Middle East Technical University
Electrical and Electronics Engineering
EE464 STATIC POWER CONVERSION II

"Hardware Project Final Report: FLY#5"

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I) Introduction

In this project, our aim was to design and implement an isolated DC supply topology called "Flyback". For this purpose we were supplied with some requirements that are listed below and also the overall design schematic is available in Figure 1:

FLY#5:

Minimum input voltage: 24V

Maximum input voltage: 48V

Output voltage: 12V

Output power: 70W

Output voltage ripple: 4%

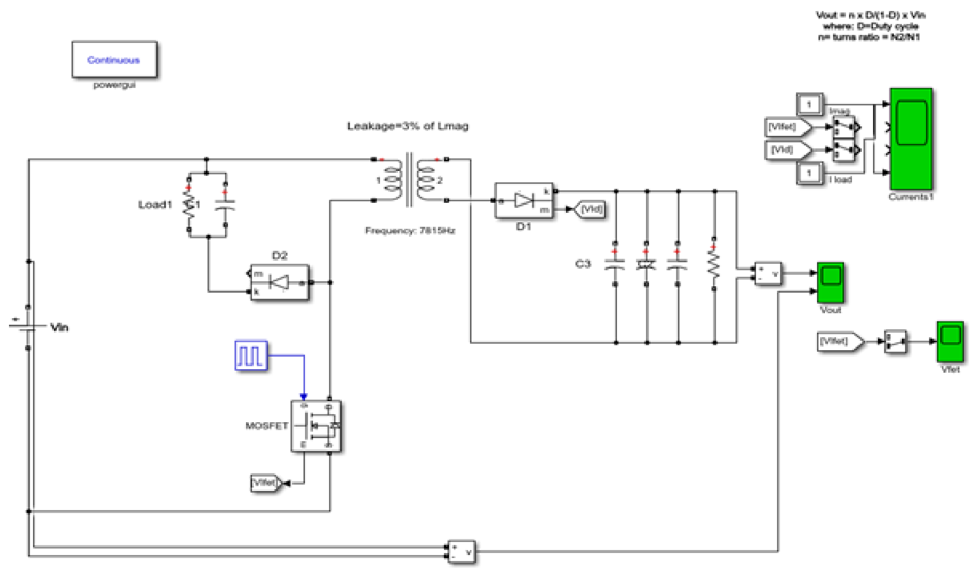

Figure 1- Overall design schematic of the Flyback converter topology

The project is implemented after a couple of simulations to see if our system works well,i.e. obeys them specifications, with chosen components. Meanwhile, there were a number of challenges related to design and implementation process that are; operating with an efficiency at least 70%, building a system having high-power-density, applying closed loop without distorting the isolation, operating soft-switching, obeying line and load regulation limits, obtaining a reasonable output voltage limitation and operating the system for at least two minutes while rated load connected.

In the rest of this report, design strategy is going to be evaluated by giving the main criteria while choosing necessary equipments. Afterwards, simulation and test results are going to be given and also the compliance between them is going to be investigated. Finally, a concluding part is going to be the last section of the report except from appendices and references.

II) Design Strategy

Before interfering to design stage, we have accepted that the most critical part in this project is the magnetic design. Hence, we prefered to follow a design guide for the Flyback Converter transformer design which is available for a similar power rating and leads us to design our topology step by step approach. Note that, obtaining the values of some parameters by using this tool depend on the values which should be obtained by simulation results. That is, for example, finding Magnetizing Inductance (Lm) depends on the peak value of the current of the transformer which is obtained by simulation results.

While utilizing this guide, we wrote a MATLAB in order not to deal with repetitive calculations by hand. Related script is as follows which is written for ON Semiconductor Guide:

```
Turns=3/2;
%calculated from avg input voltage divided by output voltage
Vo=12;
Vin_min=24;
Vin_max=48;
Eff=0.90;
%efficiency
fs=10^5; %frequency
Po_max=72;
Pin_max=Po_max/Eff;
Vo_reflected=Turns*Vo;
Io_max=6;
%%
Dav=0.5;%purpose is Dav=0.5
Dmin=Vo_reflected/(Vin_max+Vo_reflected);
Dmax=Vo_reflected/(Vin_min+Vo_reflected);
%%
Krf=1; %for DCM
Lm=(Vin_min*Dmax)^2/(2*Pin_max*fs*Krf);%primary inductance

Iin=Pin_max/(Vin_min*Dmax);
I_ripple=Vin_min*Dmax/(Lm*fs);
I_lm_peak=Iin+I_ripple/2;
%rms hesab?na gerek var m?
%%
Vo_ripple=0.04*12;
C_out=Io_max*Dmax/(fs*Vo_ripple);
```

Figure 2- Matlab Script written for ON Semiconductor Guide

In this guide, we focused on the fact that our transformer should be in the Discontinuous Conduction Mode (DCM). That is, duty cycle should be smaller than 0.5. The reason of this is that in Continuous Conduction Mode (CCM), there is always some current on the transformer which is not desired since it may saturate the transformer core.

Then by assuming DCM, we adjusted some other parameters such that turns ratio. Firstly, we select the turns ratio to be 3. However, the resulting duty cycle for some input voltages is obtained as greater than 0.5 which is not dessired. Therefore, we adjusted turns ratio to be 3/2.

After some additional steps, we found the necessary parameters to make our transformer design such as magnetizing inductance (Lm), output capacitor, turns ratio etc.

Then, in this step, we did some simulations in the Simulink to confirm the correctness of the above calculations which is further explained in “simulation results” part of the report. To summarize, we observed that almost in all conditions, a little CCM happens only for 24V input, our transformer stays in the Discontinuous Conduction Mode (DCM).

Afterwards, we continued with transformer design and searched for some cores and we found the most suitable core as 00K4022E90 for our specs and expectations such as high permeability and high A_L values. However, this core was not available in the lab anymore since it was broken by some groups. Therefore, we could not use them. Then, we researched for another one and found 00K6527E060, however it was too large in size and the window area was too much hence yielding a large leakage inductance value such that Lm was 24 µH as we wanted, but leakage inductance was measured as 8 µH which is not okay. Nevertheless, conducted some test with this core and observed the efficiency as 10% due to the high leakage inductance. Thus, we found a new core that is 0P43434EC whose relative permeability is 2400 nH and smaller in size than the previous core. Then, we measured the Magnetizing Inductance (Lm) as 120 µH when 4/6 turns is applied. Therefore, we put some air gap to obtain required Magnetizing Inductance (Lm) whose value is about 24 µH. In addition, leakage inductance was measured as 0.8 µH (10 times smaller than the previous core). After placing the transformer into our configuration, we observed the efficiency as 75% in average.

Completing the transformer design, we started to pick our additional components. Let us continue with snubber circuitry. An RCD snubber is placed between the primary side of transformer and the source side of the MOSFET. In this configuration we prefered to use 3 series sand-stone resistances, 1 large capacitor and a Schottky diode which has further explained in the component selection part.

