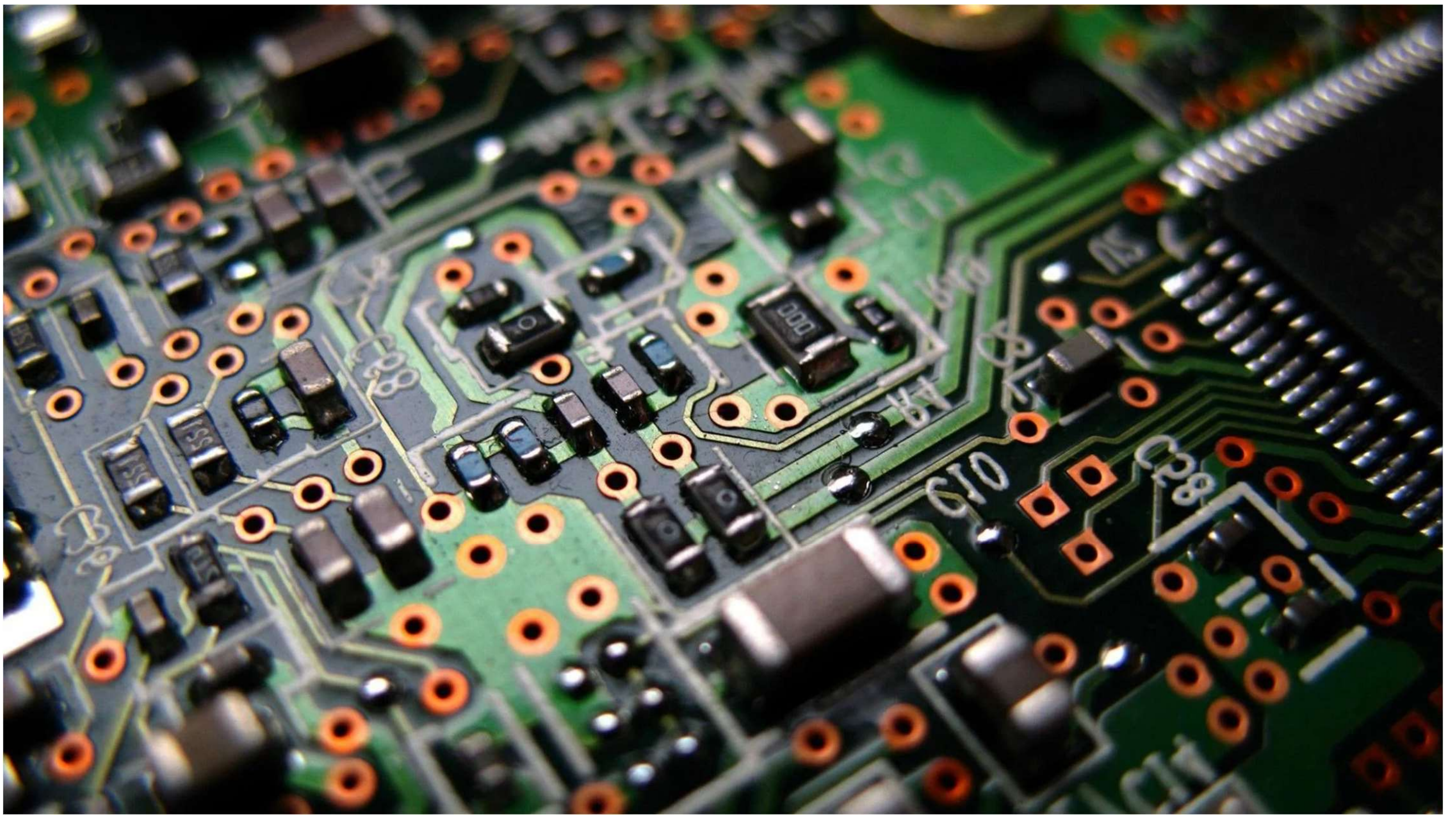

Forward Design

DC-DC Forward Converter Design

Ömer Karslıoğlu

6/7/22

[Course title]

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1-Introduction

The aim of the project is to design and produce a dc-dc forward converter according to following requirements:

Vin: 36-9 V

Vout: 28 V

Power: 50 Watt

Ripple Ratings: 2%

Fsw : 50 KHz

Control System: PI with a MCU

In addition to this, this paper shows formulas, calculations, experimental and simulation results of dc-dc forward converter.

2- Forward Converter

A forward converter is a switched-mode power supply (SMPS) circuit that transfers energy to secondary side from primary side and ensures to decrease secondary side input voltage. Forward converter circuit is similar to the fly-back converter circuit but it is more efficient than fly-back converter circuit. Forward converter is mainly used for the application which requires higher power output.

Secondary side of forward converter basicly derives from buck converter. But forward converter can increase or decrease the input voltage thanks to transformer.

Forward converter is an isolated circuit as it has transformer.

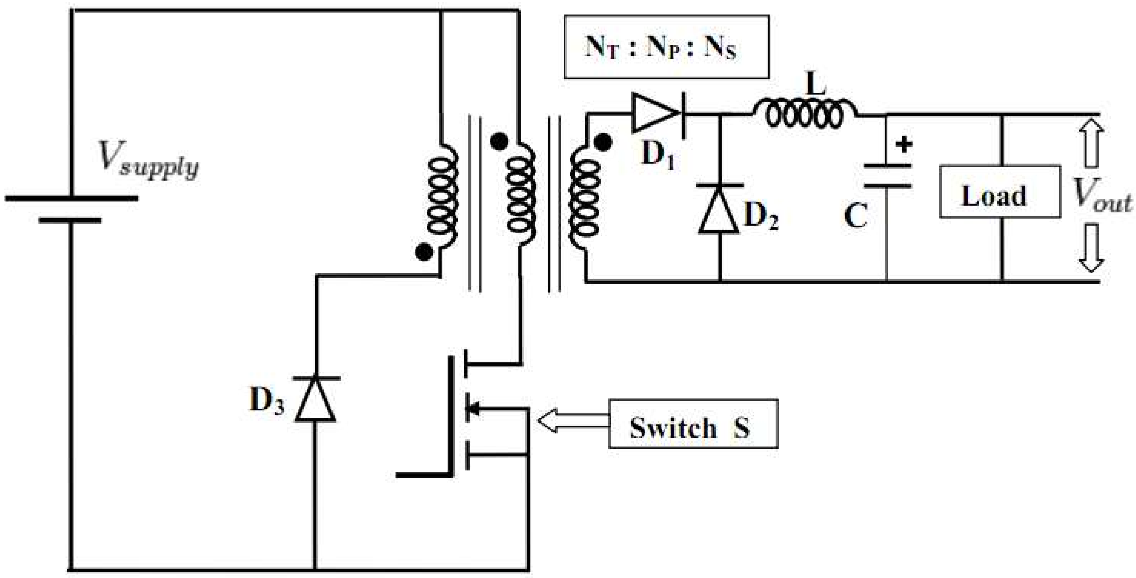


Figure 1: Forward Cicuit Topology

As per the above block diagram, when the switch is turned ON, the input is applied to the primary winding of the transformer and a voltage is appeared at the secondary winding of transformer. Therefore, the dot polarity of the windings of transformer is positive, due to this the diode D1 gets forward biased. Then the output voltage of the transformer is fed to the low pass filter circuit which is connected to the load. When switch is turned OFF, the current in the windings of transformer comes down to zero (assuming the transformer to be ideal).

A typical forward converter consists of a:

- Transformer which is either a step-up or step-down with a single or multiple secondary windings. The type used depends on the available input voltage and desired output voltage. It also provides isolation of the load from the input voltage.
- Switching components
- Diodes
- Capacitors
- Inductor

2.1- Difference between Forward and Fly-back Converter

S. No.	**Forward Converter**	**Fly-back Converter**
1.	Transformer isolated Buck Converter	Essentially a Buck-Boost Topology
2.	Require one more additional output inductor	Not required
3.	Resetting circuit is needed	Not required
4.	No requirement for output capacitor	Required
5.	More energy efficient	Lower than forward converter
6.	Costlier than flyback converter	Cheaper in comparison with forward converter
7.	Stores energy in inductor when the Transistor turns ON and transfer the stored energy when transistor turned OFF	Transformer of the forward converter doesn't stores energy

Table 1: Differences between Forward and Flyback Converter

2.2- Working Principles Of Forward Converter

We must examine forward converter on two modes to understand working principles of forward. These are on-state and off-state associated with switching component.

So, when we look forward converter at on-state:

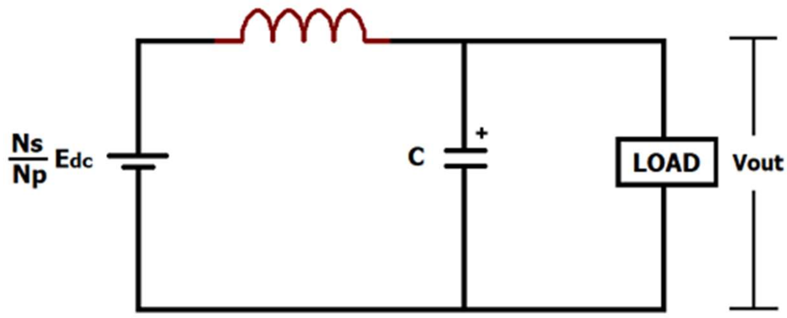


Figure 2: Forward Converter is at on-state

The forward converter said to be in powering mode when the transistor/switching component is in ON state. In this condition, the supply voltage is connected to the primary side winding of the transformer and also diode D1 gets forward biased in this condition. Diode D2 will not conduct in this condition, as it will remain reversed biased. Both the windings starts conducting simultaneously when transistor is in ON state. The output at the secondary side of the transformer depends upon the turn ratio (Np / Ns) of the transformer. And, this output voltage is applied to the secondary circuit, which consists of L-C filter. The maximum received output voltage, in case of ideal transformer, at the load will be:

$$V_{in} * N_s / N_p$$

If we examine off-state:

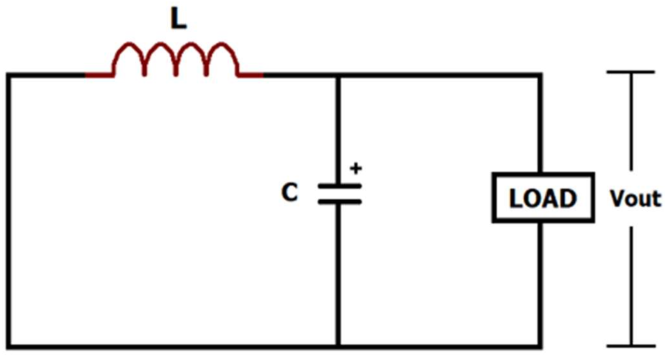


Figure 3: Forward Converter is at off-state

The forward converter said to be in off-state (Freewheeling Mode) when the transistor/switching component is in OFF state. As the transistor turns off, the current of windings of transformer falls to zero (ideally). D1 will be reversed biased in this condition, therefore separates the output section of circuit from the transformer and the input. However, the inductor at the secondary side maintains a continuous flow of current through the freewheeling diode D2. As the input is separated, there is no power flow from the input, but still the load voltage is maintained nearly constant by the charged capacitor and the inductor. Stored energy in the inductor and the capacitor slowly dissipates into the load. Before it dissipates completely the transistor turns ON again to end the freewheeling mode and to maintain the magnitude of load voltage within the required tolerance band.

