EE464 Static Power Conversion II

Term Project Final Report

Hiper-Optik Basküler Converter

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Introduction

In this project, an isolated DC-DC converter will be designed and implemented. Required converter will have 12-18V input voltage range and 48V output voltage. Output voltage will have at most 3% voltage ripple and output power rating will be 48W. Deviation of percent output voltage when input voltage is changed from its minimum to maximum will be at most 3%. Deviation of percent output voltage when load current is changed from 10% to 100% will be at most 3%. Push

Component Selection

Component	Quantity	Price
LM5030	1	2.81$
LTV-816W	1	0.11$
TL431ACZ	1	0.135$
IRF540N	2	1.66$
MBR20200	1	0.59$
Custom Transformer(00K6527E060x2)	1	20$
Custom Inductor(55928A2)	1	8-10$
SF34 (Schottky)	2	0.24$
Various Capacitor and Inductors	xx	1$
PCB	1	16$
Total	**-**	**50.5-52.5$**

Table 1. Cost Analysis and Component Selection

LM5030 100-V Push-Pull Current Mode PWM Controller

LM5030 controller is chosen as controller since it is push-pull controller, it has voltage and current feedback, which will provide much accurate control and controller bonuses. Even if its lower limit of the controller, input voltage is appropriate for the application.

LTV816

This component is selected because it was readily available at the laboratory, and there were not any sharp limits about the optocoupler so it is used for isolated feedback design in the type-II compensator.

TLC431ACZ

This component is used to bias the feedback by creating a reference voltage such that we can get a reference from the output by a voltage division using two resistors.

IRF540N

This component is selected because it was readily available at the laboratory. However, the switching losses were high compared to conduction losses. Anyway, it is used and tested in the design.

MBR20200

This component is selected because it is a Schottky diode so it has very low losses. Moreover, our design required a voltage of around at least 168V. This was a cheap and available component that is used.

SF34

This component is used as a replacement of the MBR20200, when we didn’t have stock for MBR20200.

Design Decision

Since one of the most important requirements is isolation, applicable topologies are limited. At that point, based on the industrial experience, it is advised that the most important component is the controller for the application. Therefore, the topology must be built around the controller. Through the market research, Flyback and Push-Pull controllers are found. Hiper-Optik Basküler Converter chose Push-Pull topology to be implemented. Some of the reasons to choose Push-Pull converter are following

- Reduced voltage stress: In a push-pull converter, the primary winding of the transformer operates in a center-tapped configuration, allowing for symmetrical voltage waveforms. This results in reduced voltage stress on the primary side components compared to a flyback converter.
- Higher efficiency: Push-pull converters typically exhibit higher efficiency compared to flyback converters. The symmetrical operation of the push-pull configuration helps to minimize power losses and improve overall converter efficiency.
- Lower output ripple: The push-pull converter's center-tapped transformer configuration and its ability to operate in a continuous current mode result in lower output voltage ripple compared to a flyback converter. This can be beneficial for applications requiring lower output voltage ripple.

- Utilizing 2 switches: It is decided that for both of the converter topologies, 2 switches implementation should be done. At that point, it is stated that “if two switches will be controlled, then it should be push-pull”.

Next, turns ratio is supposed to be chosen. Based on the Push-Pull input output relationship, duty cycle limits, input voltage range and output voltage, N_2/N_1 is decided as 40/9 and duty cycle is set as 0.3<D<0.45, to not operate at upper limits and to not increase burden of output capacitor.

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

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

$$0.30 \leq D \leq 0.45$$

Based on the frequency range of the controller, 100kHz switching frequency is decided. After, some working conditions are set, such as magnetic field is set as 0.2T, current density is set as 4A/mm^2. Based on the output voltage, switching frequency, magnetic field and current density, Core-Window area is decided. After, a core is chosen and according to its dimensions, numbers of primary and secondary windings are calculated. Then, primary referred L_m is calculated by using number of turns and core specifications. Based on the max expected current to be flown and, required cable cross sectional area is calculated. Then, due to skin effect, appropriate awg cable is decided and required numbers of parallel cables are calculated. Finally, kcu is calculated to observe whether the design is under-design or over-design or proper.

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

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

$$B_{max} = 0.02T(reason\ explained\ later)\ J = 4\frac{A}{mm^2}\ D_{cma} = 715\ circ.\ mils/A$$

Then, $W_a * A_c$ is calculated as

$$W_a * A_c = \frac{P_o * D_{cma}}{K_t * B_{max} * f} = \frac{48W * \left(\frac{1}{4\frac{A}{mm^2} * 0.00035}\right)\frac{circular\ mils}{A}}{0.001 * 200Gauss * 100kHz} = 1.74cm^4$$

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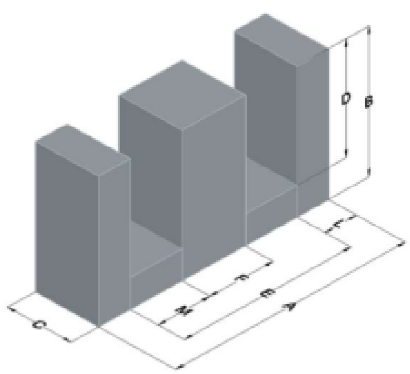


Kool Mμ Permeability (μ)	A_L (nH/T²)	Core Marking	
		Lot Number	Part Number
60	300 ± 8%	XXXXXX	K6527E060

	Dimensions		Tolerance (±)			Packaging
	(mm)	(in)	(mm)	(in)		
A	65.15	2.564	1.27	0.050		Box Qty= 56 Pcs
B	32.51	1.279	0.38	0.015		
C	27.00	1.063	0.41	0.016		
D	22.20	0.874	-	-	Min	Available Hardware
E	44.20	1.739	-	-	Min	00B652701
F	19.66	0.774	0.36	0.014		00B6527B1
L	10.01	0.394	-	-	Nom	
M	12.09	0.476	-	-	Min	

Electrical Characeristics			Physical Characteristics					
Watt Loss @ 100 kHz,100mT max (mW/cm³)	DC Bias min (oersteds)		Break Strength Min (kg)	Window Area W_a (mm²)	Cross Section A_e (mm²)	Path Length L_e (mm)	Volume V_e (mm³)	Est. Weight (Ea. Piece) (g)
800	80%	50%	68	537	540	147	79,400	226
	35	80						

Figure 1: Chosen Core Specifications

$$W_a = 5.37cm^2 \quad A_c = 5.4cm^2 \quad A_L = 300\frac{nH}{Turn^2}$$

$$N_{primary} = \frac{V_{primary} * 10^8}{4 * B * A_c * f} = \frac{12V * 10^8}{4 * 2000\ Gauss * 5.37cm^2 * 100kHz} = 2.79\ Turns \cong 3\ Turns$$

$$N_{secondary} = N_{primary} * \frac{40}{9} = 13.33\ Turns \cong 13\ Turns$$

$$L_m = \left(\frac{N_{primary}}{10^3}\right)^2 * A_L = 2.7mH$$

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

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

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

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

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Ohms per 1000 ft	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum freqency for 100% skin depth for solid conductor copper
24	0.0201	0.51054	25.67	84.1976	3.5	0.577	68 kHz
25	0.0179	0.45466	32.37	106.1736	2.7	0.457	85 kHz
26	0.0159	0.40386	40.81	133.8568	2.2	0.361	107 kH
27	0.0142	0.36068	51.47	168.8216	1.7	0.288	130 kHz
28	0.0126	0.32004	64.9	212.872	1.4	0.226	170 kHz

Figure 2: AWG Table

4x26AWG for secondary, which can operate with 100% skin depth at 100kHz.

8x26AWG for primary, which can operate with 100% skin depth at 100kHz.

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

$$= \frac{2 * 1.026mm^2 * 3\ Turns + 2 * 0.513mm^2 * 13\ Turns}{537mm^2} = 0.036$$

0.036 fill factor shows that the core is over design for the required specs and application. Initially, more reasonable core with 0.34 fill factor was used, which is stated and show in Homework2 report. However, it was suspected during practice and testing that it might go into saturation, which was later found to be not the case. To be sure that the core does not go into saturation region; maximum B field is decreased to 1/10 of initial design, which is the reason of 0.02T max B field. As a result, dimensions of the required core were got bigger and fill factor decreased significantly. It is also believed that initial core is also works perfectly.

During the test it is observed that there is a great amount of power on the snubber circuits. In order to keep maintenance, high power resistances are used, which can withstand the power.

During the research, it is observed that usually type 2 error amplifier is utilized for the Push-Pull applications. Also, it has been observed that type 2 error amplifier is utilized with LM5030 controller.

