EE 464
STATIC POWER CONVERSION-II
Fall 2022-2023

Homework 2

Magnetic Design of an Isolated Power Supply

Hiper-Optik Basküler Converter

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Topology Selection

There are many isolated topologies studied as DC-DC converter such as flyback, forward and push-pull converter. We decided to use push-pull converter due to several advantages.

1. Flyback Converter

Flyback converter is widely used and a good option for the project; however, it is not preferred.

Advantages	**Disadvantages**
Widely studied	Bigger core
Easier to control	Large Lm causes voltage spikes
	Needs a bigger snubber (less efficient)

2.Forward Converter

Forward converter solves the problems caused by Lm; however, it requires

Advantages	**Disadvantages**
Better core utilization	Three windings
Output inductor gives better output current	More components
Less energy storage needs in the core (gapless)	Gain changes a lot in DCM

3.Push-Pull Converter

Push-Pull converter solves the problems and utilizes core the best.

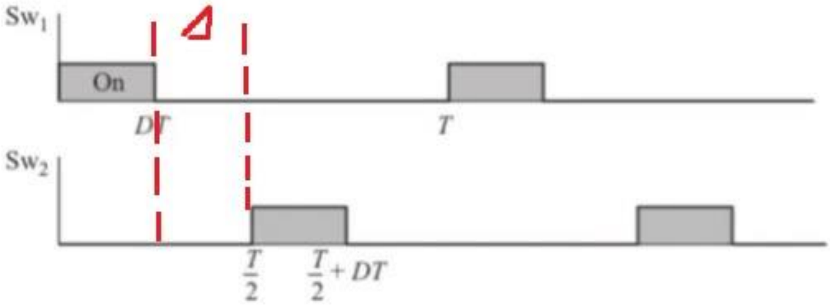
Advantages	**Disadvantages**
Better core utilization	Four windings
Output inductor gives better output current (twice frequency)	More components (2 diode- 2 mosfet)
Smaller transformer	Harder control

Push-pull converter topology is selected because it utilizes core better. Moreover, it has less ringing due to Lm. Output frequency is naturally doubled reducing inductor and capacitor size.

a)

Chosen topology for the hardware project is push-pull converter.

Since



$$Δ = \frac{(1 - 2 * D)}{2} * T_s \quad \Rightarrow \quad D < 0.5$$

Based on the duty cycle and V_{in}-V_{out} relation, $N_{seconday}/N_{primary}$=40/9 is chosen.

$$\frac{V_{out}}{V_{in}} = 2 * \frac{N_{secondary}}{N_{primary}} * D$$

$$\frac{48V}{12V} = 2 * \frac{40}{9} * D \quad \Rightarrow \quad D = 0.45$$

$$\frac{48V}{15V} = 2 * \frac{40}{9} * D \quad \Rightarrow \quad D = 0.36$$

$$\frac{48V}{18V} = 2 * \frac{40}{9} * D \quad \Rightarrow \quad D = 0.30$$

Therefore, duty cycle range is found as

$$0.30 \leq D \leq 0.45$$

b)

$$P_{out} = V_{out} * I_{out}$$

$$48W = 48V * I_{out} \quad \Rightarrow \quad I_{out} = 1A$$

- In order to minimize the leakage inductance, E core is chosen. The windings will be on the middle leg to minimize the leakage inductance. Also, E cores are much easier to obtain in the market, which is another reason to choose E core. Using the guideline given on magnetics.com, we determined the B_{max} ,J and D_{cma} values as follows;

$$B_{max} = 0.2T \quad J = 4\frac{A}{mm^2} \quad D_{cma} = 715\ circular\ mils/A$$

Then we calculated $W_a * A_c$ for required core.

$$W_a * A_c = \frac{P_o * D_{cma}}{K_t * B_{max} * f} = \frac{48W * \left(\frac{1}{4\frac{A}{mm^2} * 0.00035}\right)\frac{circular\ mils}{A}}{0.001 * 2000Gauss * 40kHz} = 0.43cm^4$$

Chosen core is CF139EE2507 ($W_a * A_c = 0.454cm^4$)

COSMO FERRITES LIMITED

PRODUCT DATA APPROVAL SHEET

Core- EE2507 | Cosmo Ferrites Ltd. - INDIA

Appearance & Shape: To be free from any defect such as flow, burrs, unevenness etc, As per IEC standards.

Effective Parameters irrespective of material grade (per set)

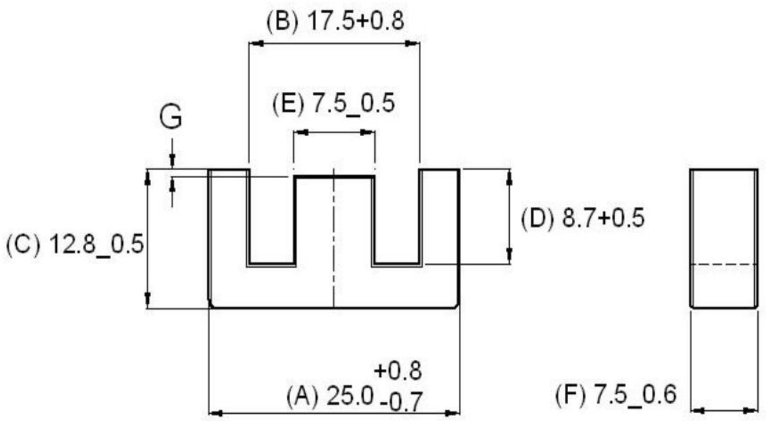
- Effective Length (L_e): 57.5mm
- Effective Area (A_e): 52.5mm^2
- Effective Area (A_{Min}): 51.5mm^2
- Effective Volume (V_e): 3020mm^3

Approximate weight (without Gap): 15g/Set

EE2507 Un-gapped (OL)

Test Conditions: 1kHz/1mT/CFR COIL,N=100/25˚C

Material Grade	Initial Permeability (μ_{iac})	AL Value (nH)/Set	P_V (W/set)	Ordering code
CF196	2000 ±20%	1800 +30%/-20%	≤0.42(200mT,16kHz,100⁰C)	CF196 EE2507 OL
CF139	2100 ±20%	1900 +30%/-20%	≤0.30(100mT,100kHz,100⁰C)	CF139 EE2507 OL
CF297	2300 ±20%	2050 +30%/-20%	≤0.27(100mT,100kHz,100⁰C)	CF297 EE2507 OL
CF130	3000 ±20%	2500 +30%/-20%	≤0.45(200mT,16kHz,100⁰C)	CF130 EE2507 OL
CF195	5000 ±20%	3500 +30%/-20%	-	CF195 EE2507 OL
CF197	7000 ±20%	4300 +30%/-20%	-	CF197 EE2507 OL



Remarks: Value of “G” is Zero (0) for Un-Gapped Cores, for Gapped Cores the value of “G” varies as per the Gap/AL value

- Number of turns and L_m

$$W_a = 0.865cm^2 \quad A_c = 0.525cm^2 \quad A_L = 1900\frac{nH}{Turn^2}$$

$$N_{primary} = \frac{V_{primary} * 10^8}{4 * B * A_c * f} = \frac{12V * 10^8}{4 * 2000\ Gauss * 0.525cm^2 * 40kHz} = 7.14\ Turns \cong 7\ Turns$$

$$N_{secondary} = N_{primary} * \frac{40}{9} = 31.11\ Turns \cong 31\ Turns$$

$$L_m = \left(\frac{N_{primary}}{10^3}\right)^2 * A_L = 93.1\mu H$$

- Cable selection

$$I_{secondary,rms} = \sqrt{D * I_o^2 + 2 * D * \left(\frac{I_o}{2}\right)^2} = \sqrt{0.45 * 1^2 + 2 * 0.45 * \left(\frac{1}{2}\right)^2} = 0.82A$$

$$I_{primary,rms} = \sqrt{0.45 \times I_{pri,average}^2} = 2.68A$$

$$J = \frac{I}{A_{cable}} \quad \Rightarrow \quad 4\frac{A}{mm^2} = \frac{0.82A}{A_{sec}} \quad \Rightarrow \quad A_{sec} = 0.21mm^2$$

$$J = \frac{I}{A_{cable}} \quad \Rightarrow \quad 4\frac{A}{mm^2} = \frac{2.68A}{A_{pri}} \quad \Rightarrow \quad A_{pri} = 0.67mm^2$$

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Conductor cross section in mm^2	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper
0000	0.46	11.684	107	0.049	0.16072	380	302	125 Hz
000	0.4096	10.40384	84.9	0.0618	0.202704	328	239	160 Hz
00	0.3648	9.26592	67.4	0.0779	0.255512	283	190	200 Hz
0	0.3249	8.25246	53.5	0.0983	0.322424	245	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	211	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	181	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	158	75	500 Hz
4	0.2043	5.18922	21.1	0.2485	0.81508	135	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	118	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	101	37	1100 Hz
7	0.1443	3.66522	10.6	0.4982	1.634096	89	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	73	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	64	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	55	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	47	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	41	9.3	4150 Hz
13	0.072	1.8288	2.63	2.003	6.56984	35	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	32	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	28	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	22	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	19	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	16	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	14	1.8	21 kHz
20	0.032	0.8128	0.519	10.15	33.292	11	1.5	27 kHz
21	0.0285	0.7239	0.412	12.8	41.984	9	1.2	33 kHz
22	0.0253	0.64516	0.327	16.14	52.9392	7	0.92	42 kHz
23	0.0226	0.57404	0.259	20.36	66.7808	4.7	0.729	53 kHz
24	0.0201	0.51054	0.205	25.67	84.1976	3.5	0.577	68 kHz
25	0.0179	0.45466	0.162	32.37	106.1736	2.7	0.457	85 kHz

1x22AWG for secondary, which can operate with 100% skin depth at 40kHz.