3- Forward Converter Fundamental Formulas

In this section, I am gonna mention about basic formulas about dc-dc forward converter and their profs. First of all, we must examine the waveform of typical dc-dc forward converter.

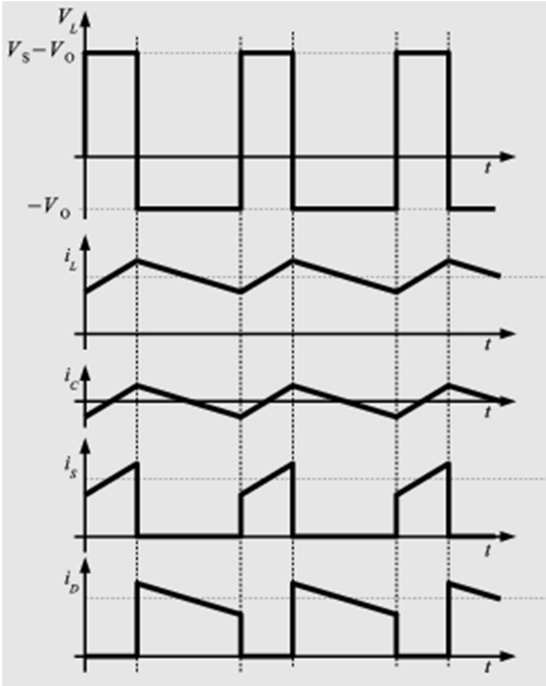


Figure 4: Waveform Of The Typical Forward Circuit

Vavg of inductance value must equal to 0. In Ton state inductance voltage equal to Vin*n-Vout, and in Toff state inductance voltage equal to -Vout.

$$\frac{D * T * (V_{in} * n - V_{out})}{L} + \frac{(1 - D) * T * (-V_{out})}{L} = 0$$

From the above equation we have the following formula:

$$V_{out} = D * V_{in} * n$$

Calculation of inductuctance value:

$$V_L = \frac{di_L}{dt} * \mathrm{L}$$

$$\lambda i = \frac{(V_{in} * n - V_{out}) * D}{f * L}$$

For inductor current:

$$I_{RMS}^2 = I_{avg}^2 + \frac{1}{12} * I_{PP}^2$$

From the above equation we have the following formula:

$$I_{L-RMS} = \frac{2}{\sqrt{3}} * I_{out}$$

Calculation of capacitance of the output capacitor formula:

$$\Delta Q = C * \Delta V$$

From the above equation and capacitor charging area (there is a triangle for ▲Q) we have the following formula:

$$C = \frac{\frac{1}{2} * \frac{\Delta i_L}{2} * \frac{T}{2}}{\Delta v} = \frac{\Delta i_L}{8 * f_{sw} * \Delta v}$$

Also we must calculate the transformer formula for isolation.

Components of magnetizing current, referred to primary:

$$I_M = \left(\frac{n_2}{n_1}\right) \frac{1}{D'} \frac{V}{R}$$

$$\Delta_{im} = \text{ Magnetizing current ripple} * \ I_m$$

$$I_{M,max} = I_M + \Delta i_M$$

Choosing magnetizing inductance:

$$L_M = \frac{V_g D T_s}{2 \Delta i_M}$$

RMS winding currents:

$$I_1 = I_M \sqrt{D} \sqrt{1 + \frac{1}{3}\left(\frac{\Delta i_M}{I_M}\right)^2}$$

$$I_2 = \frac{n_1}{n_2} I_M \sqrt{D'} \sqrt{1 + \frac{1}{3}\left(\frac{\Delta i_M}{I_M}\right)^2}$$

$$I_{tot} = I_1 + \frac{n_2}{n_1} I_2$$

Choosing core size:

$$K_g \geq \frac{\rho L_M^2 I_{tot}^2 I_{M,max}^2}{B_{max}^2 P_{cu} K_u} 10^8$$

Choosing air gap and turns:

$$\ell_g = \frac{\mu_0 L_M I_{M,max}^2}{B_{max}^2 A_c} 10^4$$

$$n_1 = \frac{L_M I_{M,max}}{B_{max} A_c} 10^4$$

$$n_2 = \left(\frac{n_2}{n_1}\right) n_1$$

Wire gauges:

$$\alpha_1 = \frac{I_1}{I_{tot}}$$

$$\alpha_2 = \frac{n_2 I_2}{n_1 I_{tot}}$$

$$A_{W1} \leq \frac{\alpha_1 K_u W_A}{n_1}$$
$$A_{W2} \leq \frac{\alpha_2 K_u W_A}{n_2}$$

For core loses:

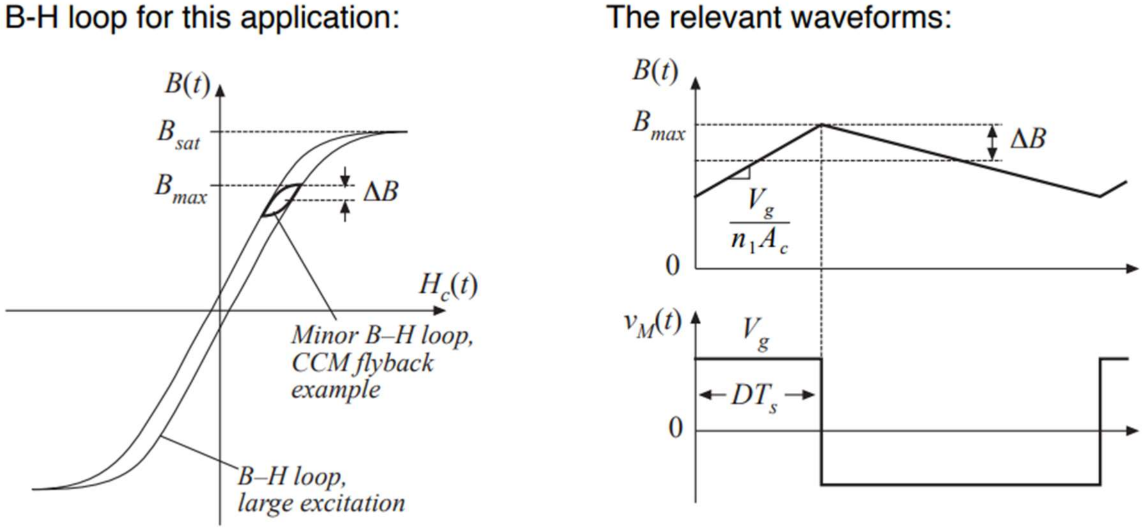


Figure 5: B-H Curve And The Relevant Waveforms

B (t) vs. applied voltage, from Faraday's law:

$$\frac{dB(t)}{dt} = \frac{v_M(t)}{n_1 A_c}$$

For the first subinterval:

$$\frac{dB(t)}{dt} = \frac{V_g}{n_1 A_c}$$

Solving for ▲B:

$$\Delta B = \left(\frac{V_g}{n_1 A_c}\right)\left(DT_s\right)$$

From manufacturer's plot of core loss (at left), the power loss density is the value of ▲B W/cm^3.

Hence core loss is:

$$P_{fe} = \Delta B * A_C * l_m$$

4- Designing The DC-DC Forward Converter

First of all, I analyzed all formulas and the waveforms of the component on DC-DC Forward Converter Circuit.

For this analyze, I drawed forward cicuit and its waveform with thinking and some electronic circuit methods.

After drawing the waveforms, I extracted the formulas by analyzing the circuit.

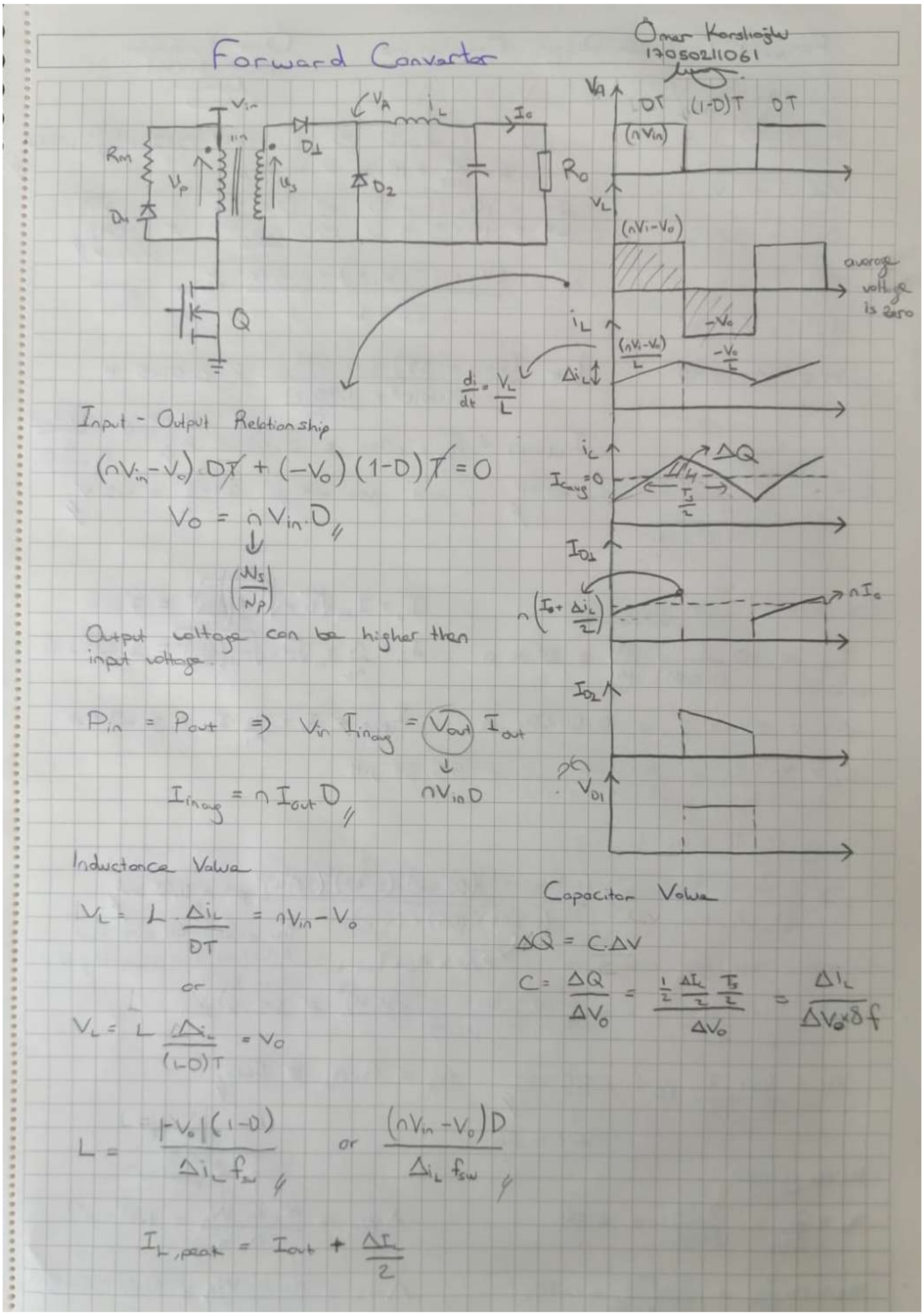
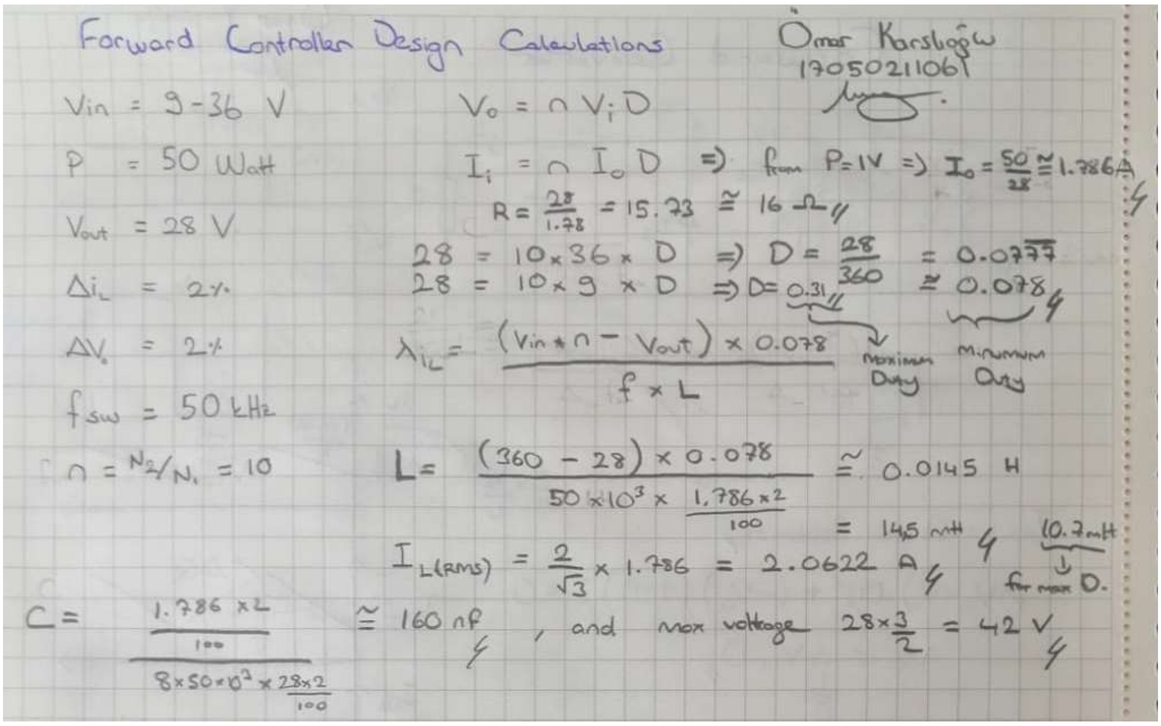


