MIDDLE EAST TECHNICAL UNIVERSITY
Electrical & Electronics Engineering

Hardware Project

EE 464 – Static Power Conversion - II

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Introduction

In our hardware project of the EE464 course, we are asked to design an Isolated Power Supply. In this project, the design, simulations and hardware implementations are to be performed for hardware project. As Anka Inc. group, we have chosen the project designing an Isolated Flyback Converter. The specifications are as follows;

Minimum Input Voltage (V)	210 Vac
Maximum Input Voltage (V)	230 Vac
Output Voltage (V)	15
Output Power (W)	15
Output Volt. Peak-to-Peak Ripple (%)	5
Line Regulation (%)	3
Load Regulation (%)	3

Table 1: Flyback Converter Specifications

The main motivation selecting this topology is to overcome efficiency problems as our output current value is smaller, which results in less power loss in overall system. Also, there is no 3rd winding in transformer designed for Flyback Converter as well as output inductance for filtering purposes as in Forward Converter topology.

1. Flyback Converter Design

Our input voltage is AC voltage with 210 Vrms. Firstly, we establish the single phase full bridge rectifier to convert AC to DC and the DC voltage is filtered by DC-Link Capacitor. Then, a Flyback Converter is established by PI controller. PI controller is required to adjust the output power 15 V for not considering input voltages change. The overall schematic is depicted in Figure 1.

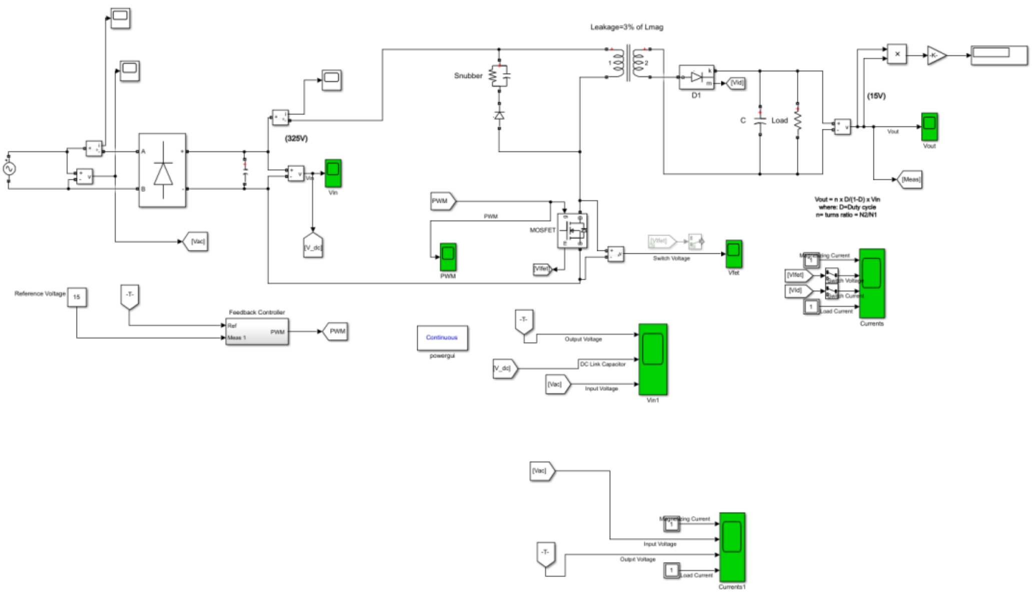

Figure 1: Simulink Setup of Flyback Converter

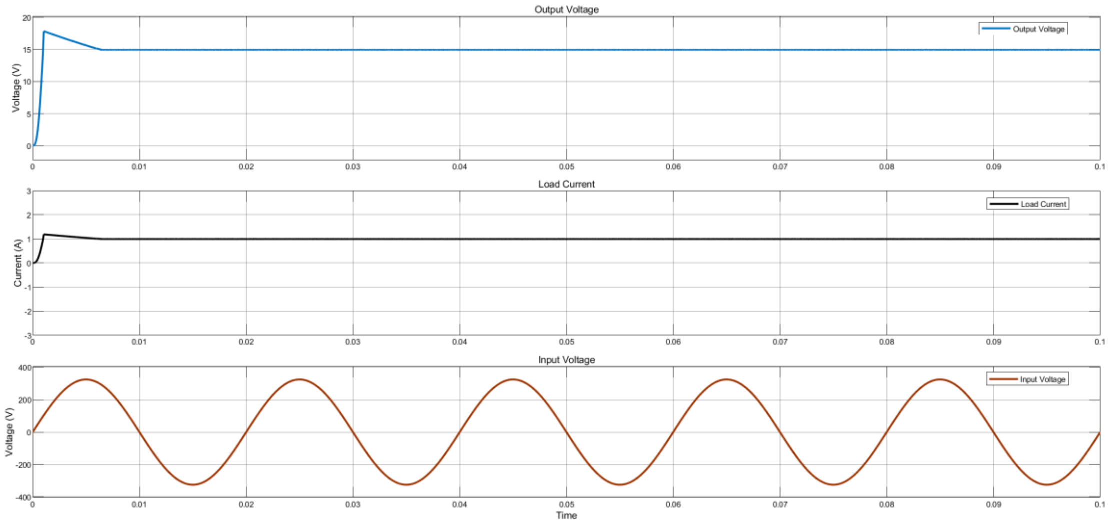

Figure 2: Input and Output Voltages and Output Current waveforms

1.1. Steady State Operation and Calculations

There are 5 steps to calculate the parameters to provide specification:

1- DC link capacitor determination for Single Phase Rectifier:

DC link capacitor is determined by AC voltage and frequency with desired ripple at output of the single phase rectifier.

$$C_{dc} = \frac{2 * V_{line}^2 - V_{Dc}^2}{P_{in}(1 - D_{ch}) f_l}$$

$$V_{line} = 210\ V\ (\ minimum)$$

$$V_{Dc} = 280\ V\ (\ minimum)$$

$$P_{in} = P_{out} * Efficiency$$

$$f_l = 50\ Hz\ and\ Dch = 0.2\ (\ charging\ duty)$$

The DC link capacitor is calculated easily as 33uF, 400 V.