2x22AWG for primary, which can operate with 100% skin depth at 40kHz.

- k_{cu} fill factor and copper losses.

$$k_{cu} = \frac{2 * A_{pri,cable} * N_{primary} + 2 * A_{sec,cable} * N_{secondary}}{W_a}$$

$$= \frac{2 * 0.654mm^2 * 7\ Turns + 2 * 0.327mm^2 * 31\ Turns}{86.5mm^2} = 0.34$$

0.34 fill factor is a reasonable fill factor for the transformer.

$$MLT_{core} = 2\pi \frac{B - E}{2} 31.42mm$$

$$R_{primary} = \frac{N_{primary} * MLT_{core} * R_{cable}}{\#\ parallel\ cables} = \frac{7 * 31.42mm * 52.94 * 10^{-6} \frac{\Omega}{mm}}{2} = 5.8m\Omega$$

$$R_{secondary} = \frac{N_{secondary} * MLT_{core} * R_{cable}}{\#\ parallel\ cables} = \frac{33 * 31.42mm * 52.94 * 10^{-6} \frac{\Omega}{mm}}{1} = 54.9m\Omega$$

Since cables are used with 100% skin depth, AC and DC resistances are expected to be same.

$$P_{copper} = 2 * \left(I_{primary,rms}^2 * R_{primary} + I_{secondary,rms}^2 * R_{secondary}\right)$$

$$P_{copper} = 2 * (2.68A^2 * 5.8m\Omega + 0.82A^2 * 54.9m\Omega) = 0.17W$$

- Core losses of the transformer

In the datasheet, 0.42W/cm^3 is indicated for 0.2T operating condition.

$$P_{core} = 0.42 \frac{W}{cm^3} * 3.02cm^3 = 1.268W$$

Even if the ratio of P_{copper} to P_{core} is very small and in an ideal case they should be equal, it is decided to not iterate since summation of the losses is not very large.

c)

Converter is simulated using Simulink with the following model in Figure xxx.

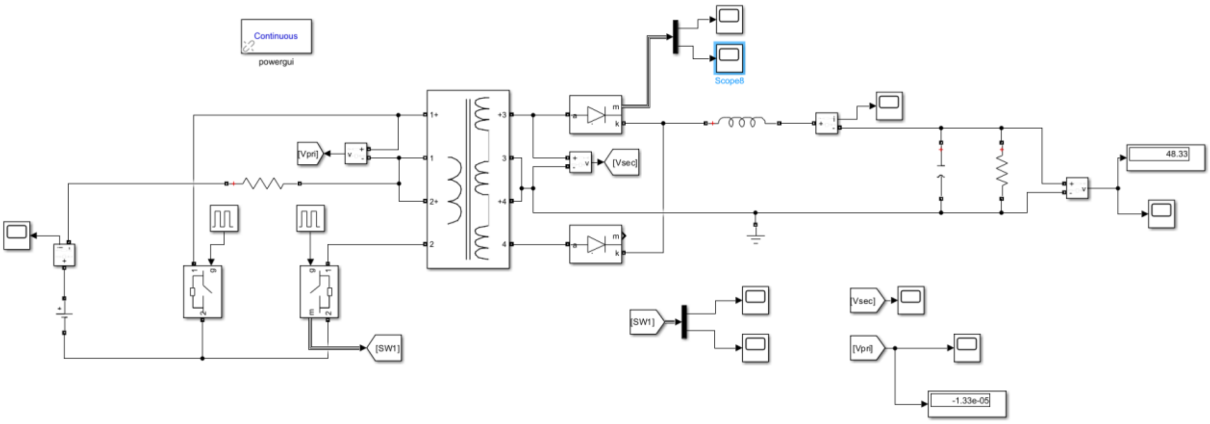


Figure 1 Push-Pull Converter in Simulink

Input and output currents, switch voltages and other measurements gave us the expected results with the theoretical ones shown between Figure 2-10.