Figure 6: Forward Cicuit Analyze On The Paper

4.1- The Calculations Of Duty, Output Current, Inductance, Output Capacitor Parameter Values

The next step is to calculate all parameters associated with DC-DC Forward Converter.

Firstly, I calculated duty, Iout, inductor values and output capacitor values:


Forward Controller Design Calculations
Ömer Karslıoğlu
17050211061

$V_{in} = 9\text{-}36\ V$

$P = 50\ Watt$

$V_{out} = 28\ V$

$\Delta i_L = 2\%$

$\Delta V_o = 2\%$

$f_{sw} = 50\ kHz$

$n = N_2/N_1 = 10$

$V_o = n V_i D$

$I_i = n I_o D \Rightarrow$ from $P = IV \Rightarrow I_o = \frac{50}{28} \cong 1.786A$

$R = \frac{28}{1.78} = 15.73 \cong 16\ \Omega$

$28 = 10 \times 36 \times D \Rightarrow D = \frac{28}{360} = 0.0777 \cong \underbrace{0.078}_{\text{Minimum Duty}}$

$28 = 10 \times 9 \times D \Rightarrow D = \underbrace{0.31}_{\text{Maximum Duty}}$

$\Delta i_L = \frac{(V_{in} * n - V_{out}) \times 0.078}{f \times L}$

$L = \frac{(360 - 28) \times 0.078}{50 \times 10^3 \times \frac{1.786 \times 2}{100}} \cong 0.0145\ H = 145\ mH$; $10.7\ mH$ for max D.

$I_{L(RMS)} = \frac{2}{\sqrt{3}} \times 1.786 = 2.0622\ A$

$C = \frac{\frac{1.786 \times 2}{100}}{8 \times 50 \times 10^3 \times \frac{28 \times 2}{100}} \cong 160\ nF$, and max voltage $28 \times \frac{3}{2} = 42\ V$

Figure 7: Duty,Output Current, Inductor & Output Capacitor Values

As a result of the calculation, I found:

Iout(max) = 1.786 A

Max. Duty = 31%

Min. Duty= 7.78%

L = 145 Mh

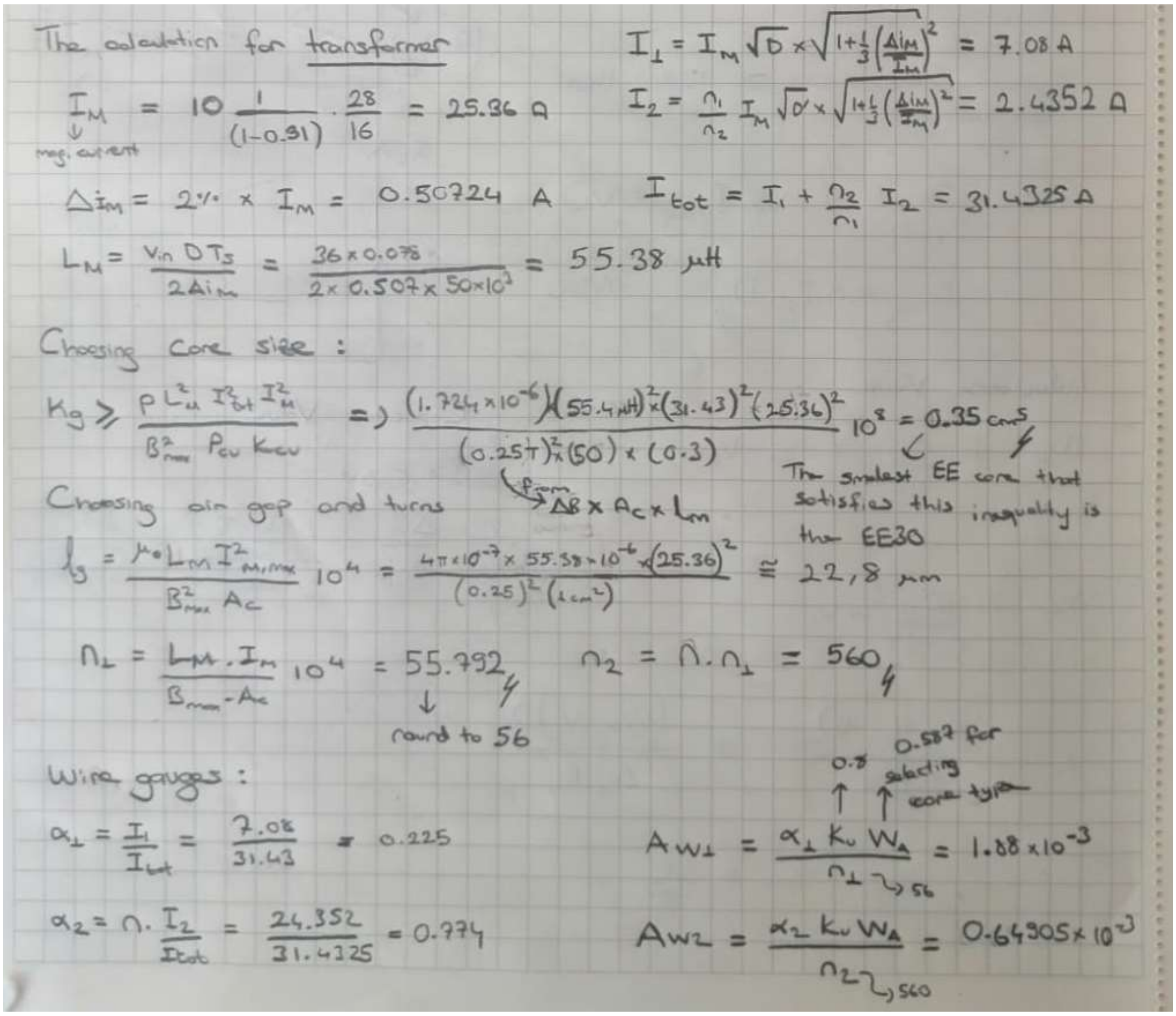
$I_{L(MAX.RMS)}$ = 2.066 A

C = 160 nF (0.3 uF in pratical)

$V_{C(MAX)}$.= 42 V

4.2- The Calculations Of The Transformer Parameters

After the calculations of fundamental parameters which belong the DC-DC Forward Converter, I started to calculate transformer parameters.



The calculation for transformer

$I_M = 10 \frac{1}{(1-0.31)} \cdot \frac{28}{16} = 25.36$ A

mag. current

$\Delta i_M = 2\% \times I_M = 0.50724$ A

$L_M = \frac{V_{in} D T_s}{2 \Delta i_m} = \frac{36 \times 0.078}{2 \times 0.507 \times 50 \times 10^3} = 55.38\ \mu H$

Choosing core size :

$K_g \geq \frac{\rho L_M^2 I_{tot}^2 I_M^2}{B_{max}^2 P_{cu} K_{cu}} \Rightarrow \frac{(1.724 \times 10^{-6})(55.4 \mu H)^2 \times (31.43)^2 (25.36)^2}{(0.25T)^2 \times (50) \times (0.3)} 10^8 = 0.35\ cm^5$

from $\Delta B \times A_c \times l_m$

The smallest EE core that satisfies this inequality is the EE30

Choosing air gap and turns

$l_g = \frac{\mu_0 L_m I^2_{M,max}}{B^2_{max} A_c} 10^4 = \frac{4\pi \times 10^{-7} \times 55.38 \times 10^{-6} \times (25.36)^2}{(0.25)^2 (1 cm^2)} \cong 22,8\ \mu m$

$n_1 = \frac{L_M . I_M}{B_{max} \cdot A_c} 10^4 = 55.792$ round to 56

$n_2 = n . n_1 = 560$

$I_1 = I_M \sqrt{D} \times \sqrt{1 + \frac{1}{3}\left(\frac{\Delta i_M}{I_M}\right)^2} = 7.08$ A

$I_2 = \frac{n_1}{n_2} I_M \sqrt{D} \times \sqrt{1 + \frac{1}{3}\left(\frac{\Delta i_M}{I_M}\right)^2} = 2.4352$ A

$I_{tot} = I_1 + \frac{n_2}{n_1} I_2 = 31.4325$ A

Wire gauges :

$\alpha_1 = \frac{I_1}{I_{tot}} = \frac{7.08}{31.43} = 0.225$

$\alpha_2 = n \cdot \frac{I_2}{I_{tot}} = \frac{24.352}{31.4325} = 0.774$

0.8 0.587 for selecting core type

$A_{w1} = \frac{\alpha_1 K_u W_A}{n_1 \to 56} = 1.88 \times 10^{-3}$

$A_{w2} = \frac{\alpha_2 K_u W_A}{n_2 \to 560} = 0.64305 \times 10^{-3}$

Figure 8: The Calculation Of Transformer

As a result of the calculations, I found:

I_M = 25.36 (referred primary)

Δ_{im} = 0.507 A

L_M = 55.38 uH

I_1 = 7.08 A

I_2 = 2.4352 A

I_{tot} = 31.43 A

$K_{g(min)}$ = 0.35 cm^5

l_g = 22.8 um

n1 = 56 turns

n2 = 560 turns

α_1 = 0.225

α_2 = 0.774

A_{w1} = 1.88 $* 10^{-3}$

A_{w2} = 0.650 $* 10^{-3}$

5- Simulations Of The Forward Converter Designed

I designed the circuit in MATLAB Simulink with the parameteres calculated in previous step and I added to the this circuit PID controller to make close loop system.