2- Magnetizing Inductance is calculated by formula:

$$L_m = \frac{(\ V_{DC} D_{max})^2}{2 P_{in} * f_s * K_{rf}}$$

Maximum duty can be selected for mode of converter. We want our converter to operates at discontinuous conduction mode. Thus, standard duty ratio is near the 0.3. Maximum duty is 0.45. Ripple factor (Krf) is 1 at DCM and it is between 0.2 and 0.5 at CCM. Switching frequency was determined as 40 kHz.

$$L_m = 10.58 mH$$

3- Calculation of Peak Current of Switch

$$\Delta Ids = \frac{V_{dc}\, D_{max}}{L_m f_s}$$

$$I_{eds} = \frac{P_{in}}{V_{DC} D_{max}}$$

$$I_{ds}^{peak} = I_{edc} + \frac{\Delta I_{ds}}{2} = 0.297A$$

The calculation is important to determine the CCM and DCM mode. Change in switch current is equal to half of peak current or equals to I_eds.

4- Determination of primary side Turn number

$$N_p = \frac{L_m I_{ds}^{peak}}{B_{sat} * A_e}$$

Minimum turn number depends on core. The core area and saturation flux density. They are found at our core datasheet.

$$A_e = 233\ mm^2$$

$$B_{sat} = 0.3T$$

$$N_p = 45.06$$

5- Determination of primary side Turn number

$$N_s = \frac{N_p V_{Ro}}{V_{out} + V_d}$$

$$N_s = 3.08$$

Secondary side turn ratio depends on primary side voltage and secondary side voltage. Secondary side voltage includes output voltage and opening voltage of diodes.

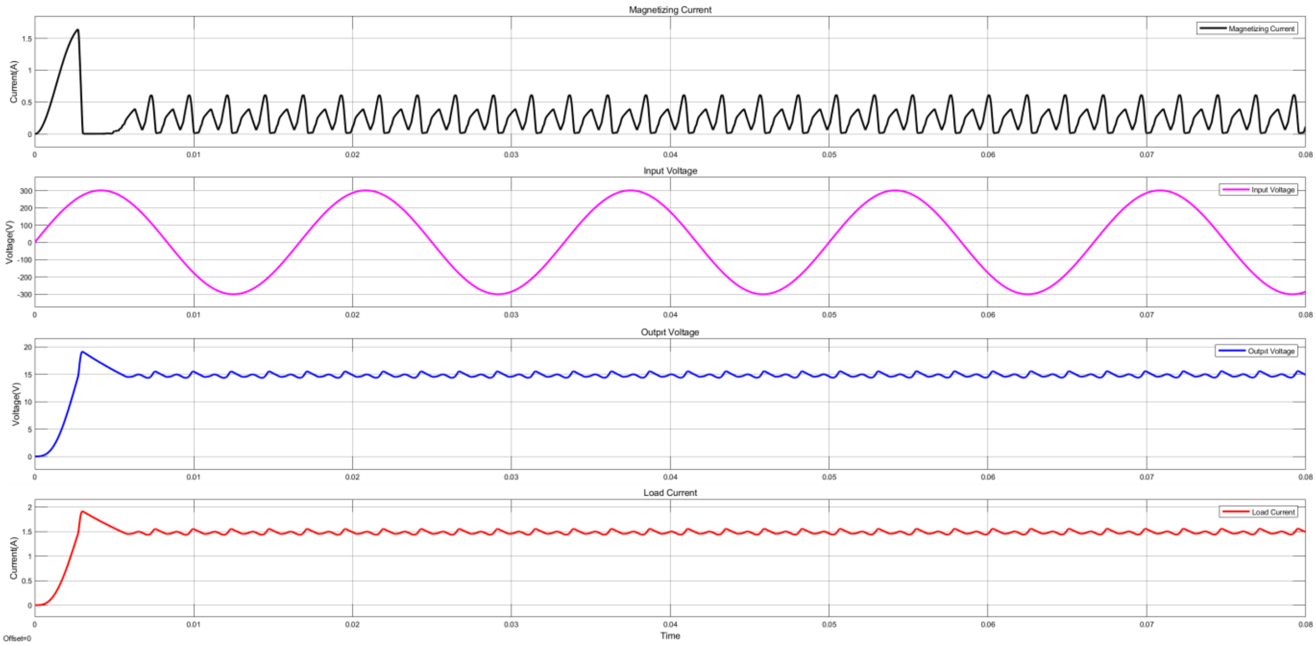

Figure 3: Corresponding waveforms with ideal switches and elements

Leakage inductance is taken as 3 percentage of magnetizing inductance. The MOSFET conduction resistance is 10 ohms, and diode conduction resistance is 5 ohms. Switch Voltage and Switch current are taken at only conduction time.

Without Snubber Circuit:

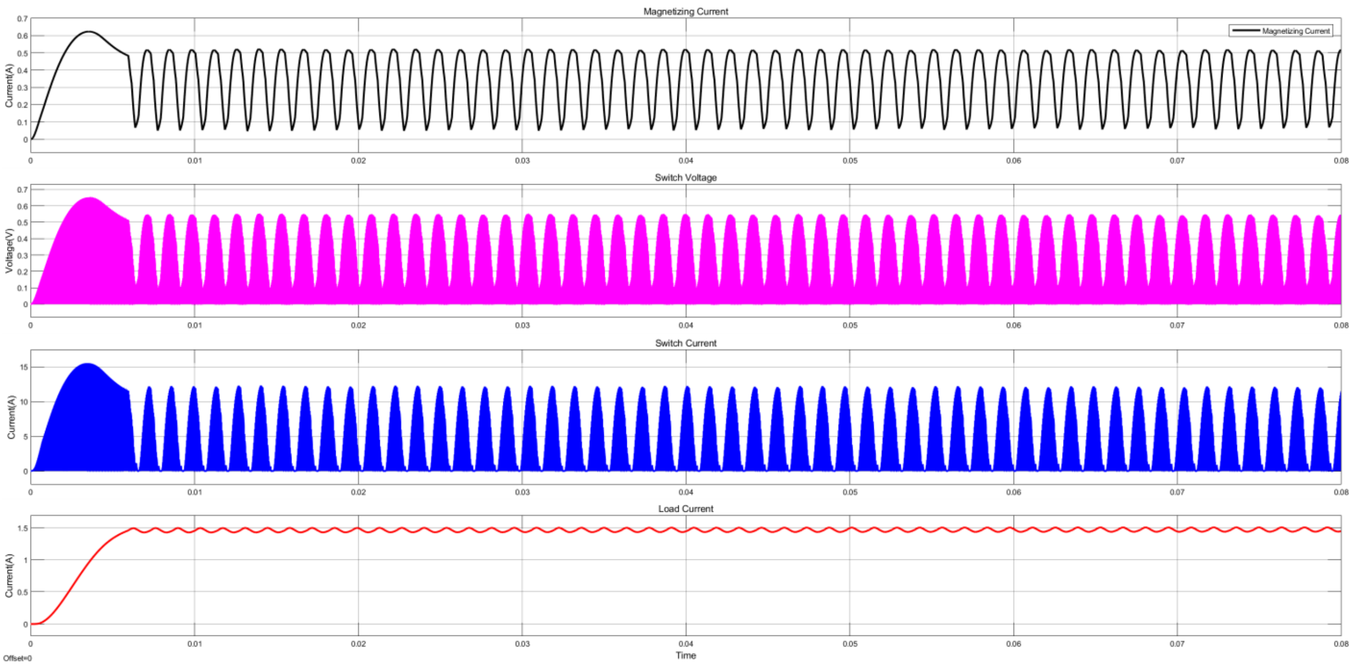

Figure 4: Corresponding waveforms without snubber circuit

With Snubber Circuit:

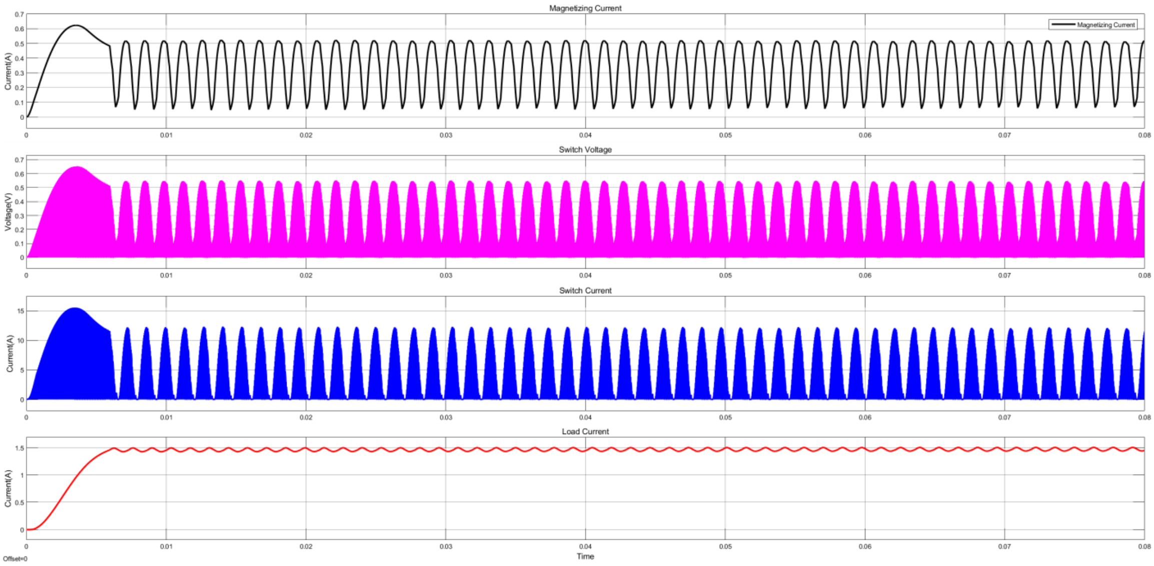

Figure 5: Corresponding waveforms with snubber circuit

Without snubber circuit, the energy storage is not transferred to load. Load current decreases and output voltage is not provided successfully.

RCD snubber circuit is established. The value of components is found considering switching frequency and time constant RC of the snubber circuit.

R=40k ohm
C= 100 pF

1.2. Transformer Design

At this part, we are supposed to design a transformer for our Flyback Converter. There are some properties that are important for designing such as permeability, saturation flux and core loss. Geometry and core type of the transformers determines the properties.

Transformer geometry toroid changes with respect to applications and some geometries are E-core I-core and Toroid core. E- cores are easier to wind and mount by using transformer core former. We chose the core geometry as E-core for that reason. Saturation flux depends on current ratings. Our current rating is small, 1A and we can choose saturation flux density as small. Also, permeability affects the magnetizing inductance which is very important to Flyback design because transformer is used for energy storage elements in Flyback. In addition to this, core loss is very important to determine switching frequency because of the efficiency consideration.

We, as Anka Inc. Team, made a Matlab Script to determine the design parameters with respect to our requirements. The script is given as APPENDIX.

By using this script, we found that:

Requirement Magnetizing Inductance: 10.58mH
Np/Ns= 15 (maximum duty is determined as 0.45) and minimum Np=45 turns

1.3. Simulation Results

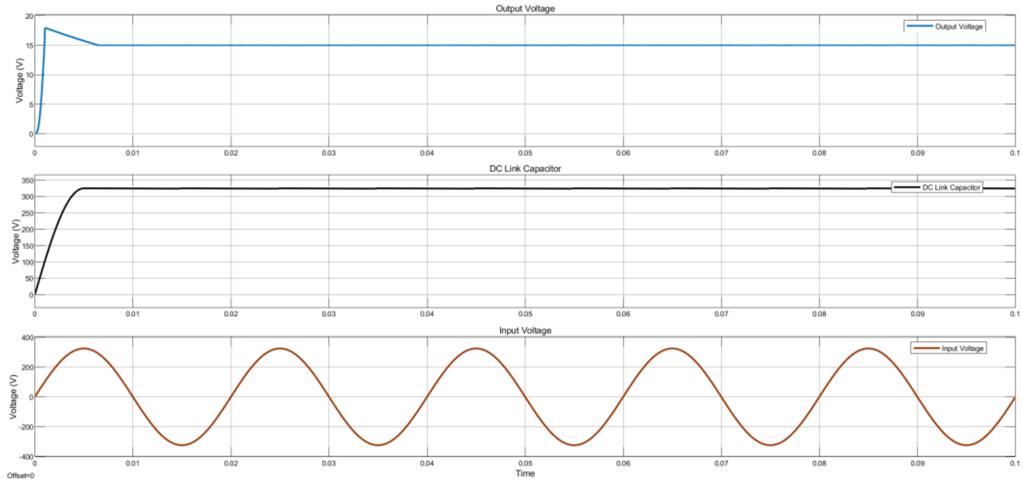

Figure 6: Output, DC Link Capacitor and Input voltage waveforms

With the calculated values and parameters, voltage values are matched with simulation as shown in Figure 6.

