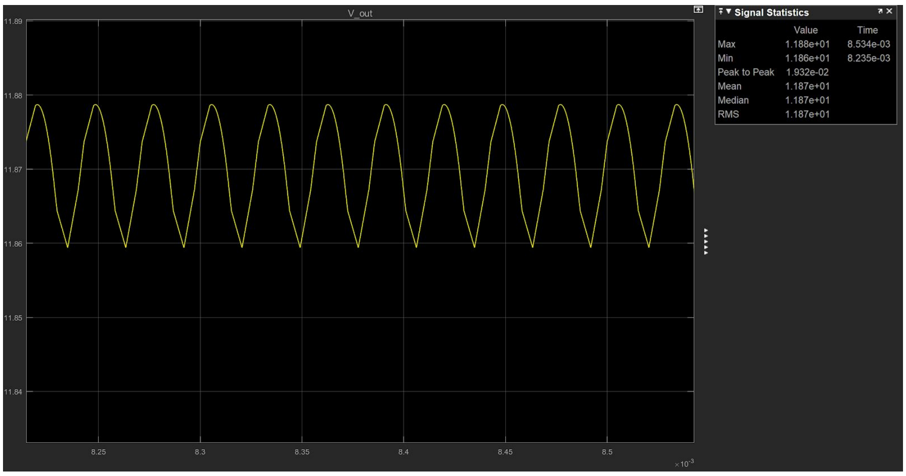


Figure 7 – Output voltage ripple of the ideal forward converter

Output current waveform can be seen in Figure 8.

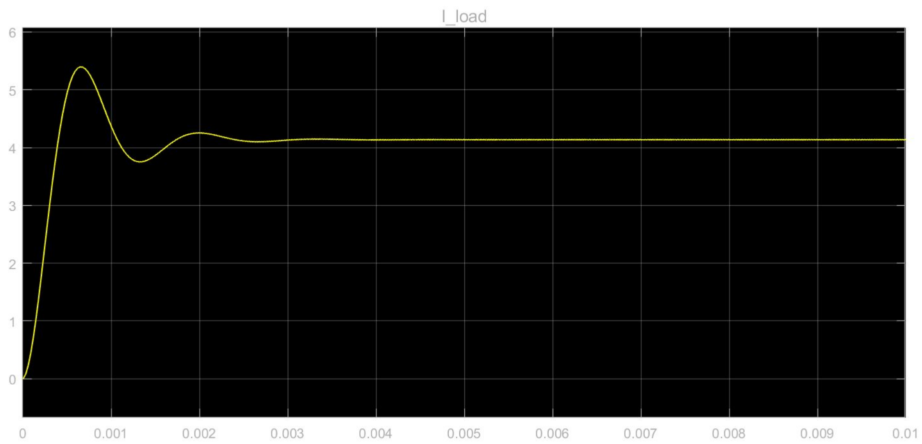


Figure 8 – Output current waveform of the ideal forward converter

2.4. Part D

In this part, we calculated transformer and load currents. Following calculations show that minimum and maximum current for transformer and maximum load current of the forward converter under defined parameters.

Forward Converter:

V_s= 24V   R= 3Ω L_m= 0.66mH

V_o= 12V   L= 0.4mH   f= 35kHz   D= 0.4

$I_L = V_o / R = 4A$

$\Delta i_L = V_o*(1\text{-}D) *T_s/L = 12*(1\text{-}0.4) /(0.4m*35kHz) = 0.52A$

$\dot{I}_{L\,(max)} = i_{L\,(ave)} + \Delta i_L/2 = 4.26A$

$\dot{I}_{L\,(min)} = i_{L(ave)} - \Delta i_L/2 = 3.74A$

$\dot{I}_{LM\,(max)} = V_s*D*T/L_m = 24*0.4/(0.66mH*35kHz) = 0.42A$

2.5. Part E

The forward converter now simulated with non-ideal switch and transformer. Simulink model of it can be seen in Figure 9.

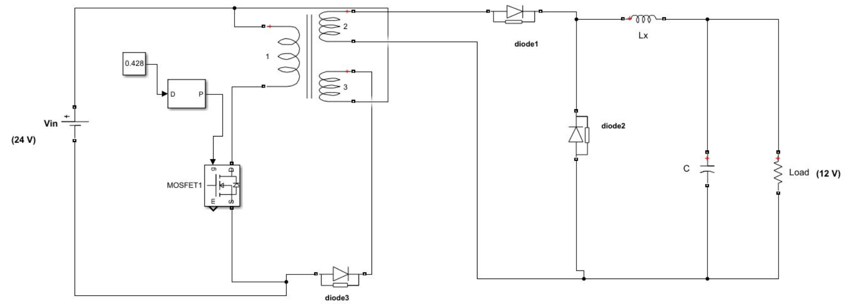


Figure 9 – Simulink model of the forward converter

As the switch a mosfet is used, which is the one we chose for our hardware implementation. Diodes are also simulated with the parameters of chosen components. The voltage and current characteristics of the switch can be seen in Figure 10.