The circuit that I designed in Simulink:

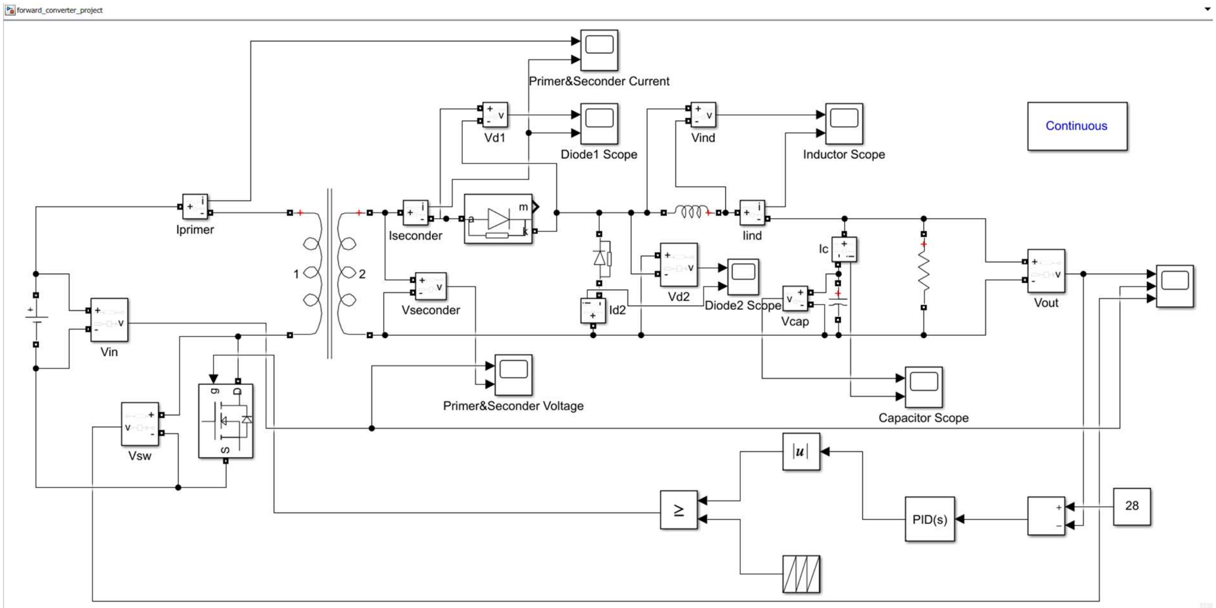


Figure 9: The circuit which is designed in MATLAB Simulink

5.1- Simulation Results

- According to input voltage, PWM generated in closed loop changes to hold constant output voltage at 28 V:

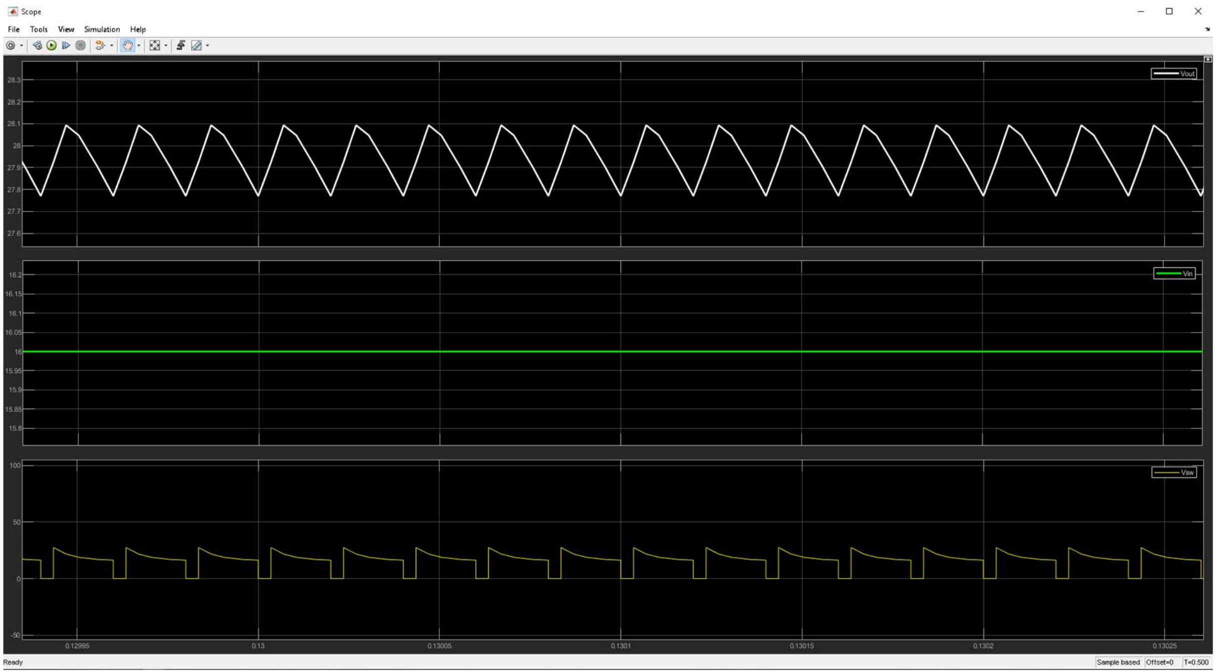


Figure 10: Vout and PID Sets PWM Vin=16 V, Vout=28 V

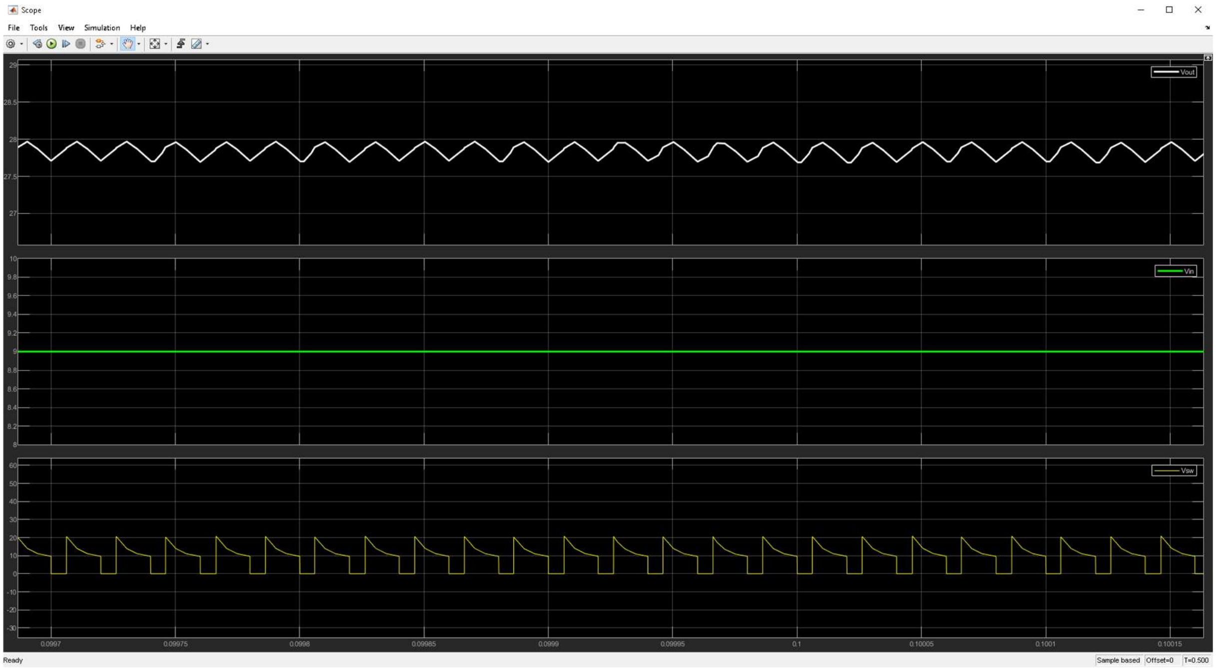


Figure 11: Vout and PID Sets PWM Vin=16 V, Vout=28 V

- The inductor current and voltage at seconder side:

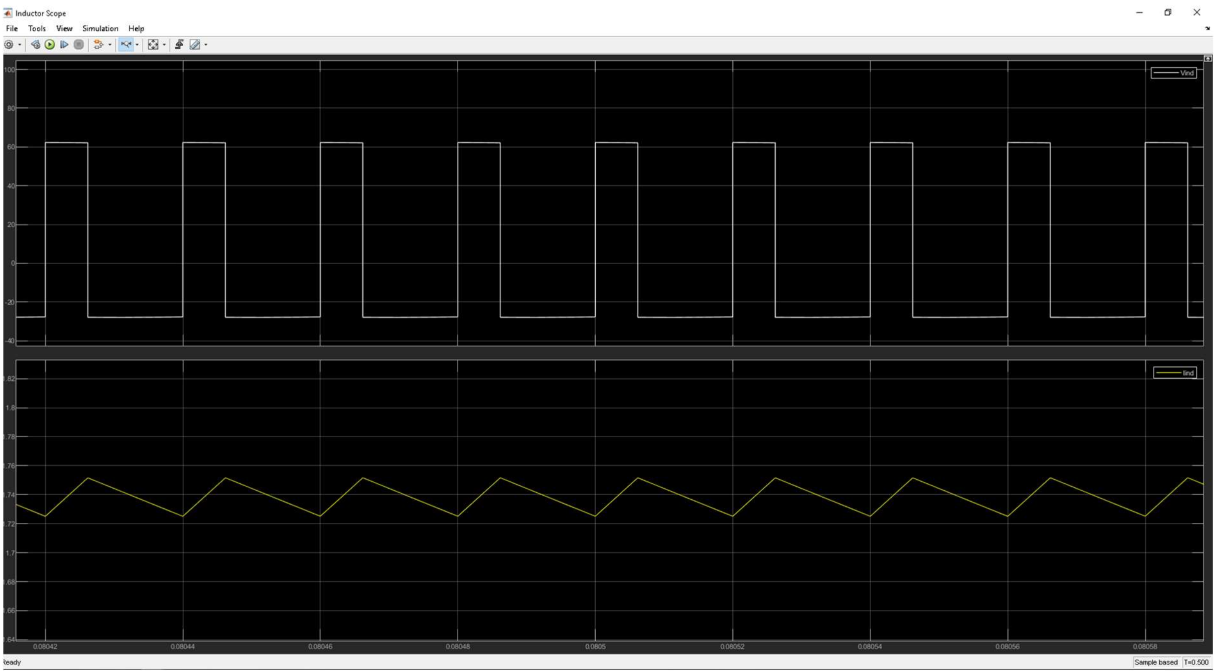


Figure 12: The inductor current and voltage at seconder side

- The output capacitor current and voltage at seconder side:

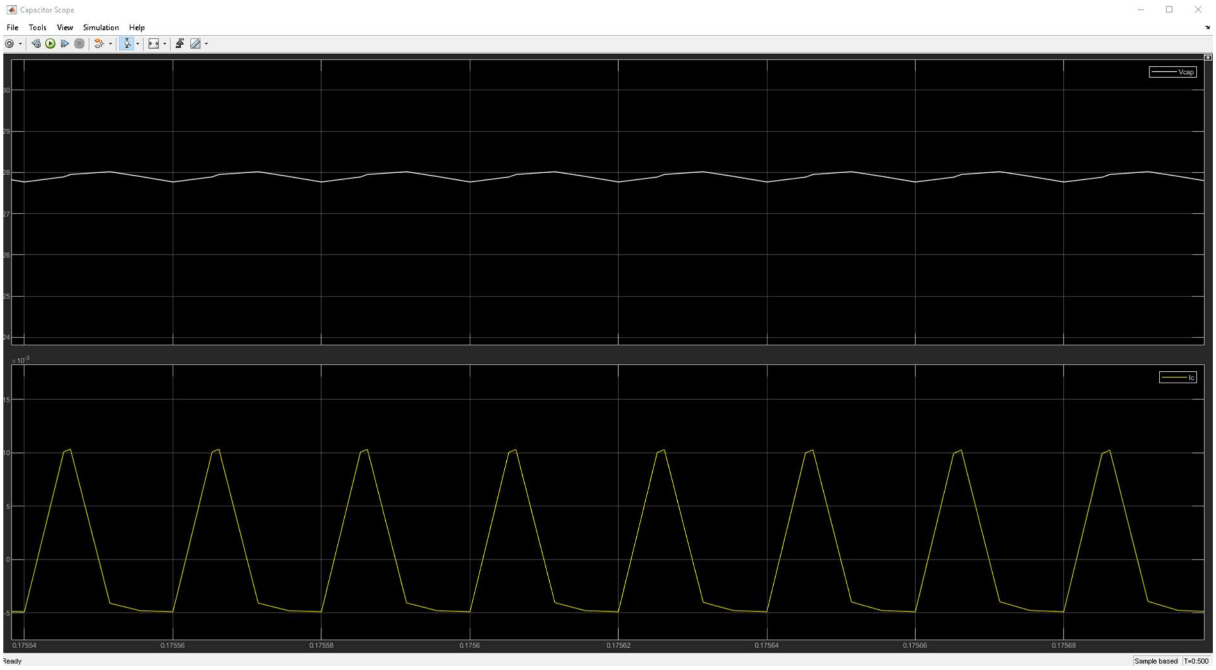


Figure 13: The output capacitor current and voltage at seconder side

- The diode1 current and voltage at seconder side:

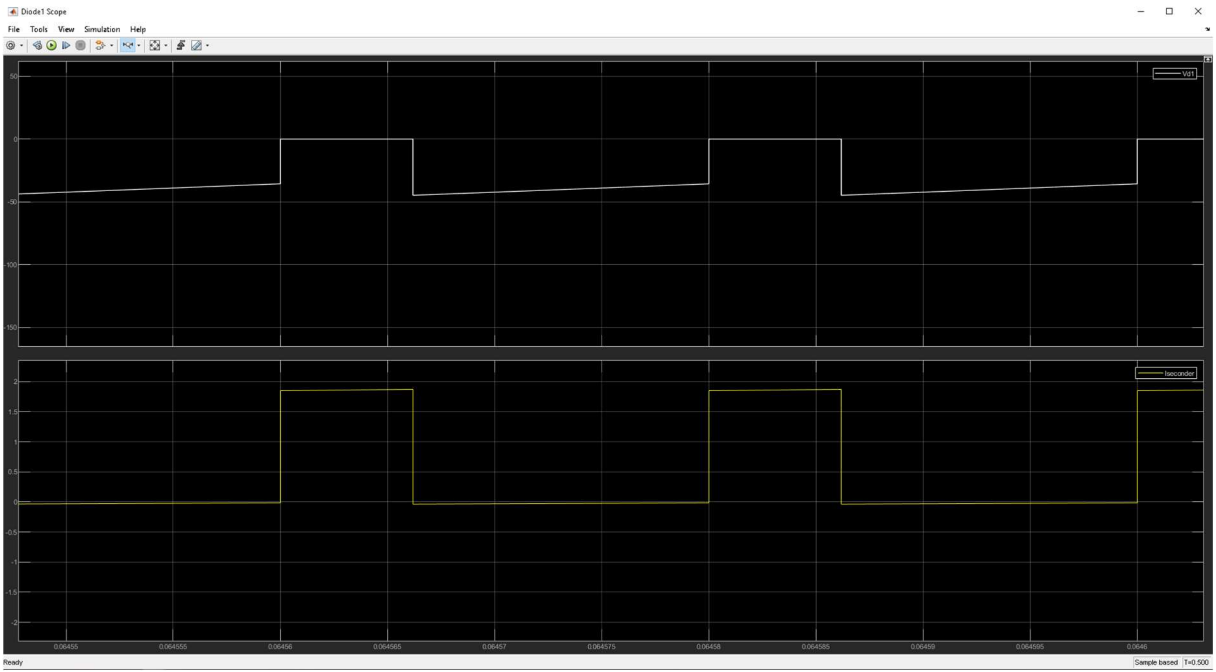


Figure 14: The diode1 current and voltage at seconder side

- The diode2 current and voltage at seconder side:

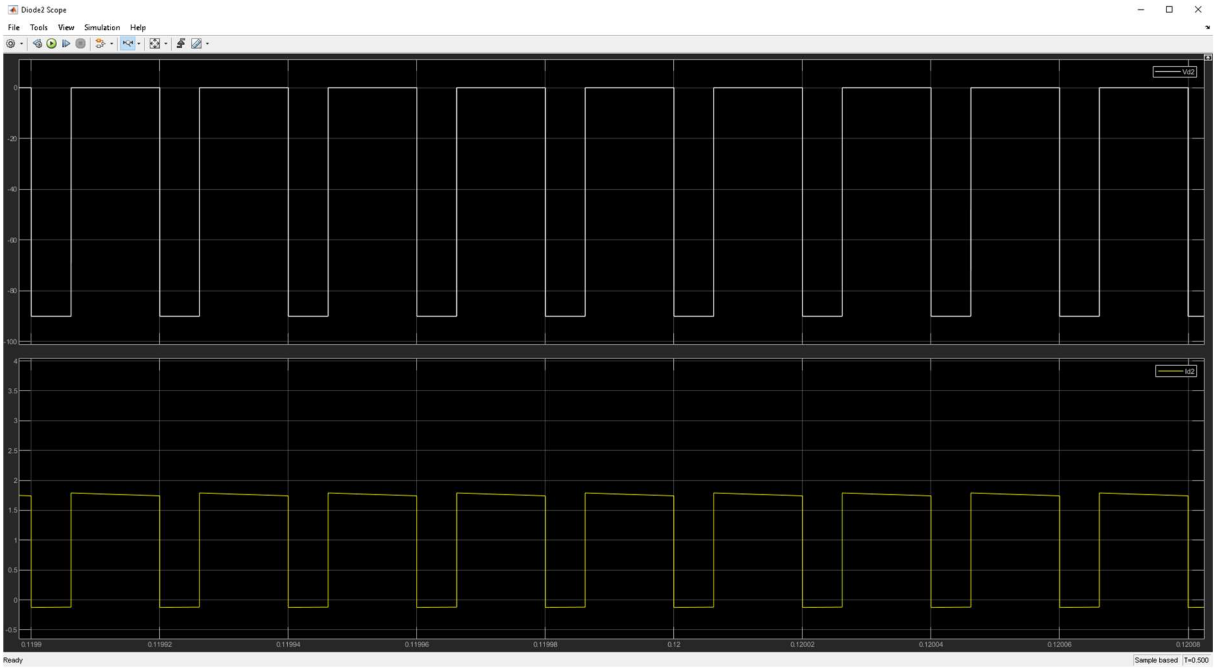


Figure 15: The diode2 current and voltage at seconder side

- The mosfet current and voltage at seconder side:

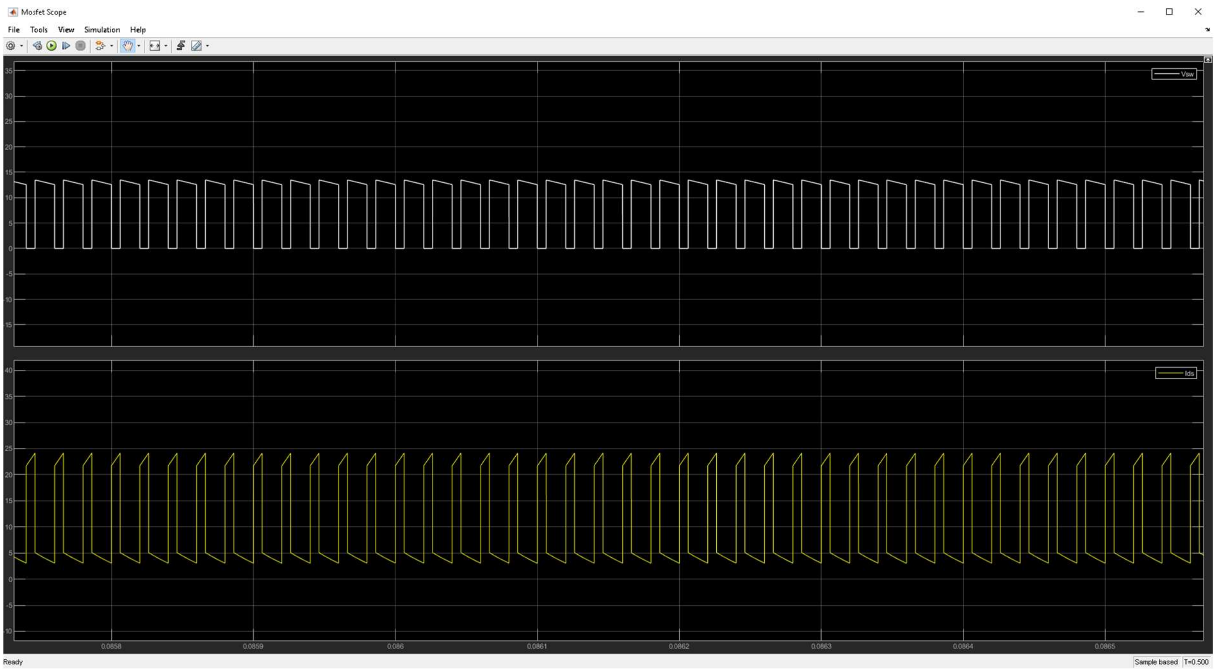


Figure 16: The mosfet current and voltage at seconder side

- Primer and seconder side voltages:

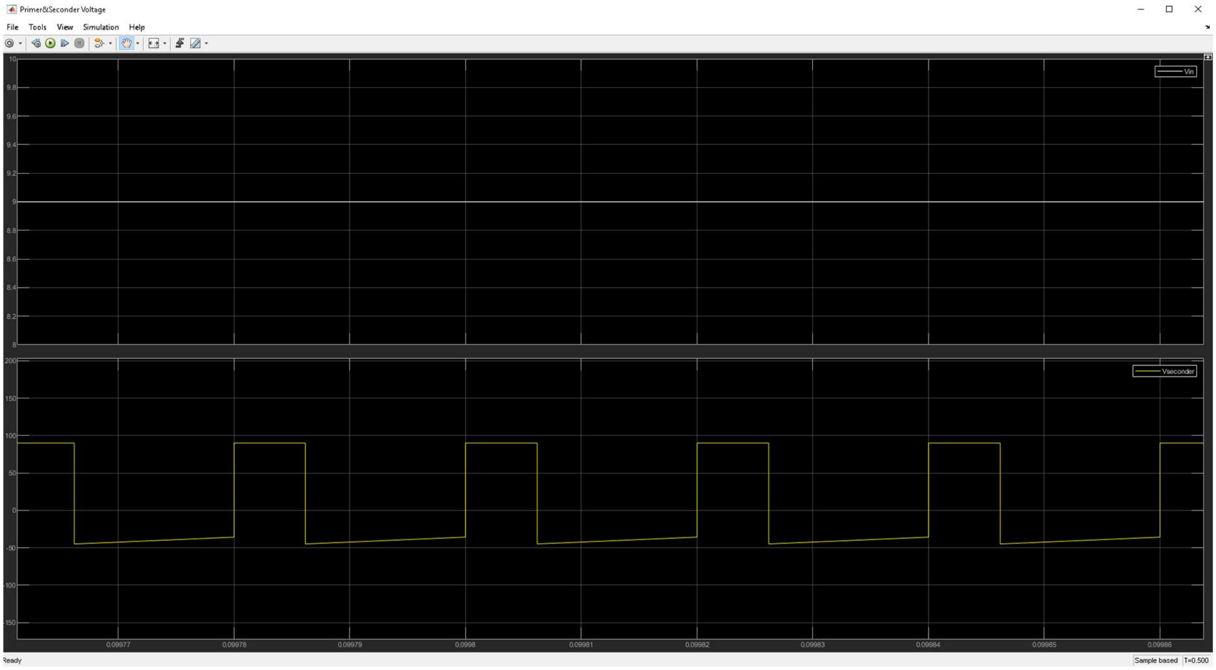


Figure 17: Primer and seconder side voltages

- Primer and seconder side currents:

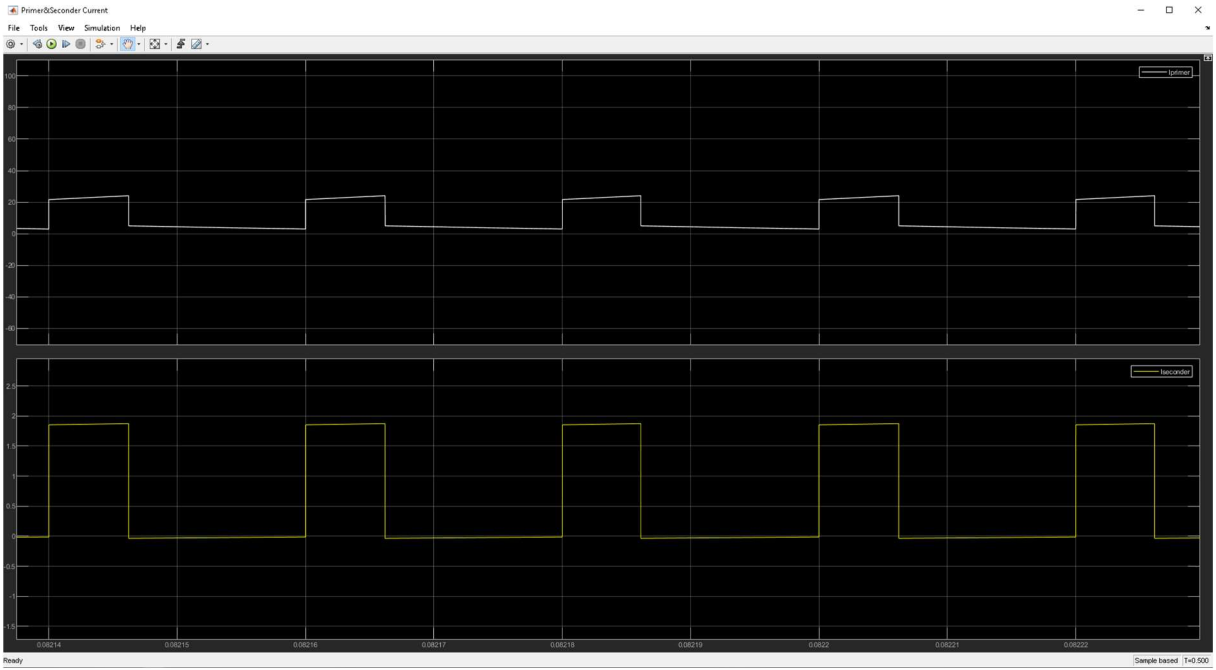


Figure 18: Primer and seconder side currents

6- Snubber Circuit Design

All simulation parameters were prepared according to reel component values.

The parameters of my smps high frequency trnsformer:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	3–4	@20°C	0.220 ohms ±10%
D.C. RESISTANCE	10–8	@20°C	28.50 ohms ±10%
D.C. RESISTANCE	9–7	@20°C	28.50 ohms ±10%
INDUCTANCE	3–4	50kHz, 100mVAC, Ls	100uH ±10%
SATURATION CURRENT		20% rolloff from initial	2ADC
LEAKAGE INDUCTANCE	3–4	tie(7+8+9+10), 100kHz, 10mVAC, Ls	3.0uH max.
INTERWINDING CAPACITANCE	3–10	tie(8+9), 100kHz, 100mVAC, Cs	30pF max.
DIELECTRIC	3–10	tie(8+9), 1500VAC, 1 second	–
TURNS RATIO		(10–8):(3–4)	10:1, ±2%
TURNS RATIO		(9–7):(3–4)	10:1, ±2%

Table 2: The parameters of my smps high frequency trnsformer

The electrical chracteristics of the switching component (IRFZ44N):

ELECTRICAL CHARACTERISTICS

T_C=25℃ unless otherwise specified

SYMBOL	PARAMETER	CONDITIONS	MIN	MAX	UNIT
$V_{(BR)DSS}$	Drain-Source Breakdown Voltage	V_{GS}= 0; I_D= 0.25mA	55		V
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS}= V_{GS}; I_D= 0.25mA	2	4	V
$R_{DS(on)}$	Drain-Source On-Resistance	V_{GS}= 10V; I_D= 25A		0.032	Ω
I_{GSS}	Gate-Body Leakage Current	V_{GS}= ±20V;V_{DS}= 0		±100	nA
I_{DSS}	Zero Gate Voltage Drain Current	V_{DS}= 55V; V_{GS}= 0 V_{DS}= 55V; V_{GS}= 0; T_j= 150℃		25 250	μA
V_{SD}	Forward On-Voltage	I_S= 25A; V_{GS}= 0		1.3	V

Table 3: The electrical chracteristics of the switching component (IRFZ44N)

The circuit that is prepared to simulate without snubber circuit:

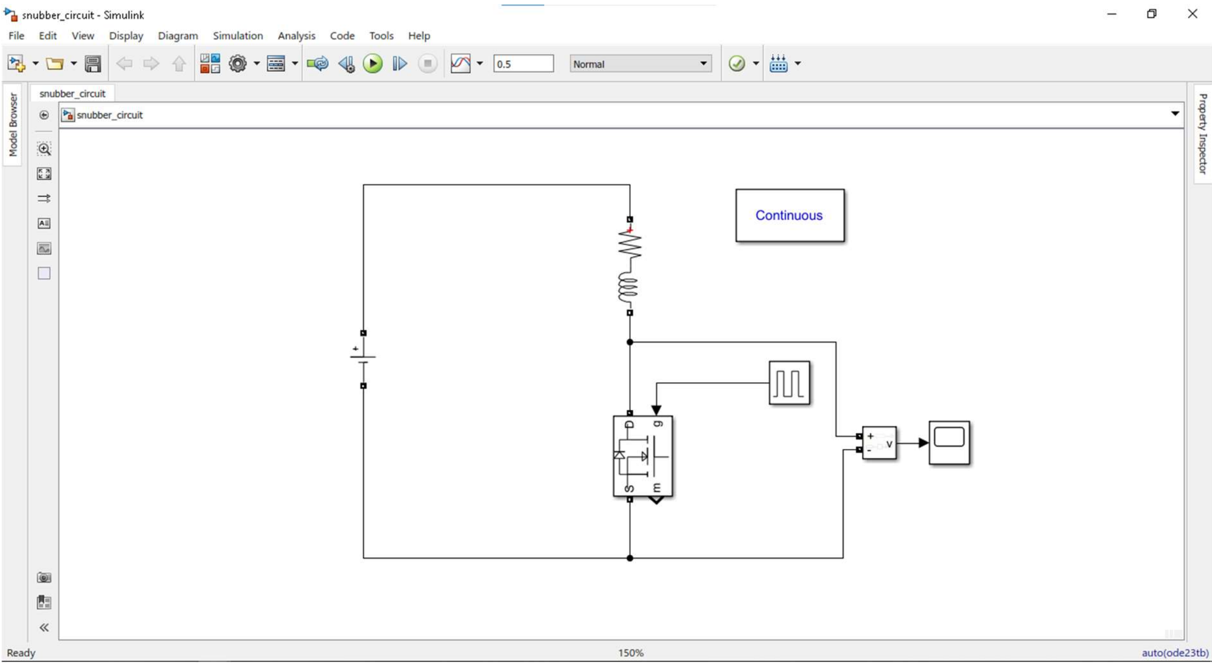


Figure 19: Snubber circuit simulation

Mosfet parameter for simulation:

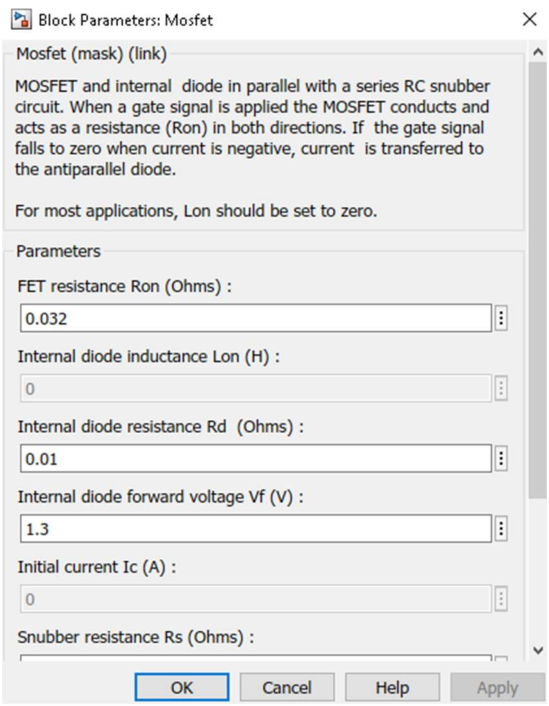


Figure 20: Mosfet parameter for simulation

Primer side of the transformer:

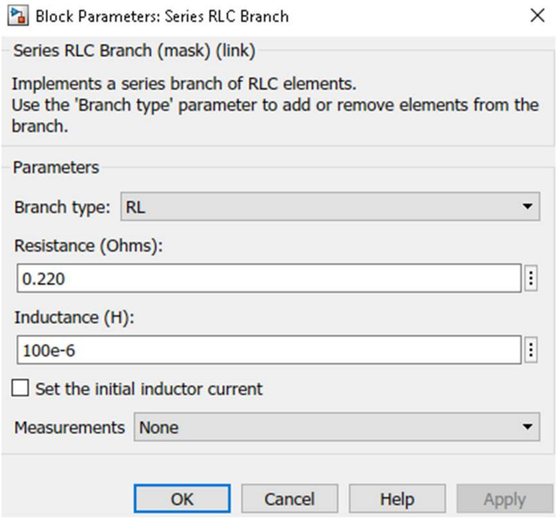


Figure 21: Primer side of the transformer for snubber circuit simulation

The drain-source voltage of N-channel mosfet without snubber circuit:

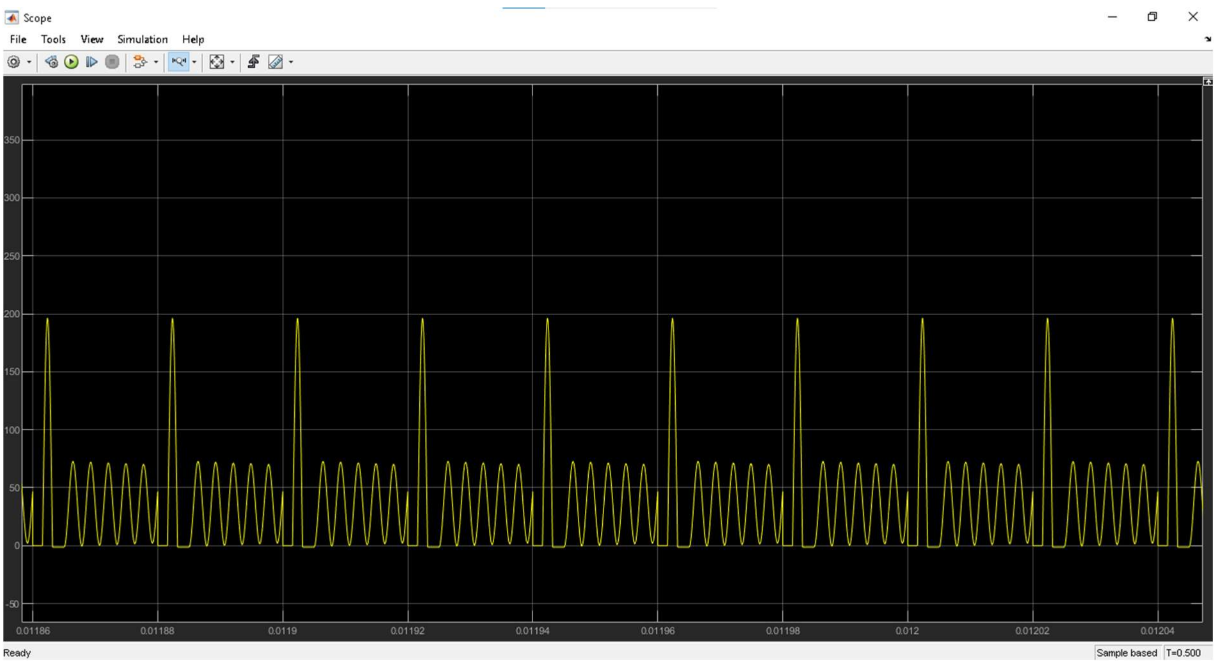


Figure 22: Vds before adding snubber circuit

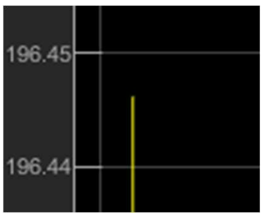


Figure 23: Vds peak value

RC snubber calculation:

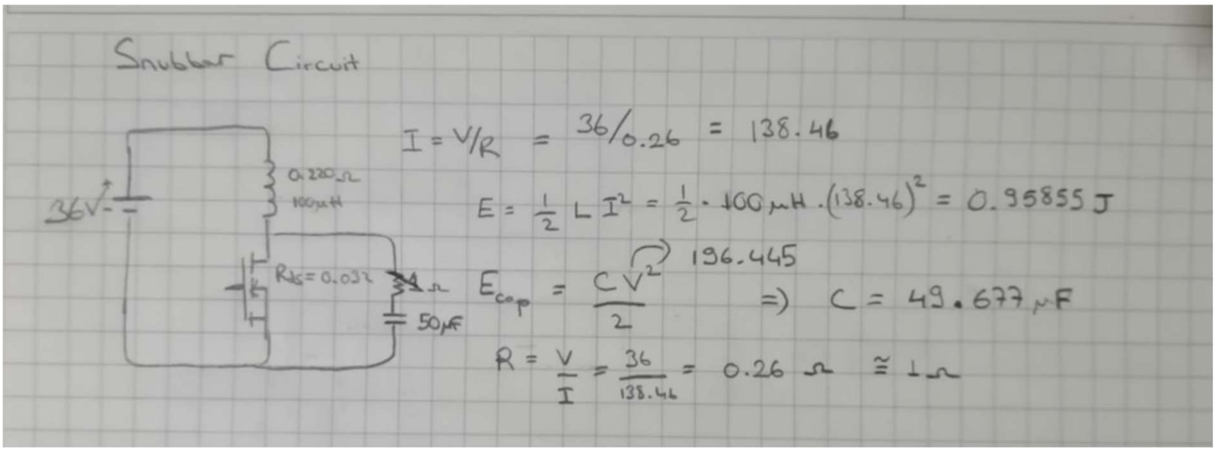


Figure 24: Snubber circuit calculations

After adding the RC snubber circuit:

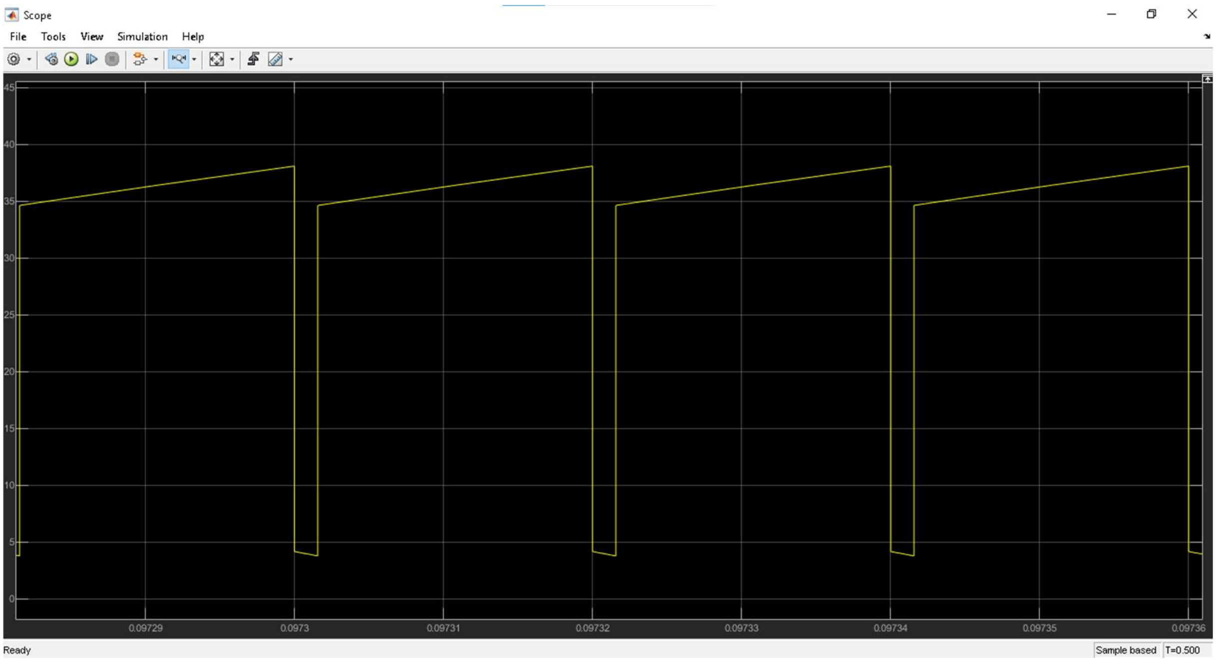


Figure 25: Vds after adding snubber circuit

7- Forward Converter PCB Design

I completed all of my designs on KiCad. While performing the schematic design, I also recorded the footprint drawing processes and the places where the materials will be supplied. After my schematic design was completed, I made my PCB layout drawing.

7.1- Schematic

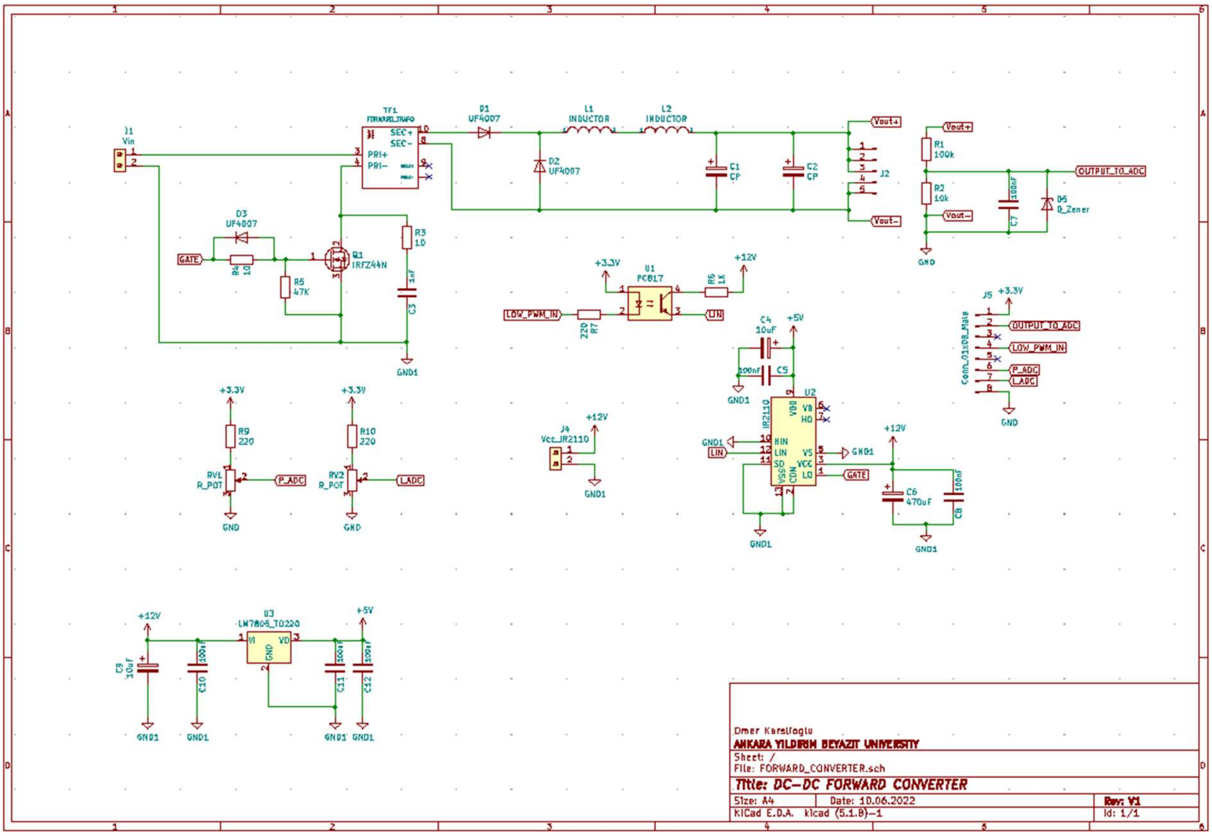


Figure 26: Schematic Of The Design

I designed the same Forward Converter that I designed for the simulation in the schematic. I used an IR2110 for the Mosfet driver circuit and I put an optocoupler between Mcu and IR2110 to provide isolation between primary and secondary. I added a terminal block since I will be feeding the IR2110 with +12v from outside. I added two potentiometers to adjust the P and I coefficients. To provide close loop control, I added a zener diode to the wire part of the MCU going to the ADC pin. Thus, I ensured the protection of the MCU. I added a diode to the mosfet gate to speed up the turn-off period. I added my snubber circuit according to the values in the simulation I designed.