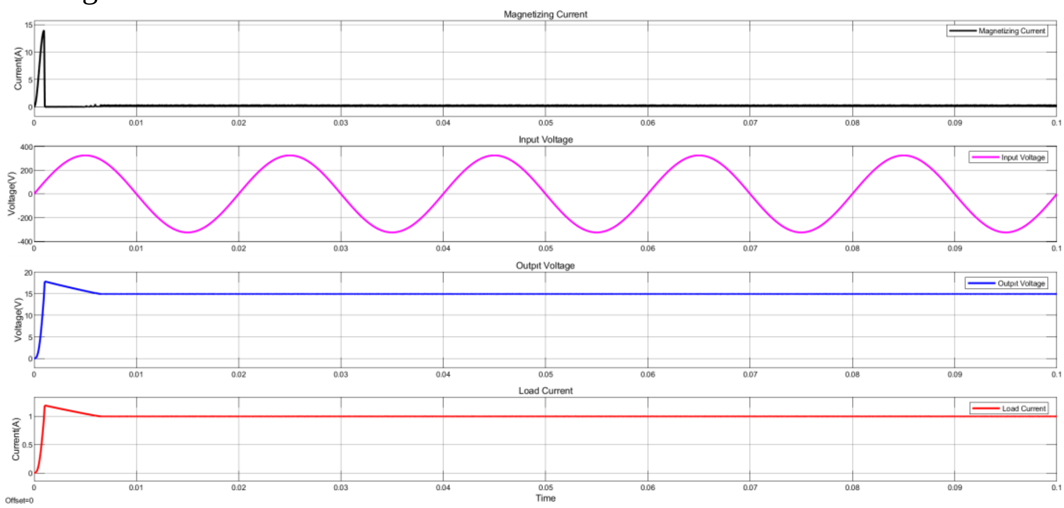

Figure 7: Magnetizing and Output Current waveforms as well as Input and Output Voltages

As shown in Figure 7, the desired voltage and current values are reached. In initial time period, there seems a peaky increase in magnetizing current but it is directly eliminated. Hence, proper operation is proved by simulation results.

	Input Power (W)	Output Power (W)	Efficiency (%)
%100	21.12	14.98	71
%75	17.6	11.24	63
%50	12.1	7.48	60
%25	8.3	3.74	45

Table 2: Efficiency calculation with different load characteristics

As the load is decreased, the efficiency is decreased as shown in Table 2. The reason for that is the losses in transformer stays constant although the changes in output and input powers. Transformer losses have bigger portion in the loss calculations in that case. Therefore, efficiency is decreased with decreasing load. Also, the controller and converters are designed considering %100 load. Therefore, the efficiency is expected to be lower than designed circuit with different load characteristics.

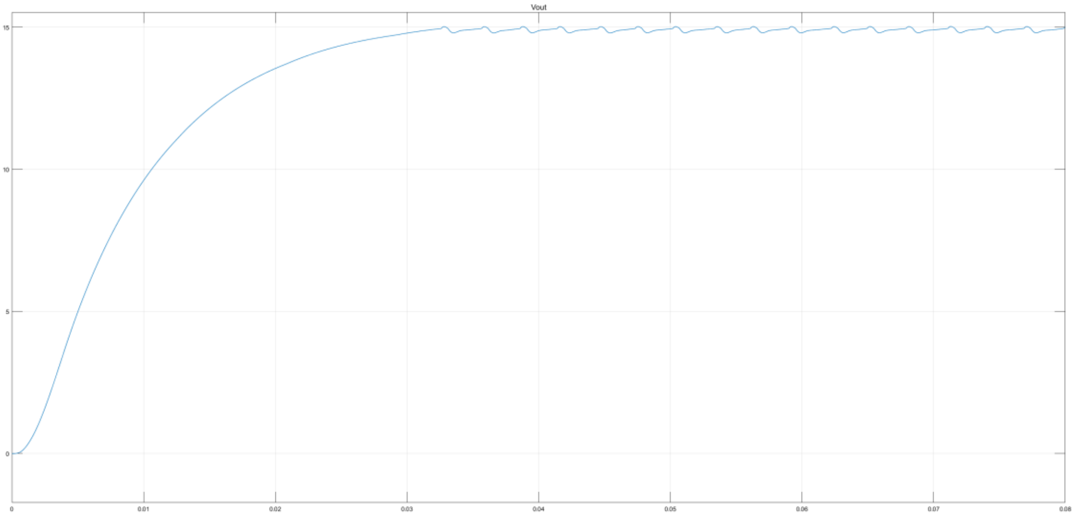

Figure 8: Output waveform with input voltage 210 Vac

%1.3 ripple at 210 Vac is observed in the output voltage waveform which is a reasonable value with desired ripple value less than 5%.