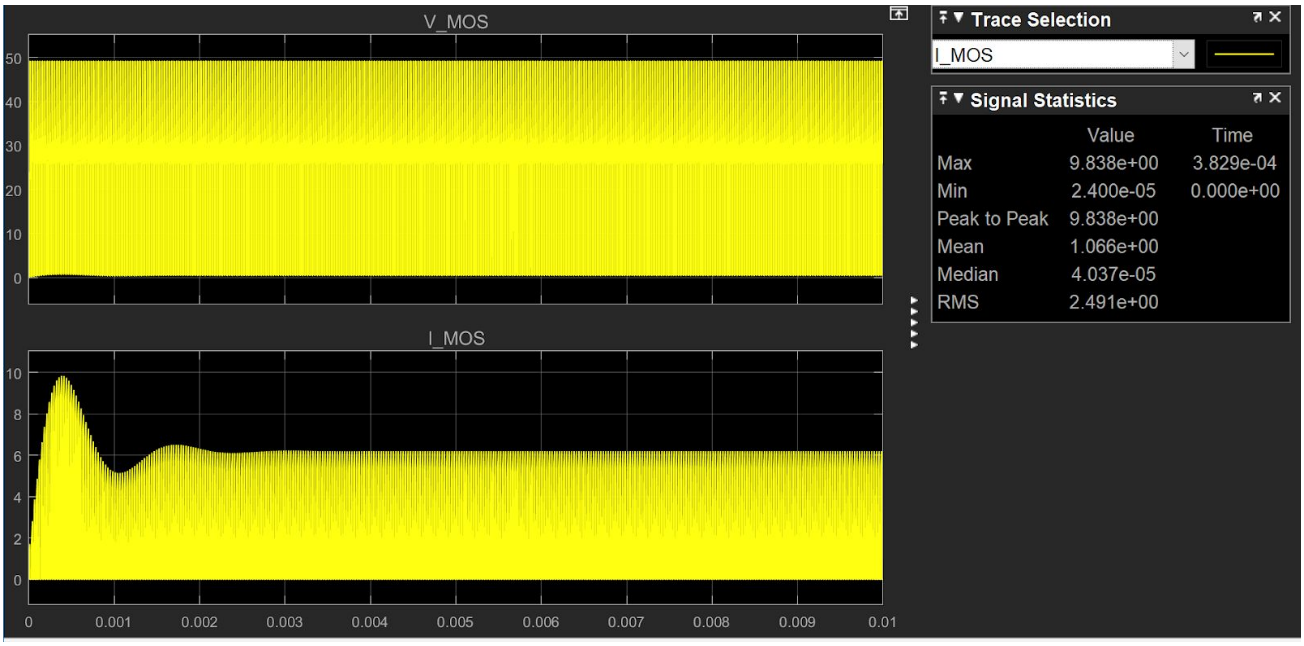


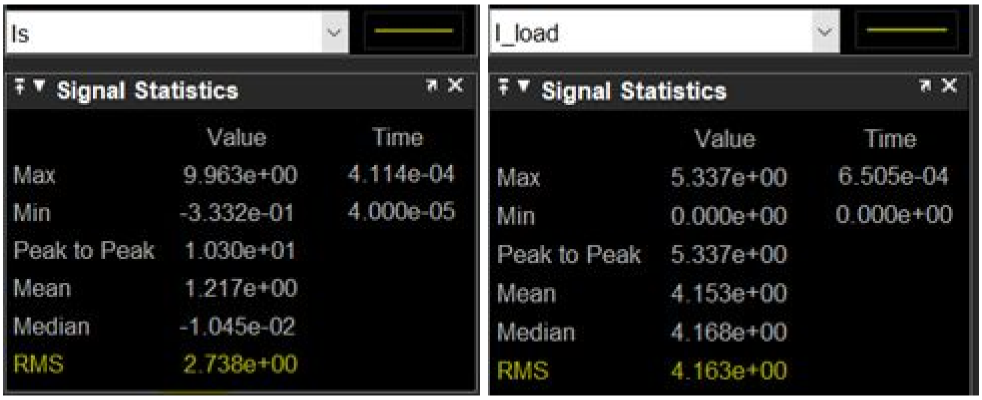
Figure 10 – Voltage and current waveforms of the switch

As can be seen from the above figure, the voltage of the mosfet becomes approximately two times of the input voltage. So, components should be selected taking this into consideration.