Moreover, we placed an input capacitor just before the transformer primary to get rid of the inductance effect of the input cables.

In order to apply soft start, we used a digital controller (Arduino) by starting the duty from a non-zero value (20%) and increasing the PWM percentage slowly. Also for load regulation concerns, we needed to have a closed loop control by taking the feedback from the output using parallel branch of the load by utilizing 1/4 resistive voltage divider and supplying it to controller input. Noting that, one of the main advantage of the Flyback Converter is the isolation between input and output, we placed an isolating device i.e. TLP250 between Arduino and gate of the MOSFET in order not to distort isolation between primary and secondary.

Finally, we placed our fast switching diode on the secondary and also connected a couple of output capacitors to decrease output voltage ripples which terminates the design procedure.

III) Simulation Results

Simulations constitute great importance in terms of making trail and errors that would be useful while choosing our components and to see if the designed topology gives the expected results. For this purpose, we have conducted mainly two simulations corresponding to Vin=24V and Vin=48V cases to see the differences among and guarantee the sizes of the components are suitable for both extremities. Note that, in order to obtain more realistic results, we have also entered the loss components in used equipments i.e. non-ideaities.

a)V_{in}= 24V

This input voltage level is the minimum required level of the input as asked in the description of the project. As it is the lowest value, the duty cycle has its higher value at this configuration. Due to these configurations, the design shifts its state to continuous conduction mode. Although the calculations were done in order to keep the system in discontinuous conduction state, this shift brings a question mark in the project. However, if the system is observed in detail, it works just in the edge of the CCM operation, so the configurations in the system are applicable for the project. The detailed analysis of the system is done and the information is available in the figures below:

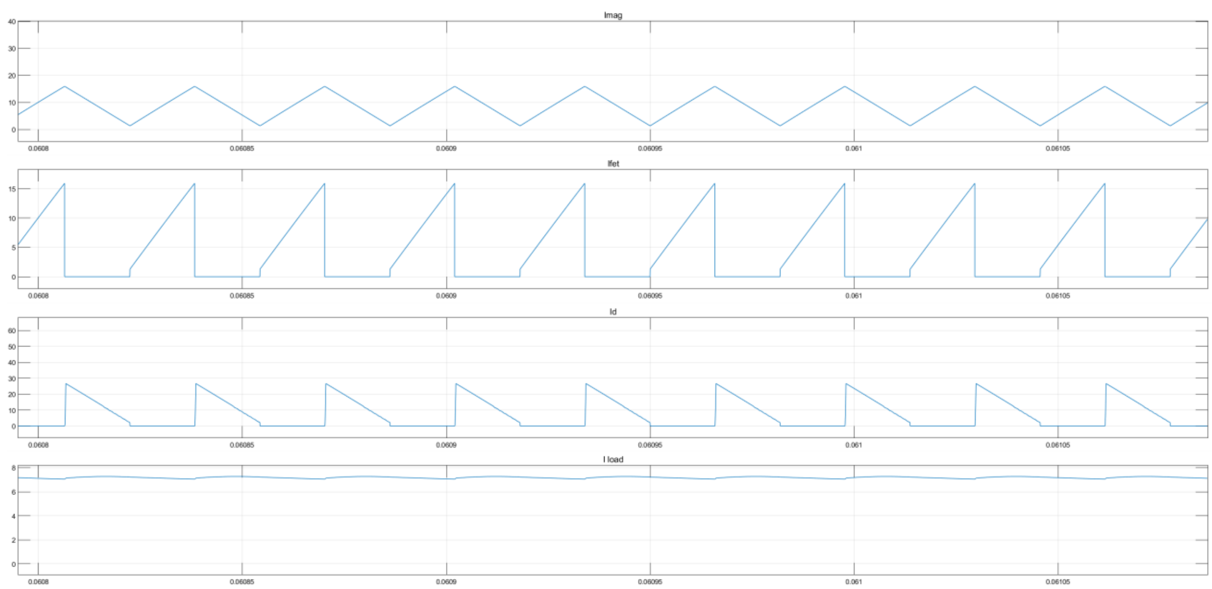

Figure 3- The current characteristics of Imag, Ifet and Id

The average and peak-to-peak values of these current are:

- I_{mag}: 8,332A average and 1,464 A p-p
- I_{fet}: 1,022A average and 15,94 A p-p
- I_d: 8,3A average and 26,66 A p-p

In order to have a reliable system, the output voltage and current waveforms are important. The average and ripple values of them can be shown in the figures below:

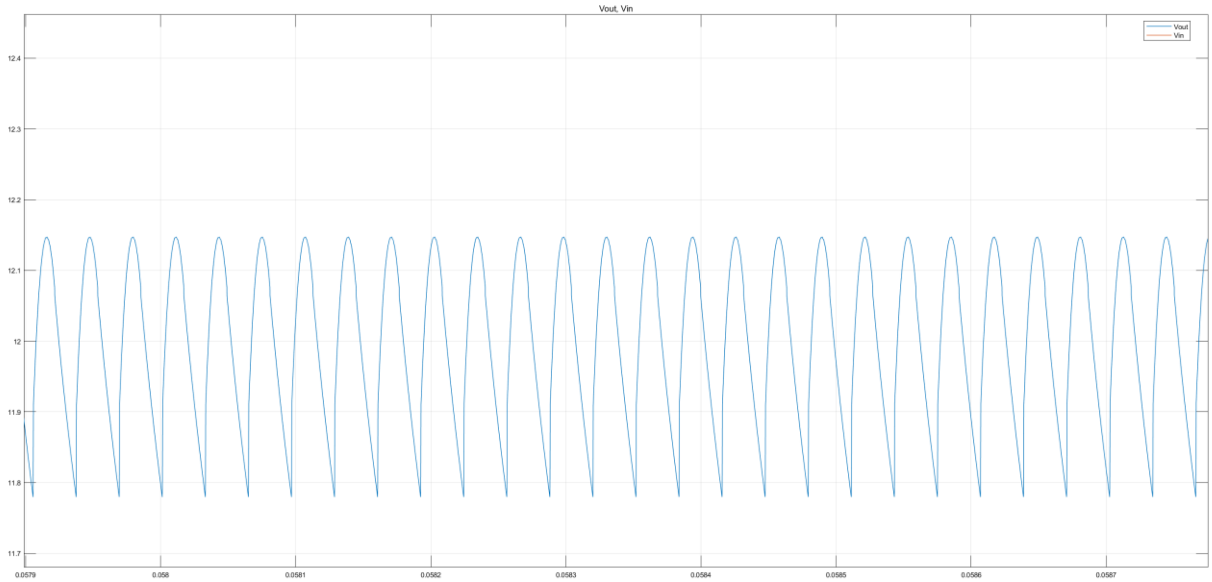

Figure 4- Output voltage waveform when the input voltage is 12V

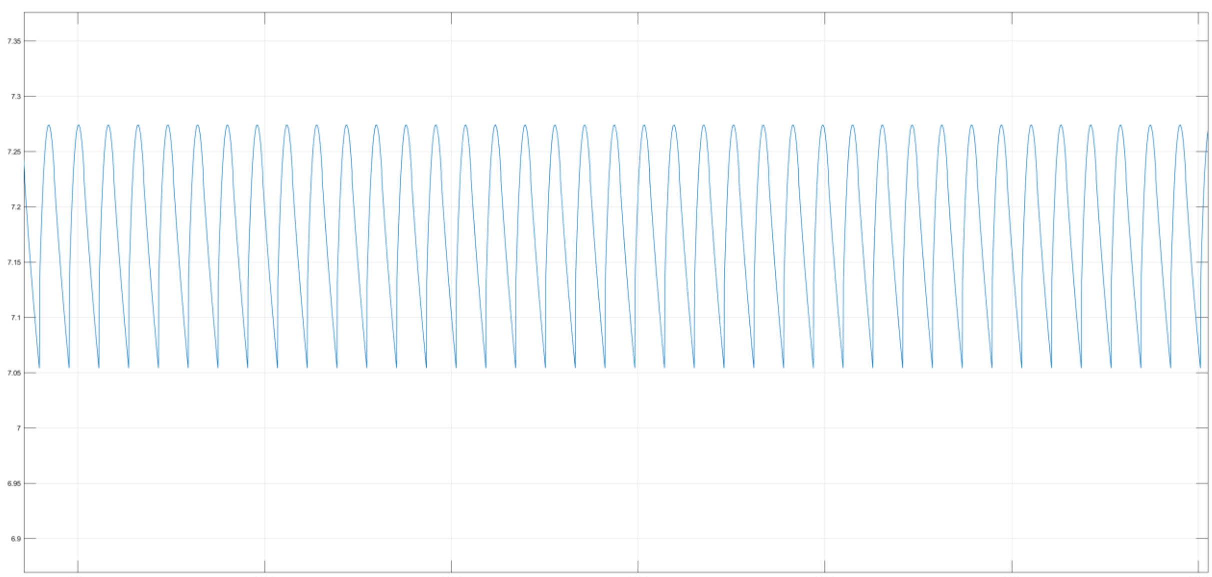

Figure 5- Output current waveform when the input voltage is 12V

As can be seen from Figure 4, average output voltage is 12,02 Volts and it has 0,3677 Volts p-p value. Hence, it has 3,05% ripple value. These values meet the requirements of the project. The ripple value can be further decreased by adding more shunt capacitors to the load side of the transformer. Secondly, the average value of the output current is 7,2 Amperes and it has 0,22 A p-p value (3,06% ripple) ,as shown in Figure 5 ,which is good enough for our purposes.

Another important criterion to be evaluated is the power calculations. In order to have an efficient system, the losses should be minimized. In the simulations, realistic resistance values (non-idealities) are used in order to have a more realistic approach. The input voltage is 12 Volts for this part and the input current waveform is in the figure below:

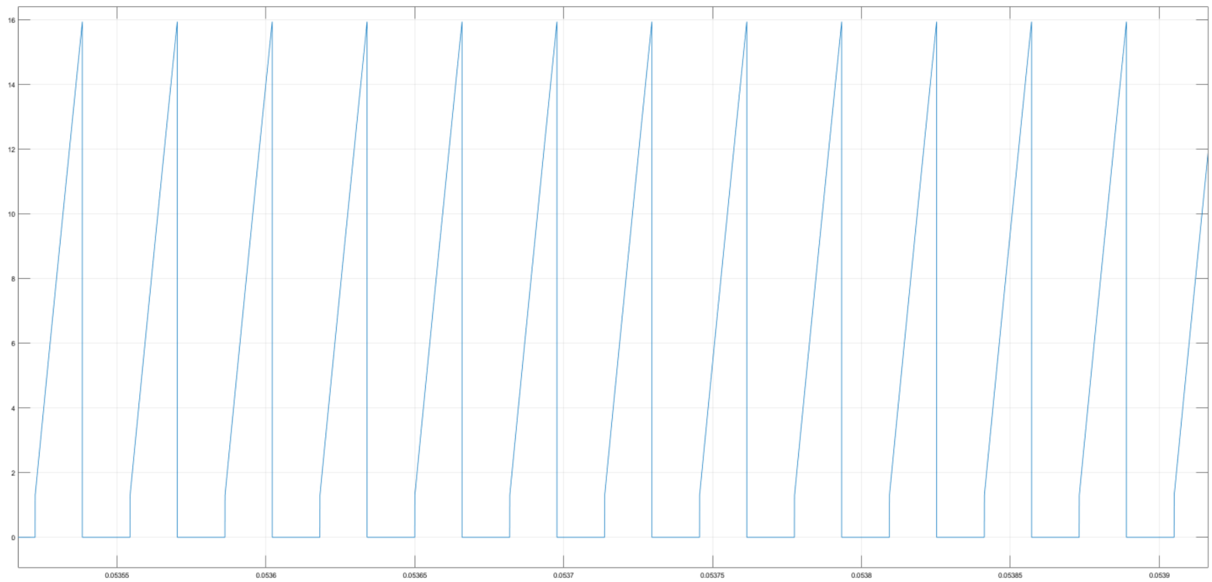

Figure 6- Input current waveform when the input voltage is 12V

The input current has 1,02 A average and 15,94 V p-p value. Then, the power measurement blocks are used in order to calculate the input and output power. The measured power values are in the figure below:

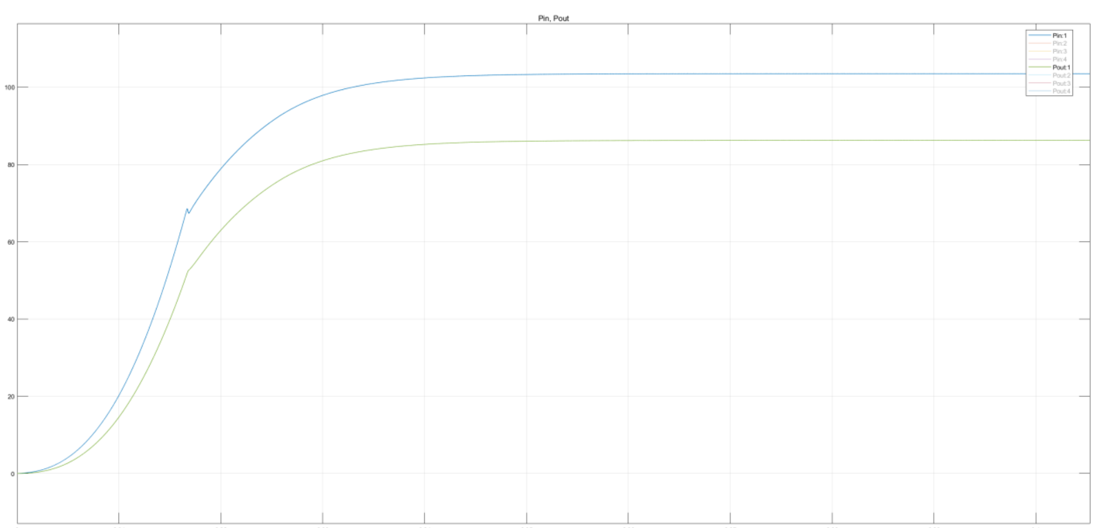

Figure 7- Input and output power waveforms

The calculated input power is 103,5W and the output power is 86,26W. The loss of the system is 17,24W. The efficiency becomes 83,3% which meets the requirement given in the project description.