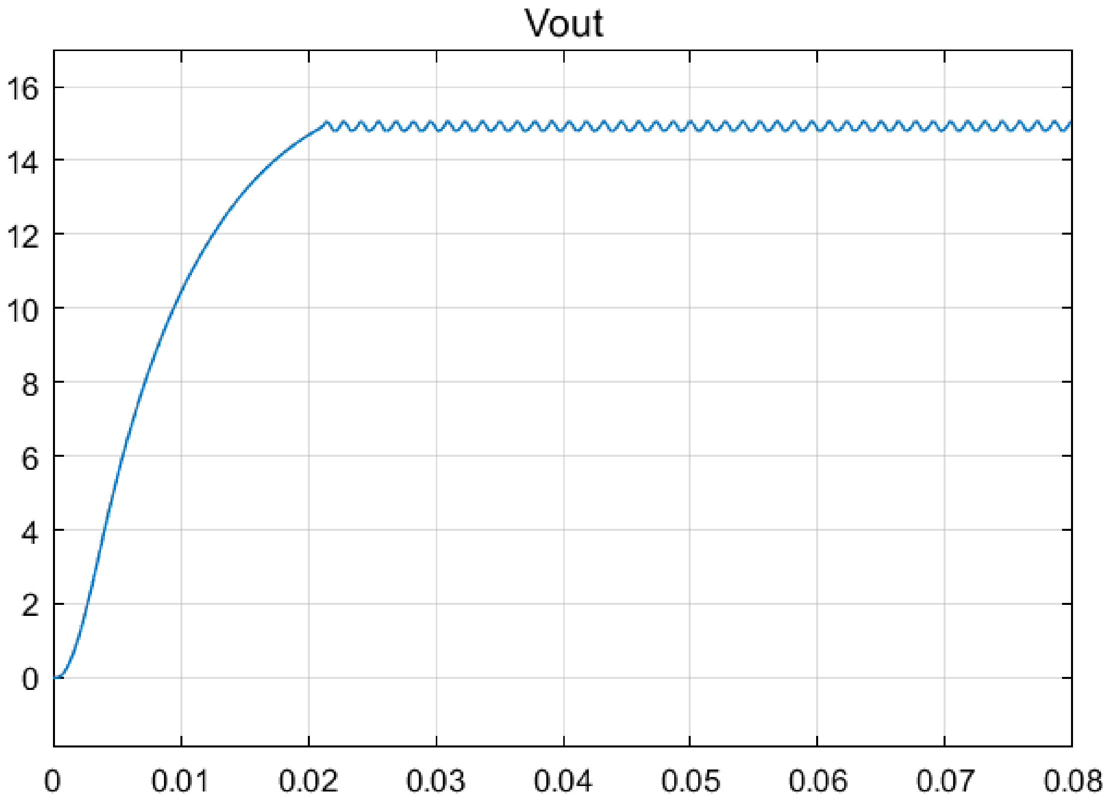

Figure 9: Output waveform with input voltage 230 Vac

%1.6 ripple at 230 Vac is observed in the output voltage waveform which is a reasonable value with desired ripple value less than 5%. Figures 8 and 9 show that the output ripple condition is satisfied with the designed converter design.

1.4. Component Selection

1.4.1. Transformer

At first we have chosen a core with a bigger transformer area. However, using AWG22 cables, we can reduce the size of transformer which is good for design and implementation. Thus, the final core is chosen as '0P43517EC'. It has Kool Mu core and the area of core is 233mm^2. The properties meet our specifications and requirements.

1.4.2. Capacitor

Three capacitors are required. One of them is placed after the single phase rectifier to make input voltage of Flyback small ripple. Input ripple of Flyback affects output voltage level in open loop control with constant duty cycle. However, our system is controlled by a PI controller and it is not an obligation to create purely DC. In steady-state operation and calculation part, DC link capacitor is chosen electrolytic 33µF and 450V.

Second capacitor is used for filtering output voltage. Output voltage is actually square wave and it should be filtered by capacitance. Duty cycle cannot exceed 40 percent and output voltage cannot exceed 25V. Thus, we chose Electrolytic 470µF and 25 V capacitor.

Final Capacitor is snubber capacitor. Snubber capacitor is used for storing energy from stray inductance at switch is off and it dissipates this energy on parallel resistance at switch is on. The voltage is on capacitor is mirror of output from transformer. Also, loss is minimized by increasing resistance and decreasing capacitance. Capacitor is chosen as 100pF and 1000V.

Product Number	**Product Feature**
SD2W336M16025PA	33uF and 450 V
PKR1-025V471MF120-T/A5.0	470uF and 25V
TMCC02-101K1000VP5A	100 pF and 1000V

1.4.3. Diode

Two diodes are used. First one is used for RCD snubber. For RCD snubber, diode keeps the DC link voltage at reverse conduction. Meanwhile, capacitor starts to charge when the switch is off. Thus, at least 400V reverse breakdown is required. Also, out system is switching at 40 kHz and reverse recovery of diode must be faster than this value to hold reverse voltages while switching periods. Thus, it is required to use ultra-fast diode. Second diode is placed on output side. Its reverse voltages are smaller because it is in output, low voltage, side. However, it is required to have fast recovery time to not led current pass at switch is on. It is chosen same as RCD snubber diode.

Product Number	**Product Feature**
DHG5I600PM	600V, 5A and trr= 35ns

1.4.4. MOSFET

Mosfet is used as switch at Flyback converter. Our switch is placed negative side of supply. Thus, we decide a Mosfet which is normally in turn-off position. Also, source is common ground for main circuit, the gate driver can be used as non-isolated with input. Our mosfet current is small thanks to our design specification. Thus, we chose a mosfet which has the required reverse voltage for a sustainable operation. Our maximum reverse voltage is calculated as 540 V. We make overdesign and we choose 900V, 3A mosfet.

Product Number	**Product Feature**
3N90	3A, 900V, N-CHANNEL

1.4.5. Rectifier Bridge

Input of our project is AC from grid. We chose single phase bridge rectifier. Our current rating is smaller thanks to design specification. We have chosen 8A, 600 V standard diode bridge rectifier.

Product Number	**Product Feature**
GBU8J_B0_10001	8A, 600V

2. Test Results

At this part, implementation and results of isolated power supply are discussed. Differences between simulation and real-time application are argued and optimization of parameters will be explained.

We tested our design one by one. Finally, we tested overall design. The results are obtained with the final product.

2.1. Overall Design

Our current specification is suitable to try our design at breadboard. First of all, we established our design at breadboard. We tested overall, we printed a PCB after that.