2.6. Part F

1. 100% Load

For the Full- Load condition, the Load resistance is taken as 2.78 Ω. The input and output current properties are shown in Figure 11.



Is — Signal Statistics

	Value	Time
Max	9.963e+00	4.114e-04
Min	-3.332e-01	4.000e-05
Peak to Peak	1.030e+01	
Mean	1.217e+00	
Median	-1.045e-02	
RMS	2.738e+00	

I_load — Signal Statistics

	Value	Time
Max	5.337e+00	6.505e-04
Min	0.000e+00	0.000e+00
Peak to Peak	5.337e+00	
Mean	4.153e+00	
Median	4.168e+00	
RMS	4.163e+00	

Figure 11 – I_s and I_{load} currents when the load is 100%.

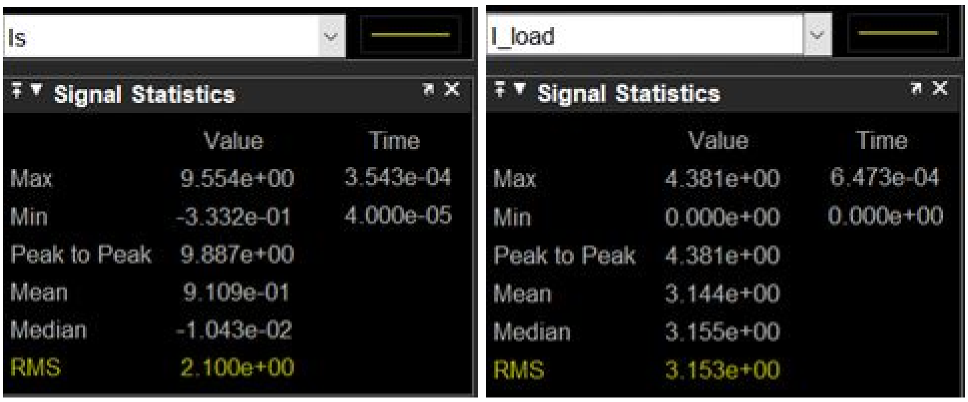
V_{in} = 24 V, V_{out} = 12 V

I_s = 2.73 A, I_{out} = 4.163 A.

$$\text{Efficiency } \eta = \frac{Pout}{Pin} = \frac{12*4.163}{24*2.73} * 100 = 76\%$$

2. 75% Load

For the 75% Load condition, the Load resistance is taken as 3.7 Ω.



Is — Signal Statistics

	Value	Time
Max	9.554e+00	3.543e-04
Min	-3.332e-01	4.000e-05
Peak to Peak	9.887e+00	
Mean	9.109e-01	
Median	-1.043e-02	
RMS	2.100e+00	

I_load — Signal Statistics

	Value	Time
Max	4.381e+00	6.473e-04
Min	0.000e+00	0.000e+00
Peak to Peak	4.381e+00	
Mean	3.144e+00	
Median	3.155e+00	
RMS	3.153e+00	

Figure 12 – I_s and I_{load} currents when the load is 75%.

V_{in} = 24 V, V_{out} = 12 V

I_s = 2.1 A, I_{out} = 3.153 A.

$$\text{Efficiency } \eta = \frac{Pout}{Pin} = \frac{12*3.153}{24*2.1} * 100 = 75.07\%$$

3. 50% Load

For the 50% Load condition, the Load resistance is taken as 5.56 Ω.

Is — Signal Statistics

	Value	Time
Max	9.184e+00	3.543e-04
Min	-3.569e-01	9.257e-04
Peak to Peak	9.541e+00	
Mean	5.779e-01	
Median	-1.289e-02	
RMS	1.472e+00	

I_load — Signal Statistics

	Value	Time
Max	3.232e+00	6.221e-04
Min	0.000e+00	0.000e+00
Peak to Peak	3.232e+00	
Mean	2.111e+00	
Median	2.115e+00	
RMS	2.118e+00	

Figure 13 – I_s and I_{load} currents when the load is 50%.

V_{in} = 24 V, V_{out} = 12 V

I_s = 1.472 A, I_{out} = 2.118 A.

$$\text{Efficiency } \eta = \frac{Pout}{Pin} = \frac{12*2.118}{24*1.472} * 100 = 72\%$$

4. 25% Load

For the 25% Load condition, the Load resistance is taken as 11.12 Ω.