Topology

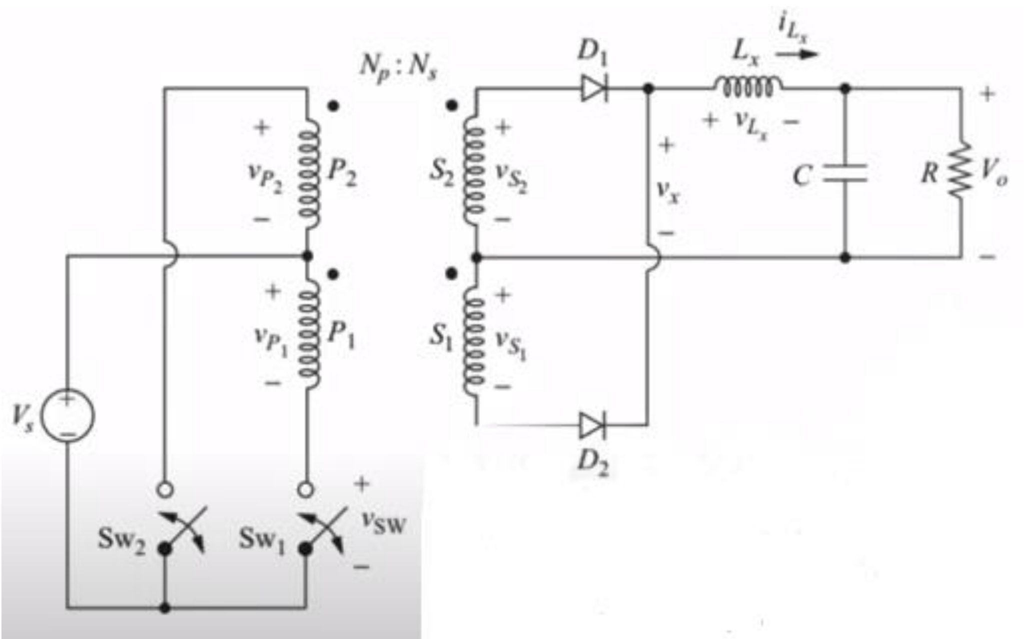


Figure 3: Push-Pull Converter Topology

Push-pull converter is a type of DC-DC converter that uses a center-tapped transformer to convert a DC input voltage into a regulated DC output voltage. It is commonly used in power electronics applications where galvanic isolation and voltage conversion are required.

The basic operation of a push-pull converter involves the following stages:

1. Input Stage: The input stage consists of two switches, typically transistors, connected in a push-pull configuration. These switches alternate between conducting and non-conducting states based on a switching signal. When one switch is on, the other is off.

2. Transformer: The center-tapped transformer is connected to the switches in the input stage. The primary winding of the transformer is split into two halves, and the center tap is connected to the DC input voltage. As the switches alternate, the current flows alternately through the two halves of the primary winding.

3. Output Stage: The secondary winding of the transformer is connected to a rectifier (diodes) and filter circuit. Diodes prevent backward current flow from regulated DC output voltage into transformer.

The operation of the push-pull converter is based on the principle of transformer action and the switching of the input stage. When one switch is turned on, it allows the current to flow through one half of the primary winding, generating a magnetic field. When the switch is turned off, the magnetic field collapses, inducing a voltage in the secondary winding of the transformer. By properly controlling the switching signals of the input stage, the push-pull converter can regulate the output voltage. The duty cycle of the switches, which represents the ratio of the on-time to the total switching period, determines the output voltage level. By adjusting the duty cycle, the output voltage can be increased or decreased.

Topology Implementation

The topology is implemented using an analog controller LM5030. Using the analog controller reduces the number of used components and makes it easier to develop a control algorithm. Voltage control and current control is implemented. Most of the resistance and capacitance values are taken from the datasheet or calculated according to the needs.

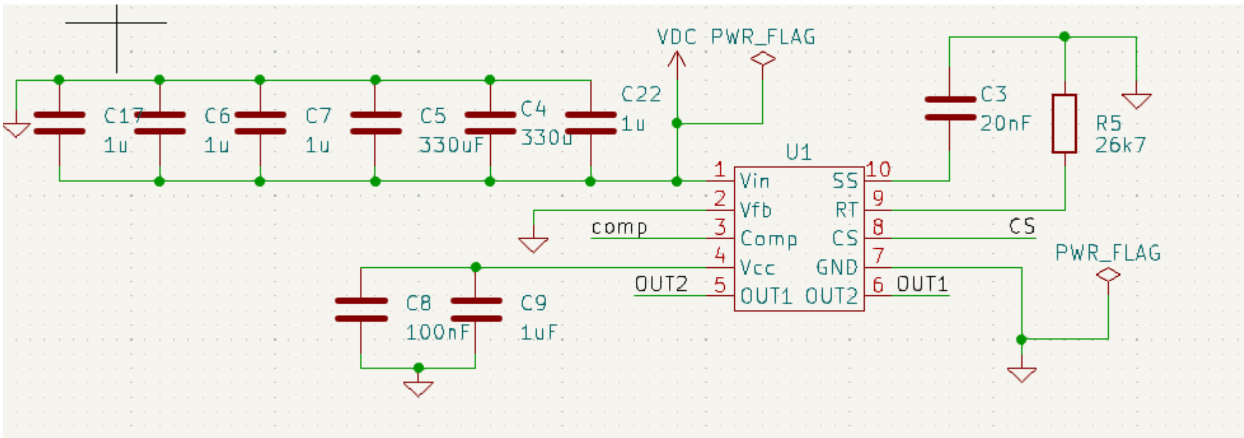


Figure 4: LM5030 Analog Controller Schematics

Pin	Description
Vin	Input voltage for the internal linear regulator
Vfb	Voltage feedback pin
Comp	Voltage feedback pin if external feedback circuitry is implemented such as isolated feedback.
Vcc	External supply for gate drivers and logic (Not compulsary)
OUT1	Gate driver 1
OUT2	Gate driver 2
GND	Ground
CS	Currents Sense pin from shunt resistor or auxiliary windings
RT	Frequency set resistor
SS	Soft start or activation pin

Tablo 2 Pin Descriptions of the LM5030

Most of the parts of the circuitry matches one to one with the implemented topology. In addition to the standard components, we added RC snubbers for MOSFETs and diodes because voltage limits may be exceeded sometimes. Snubber values are implemented using a reference manual for snubber design. After the circuit is tried at full load, snubbers burn due to use of low wattage resistances. The resistance values and used resistance are changed due to this problem.

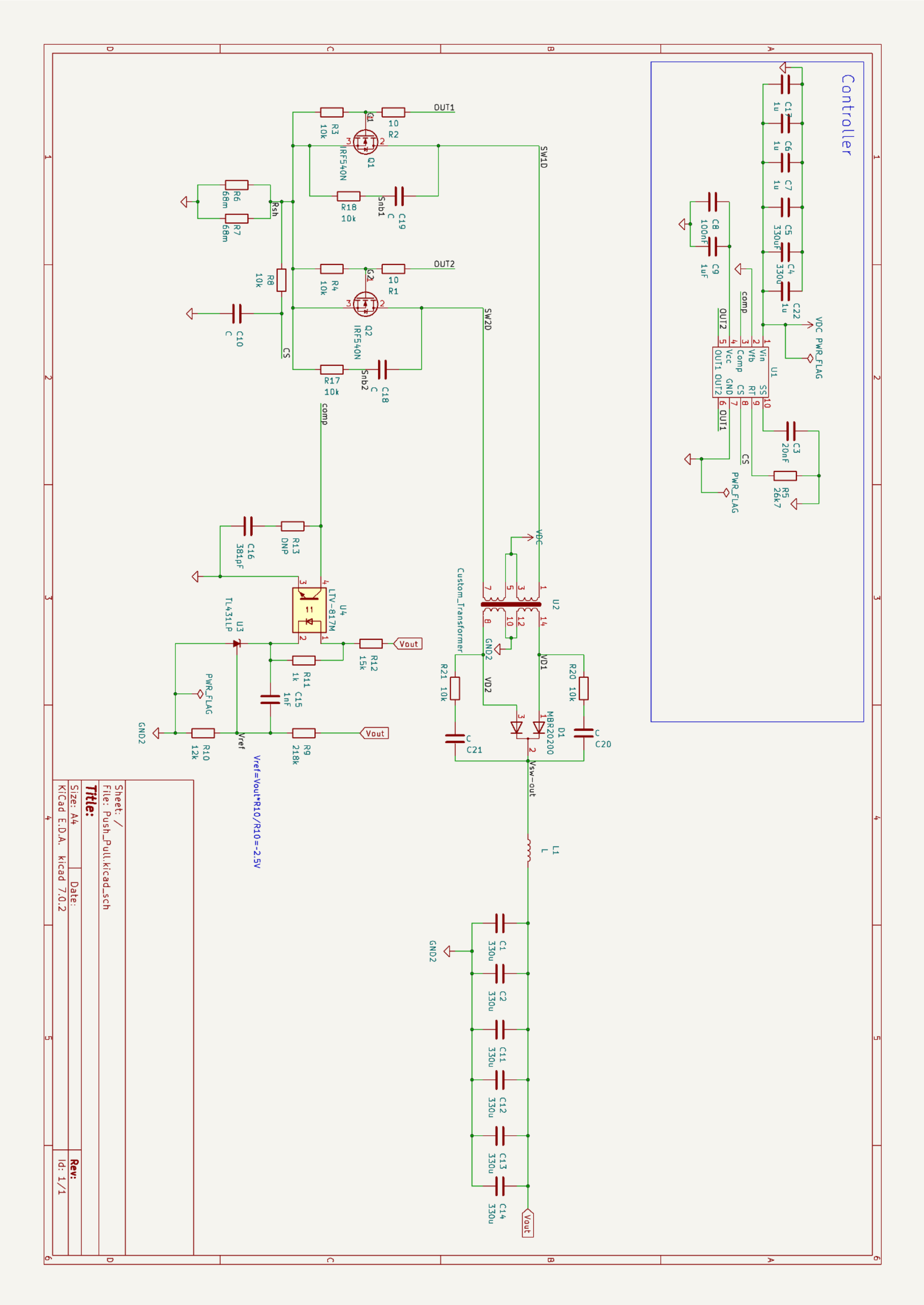


Figure 5. Final Results of the Schematics

Isolated Feedback Implementation

A type II isolated feedback is implemented using an optocoupler and a TL431 (reference generator). Frequency response is tuned using the references [2] and [3]. After the calculations, R and C values are determined.