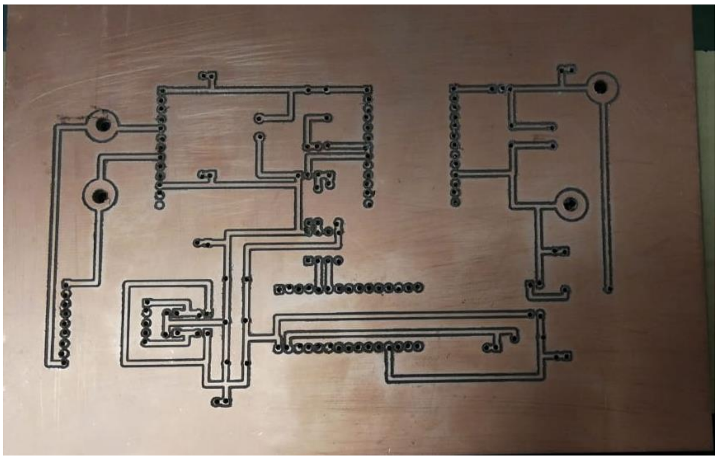

Figure 10: Printed Circuit Board

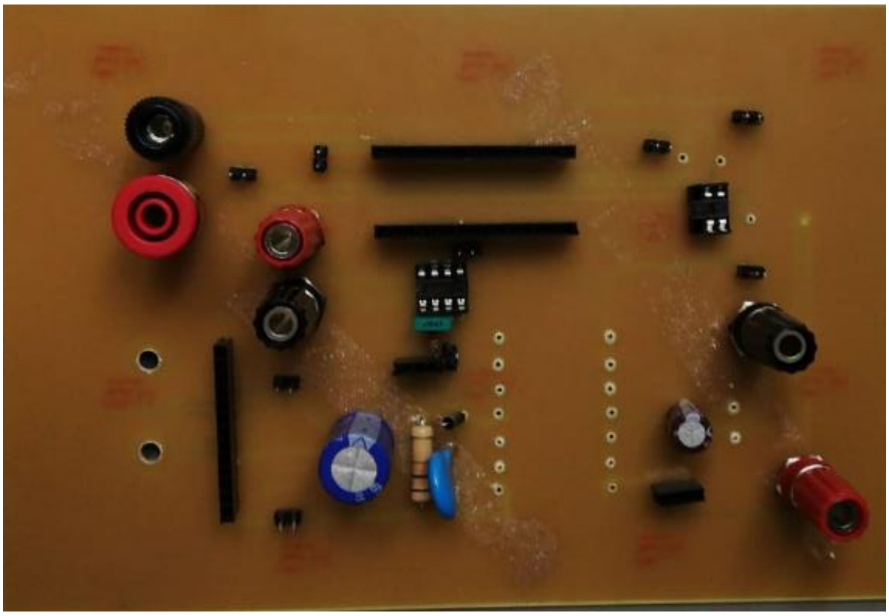

Figure 11: Soldered PCB

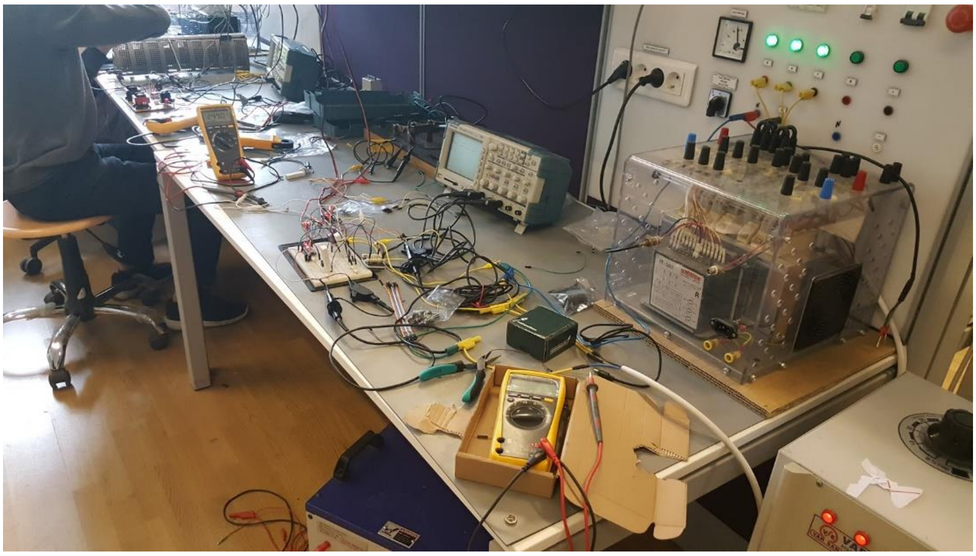

Figure 12: Breadboard Test Environment

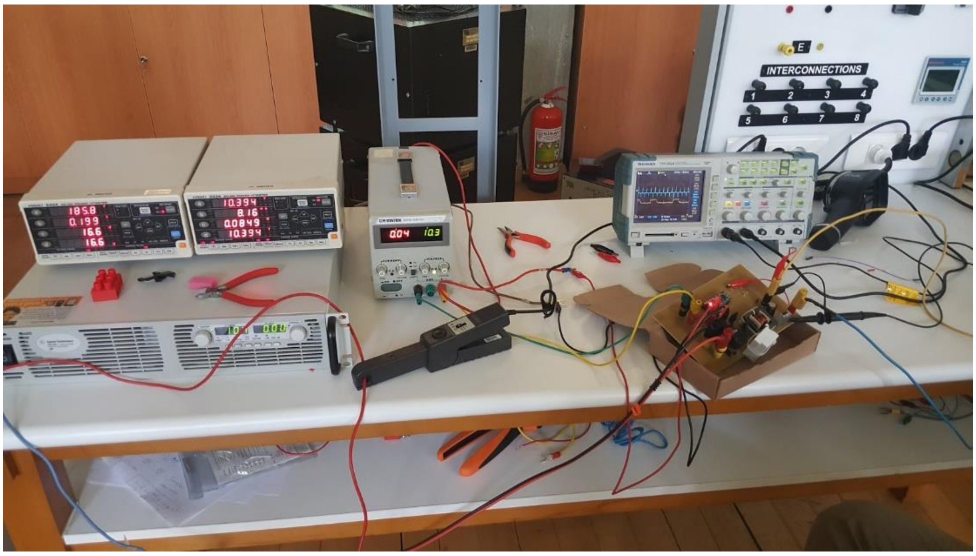

Figure 13: PCB Demo Environment

2.2. Transformer Results

We calculated transformer turns ratio as 13.88 and minimum turns ratio of primary side is 129 to obtain required voltages at transformer. We chose transformer turns as primary 129 and secondary by 8. By using signal generator, we measured real turn ratio. In order to keep the turns ratio at 13.88, we increased the secondary side turns. At this point, we did not control magnetizing inductance and we did not try to change magnetizing inductance by changing turns.

Figure 14: Flyback Transformer

2.3. RLC Measurement

For transformer design, magnetizing inductance is important because the main energy transferring element is magnetizing inductance for flyback converter. We want our magnetizing inductance is 10mH and resistance of secondary side resistance of transformer is as small as possible to reduce power loss. In addition, we want to reduce leakage as possible to increase the overall efficiency of the system.

We used RLC meter at 40kHz operation which is our operation frequency.