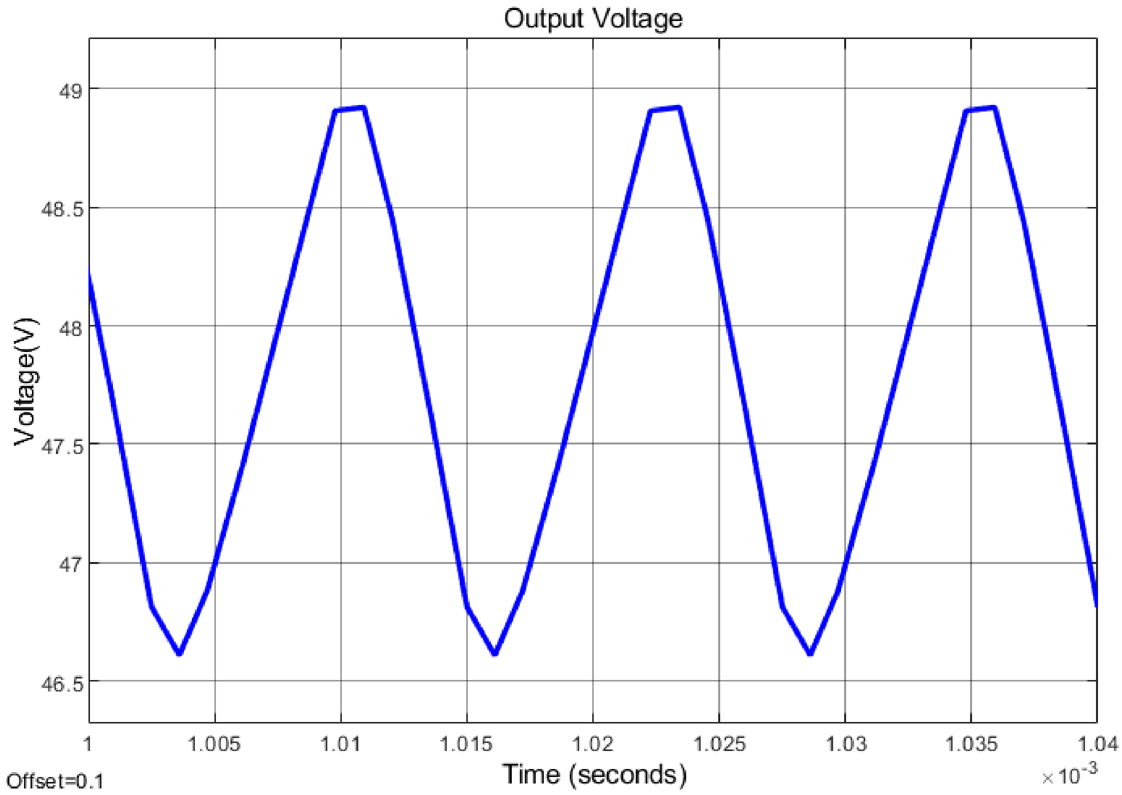


Figure 2 Output Voltage of Push Pull Converter with 18V Input

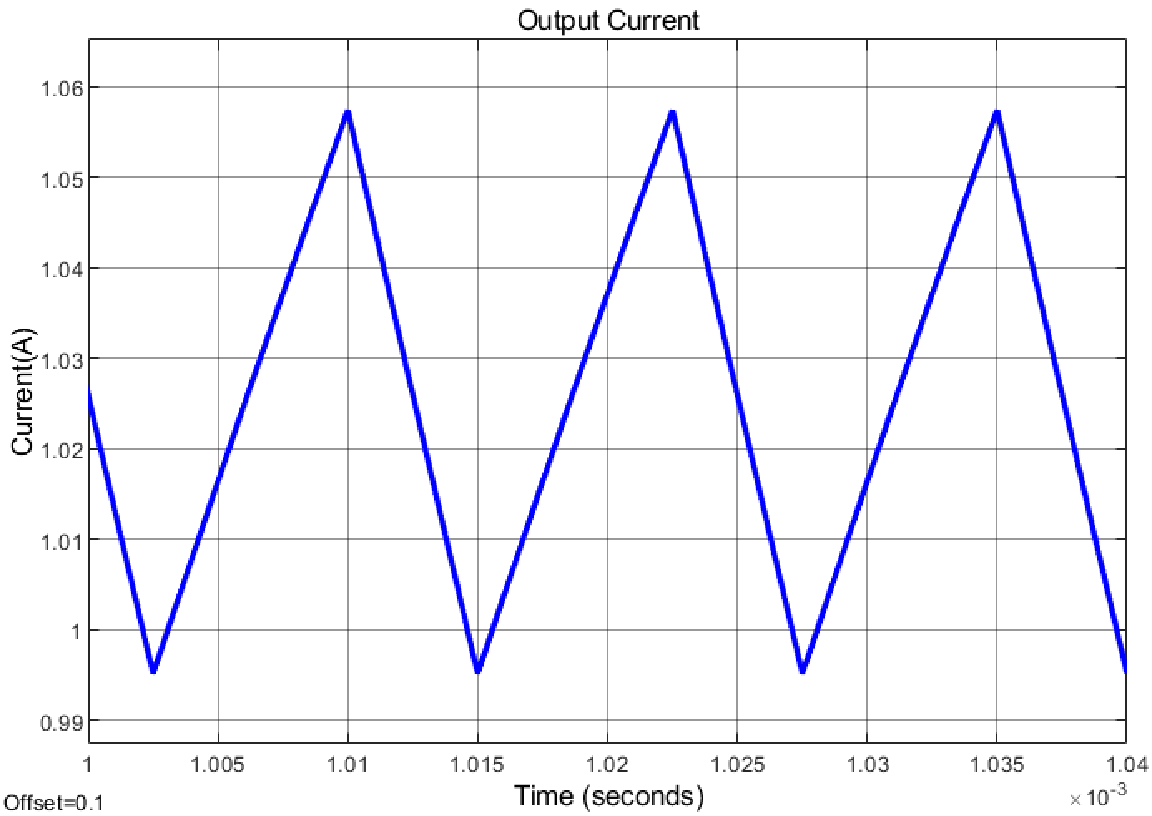


Figure 3 Output Current of Push Pull Converter with 18V Input

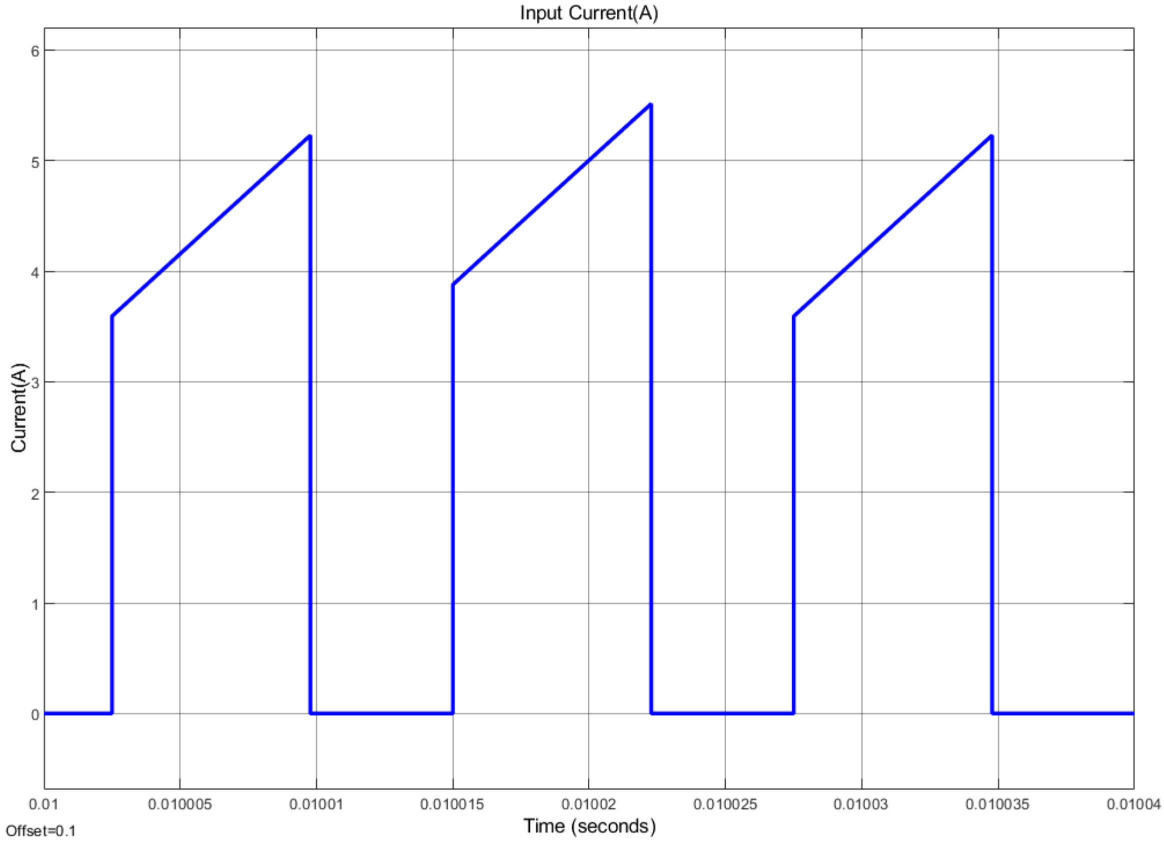


Figure 4 Input Current of Push Pull Converter with 18V Input

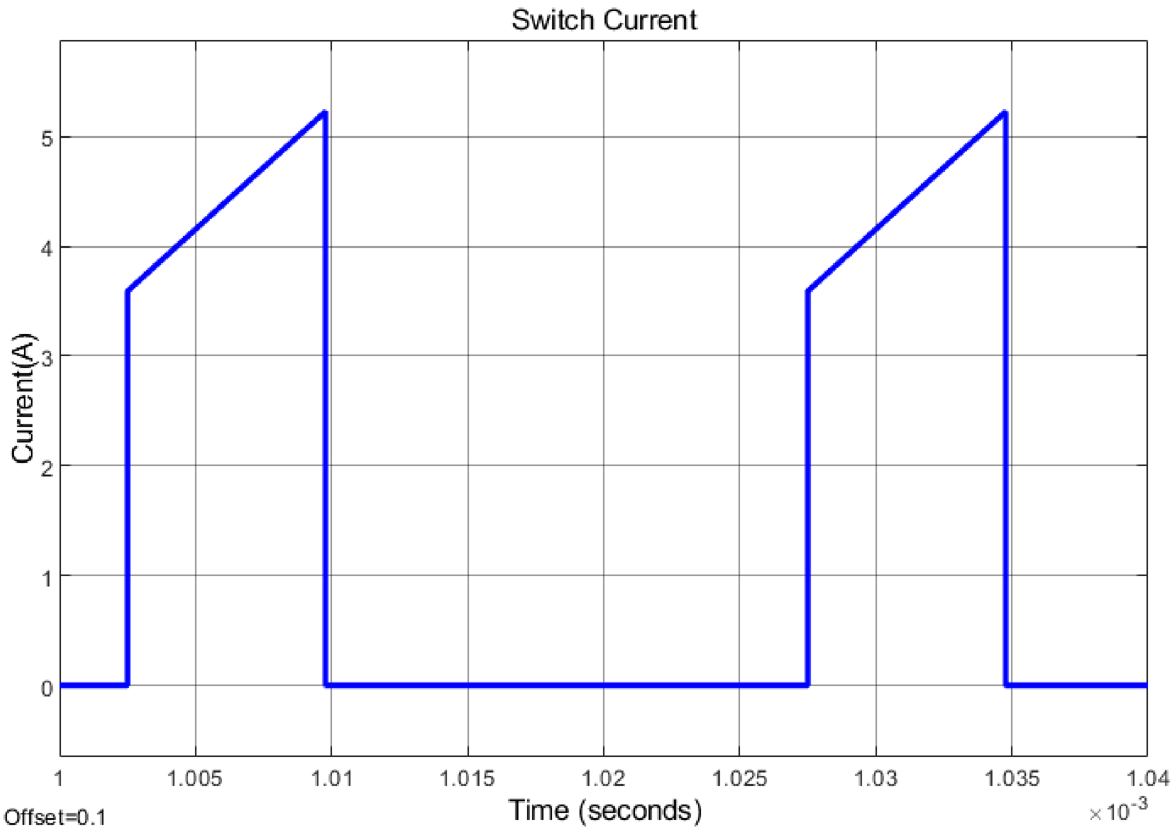


Figure 5 MOSFET Current of Push Pull Converter with 18V Input

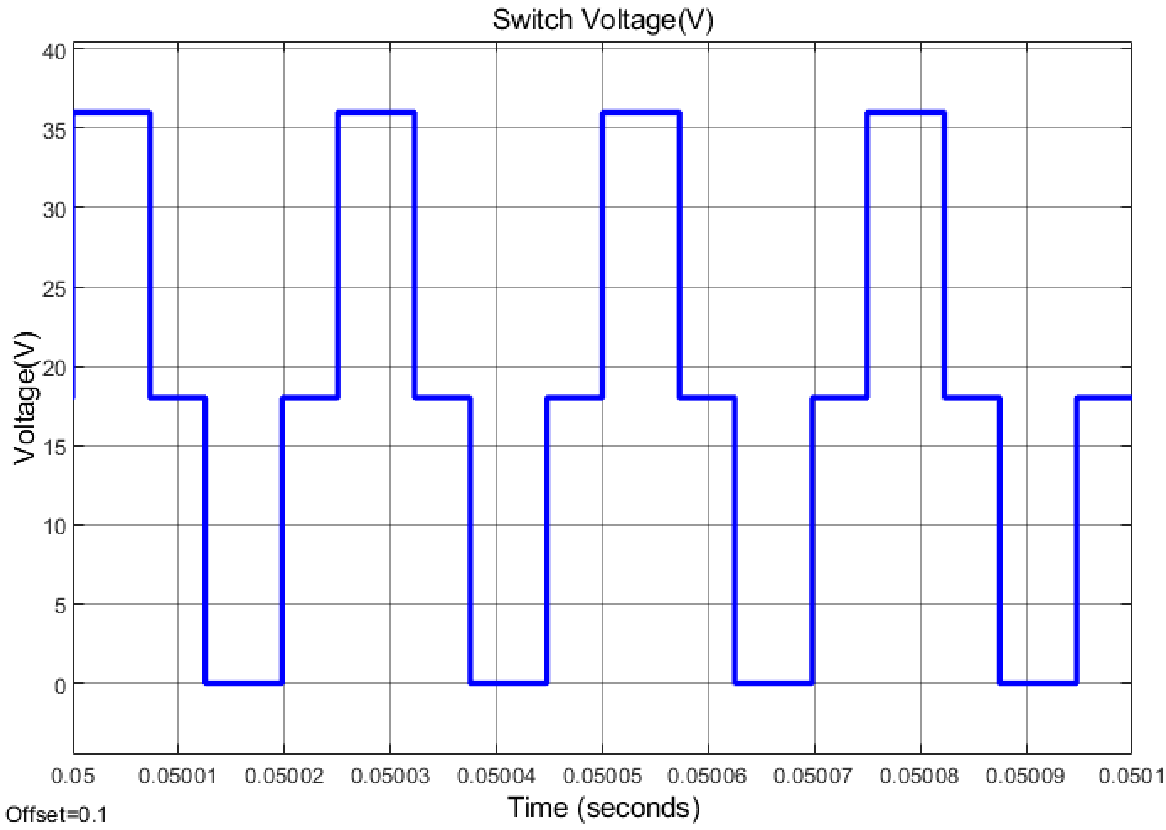


Figure 6 MOSFET Voltage of Push Pull Converter with 18V Input

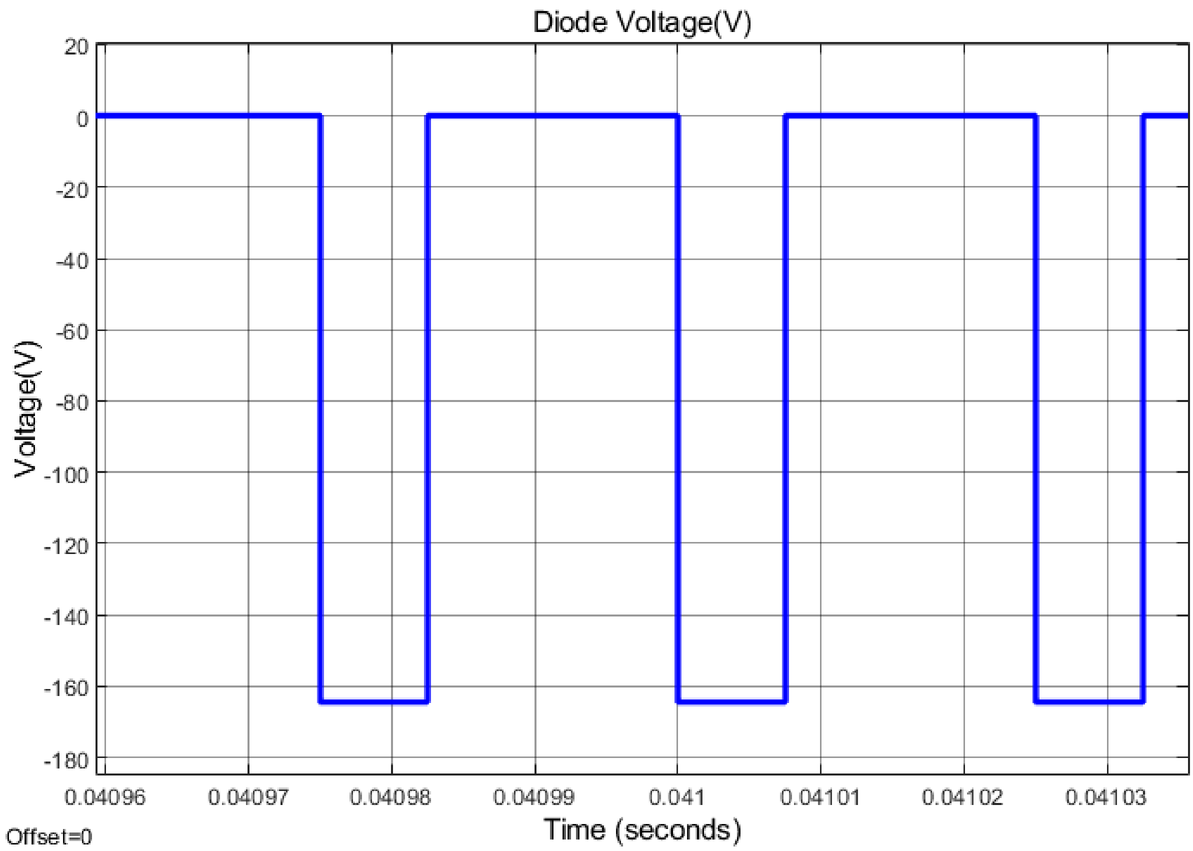