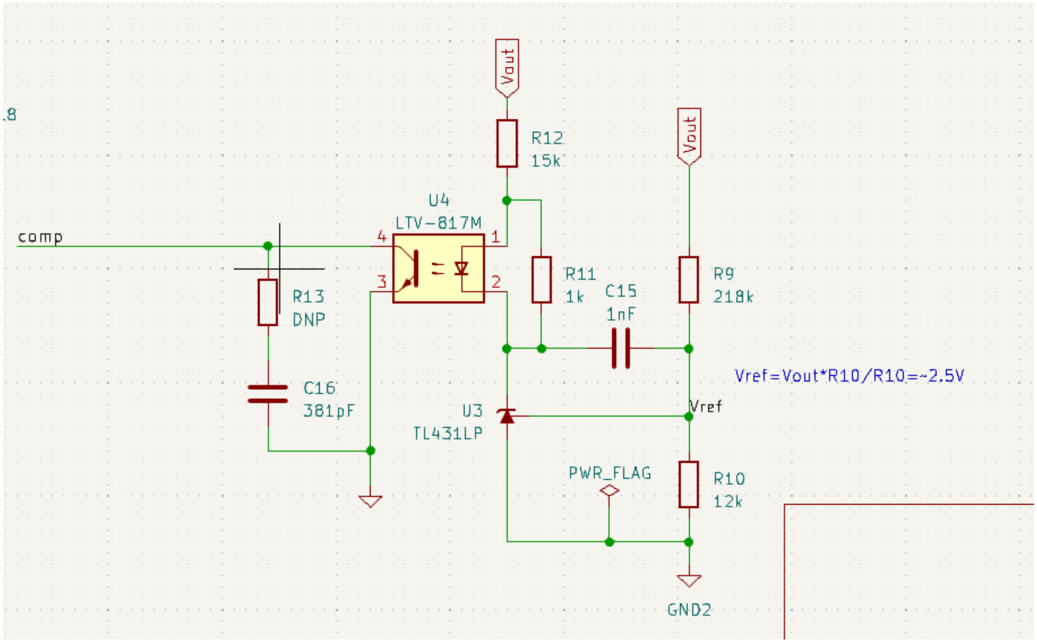


Figure 6. Isolated Feedback

Problems in the Implementation

Some problems occurred in the implementation due to operation limits of the controller. 12V input voltage wasn't sufficient for the controller so it was stuck in the soft start and tried to initiate itself again and again as can be seen in Figure 7. If Vcc pin gets below 6.1V, controller self-starts. At 12V, loaded cases our controller couldn't perform due to that reason. A solution would be adding a external voltage supply (Vcc) or increasing the input capacitance.

Figure 7: Input Current Graph when Problem Occurs

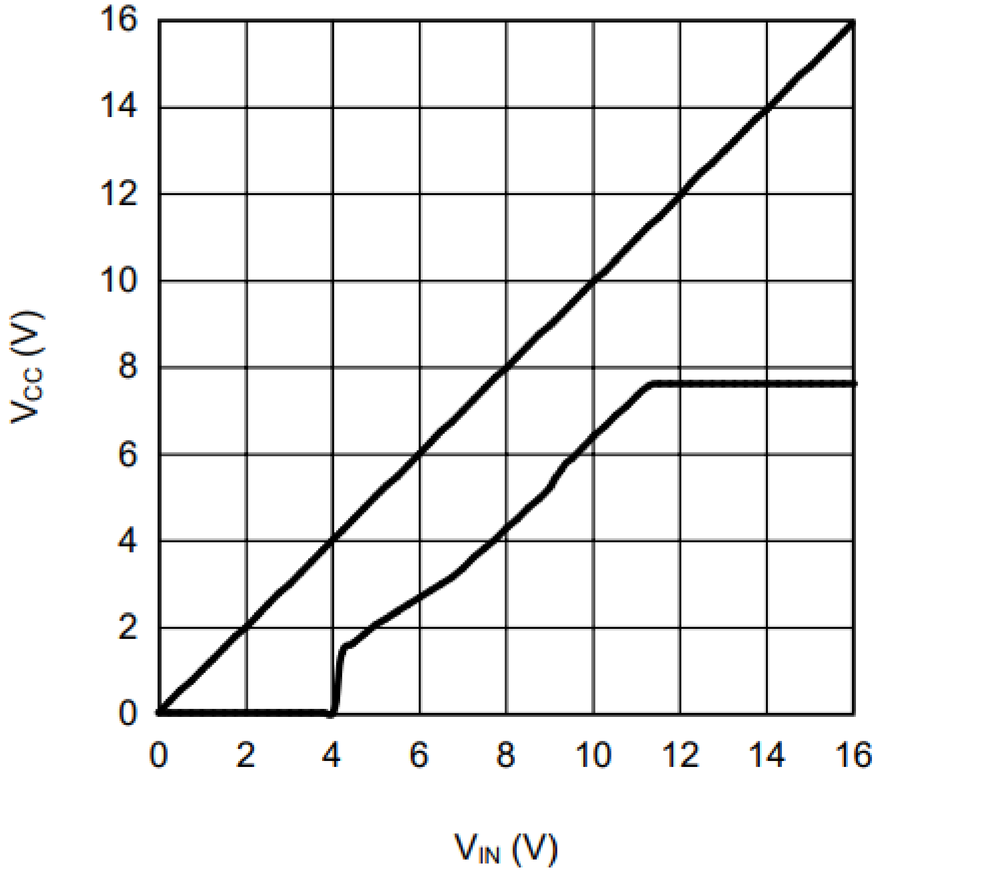


Figure 8. Vcc vs Vin Graph of the Controller

Final PCB

Board is produced in Ulus using copper plates. In the design most of the used components are through holes components due to availability. It may be more beneficial to use SMD components to reduce the size of the PCB and reduce the parasitic elements. Custom inductor and transformer footprints are created using measurements.

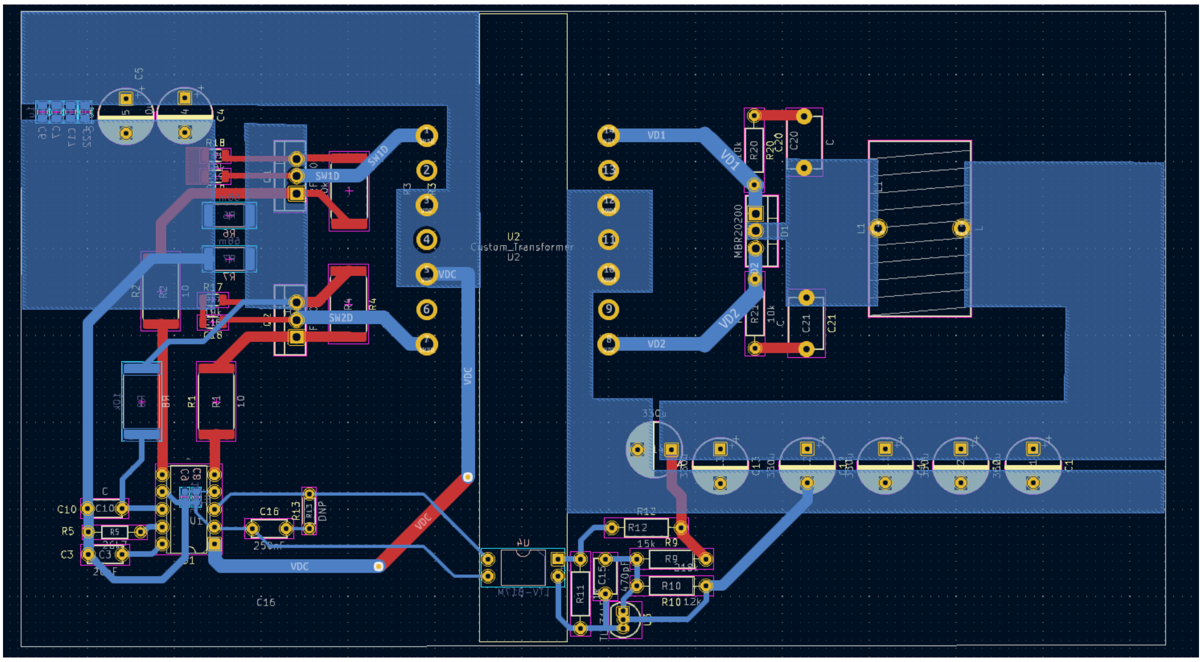
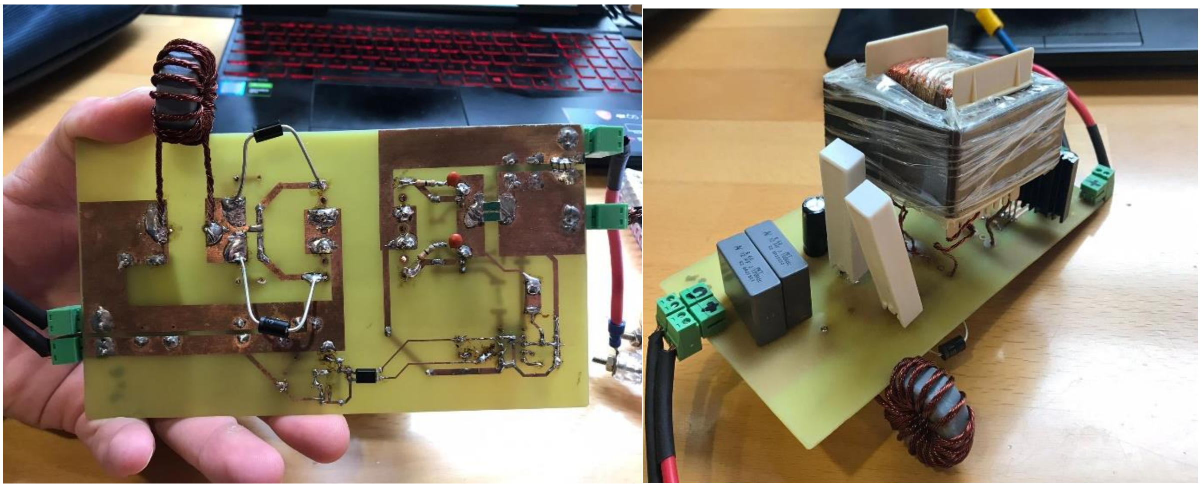


Figure 9: PCB Layout (Red: top copper, blue: bottom copper)



Figures 10: Final PCB

In final PCB, diodes are changed due to lack of MBR20200 diode. Moreover, designed transformer is replaced while testing because the problem couldn't be detected and alternatives are tried (probly designed transformer was just fine.). In addition to that the inductor is changed a few times so that we can reduce the series resistance.