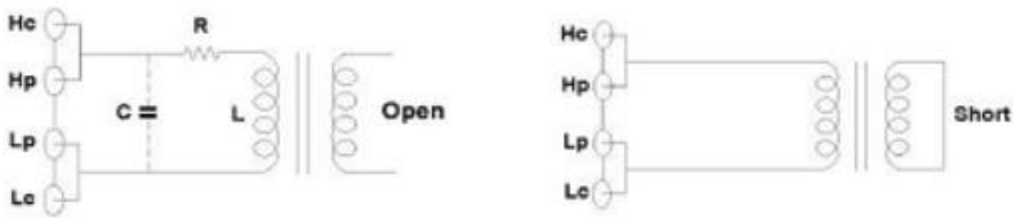

Figure 15 Measurement Setup

We measured magnetizing inductance, leakage and resistance by using RLC meter whose setup is shown in Figure 15.

Magnetizing inductance was measured by using open circuited schematic and leakage inductance and resistance was measured by short circuited schematic.

Magnetizing inductance is 3 times more than expected, which is possibly due to operating flux assumption. To reduce magnetizing inductance, we used a gap in transformer. This gap is adjusted by paper and this required paper is found by trial and error. Also, we reduced resistance of secondary side by increasing copper area.

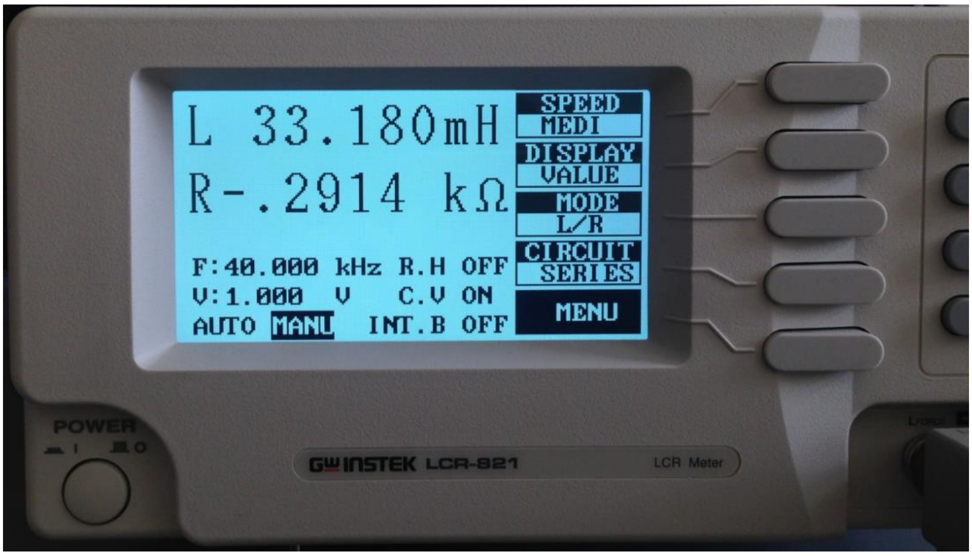

Figure 16: Magnetizing Inductance Measurement at 40kHz

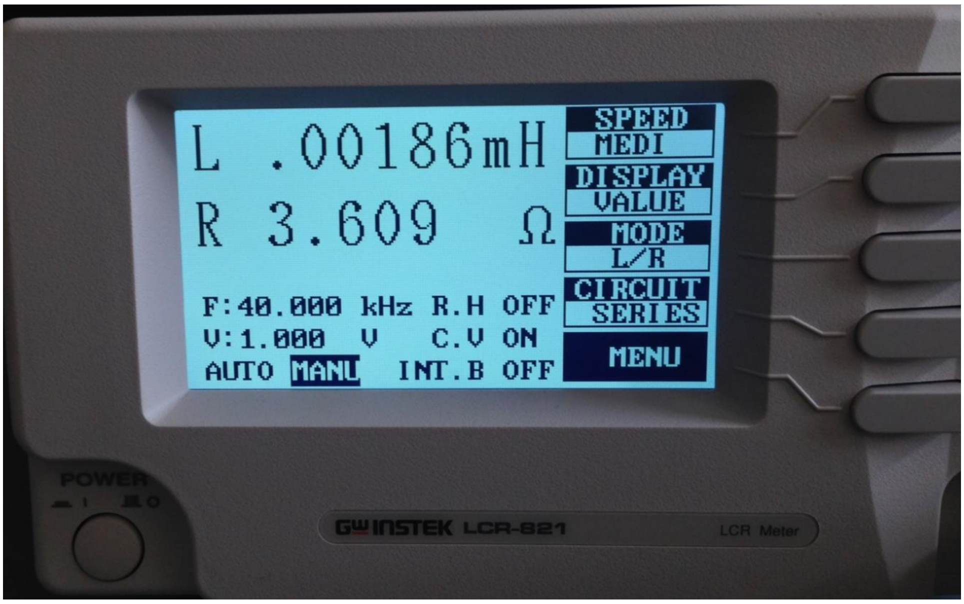

Figure 17: Leakage Inductance Measurement at 40kHz

Magnetizing Inductance	Leakage Inductance	Secondary Side Resistance
8.85mH	49.43 uH	1.2 ohm

2.4. Output Voltage and Current

Our output voltage is controlled by closed loop. We tested our output voltage at different loads. At light loads, duty cycle is reduced to keep constant voltage at the output. Increasing power of load, duty cycle is increased to keep voltage constant and it results in more ripples at output voltage. However, mean of output voltage is constant between 14.8-15.1 V independent of load type.

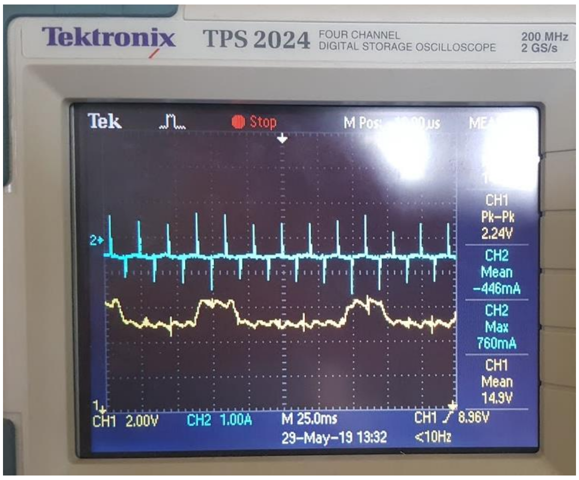

Figure 18: Current and Voltage Waveform of Output

Full Load	75 % Load	25 % Load
14.8 V	15 V	15.1 V
0.98 A	0.75 A	0.251 A

2.5. Controller

We have implemented a digital controller using Arduino Nano by taking voltage feedback from output. A P type controller is implemented to keep output voltage constant. The value optimized for P controller is 0.005. Thus, controller does not response too fast while switching actions and it catches the change in load side from behind. A PI controller can be implemented to eliminate the steady-state error in output.