Figure 7 Diode Voltage of Push Pull Converter with 18V Input

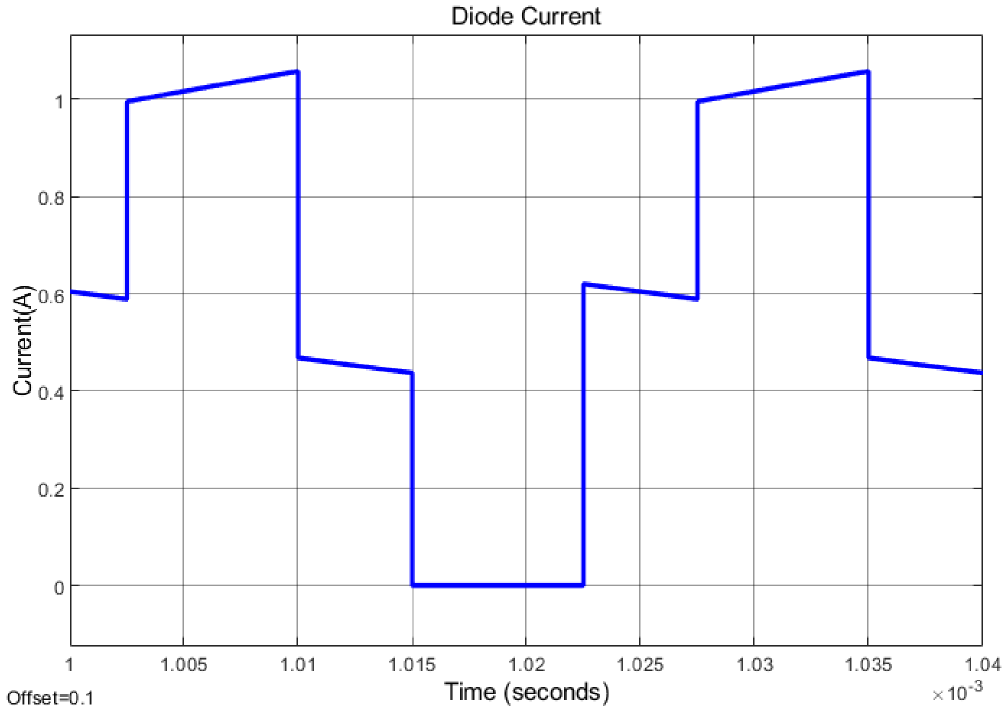


Figure 8 Diode Current of Push Pull Converter with 18V Input

12V inputs and outputs have similar shapes they are only scaled.

d)

To get into the DCM mode output current gets around 0.27A average (180 ohm resistive load 18Vinput).

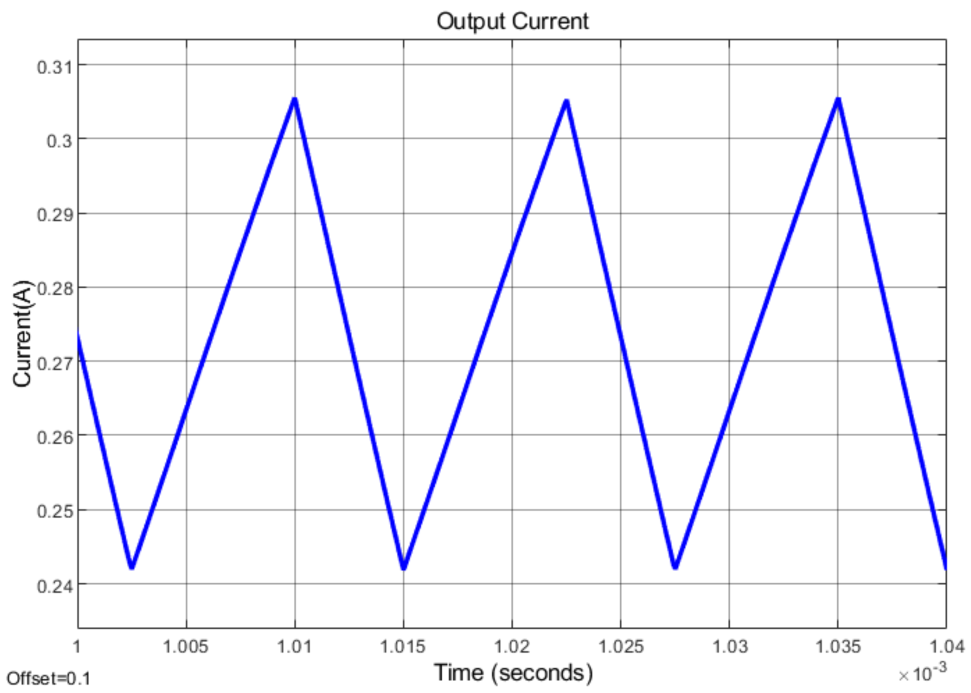


Figure 9 Output Current Before DCM with 18V

Discontinuous conduction mode is determined using the primary coil currents. When the waveform start to corrupt it means we cannot magnetize and demagnetize our core properly to work in CCM.