Is — Signal Statistics

	Value	Time
Max	8.865e+00	3.257e-04
Min	-3.885e-01	7.543e-04
Peak to Peak	9.254e+00	
Mean	2.944e-01	
Median	-1.245e-02	
RMS	8.806e-01	

I_load — Signal Statistics

	Value	Time
Max	1.817e+00	6.200e-04
Min	3.744e-18	0.000e+00
Peak to Peak	1.817e+00	
Mean	1.070e+00	
Median	1.065e+00	
RMS	1.075e+00	

Figure 14 – I_s and I_{load} currents when the load is 25%.

V_{in} = 24 V, V_{out} = 12 V

I_s = 0.88 A, I_{out} = 1.075 A.

$$\text{Efficiency } \eta = \frac{Pout}{Pin} = \frac{12*1.075}{24*0.88} * 100 = 61\%$$

2.7. Part G

In this part, we designed a controller to provide that the forward converter works within given input limits and satisfies output voltage ripple limits. In previous steps, we observed the open loop simulation of forward converter. For the feedback control is necessary which can be used in many control strategy. Out of many control strategy, closed loop PID controller is the most effective control strategy which is mostly used in industry. That's why we used PID controller in our design. For giving variable input, we also used a signal builder and controlled voltage source instead of constant dc source. Following results are shown that the converter works within given input range and output voltage ripple limits.