Also note that, in order to choose the right component at the real design of the project, the output diode voltage and current waveforms are also observed. These waveforms can be seen in the figure below:

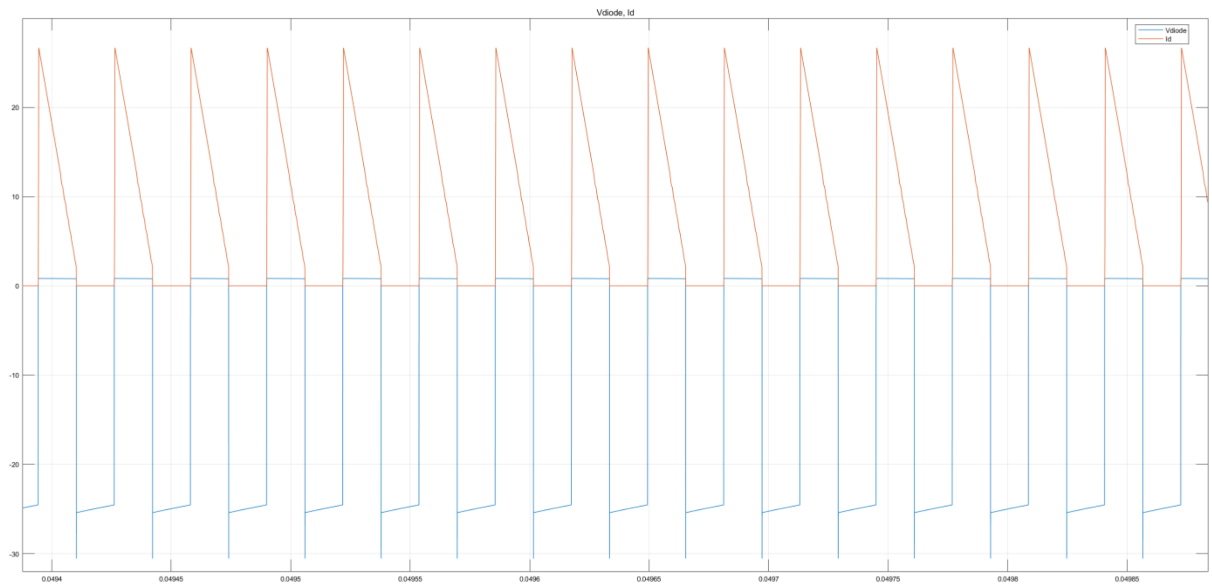

Figure 8- Output diode current and voltage waveforms

The peak value of the voltage is 30V and the peak value of the current is 26 A. These values are going to be used for component selection hence important.

The last observations are done for the snubber circuitry. This circuit have an important role in the project (discharges $L_{leakage}$), so choosing the right components becomes very critical because it should withstand the voltage and current stress on them. The current and voltage waveforms of snubber circuit are as below:

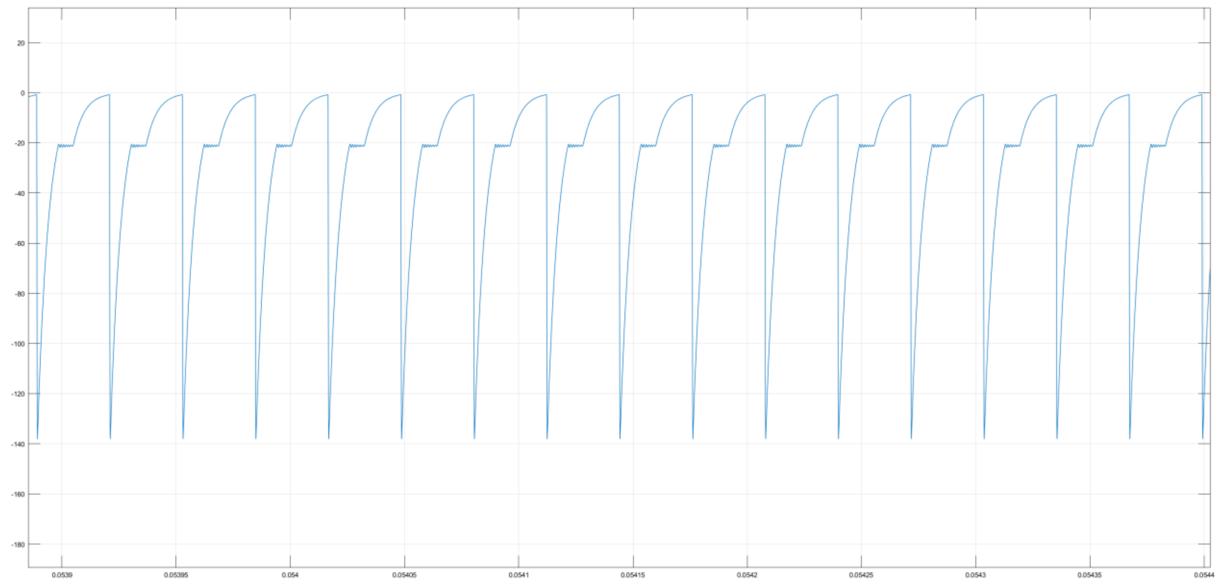

Figure 9- Snubber circuit voltage waveform

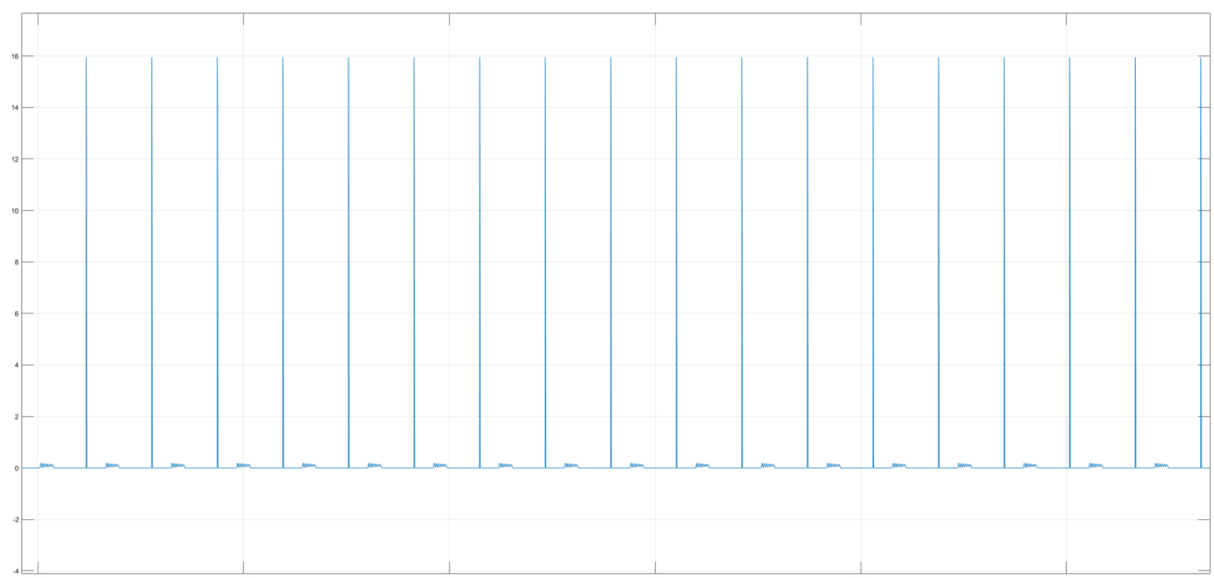

Figure 10- Snubber circuit current waveform

The voltage waveform has 197,3 V p-p value and the current waveform has 15,94 A p-p value.

b) V_{in}= 48V

48V is the maximum input voltage in the project description. The difference between this part and previous part is the duty cycle value. In order to have same voltage value at the output, the controller should work fine and adjust the duty cycle accordingly. In addition to that, with this input voltage value, the system can easily stay in the DCM mode which is desired. The same observations are done in this part.

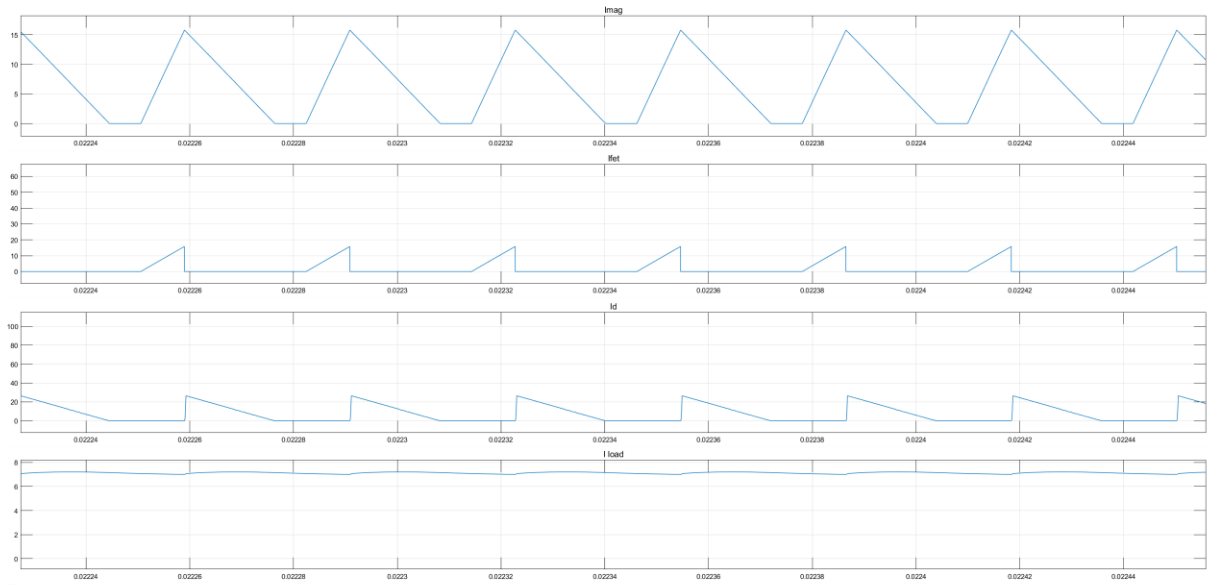

Figure 11- The current characteristics of Imag, Ifet, Id and Iout

The measured values of the currents are:

- I_{mag}: 7,133 A average and 15,78 A p-p
- I_{fet}: 0,5663 A average and 15,78 A p-p
- I_d: 5,167 A average and 2,63 A p-p
- I_{out}: 7,129 A average and 0,2188 A p-p

Then, the second observation is done to the input. The voltage waveform is as below:

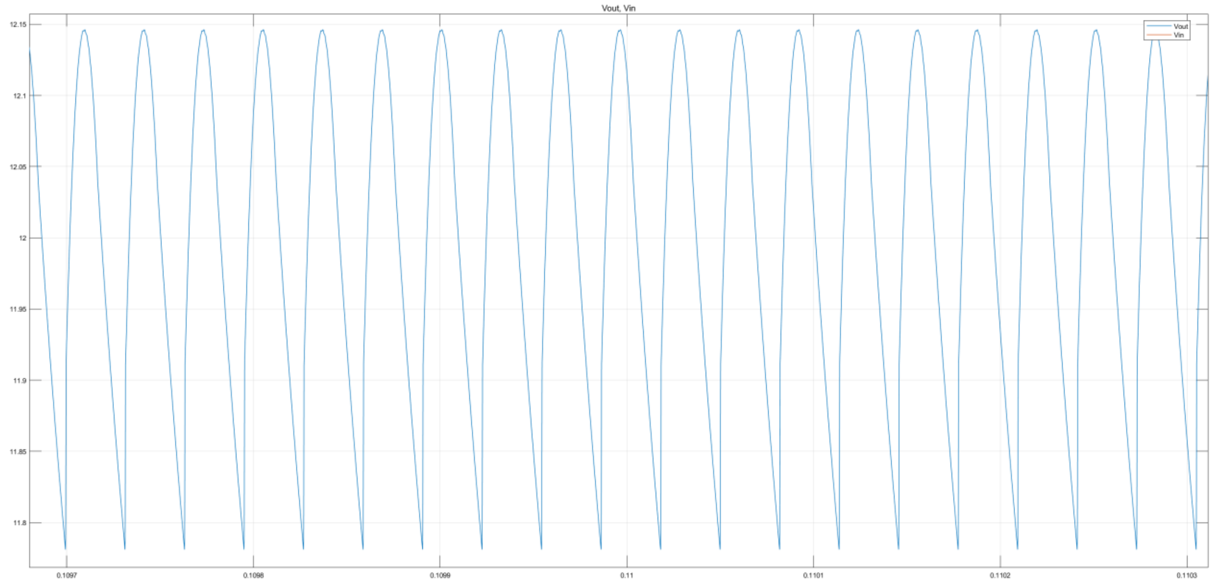

Figure 12- Output voltage waveform when the input voltage is 48V

The average value of the output voltage is 12,01V and it has 0,35V p-p value. Then the ripple becomes 2,91%.Secondly, the output current ripple value is 3,047% as can be seen above.

Next step is the comparing the input and output powers. Again, firstly the input current waveforms is observed and the waveforms is as below.