7.2- Layout

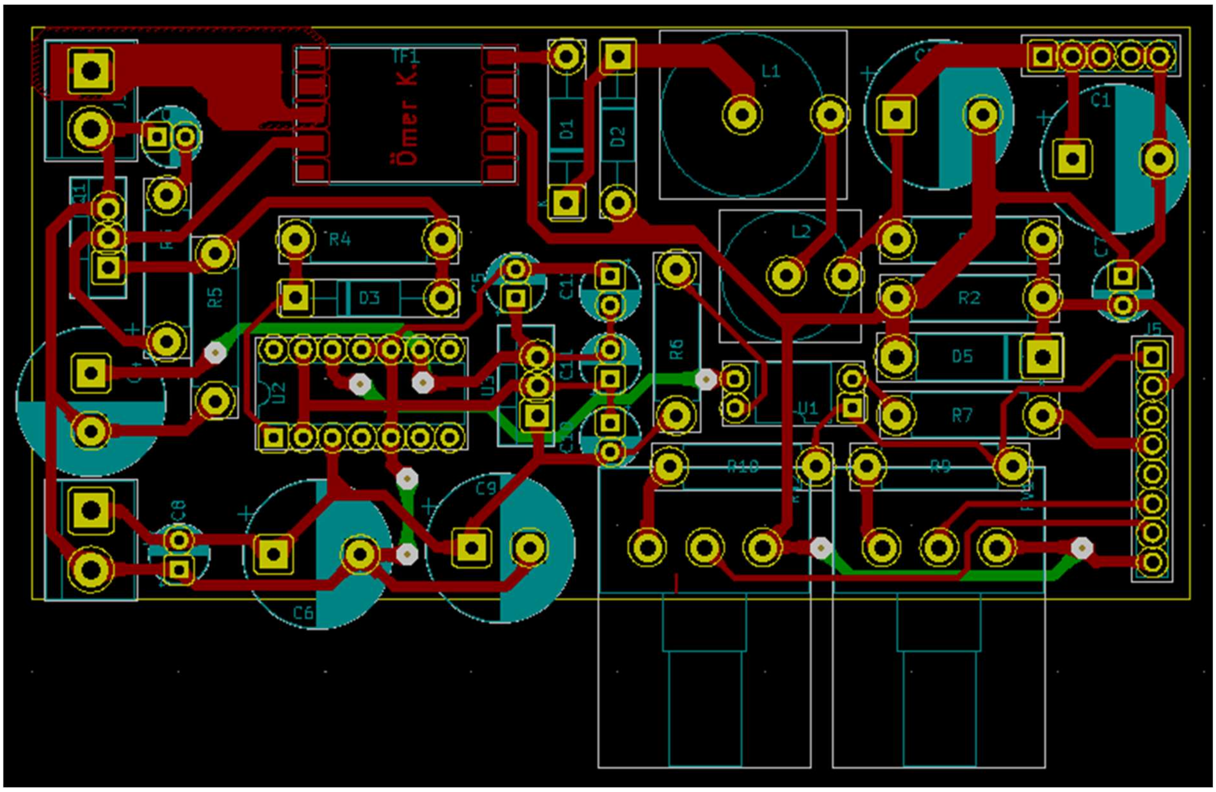


Figure 27: PCB Design Of The Forward Converter

I completed the PCB design in a 5x10cm frame. Path thicknesses were calculated using trace width calculation methods. I set my minimum road thickness to 20 mil and the minimum clearance width between roads was set to be 1.5 mm. I designed my PCB on a single layer. A 0 ohm resistor will be placed on the parts where the green paths are located.

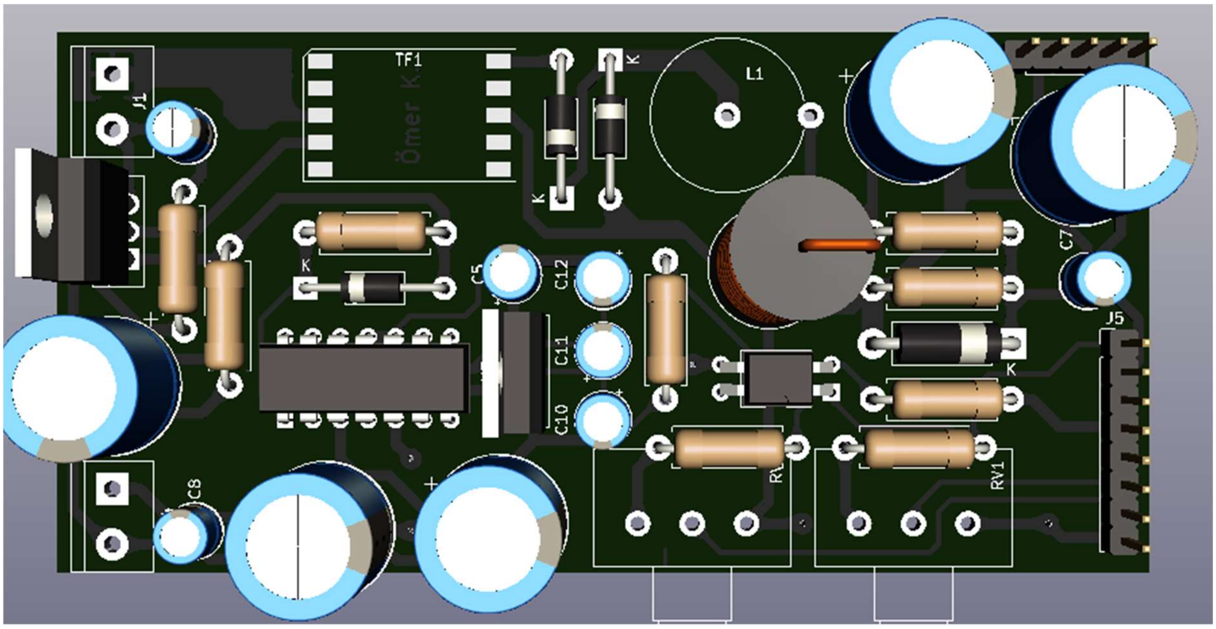


Figure 28: 3D Image Of The PCB

The pattern above is the 3d view of my Forward Converter design.

8- Software

As it is known, this designed circuit is designed as a close loop system and will be controlled by PI. The software of this circuit works as follows: voltage is read with ADC and required ratio calculation is made. This calculated value enters the PI algorithm and is compared with the setpoint. If this value is not the same as the setpoint, the PI calculates a new value close to or the same as the setpoint. This value is again proportioned and the PWM signal driving the mosfet is updated again.

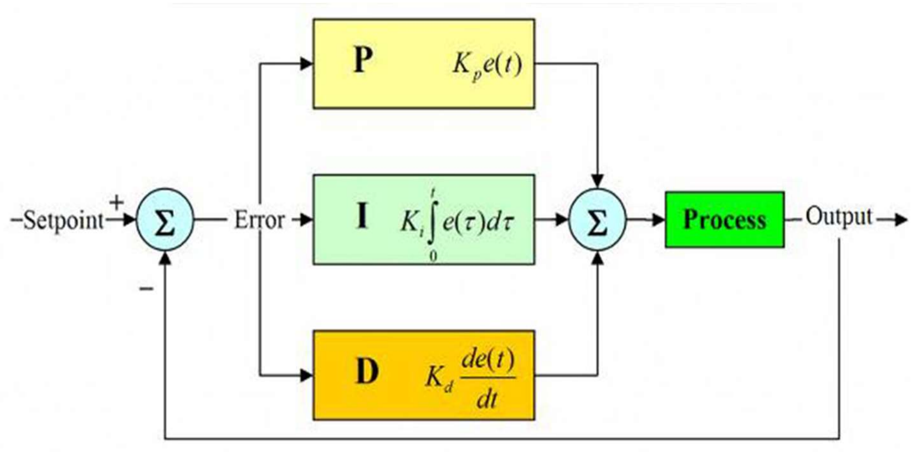


Figure 29: PID System Diagram

The closed loop system of Forward Converter is as above diagram. It is PID system. But Kd equals 0 as seting PI.

The software generally consists of two or three main modules:

1. main.c : It is the file where all the configurations are found, the main algorithm and PWM are set.
2. ADC_READ.c : It is an analog reading value module that I developed specially for the STM32F4 discovery board.
3. PID.c : It is the module where I wrote the PID algorithm.

Other folders belong to the HAL Library used and the processor's drivers.

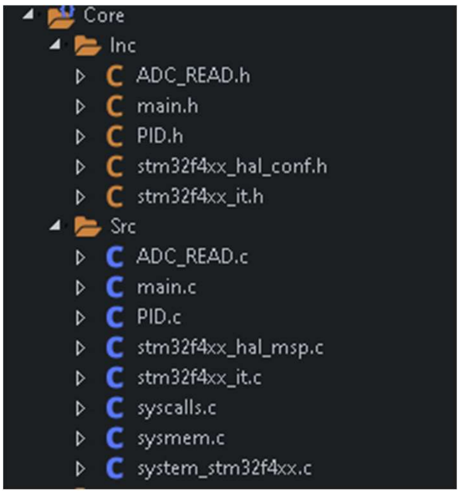


Figure 30: Software Files Explorer

All necessary explanations are in the software modules in the software folder in the project file.

9- Conclusion

Throughout the DC-DC Forward Converter project, I have studied meticulously and designed my circuit. One of the most important features of Forward Converter that distinguishes it from others is that it provides isolation between the load and the source. The transformer providing this isolation must be well designed. Because this SMPS transformer must be able to operate at high frequencies and give a precise voltage range.

Another experience I gained is in the design of the switching part of the circuit. I learned to use optocoupler to have the version of Mosfet in isolation. I have seen that the uncertain and very high waves that occur during the opening and closing of the Mosfet are prevented by the snubber circuit.

In addition to these experiences, some of the values that I calculated mathematically in some places (such as the capacitor value) I should prefer a little more in practice, various drawing tactics to get better on the copper plate while designing the PCB, designing the circuit according to the power requirements, various designs to prevent the circuit from being affected by external noises... I gained a lot of knowledge and experience such as methods.

I think my biggest gain from this project was that I learned how to successfully carry out all the troublesome processes from the beginning to the end of a project. I had serious experience on how to advance all the calculations first, then the simulation phase, then the design of the circuit and the writing of the algorithm, and finally the production of the circuit and the realization of all the testing phases. Helping us in this regard and enabling us to learn these processes, I would like to thank Prof. Dr. Ahmet KARAARSLAN.

10- Resources

1- EE462 Course Materials On Aybuzem
2- Forward Converter Design Note IFAT IMM PSD Anders Lind, https://www.mouser.com/pdfdocs/2-10.pdf
3- A Guide to Forward-mode Transformers, https://www.coilcraft.com/en-us/edu/series/a-guide-to-forward-mode-transformers/
4- 200-W Interleaved Forward Converter Design Review Using TI's UCC28221 PWM Controller, https://www.ti.com/lit/an/slua312/slua312.pdf?ts=1655191588923&ref_url=https%253A%252F%252Fwww.google.com%252F
5- LM34xx How to Design Flyback Converter with LM3481 Boost Controller (Rev. A), https://www.ti.com/lit/an/snva761a/snva761a.pdf?ts=1655188277121&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FLM3481
6- Introduction to Forward Converter, Ozan Keysan, https://www.youtube.com/watch?v=imvoBKdv09E