Simulation Results

In this part, the simulation results we have carried out with the components we prefer after the theoretical calculations are given. The results we obtained belong to the circuit formed with the core (CF139EE2507) and MOSFETs (P60B4EL ,$R_{ds,on}$=33mΩ, V_{ds}=40V, I_d=60A) that we preferred in the simulation report process. Transformer parameters with detailed calculations in the Simulation report and used for simulation are as follows,

$$N_{secondary} = 31\,Turns, \qquad N_{primary} = 7\,Turns$$

$$R_{primary} = 5.8m\Omega, \qquad R_{secondary} = 54.9m\Omega \quad R_C = 27\Omega$$

$$L_m = 93.1\mu H \qquad L_{leakage,pri}56.2nH, \qquad L_{leakage,sec} = 1.1\mu H$$

Also, 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),

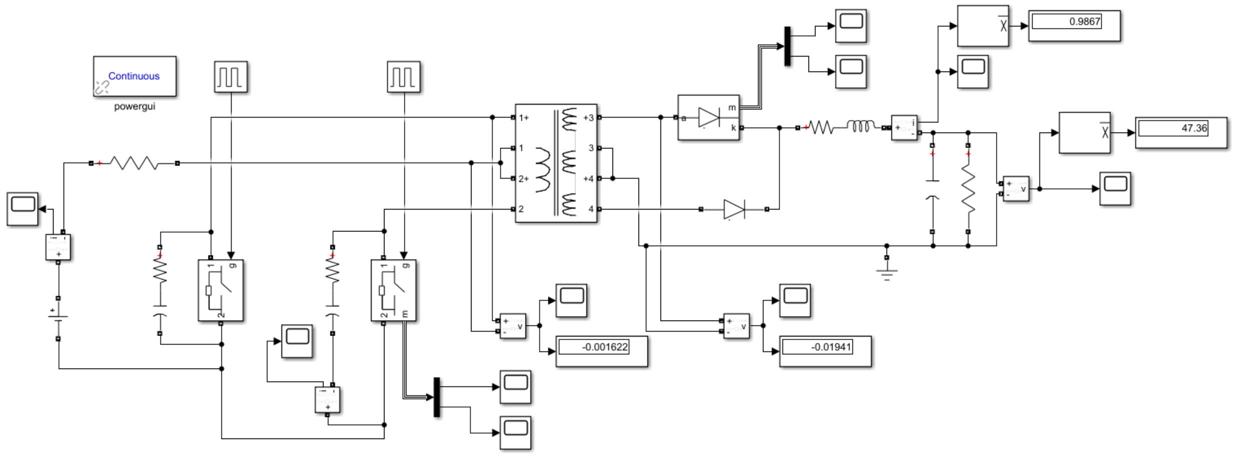


Figure 11. Simulation model of the non-ideal push pull converter.

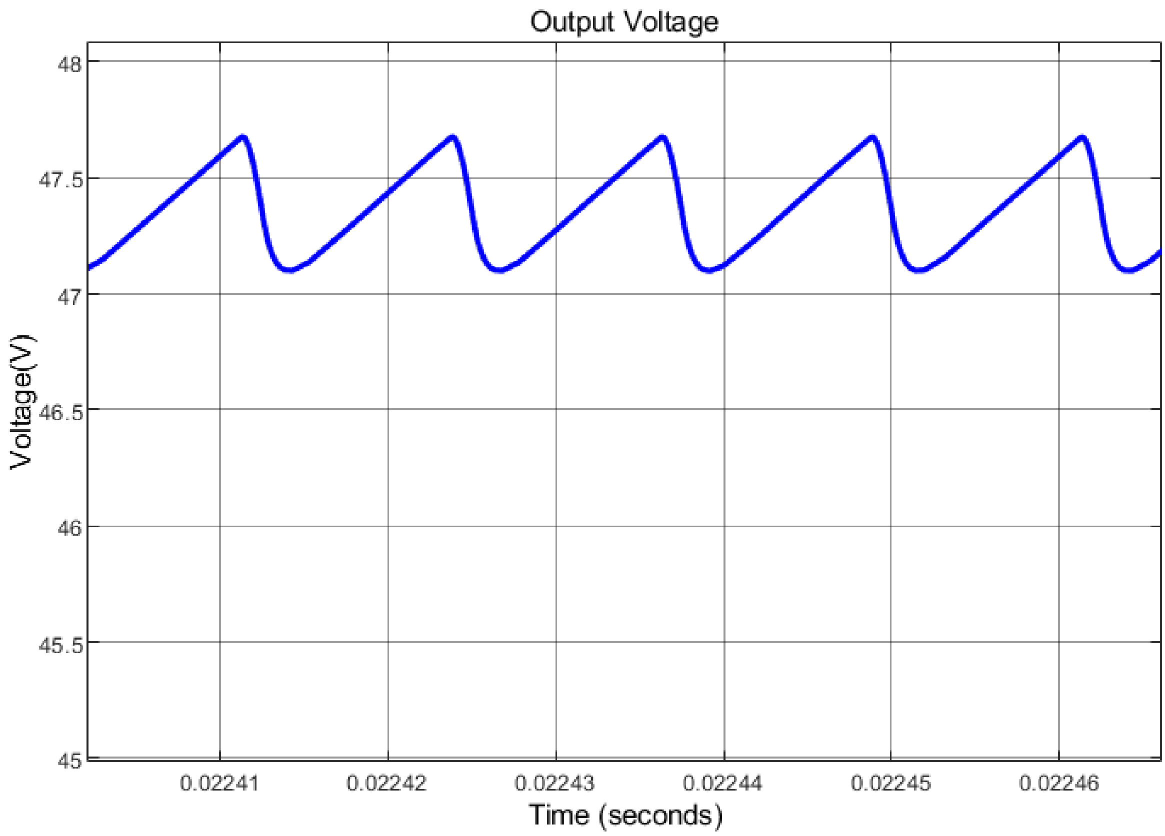


Figure 12. Output voltage waveform of non-ideal push-pull converter.

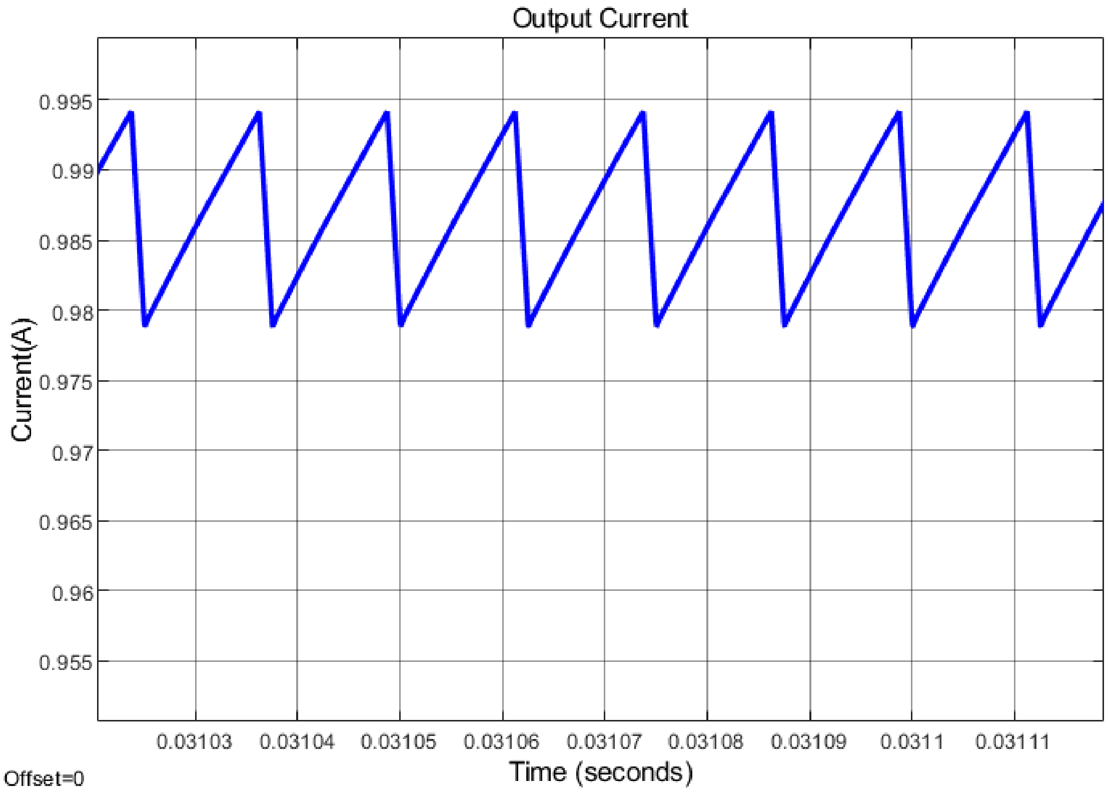


Figure 13. Output current waveform of non-ideal push-pull converter.