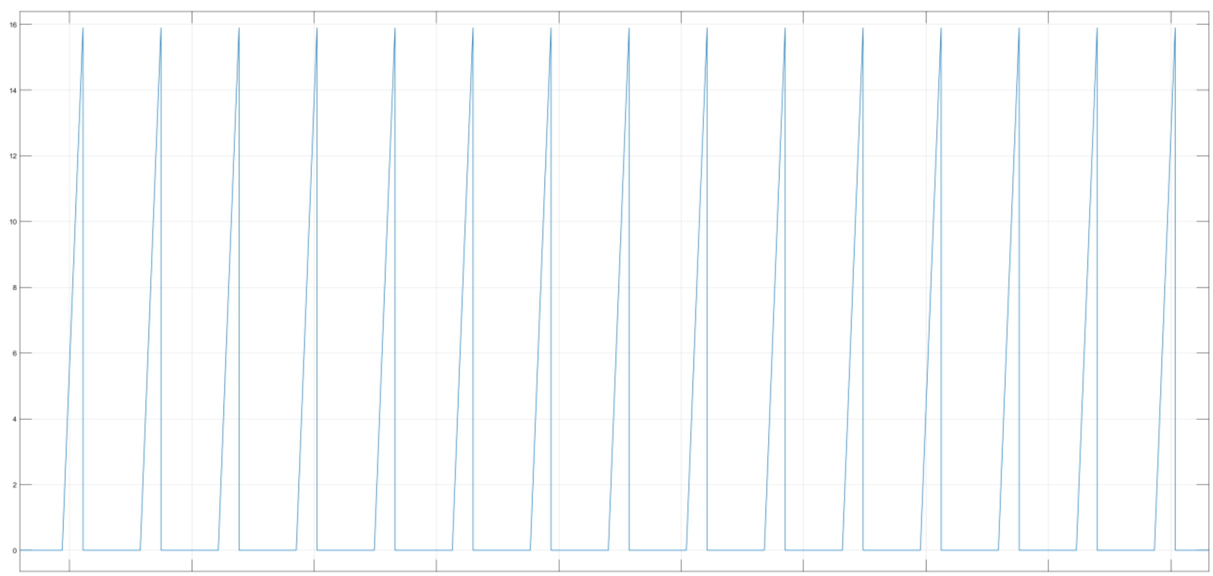

Figure 13- The input current waveform when the input voltage is 48V

The input current has 0,557A average and 15,9A p-p value. Then, the values for P_{in} and P_{out} can be obtained and corresponding waveforms are in the figure below:

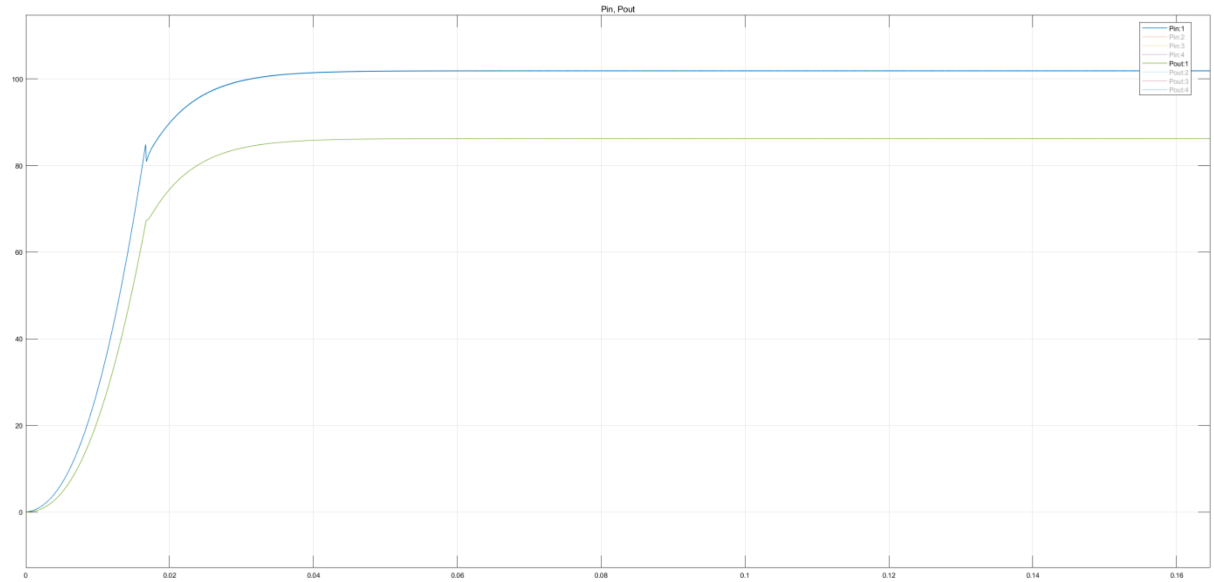

Figure 14- Input and output power waveforms when the input voltage is 48V

The measured input power is 101,9W and the output power is 86,23W. The power loss of the system is 15,67W. The efficiency becomes 84,62%. This value is higher than the previous value.

The last step is looking at the snubber circuit. The waveforms of the voltage and current are as below:

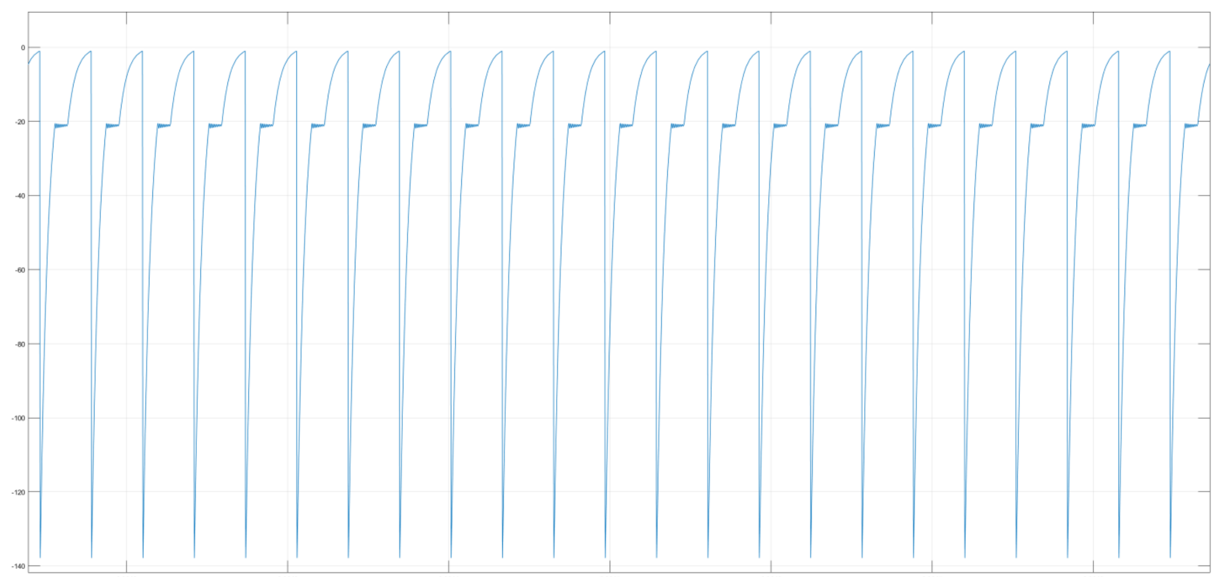

Figure 15- Snubber voltage waveform

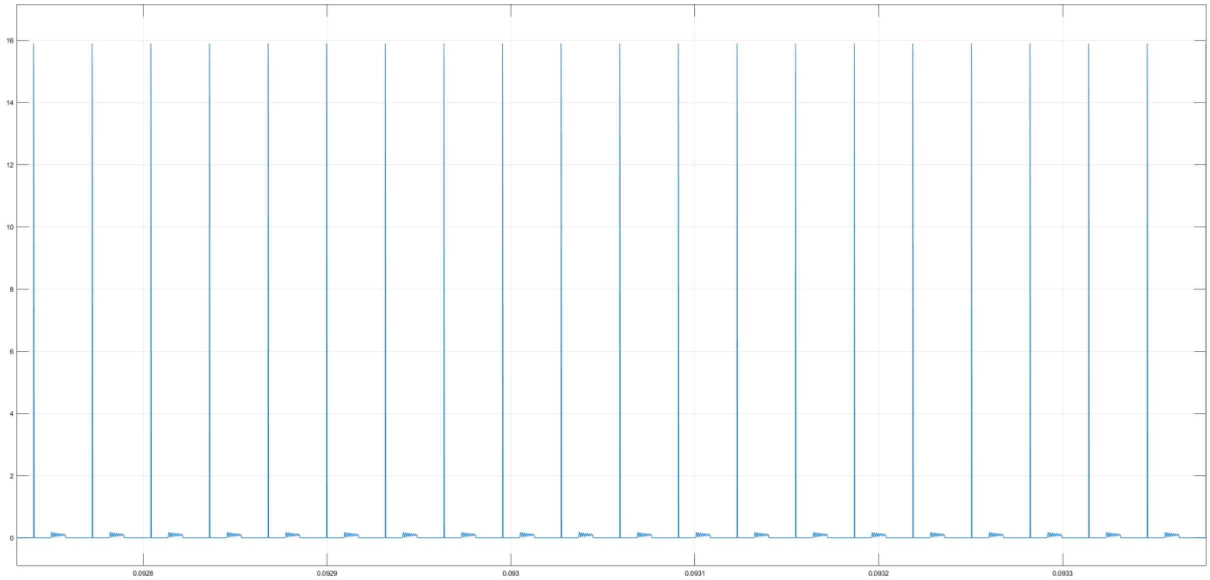

Figure 16- Snubber current waveform

The snubber circuitry has 136,8V p-p value and 15,9 A p-p value. By comparing these data with the previous ones, the component selection part will be done later in this project.

IV) Component Selection

While choosing the sizes and features of our components, we have taken the help of Simulink with commercially available values for resistors, capacitors, diodes and MOSFET also by adding their non-idealities in the software . After making sure that the topology is able to work flawless with the chosen equipments, we ordered them by taking into account the safety margins hence reasonably larger ones are prefered in order not to design a system that is in the limits i.e. thermal problems, voltage and current ratings, wattages, non-idealities are all considered. Before giving the properties of the chosen components one by one, it is better to show them together in Figure 17.

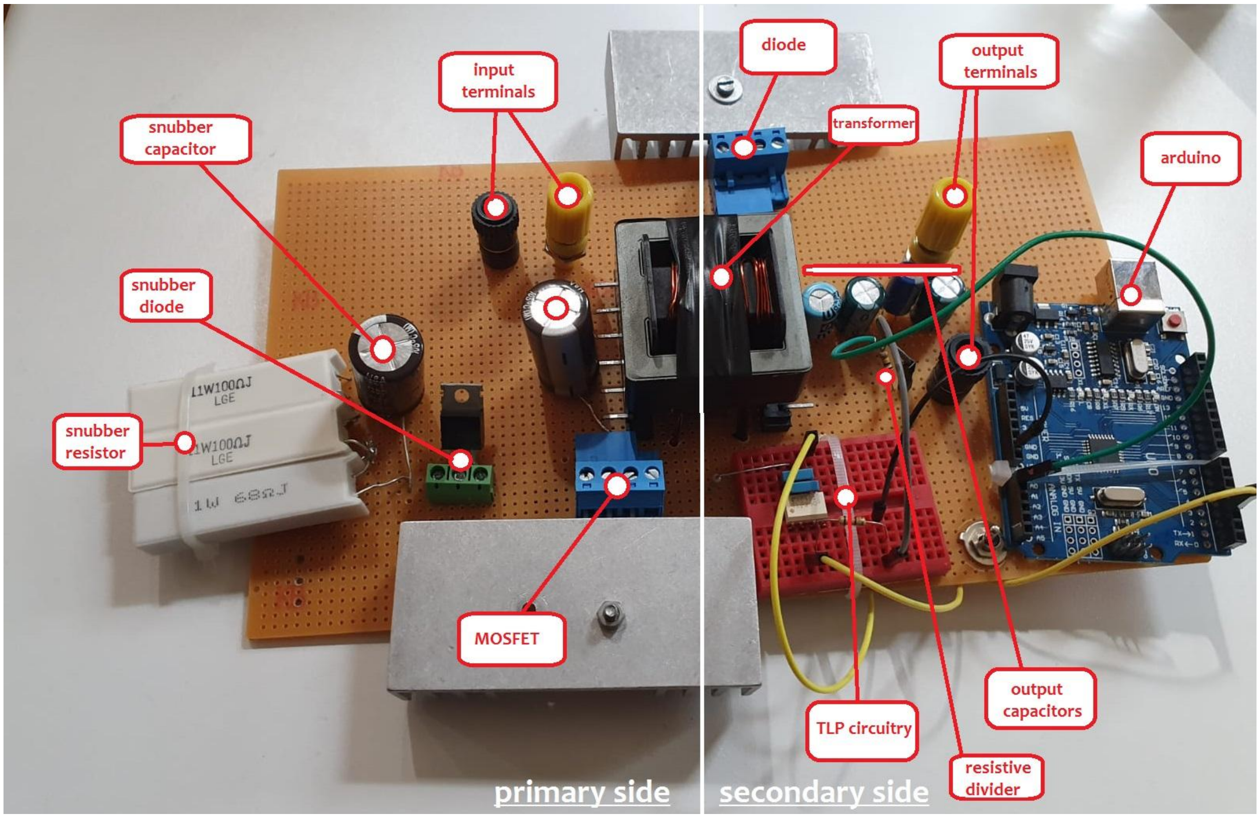

Figure 17- Overview of the designed Flyback topology with components labeled on

Chosen Equipments:

MOSFET:

IRFP250NPBF, 30A, 200V, n-channel, TO247-3 package

Considering that the largest input voltage value is 48V, it may seem unnecessary to choose a 200V MOSFET. However, there is the effect of leakage flux component of the transformer causing a larger voltage on MOSFET. Hence, we prefered to take the advantage of overdesign while choosing it. Also note that 30A current rating is enough for our purposes because primary side current is around 9A for our specs. To further decrease the effect of leakage component, we coupled our switching device with a large heat-sink.