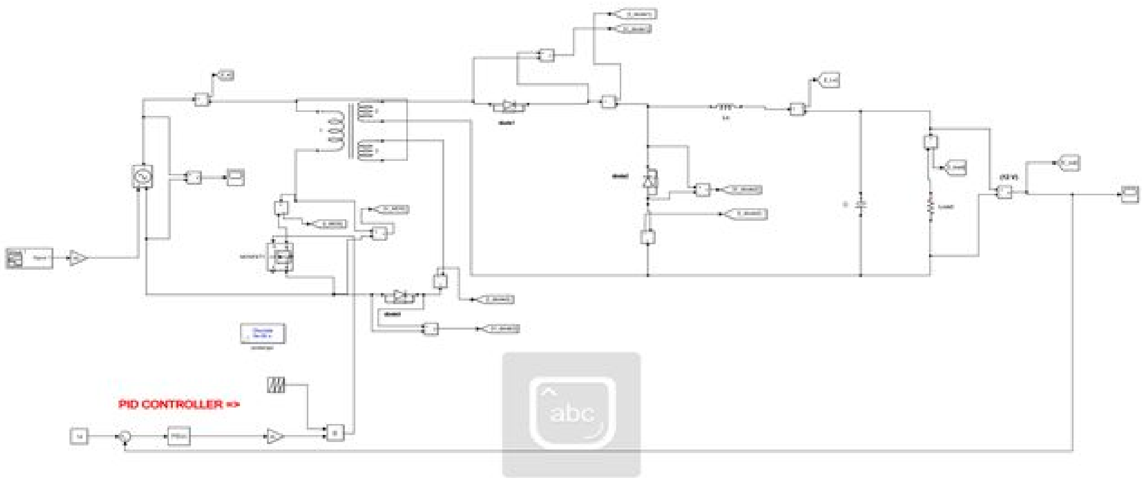


Figure 15 – The circuit schematic of forward control with PID controller

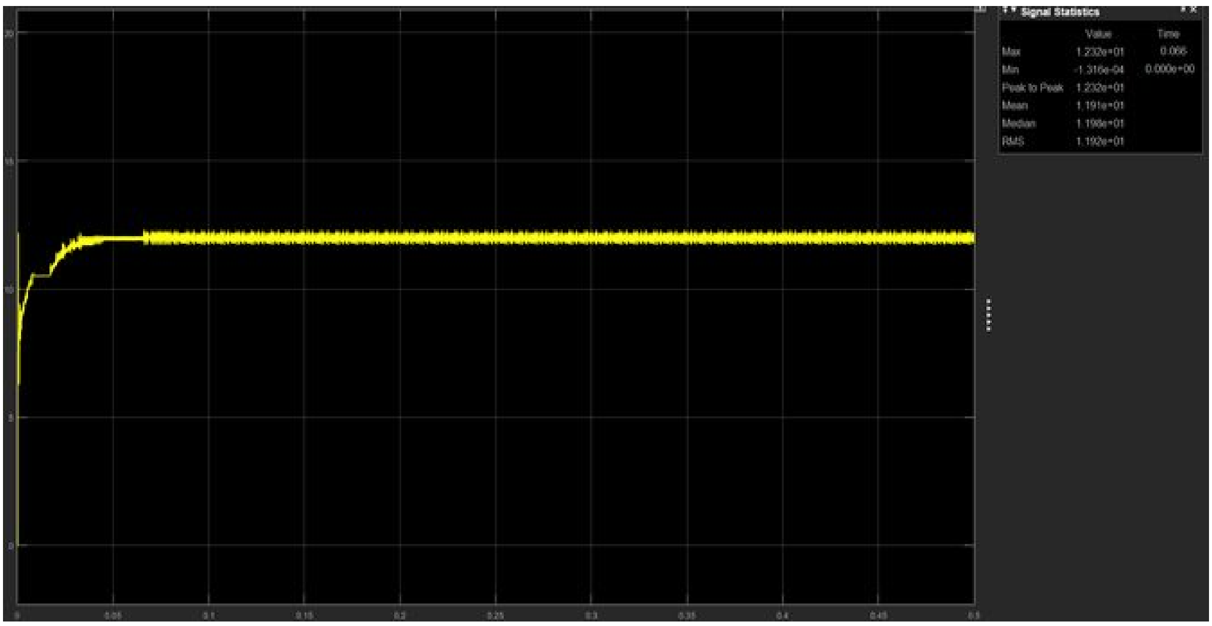


Figure 16 – The output voltage waveform of forward converter with PID controller

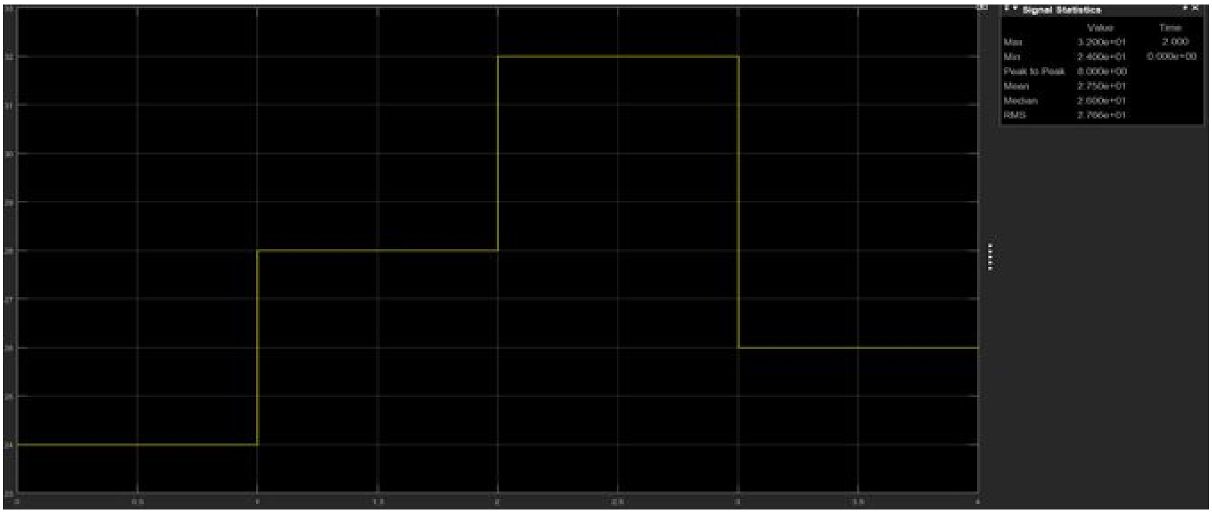


Figure 17 – The input voltage waveform of forward converter within given limits

2.8. Part H

Preliminary Component Selection

MOSFET : IRF640NPBF

While choosing the mosfet, the drain to source voltage and the drain current of the mosfet is examined in the simulation and both of them are illustrated in Figure 18. The drain to source voltage of the mosfet doesn't exceed 50V and the Mosfet current is at maximum 10A. We added a safety margin and chose our mosfet. The chosen mosfet has the following properties :

V_{DSS} = 200V
I_D = 18A.
The datasheet of the chosen mosfet can be found at [this link](#).

Thus, the chosen mosfet satisfies the requirements of our design.