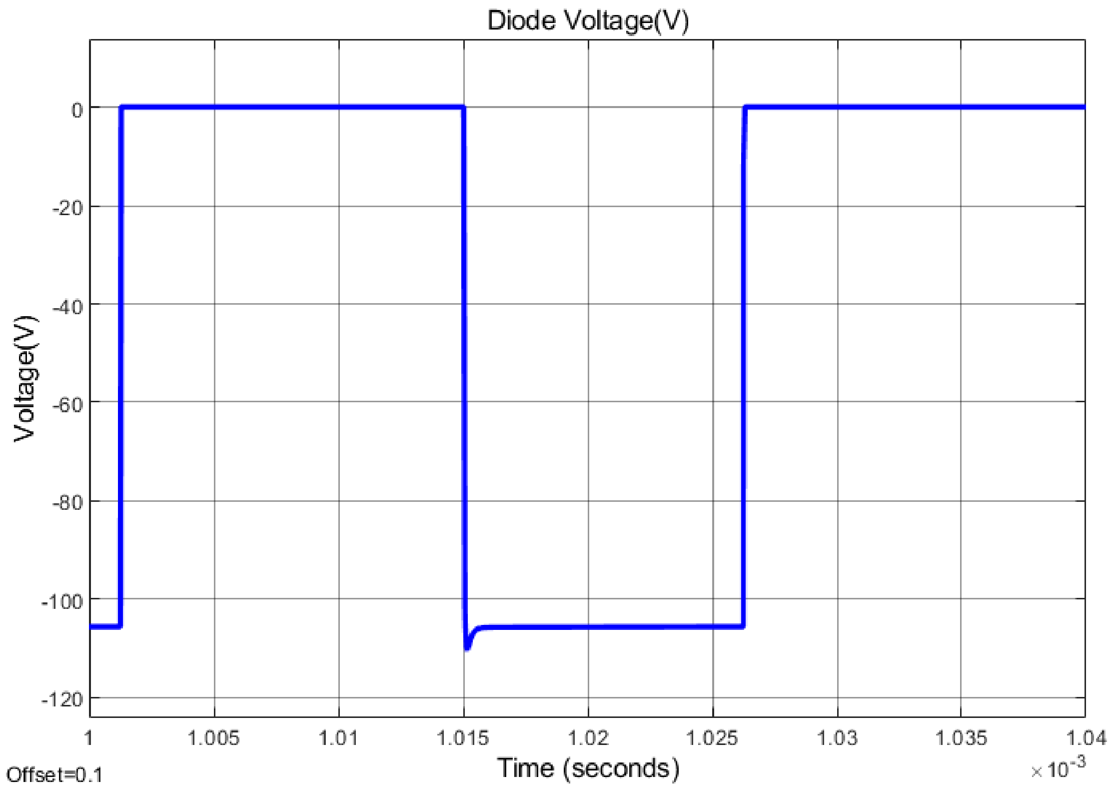


Figure 14. Voltage waveform of one of the diodes that is in the secondary side.

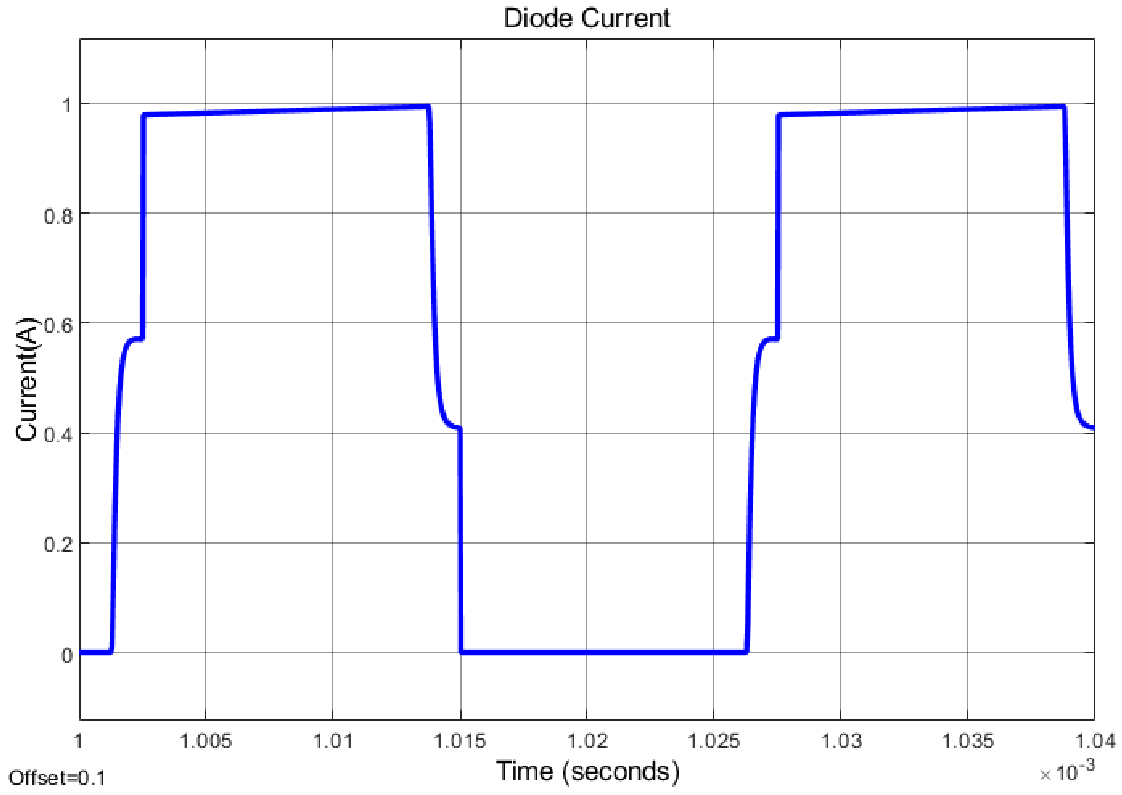


Figure 15. Current waveform of one of the diodes that is in the secondary side.

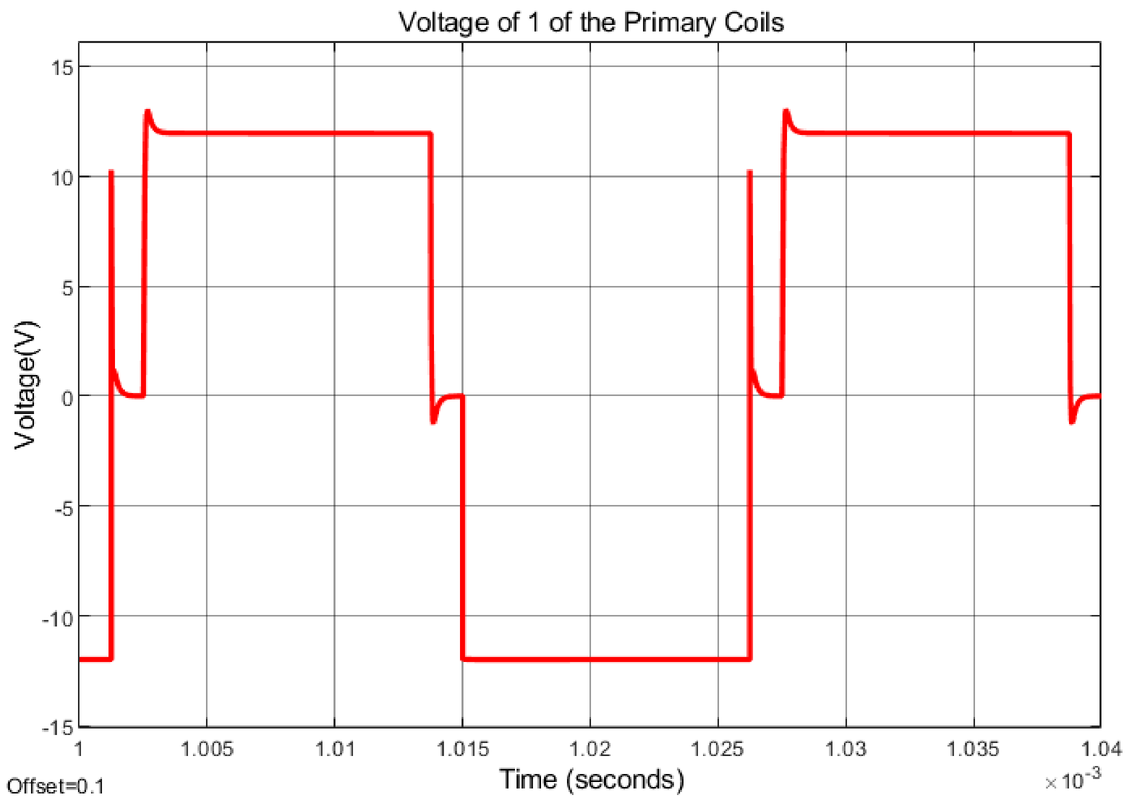


Figure 16. Voltage waveform of one of the primary coils.