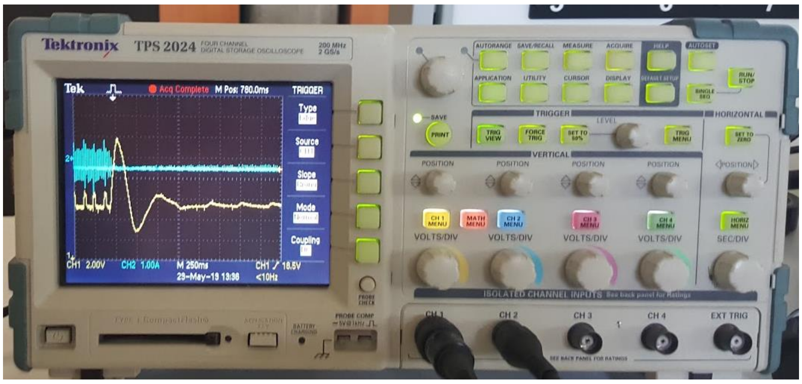

Figure 19: Controller Response of Changing Load

2.6. Switching Performance

Switching frequency is 40kHz and mosfet is driven by TLP250, Opto-coupler with gate driver. We used 40ohm gate resistance, it is enough for 40kHz switching with respect to data sheet of Mosfet.

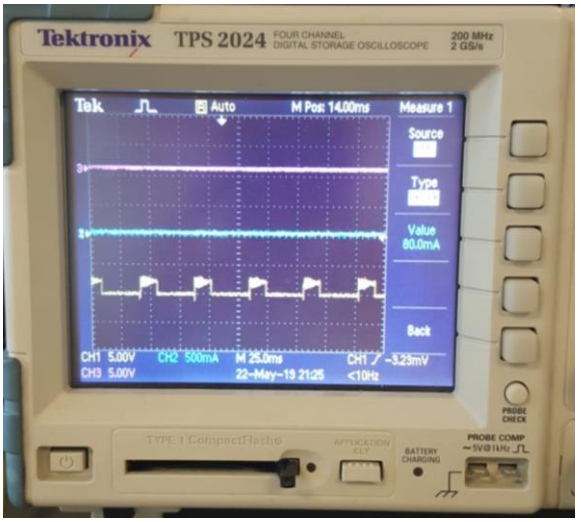

Figure 20: Gate-Source Voltage with Duty Cycle

2.7. Efficiency

Our specification is suitable for high efficiency converter topology thanks to small current values both in output and input. The main loss components are the loss in secondary side resistance and voltage drop at diodes. Other components' loss and transformer core loss is very small; it can be ignored.

Output Power	Secondary Side Resistance Power Loss	Output Diode Power Loss	Total Measured Efficiency	Other Power Losses
15 W	1.2 W	1.41 W	84 %	0.24W

Conclusion

In this project, isolated single output Flyback Converter is designed and implemented in hardware. Input of converter is 210-230V AC supply and it is expected to have output voltage as 15 Volt with rated 15 W power. The project includes some parts which is rectifier circuit, transformer design and wrapping, semiconductor device implementation with driver and controller.

Firstly, rectifier circuit is chosen as single phase bridge rectifier. For this part, we observed that DC link capacitance is important to keep DC voltage as constant at changing load current.

Secondly, we observed that lower magnetizing inductance of transformer is required in order to implement Flyback converter which is not the case with other converter topologies which does not require storing and transferring energy principle. Also, we understood that wrapping style affects the turn ratio, copper loss and core loss of transformer. The transformer diverges from ideality if wrapping is bad.

Thirdly, we observed that semiconductor device is not selected only voltage and current ratings. Operation frequency and speed of semiconductor must be considered in order to implement semiconductor devices in converter.

Finally, we understood that closed loop controller is required if we want regulated output. Also, we observe that PI controller with suitable constant is enough to obtain regulated and fast response output.

Appendix

```
%%
clear all;
clc;
%% Flyback Parameters
V_line_minimum= 210; % V rms
V_line_max=230 ; % Vrms
V_dc_min= 280; % 5 percentage ripple
V_dc_max=sqrt(2)*V_line_max;
Output_power= 15; % Watt
Efficiency= 0.8 ; % between 0-1
Input_power= Output_power/Efficiency;

%% DC Link Capacitor Calculation
D_ch=0.2; % for capacitor charging duty
F_line= 50; % Line frequency

C_DC = (Input_power*(1-D_ch))/ ...
    (F_line*((2*V_line_minimum^2)-V_dc_min^2));

fprintf(' %f microFarad \n',C_DC*1e6);


%% Determination of Maximum Duty Cycle
D_max= 0.45 ; % for CCM mode, it is bigger than 0.5
V_Ro= (D_max/(1-D_max))*V_dc_min;
V_ds= V_dc_max+V_Ro;

%% Lm Determination
f_s= 40000; % Switching Frequecny Hertz
K_f= 1; % for ccm 0.25-0.50
L_m= (( V_dc_min*D_max)^2)/(2*Input_power*f_s*K_f)...
   *1e3; % mili Henry
fprintf('% f mH \n', L_m);
L_m=L_m*1e-3;

%% Calculation of peak current of FSP( mosfet, IGBT)
I_edc= Input_power/(V_dc_min*D_max); % average ...
... switching amplifier
Delta_Ids= (V_dc_min*D_max)/(L_m*f_s);
Ids_Peak=I_edc+(Delta_Ids/2);
Ids_rms=sqrt((3*I_edc^2) + ((Delta_Ids/2)^2*D_max/2));
fprintf('%f %f \n',Ids_Peak,Ids_rms);

%% Primary Side Turns Determination
Ae=233*1e-6; % m^2
B_sat=0.3 ; %Tesla
N_p= ((L_m*Ids_Peak)/(B_sat*Ae));
fprintf('%f \n', N_p);

%% Secondary Side Turn Ratio

N_s= N_p/((V_Ro)/(15+0.7));
fprintf('%f \n', N_s);
```