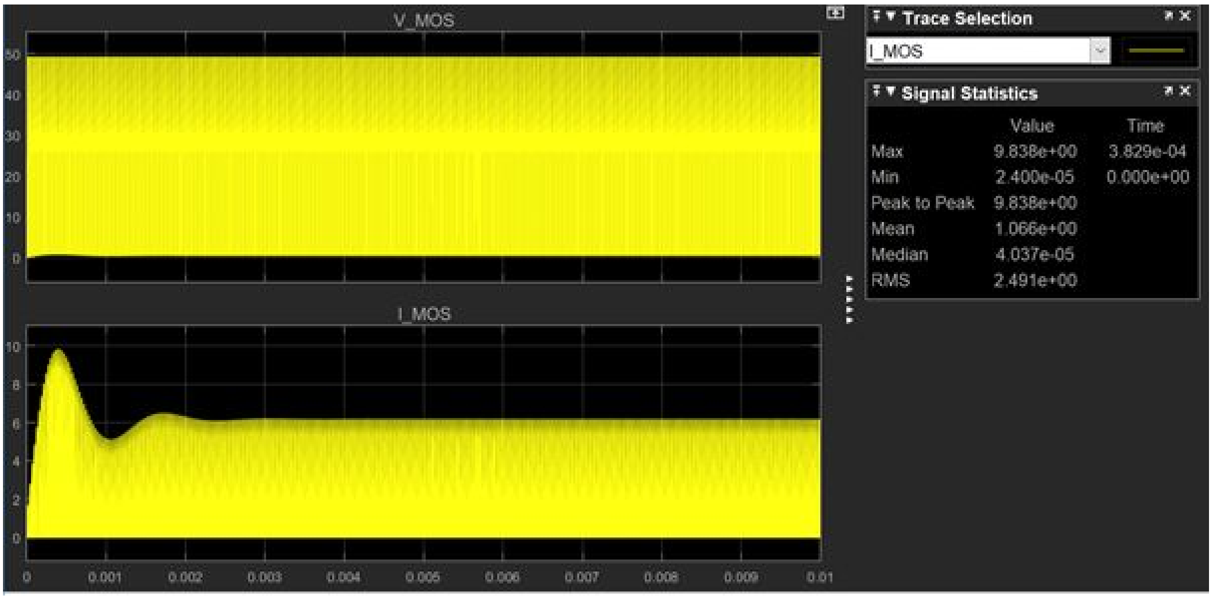


Figure 18 – Voltage and the current waveforms of the mosfet.

Diodes

- **Diode 1 :** BYW77PI100

The current and the voltage on the diode 1 is illustrated in Figure 19. While choosing the diode, forward voltage drop, repetitive reverse peak voltage and the forward current parameters are examined. The chosen diode has the following properties :

V_F = 1 V

V_{RRM} = 100 V

I_F = 50 A

The diode voltage is about 30 V and the diode current has a maximum of 7 A. Regarding the specs of the chosen diode, the diode meets the requirements of the simulation results.
The other parameters of the diode is given in the datasheet of the diode and it can be found at this link.