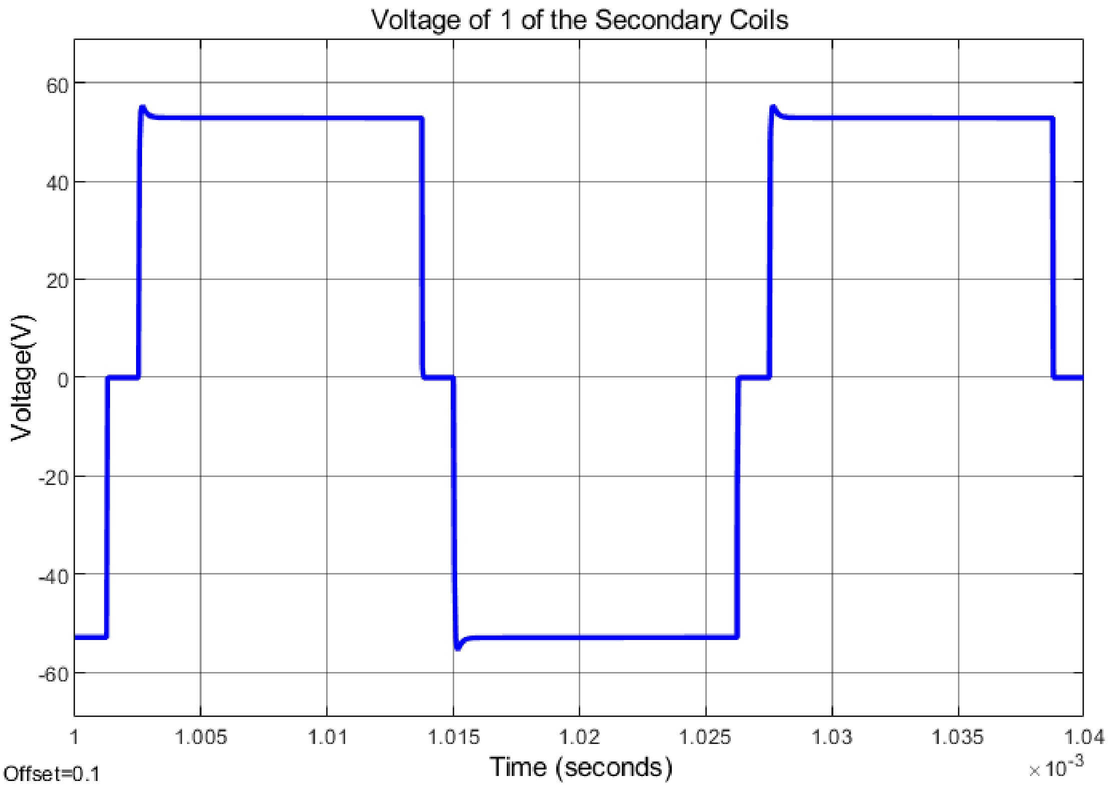


Figure 17. Voltage waveform of one of the secondary coils.

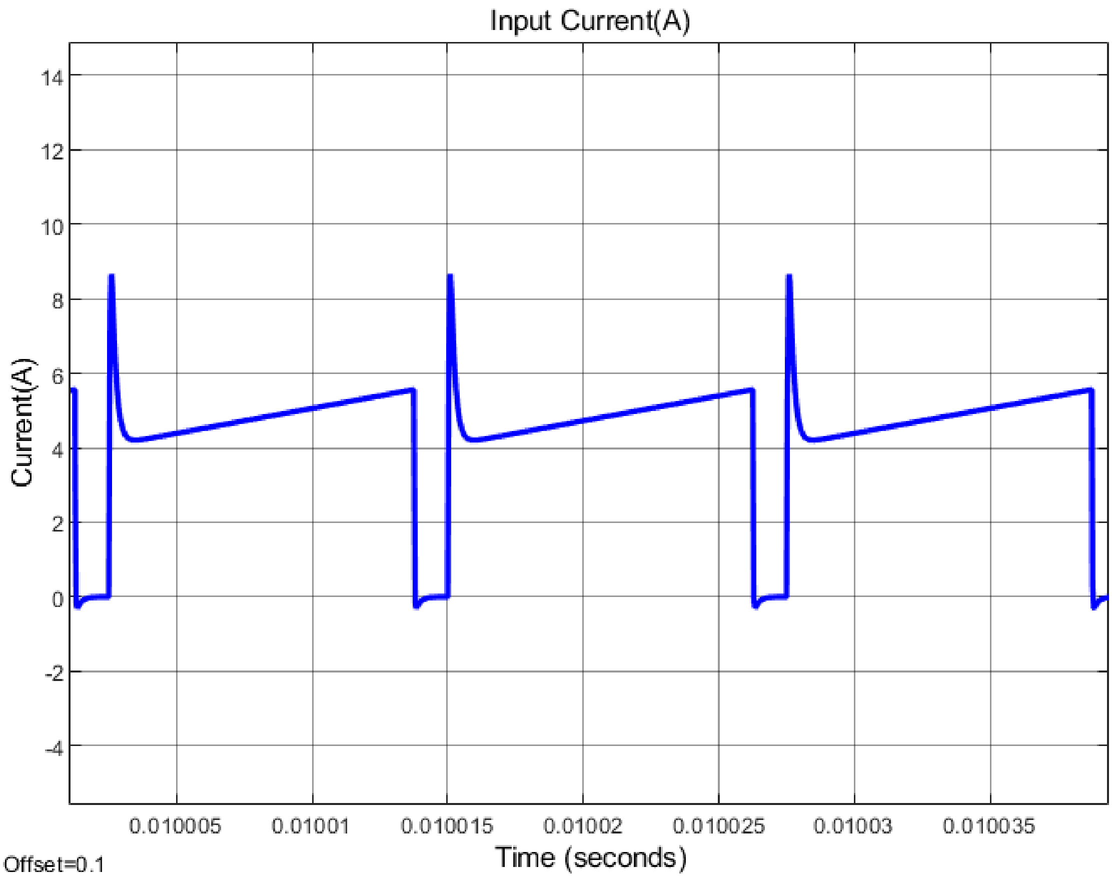


Figure 18. Input current waveform of the non-ideal push-pull converter.

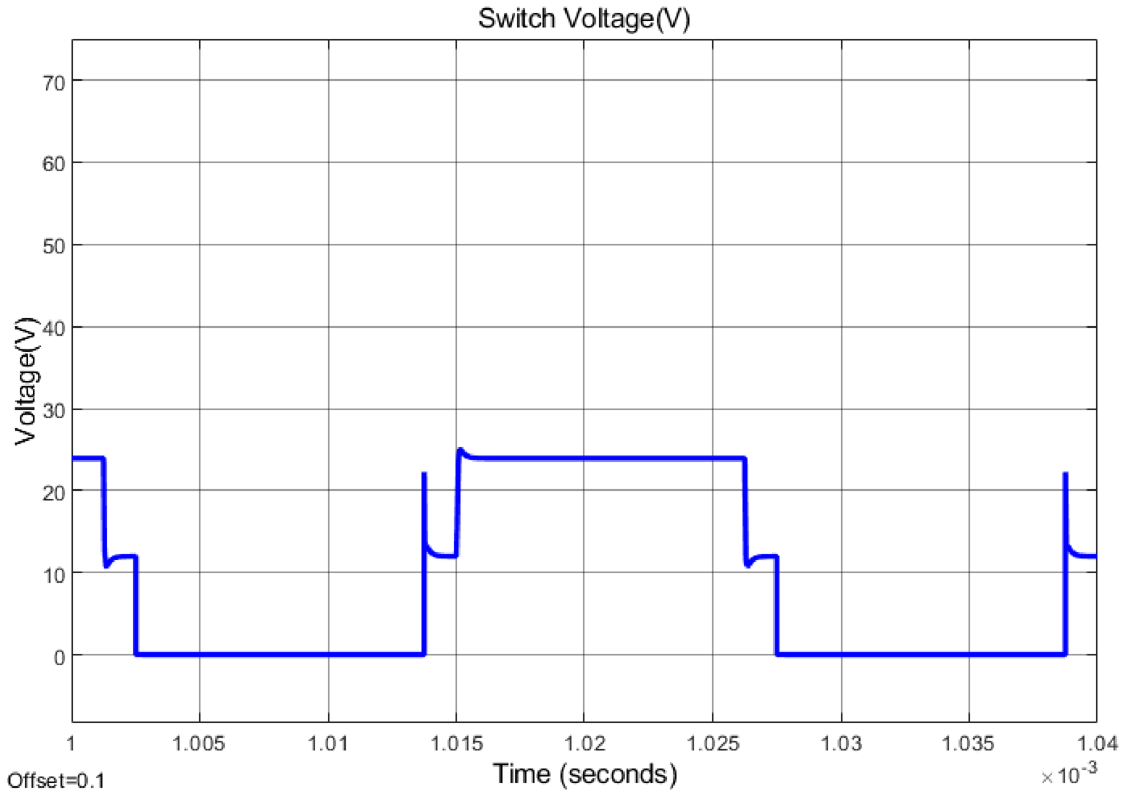


Figure 19. Voltage waveform of one of the switches in the primary side.

As can be seen from the graphics, a slight decrease from desired level (48V) 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.

After the circuit we created in line with all the parameters used for the simulation did not work as we wanted, the new components and parameters in this report were preferred in our prototype we created for the demo.

Test Results

In this part, the results of the tests performed on the circuit created for the demo are given. The components preferred in the prototype and the parameters of the transformer produced are included in the previous parts of this report.