Mode	Min Current(mean)	Max Current
CCM	0.2A (18V)	1.65A (12V)

e)

For use in the circuit, P60B4EL MOSFET ($R_{ds,on}$=33mΩ, V_{ds}=40V, I_d=60A) is preferred, which has low ON resistance and is suitable for the voltage acting on the switches in the ideal push-pull converter.

We calculate the leakage inductance value of the transformer we designed by using the following formula,

$$L_{leakage} = \frac{N^2 \mu_0 A_c}{l}$$

$$L_{leakage,pri} = \frac{7^2 \times (1.257 \times 10^{-6} H/m) \times (52.5 \times 10^{-6} m^2)}{57.5 \times 10^{-3} m} = 56.2nH$$

$$L_{leakage,sec} = L_{leakage,pri} \times \frac{31^2}{7^2} = 1.1\mu H$$

We also find the magnetizing resistance value as follows,

$$P_{core} = \frac{V_{pri}^2}{R_c}$$

$$R_c = \frac{(8.05V)^2}{2.4W} = 27\Omega$$

Non-idealities such as copper resistances and magnetizing inductances are used in the simulation as calculated in the previous parts.

Due to the voltage increase caused by the leakage induvtance on the switches, the need for a snubber circuit has occurred. In line with the information we obtained from the application notes, we created an RC snubber circuit by trying various resistor and capacitor values. In accordance with the values we can find in the market, we determined our capacitor as 47nF and our resistance as 5.6Ω.

When we made observations by placing the found non-ideality parameters in the simulation model, the results in the graphs below were obtained (V_{in}=12V, D=0.45, f_{sw}=40kHz),

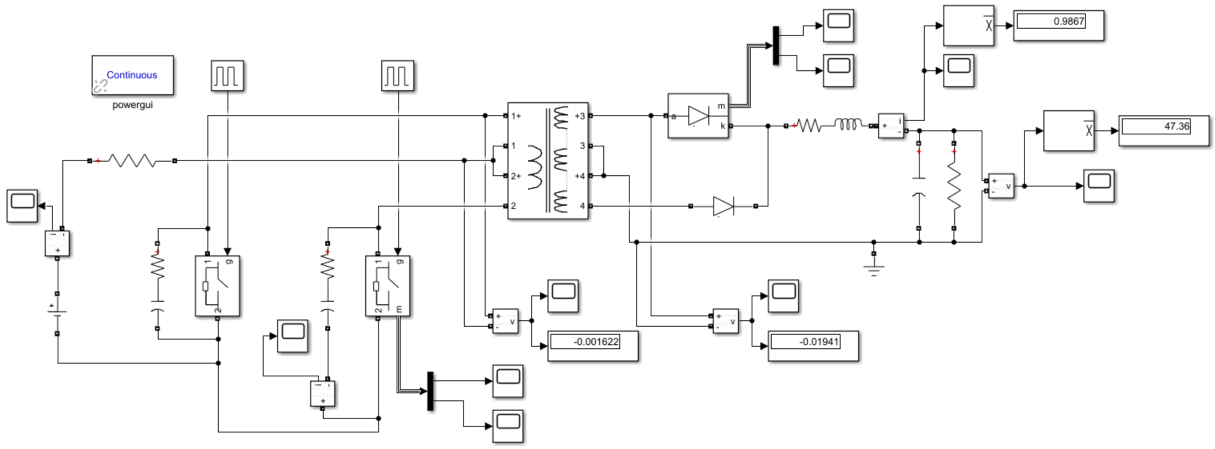


Figure 10. Simulation model of the non-ideal push pull converter.

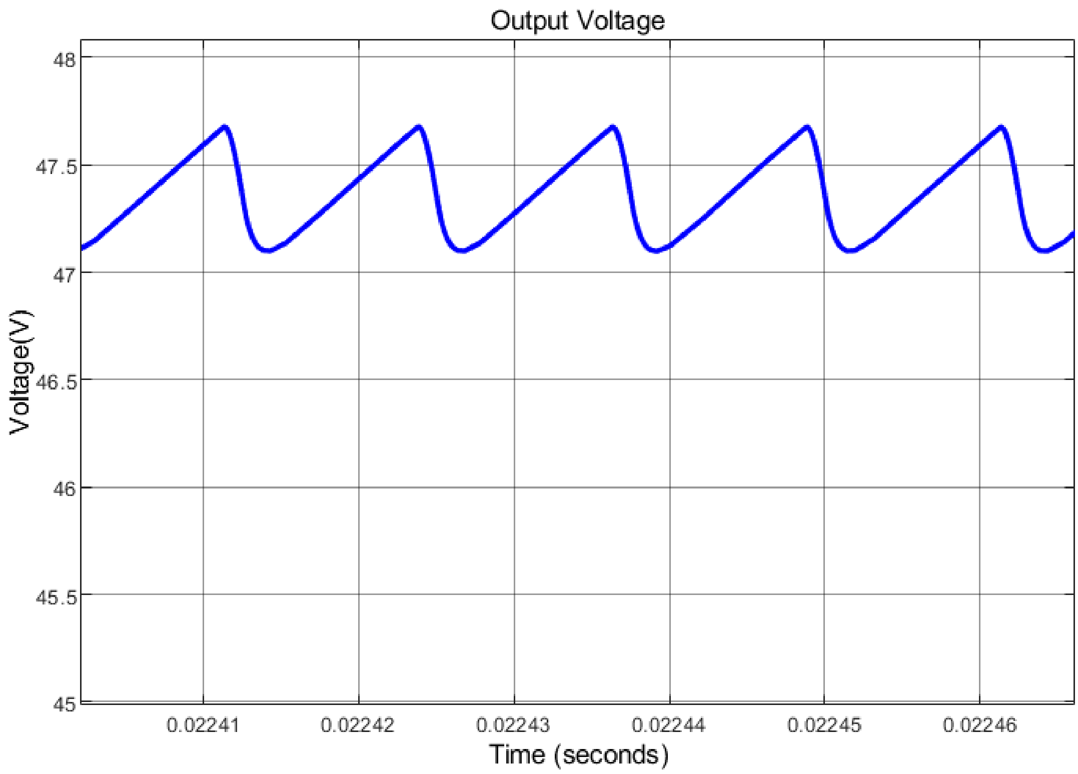


Figure 11. Output voltage waveform of non-ideal push-pull converter.

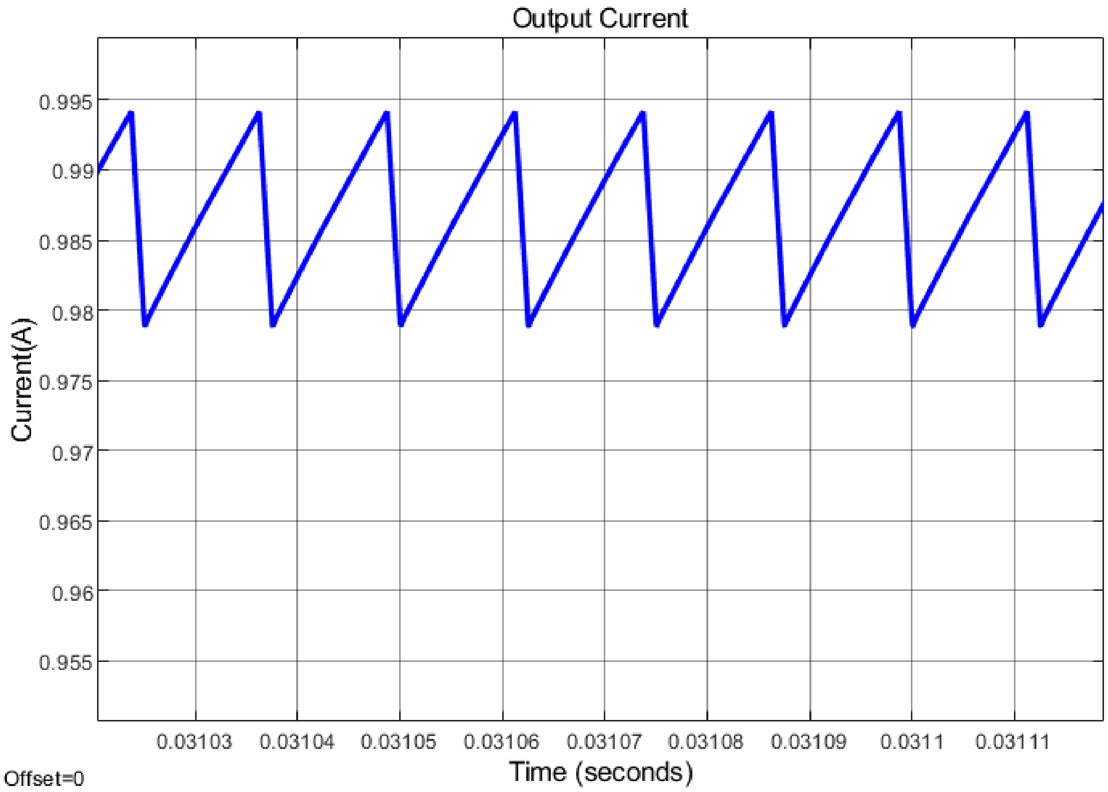


Figure 12. Output current waveform of non-ideal push-pull converter.