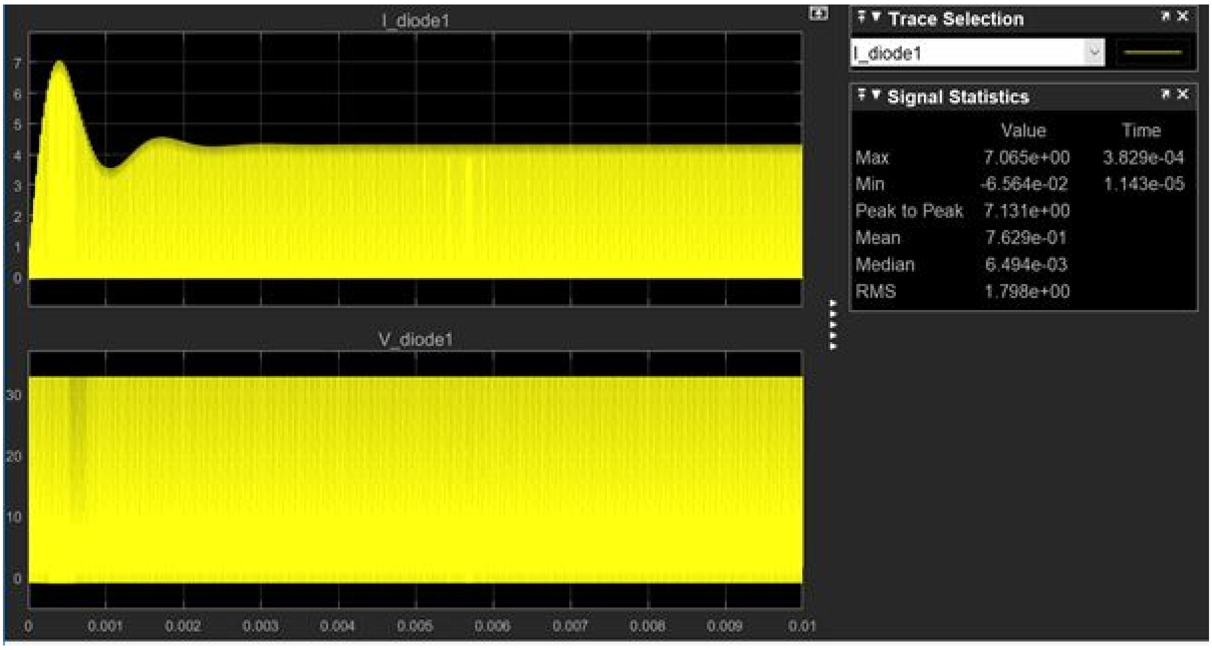


Figure 19 – Voltage and the current waveforms of the diode 1.

- **Diode 2 :** BYW77PI100

The diode 2 has the same properties with diode 1 and it is illustrated in Figure 20. Thus, the same diode chosen for diode 1 will also be used for the diode 2.

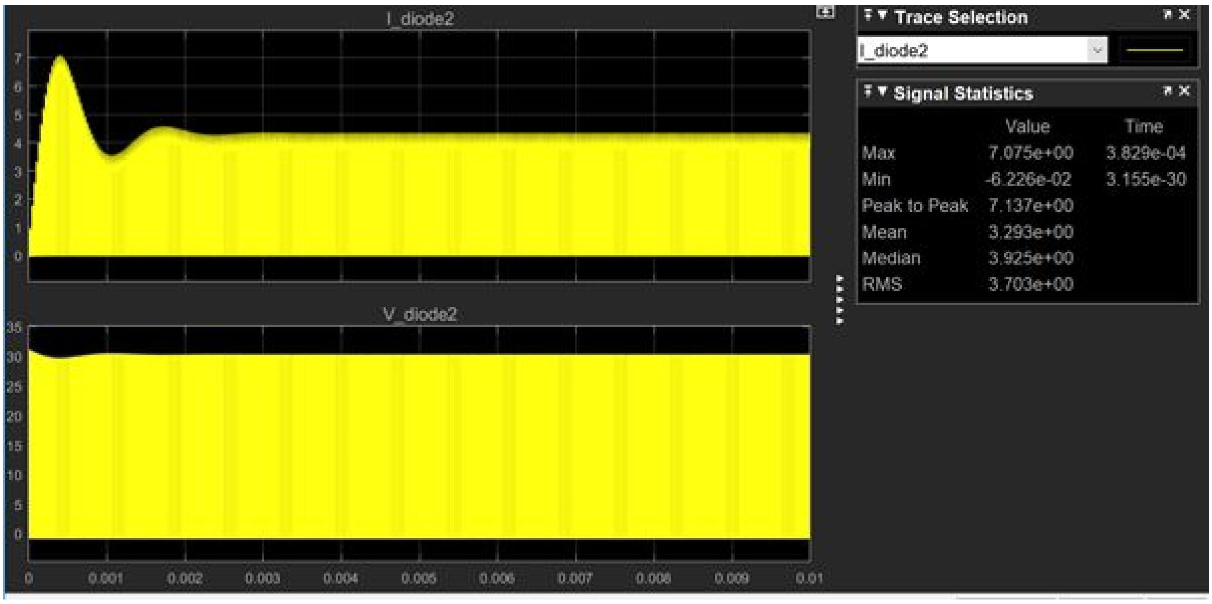


Figure 20 – Voltage and the current waveforms of the diode 2.

- **Diode 3 :** BYW77PI100

The diode 3 has a greater voltage on it compared with diode 1 and diode 2 as illustrated in Figure 21.

Hovewer, the chosen diode for diode 1 and diode 2 also satisfies the requirements of this diode. Hence, the same diode will be used for this diode too.