The biggest difference between the circuit created for the demo and the model created during the simulation report is that our transformer design has changed. Unfortunately, the circuit we created in line with the parameters we determined in the simulation report stage did not give the desired result and our output voltage was well below the desired value. In this direction, we started to examine the controller datasheet and the structure we created for feedback in more detail. After noticing that the minimum recommended switching frequency of our controller is 100kHz, we updated our switching frequency to 100kHz. Of course, with the changing switching frequency, our transformer parameters also changed. Despite the possibility that the core we preferred before was saturated, we recreated a transformer using 00K6527E060, one of the cores in the laboratory. In our later tests, we realized that the problem was not with the transformer, but with the operating voltage range of the controller. However, we did not make any changes to our transformer, staying true to the final design we created.

Although the input voltage level required for the controller to work properly in the datasheet is 12V, a minimum of 14V is recommended. Our push-pull converter, which we designed, starts to work as desired by increasing it to at least 14V levels after the input is given at low voltages.

While performing the tests, two outputs on the power supply were connected in parallel and used as input voltage source. The test results of our prototype we created for our demo are given in the following figures. **(CH1:input voltage, CH2:input current, CH3:output current, CH4: output current)**

Figure 20. Input voltage (18V) and currents for low load.

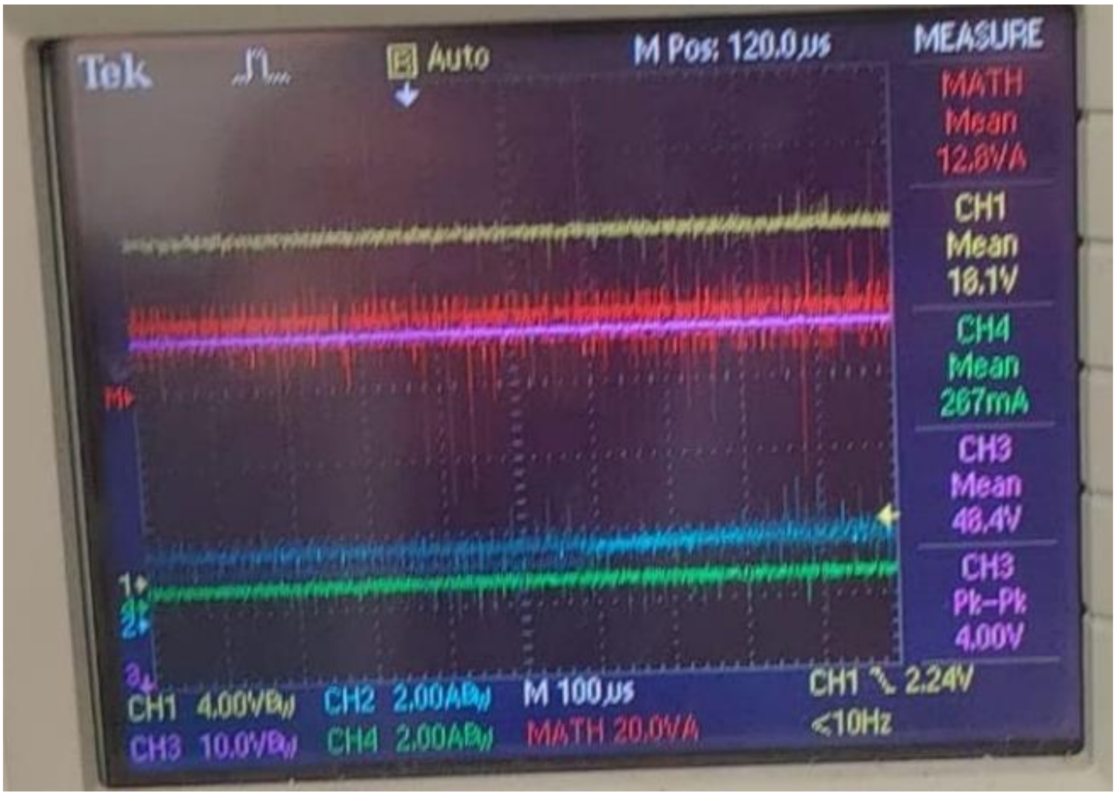


Figure 21. Voltage and current measurements for 18V input with low load case.

Figure 22. Input voltage (12V) and currents for low load.

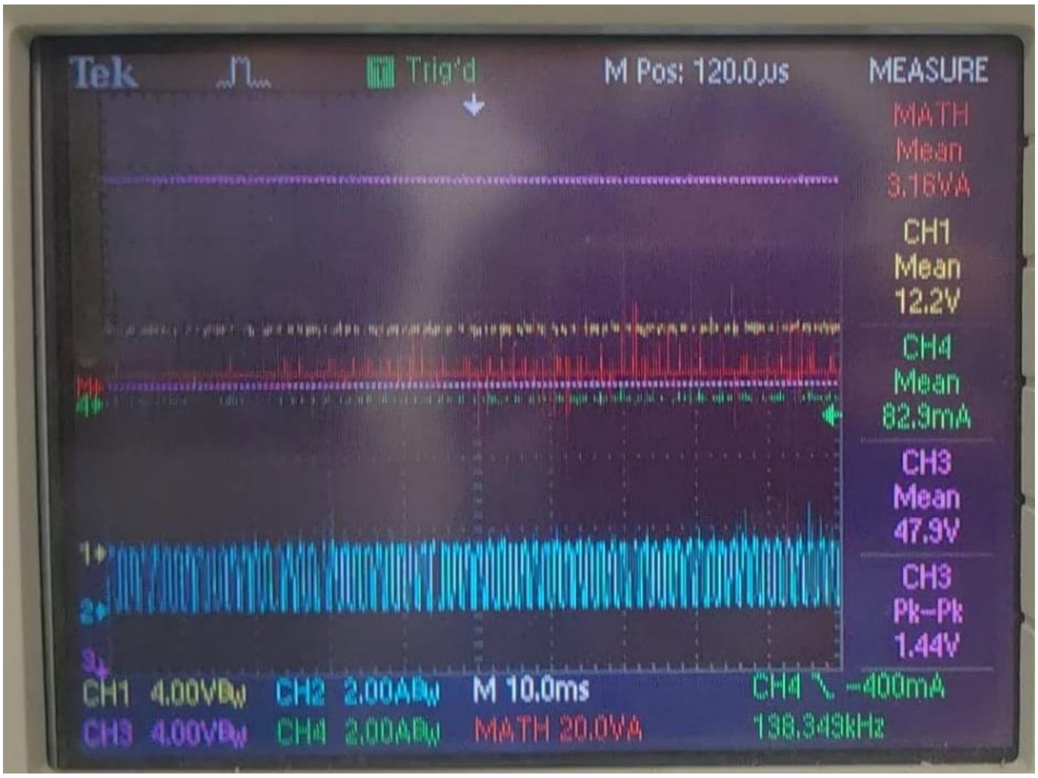


Figure 23. Voltage and current measurements for 12V input with low load case.

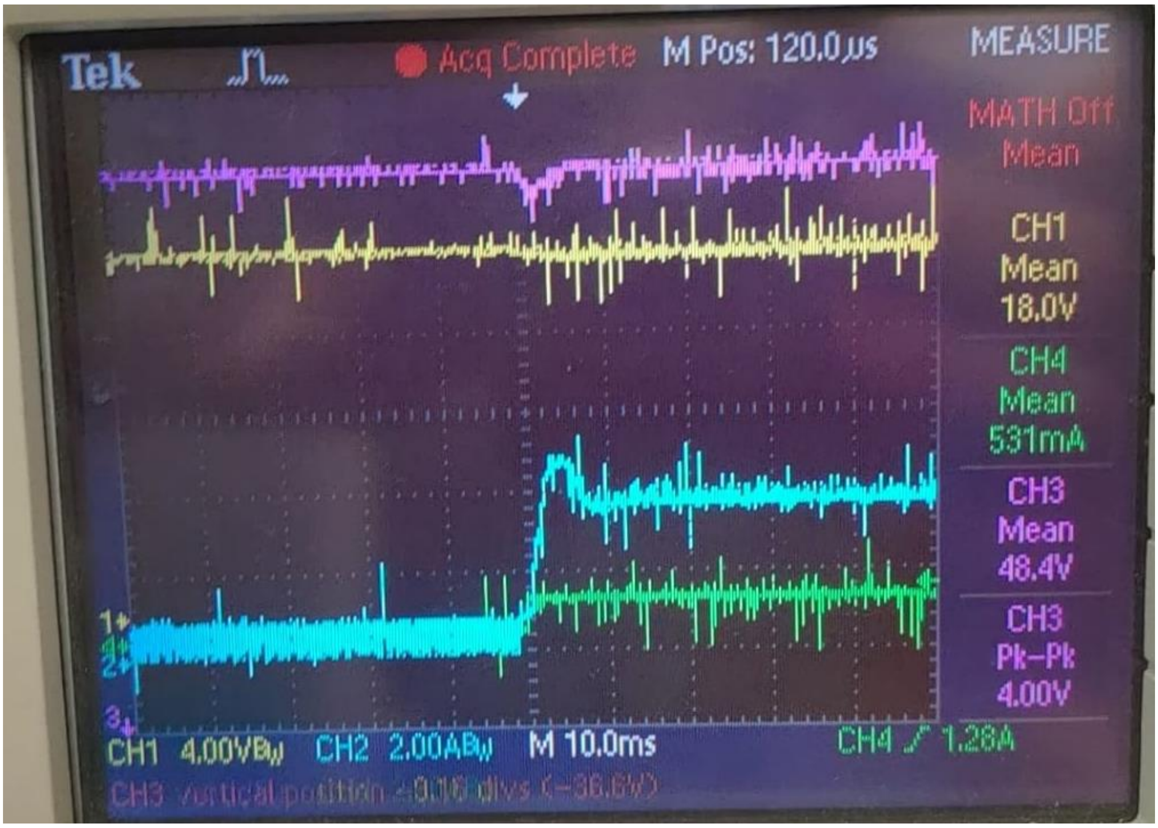


Figure 24. Low load to high load transition with 18V input.