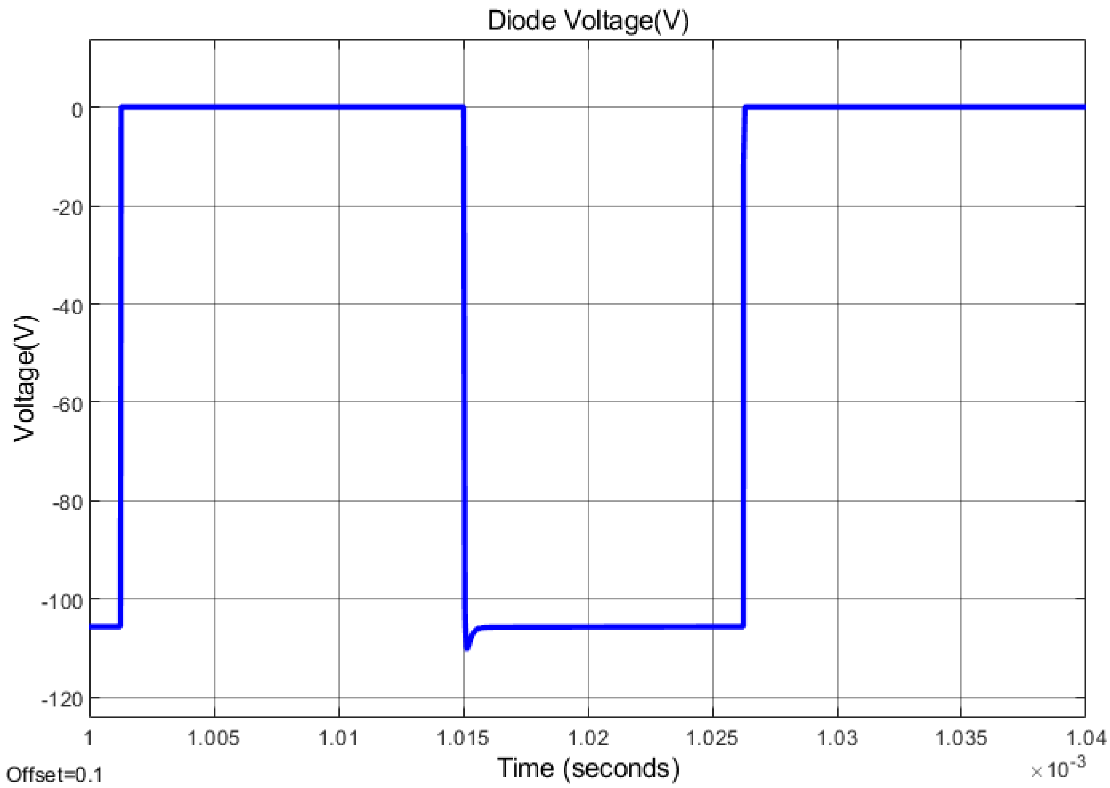


Figure 13. Voltage waveform of one of the diodes that is in the secondary side.

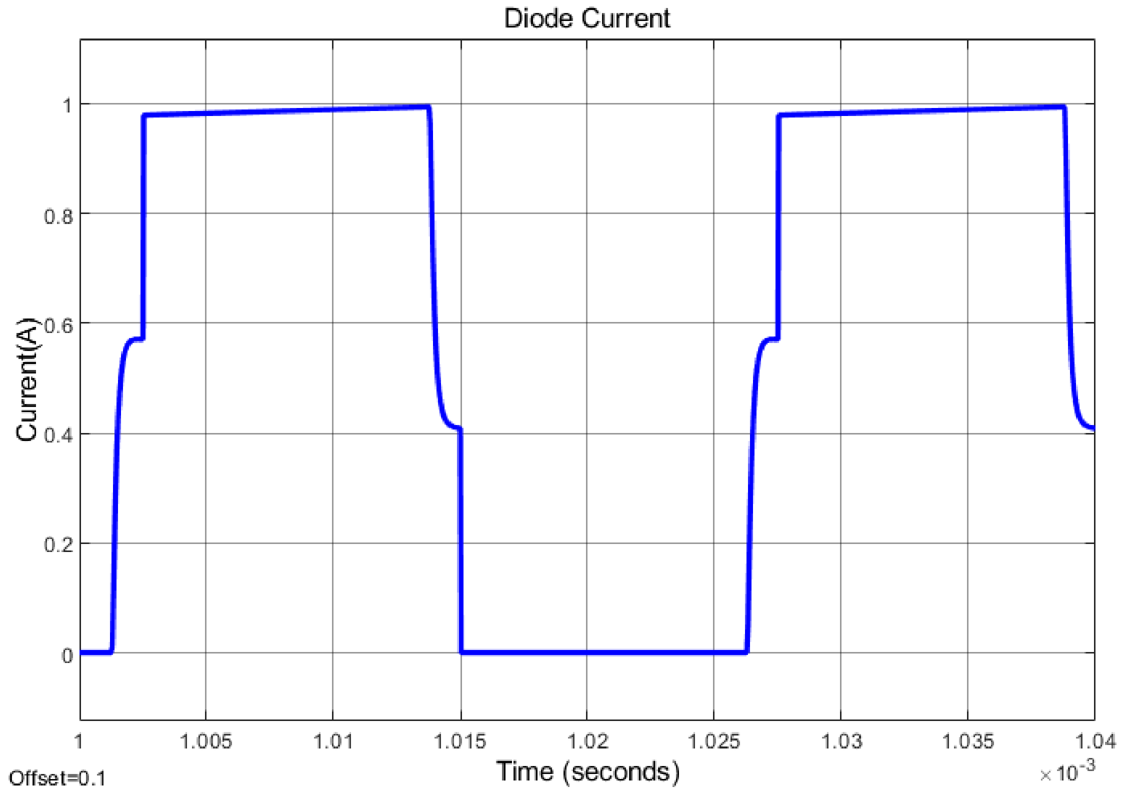


Figure 14. Current waveform of one of the diodes that is in the secondary side.

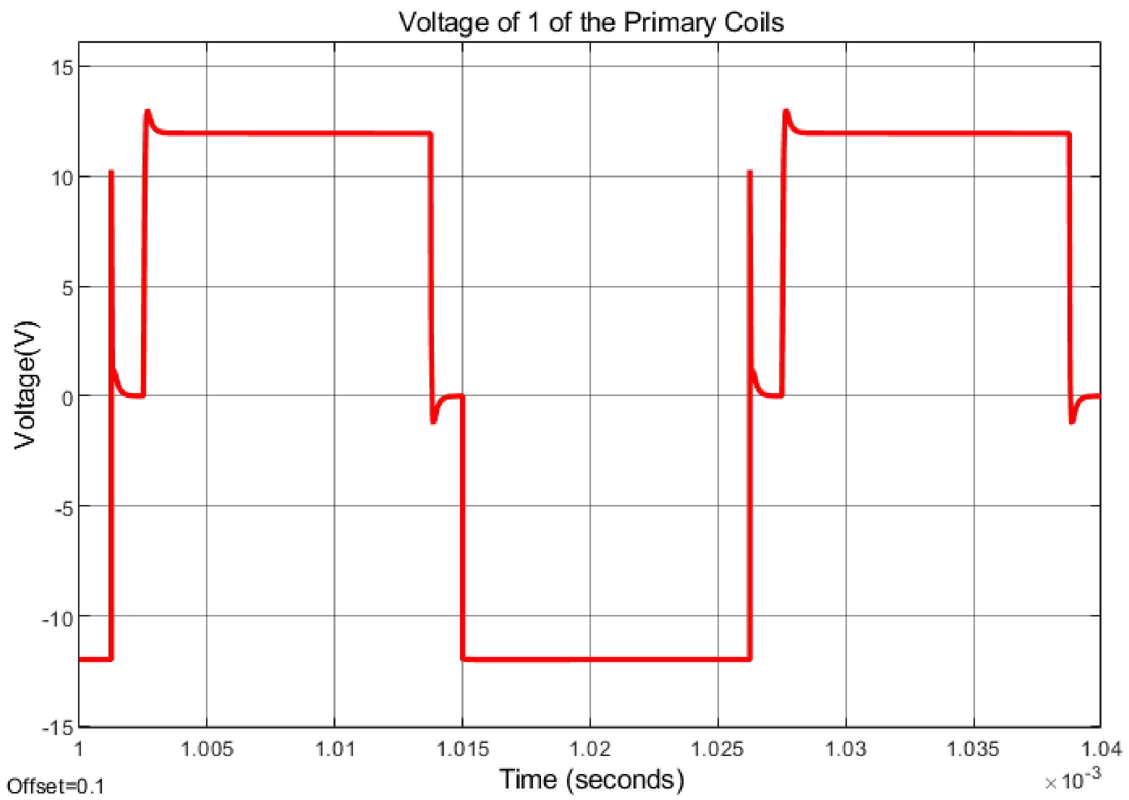


Figure 15. Voltage waveform of one of the primary coils.