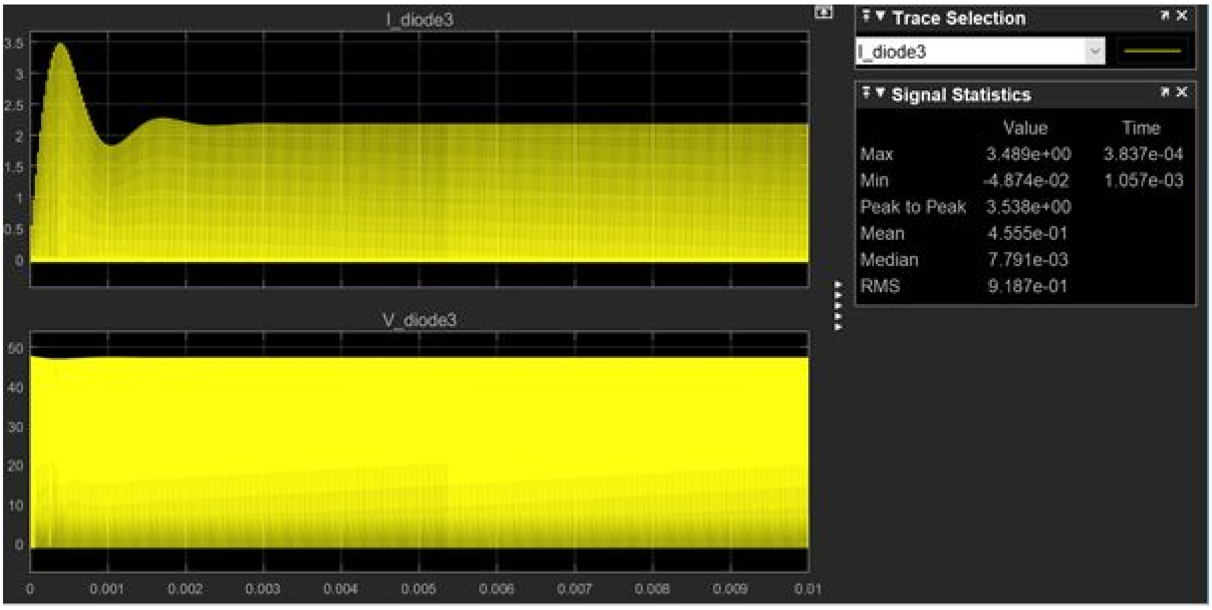


Figure 21 – Voltage and the current waveforms of the diode 3.

Capacitor : PKRM-050V101MF115-T/A5.0
While choosing the electrolytic capacitor , the most important thing to consider is the voltage rating of the capacitor. As illustrated in Figure 22, the voltage on the capacitor is the same as the voltage on the output, which is 12V. However, there may be some momentary voltage spikes on the capacitor. Hence, with an extra safety margin we chose the capacitor with 50 V rating.
The datasheet of the capacitor is can be found at this link.

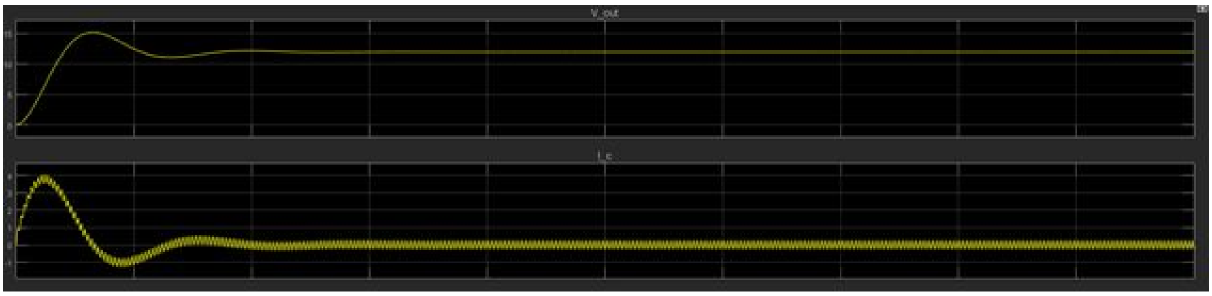


Figure 22 – Voltage and the current waveforms of the capacitor.

Transformer

- Core : 0P43434EC

The datasheet of the chosen core can be found at this link .

- Wire : 21-AWG Cable

Necessary justifications of the transformer core and the wire choice is given in part B.

3. Conclusion

In this project, we designed a DC/DC converter topology from given project alternatives. We chose a Forward Converter 5 and defined required parameters such as inductance, capacitance and resistance values of converter according to given main specifications. We also designed a transformer. And we simulated the topology and our-designed transformer for all testing requirements. Finally, we chose some components that we will use in hardware implementation according to our simulation results and datasheets of components.

This software project is covered to understand the details of hardware project. In the next process, we will construct a forward converter practically, according to our-designed and simulation parameters and specified components. Therefore, this project was really useful and instructive for future stages.

4. References

[1] https://www.onsemi.com/pub/Collateral/AN-4134.PDF

[2]https://www.mag-inc.com/Design/Design-Guides/Transformer-Design-with-Magnetics-Ferrite-Cores