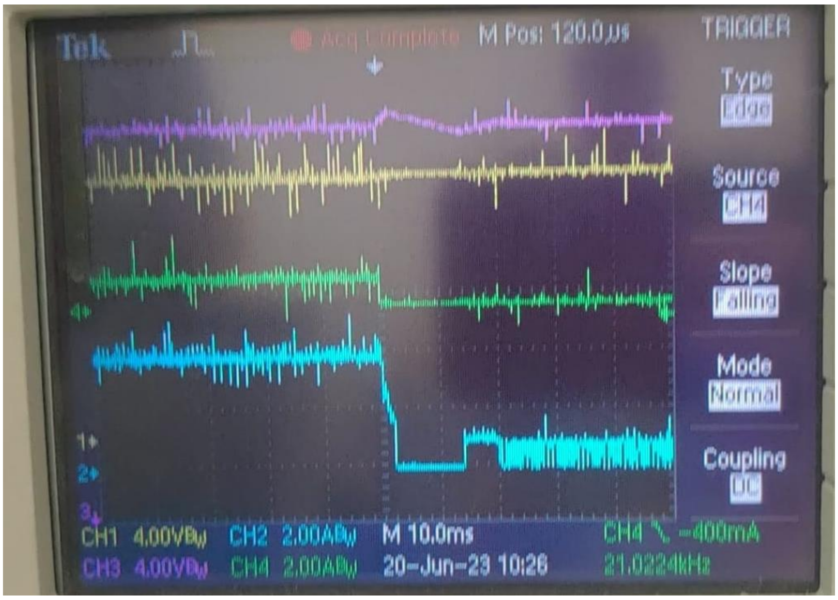


Figure 25. High load to high load transition with 18V input.

Figure 26. Input voltage (18V) and currents for high load.

Figure 27. Output load measurements for 18V input with high load case.

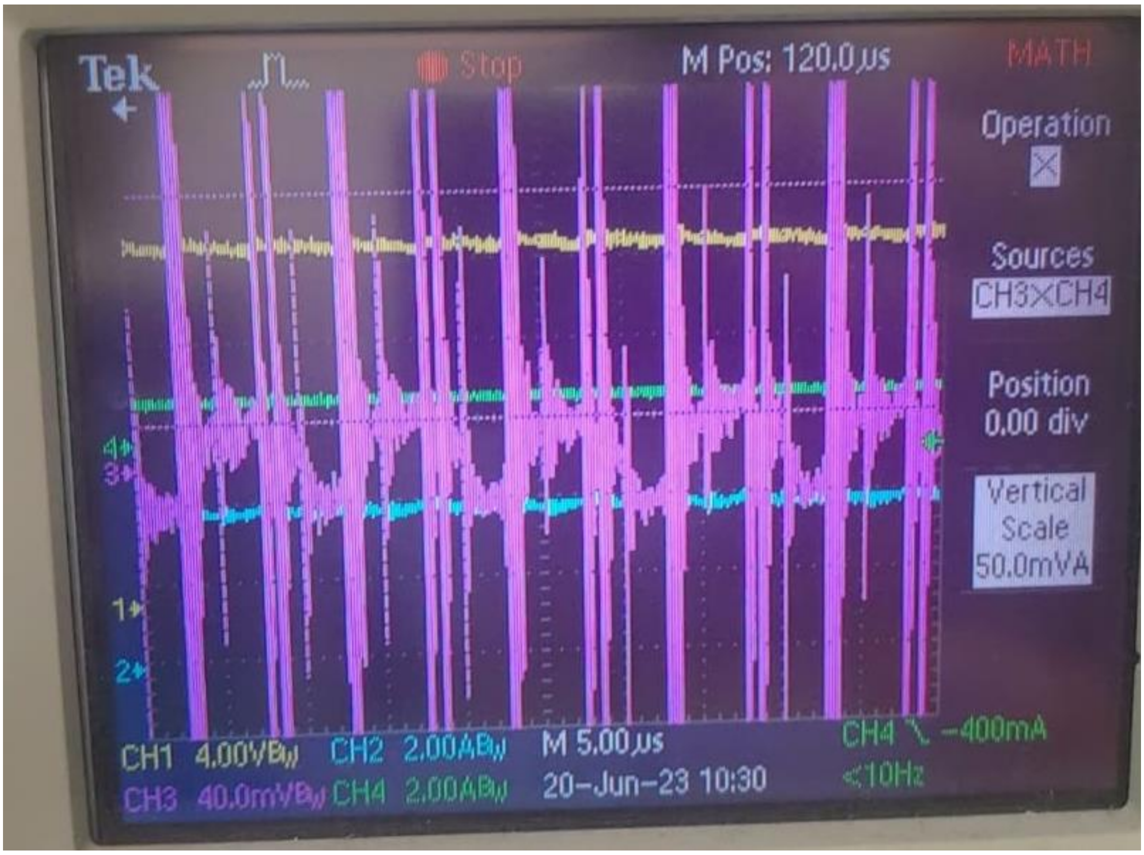


Figure 28. Output voltage ripple measurement.

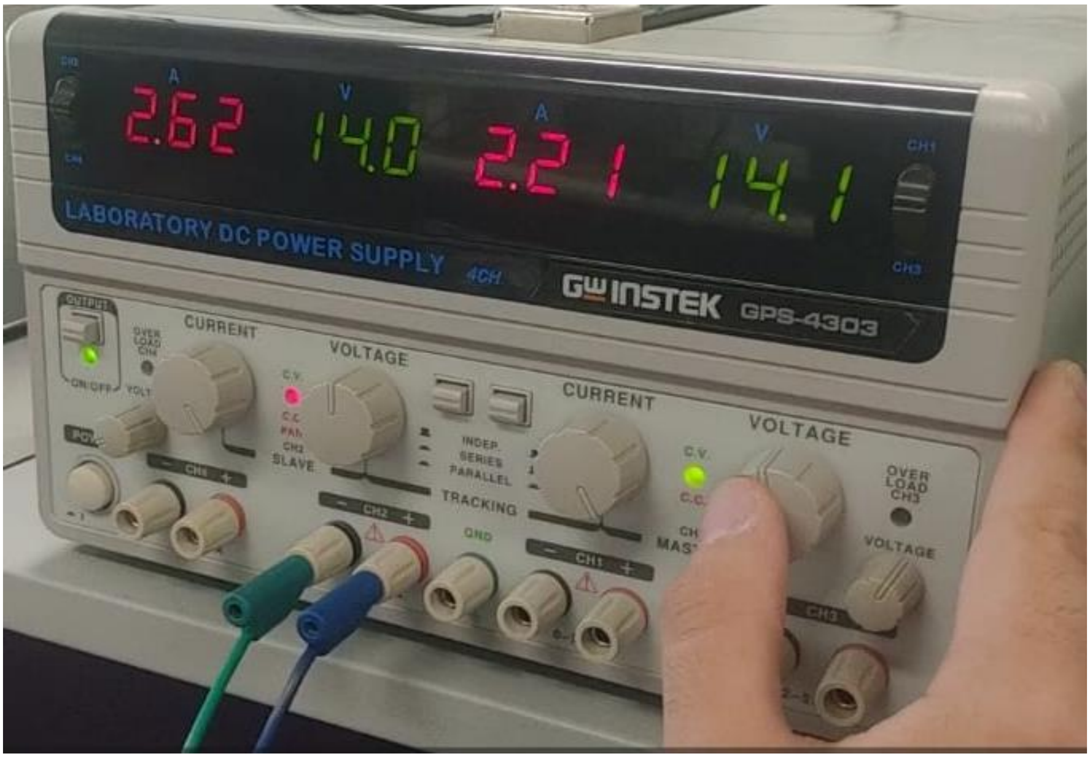


Figure 29. Input voltage (14V) and currents for high load.

Figure 30. Output load measurements for 14V input with high load case.

Figure 31. Thermal camera image that taken after 18V input with high load case.

In addition, the highest temperature measurement (120^{o}C) was observed for 12V input with high load case. However, it is not included in the report because its image cannot be obtained.

As can be seen from Figure 28, our output voltage ripple value is quite small (50mV) due to the capacitance value of our preferred output capacitors (which is overdesign). From all the other measurement results we have obtained; we see that our controller successfully keeps the output voltage level in load and line regulation situations. However, a minimum of 14V input voltage was applied to take measurements at high load, as the controller shuts itself down because voltage is applied below 14V input voltage only at high load.

Conclusion

In conclusion, there are several isolated DC-DC converter topologies with all their advantages and disadvantages. In this project, push-pull converter topology is implemented to convert 12-18V to 48V. Moreover, project covers magnetic design, analog design and feedback design for isolated DC/DC converters. Design showed that the topology is proved to be working; however, there is still room for improvement in terms of PCB design, feedback design and magnetic design.

References

1. https://e2e.ti.com/blogs_/b/powerhouse/posts/calculate-an-r-c-snubber-in-seven-steps
2. https://www.onsemi.com/pub/Collateral/TND381-D.PDF
3. https://www.youtube.com/watch?v=WvpnrrFONkY&list=PLCo39oJ_0NZ5Y-epv32ilB4zIBuWJUmW4&index=21&ab_channel=OzanKeysan