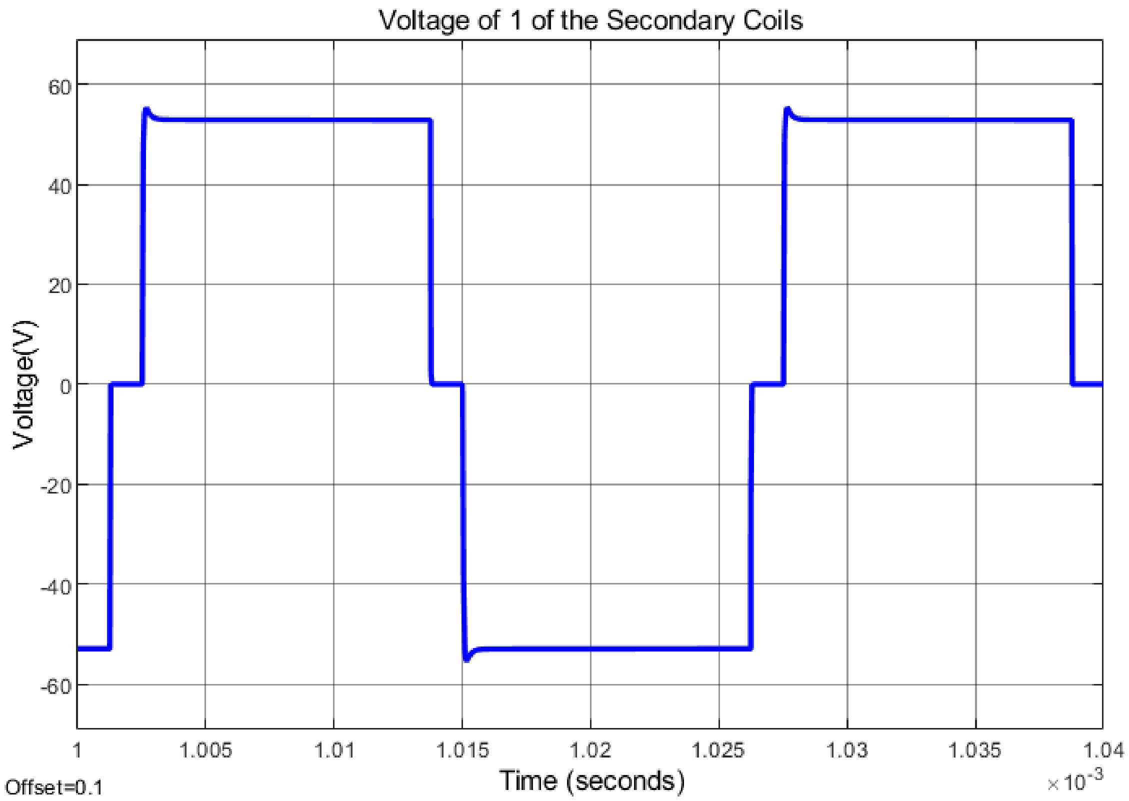


Figure 16. Voltage waveform of one of the secondary coils.

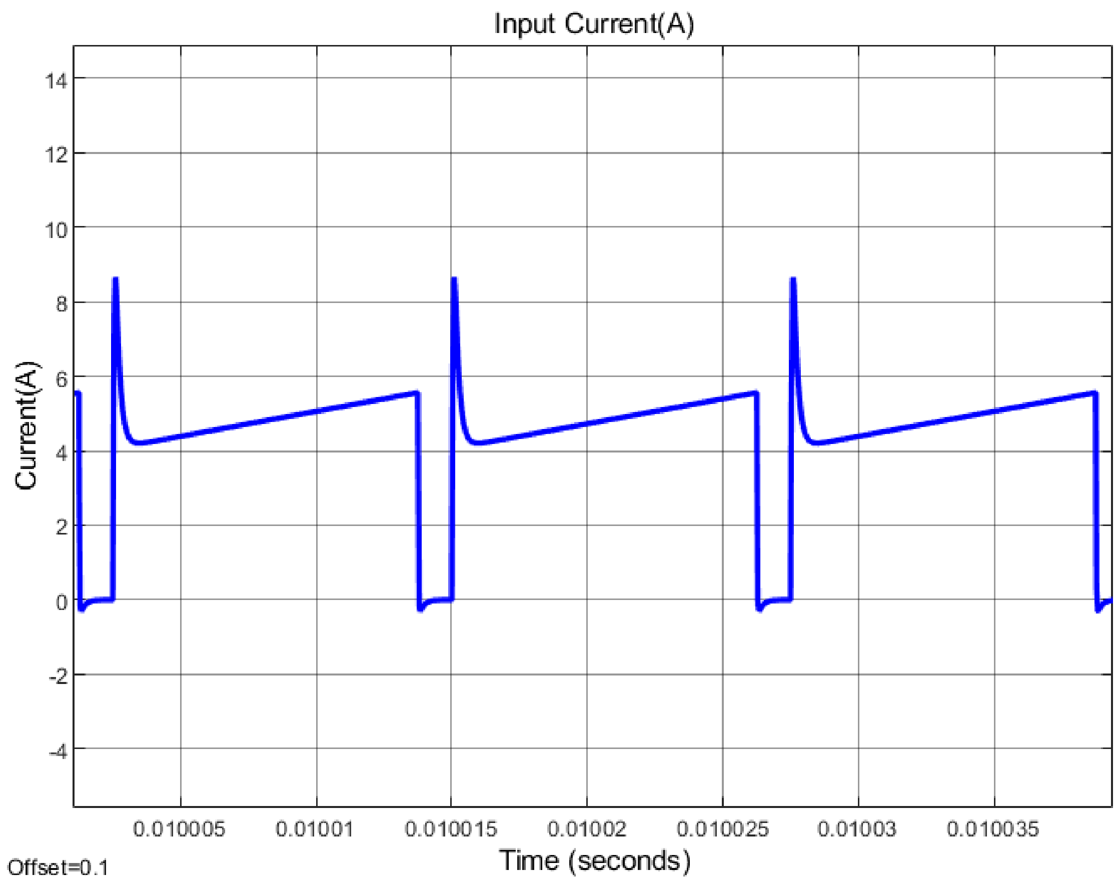


Figure 17. *Input current waveform of the non-ideal push-pull converter.*

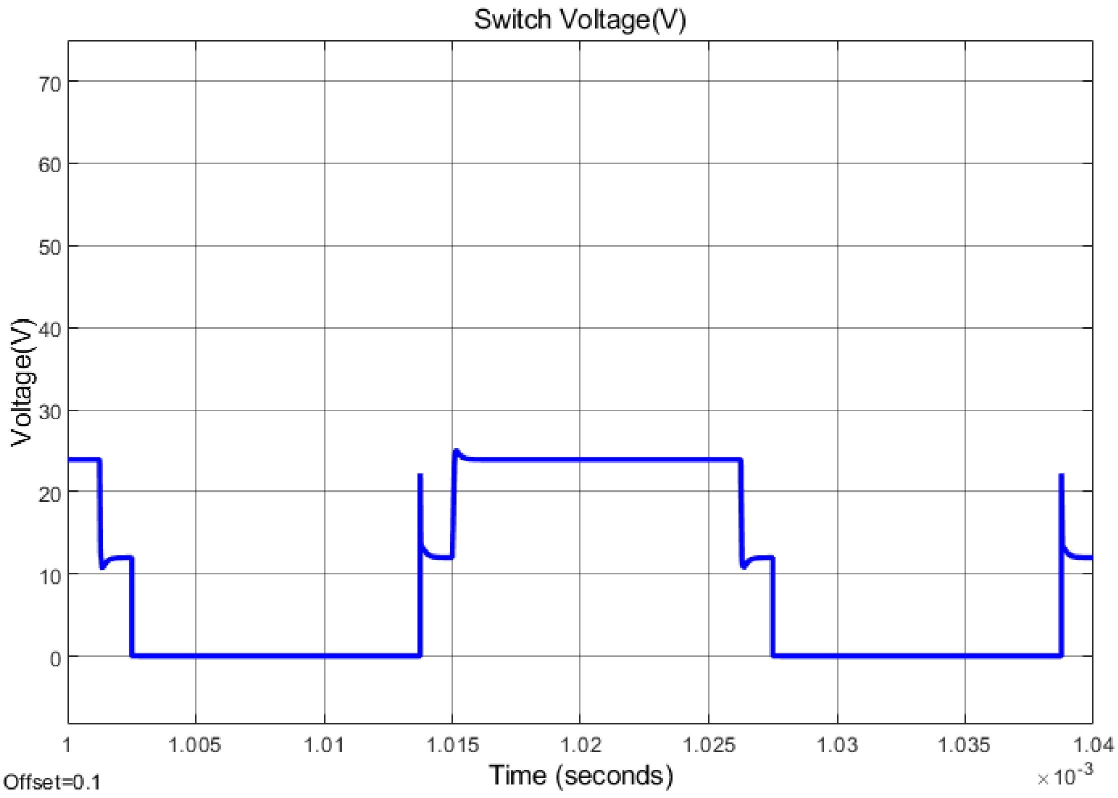


Figure 18. Voltage waveform of one of the switches in the primary side.

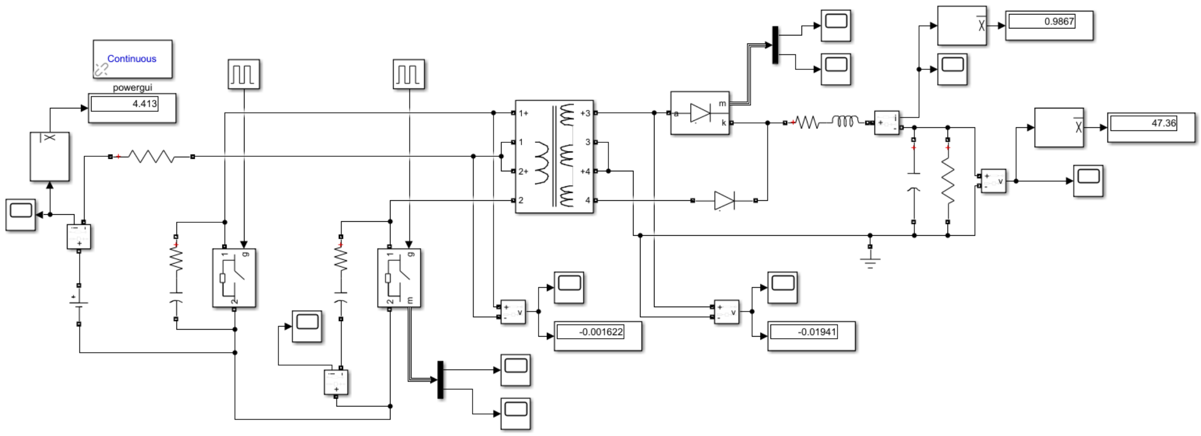
As can be seen from the graphics, a slight decrease has been observed in our output voltage. In addition, the negative effects caused by the parameters that cause non-ideality in the transformer are reduced by using the snubber circuit.

e)

$$Efficiency\ of\ the\ converter = \frac{V_{out}I_{out}}{V_{in}I_{in}} \times 100\%$$

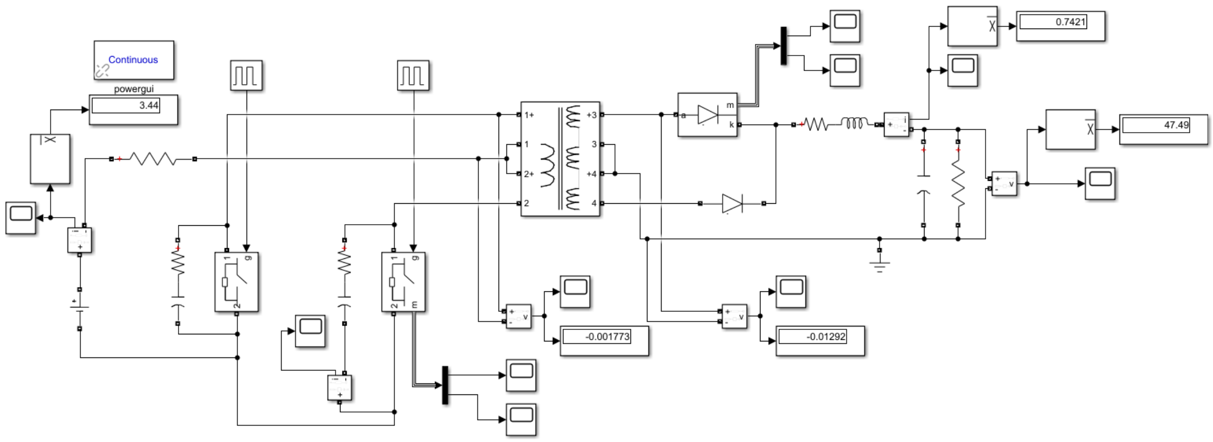
(V_{in}=12V, D=0.45, f_{sw}=40kHz)

For the 100% load condition,



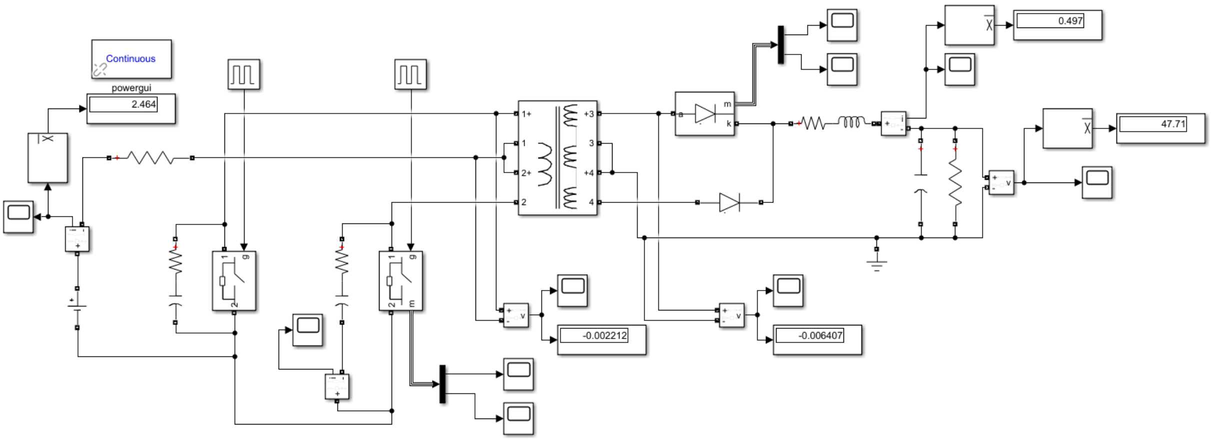
$$Efficiency\ of\ the\ converter = \frac{(47.36V) \times (0.9867A)}{(12V) \times (4.413A)} \times 100\% = 88.2\%$$

For the 75% load condition,



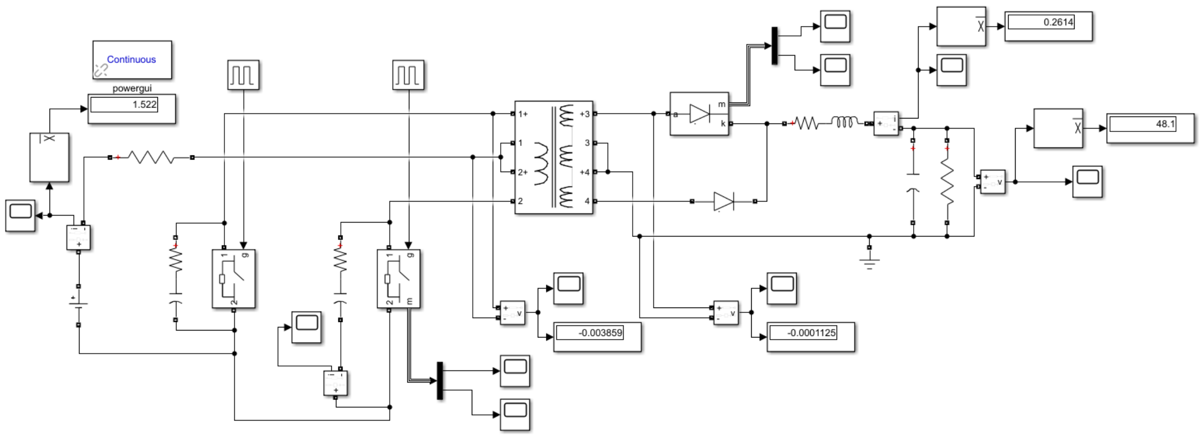
$$Efficiency\ of\ the\ converter = \frac{(47.49V) \times (0.7421A)}{(12V) \times (3.44A)} \times 100\% = 85.4\%$$

For the 50% load condition,



$$Efficiency\ of\ the\ converter = \frac{(47.71V) \times (0.497A)}{(12V) \times (2.464A)} \times 100\% = 80.2\%$$

For the 25% load condition,



$$Efficiency\ of\ the\ converter = \frac{(48.1V) \times (0.2614A)}{(12V) \times (1.522A)} \times 100\% = 68.8\%$$