RCD Snubber:

Resistor unit: 100Ω,11W sand stone resistors, 3 of them in series

Capacitor: 250V, 100uF, aluminum electrolytic

Diode: DSA30I100PA, Schottky, 30A, 100V, TO220AC package

The main purpose of utilizing an RCD snubber is to discharge leakage component originated from the transformer used. Although we accomplished to design a transformer having a relatively low leakage inductance (0.7uH), we still prefered to design a large snubber unit with bigger components than it would be needed. In our resistor unit, we used three sand stone resistors with large wattage in order not to burn them while dissipating leakage current. Selection of capacitor is again an example of overdesign since the voltage in primary never rises to 250V, but we used what we had in our hands. Finally, diode is the same with the one used in secondary side which is a fast switching device with enough ratings. Thanks to low leakage inductance value, we did not need to couple this diode with a heat-sink.

Input Capacitor:

250V,100uF, aluminum electrolytic

The motivation behind using such a component is to get away from the inductance effect of the cables reaching the primary of our transformer by connecting a capacitor between primary side of the transformer and the source side of MOSFET. By this way, we supply the system with a better DC and get rid of voltage fluctuations in this manner.

Transformer:

Chosen E-core: 0P43434EC*, Ferrite, A_L= 2200 nH/T^2*

Cable: AWG20

Noting that the aimed L_m being 24uH, D_{max} being 0.46, N_{ratio} being 4/6 and $f_{switching}$ being 31.250kHz, we needed for a core with high A_L value in order to have maximum mutual inductance value with minimum number of turns in order to have less core losses and a higher efficiency. In addition, we paid attention for the core being as small as possible to get away from leakage inductance effect as much as possible and also a high permeability to store enough energy. Considering these facts we have chosen 0P43434EC core by making our windings with AWG20 with double row (in order to have enough current rating i.e. $I_{max\text{-}AWG20}$=5A<$I_{primary}$=9A) for each turn. Note that we placed an air-gap between our E-cores to increase stored energy and also to coincide with required mutual inductance value by winding 4/6 turns instead of making it 2/3 for the sake of easiness in arranging L_m. Consequently, designed core supplied us with a $L_{leakage}$ of 0.7uH which is good in order to minimize the burder of snubber circuitry and obtain a higher efficiency. Finally, note that the obtained A.T value was around 230 which corresponds to an A_L utilization factor larger than 80% which is good enough in order not to saturate our core.

Secondary Side Diode:

DSA30I100PA, Schottky, 30A, 100V, TO220AC package

While deciding the ratings of this diode, we have taken into account that the voltage rating being larger than approximately 20V (possible fluctuations included) even though the output voltage was 12V for our specs. In addition 30A current rating is more than enough for our purposes since output current was around 6A as specified. Finally, we paid attention for this switching device to be fast enough in terms of obtaining a steady output voltage characteristic and to discharge mutual inductance rapidly in order not to saturate our core. Hence, we have chosen a Schottky one.

Resistive Divider (feedback):

100kΩ, 4 of them in series

Noting that the maximum voltage value that can be supplied to arduino being 3.3V, we divided output voltage by 4 to be 3V by using a serial resistive divider (placed in parallel to output terminals) in order to be supplied to our micro-controller for a closed-loop control. The reason behind choosing these resistors as large as 100kΩ is to pass lower current and not to burn our feedback topology.

Arduino & Controlling Algorithm:

According to the voltage magnitude coming from the resistive divider, this micro-controller manages the gating signals (with a switching frequency of 31.250kHz) in order to maintain a constant output voltage by increasing duty cycle 0.2% in each switching period. Due to this incremental ratio being small, our controller's response is a little slow i.e. it takes around 15 seconds to converge rated output voltage value. However, it maintains a lower switching loss. Also note that the arduino code makes us to operate soft-starting by starting with a duty cycle of 20%. Finally, there is an upper limit for PWM in order not to saturate our core and also an lower limit since it would be meaningless a negative PWM signal. Related arduino code is given in the appendices section.

TLP Circuitry:

Capacitors: 47nF two of them in parallel

Resistors: 100Ω from Arduino to TLP

*560kΩ*2 from TLP to gate of MOSFET*

This arrangement is placed in order not to distort the isolation between primary and secondary sides while taking feedback from the output. The critical point here is to shorten the distance while supplying the gating signals which we directly have done by using resistors without using any cable. If this distance is not short enough, gating signals gets distorted and we would not switch our MOSFET successfully.

Output Capacitors:

35V, 220uF, aluminum electrolytic capacitors 4 of them in parallel.

These capacitors are used for filtering purposes i.e. to decrease voltage ripples in output. While choosing our capacitors, we paid attention for them to have at least 20V rating with possible spikes included. Consequently, we accomplished to have 0.8V peak-to-peak ripple which is enough for our purposes.

V) Test Results

This part of the report contains the real test result of the project with the obtained characteristics during demonstrations. These tests include; core characteristics (L_m, $L_{leakagae}$), input and output voltage and current measurements, efficiency, load regulation and thermal measurements. Note that line regulation tests are not available in this part since it is somehow forgotten to take place by the instructor.

Let us start by transformer analysis but before giving the inductance values of the transformer, it would be informative to talk about design procedure. During this procedure, core selection is done by trial and error method until we get a reasonably low leakage inductance value. For this purpose, the first core tested was very big in size hence would create lots of leakage losses in the system. In order to overcome this situation, another core ,that is smaller in size, is selected and the turn ratios are fixed. Thankfully, this core has met the leakage requirements.

The figure below shows the measured inductance values of the transformer after placing a piece of paper between e-cores to obtain desired mutual inductance without changing the turn numbers.

Figure 18- Lm value obtained by shorting the secondary

Also note that obtained $L_{leakage}$ value is 0.7 uH ,that is suitably low, which is obtained by shorting the secondary.

The next step is making real time tests namely voltage and current measurements. The figure below shows the input voltage and drawn current values:

Figure 19- Measured Vs and Is values (Vin=48V)

In the following figure, output measurements corresponding to V_{in}= 48V case is shown:

Figure 20- Measured Vo and Io values with Pout included (Vin=48V)

Corresponding input power for Vin=48V case is 85,6 W as can be inferred from Figure 19, and the output power is 71.98W, shown in Figure 20. The resulting efficiency becomes 84% which more than satisfying our requirements.

In addition, it is informative to give the efficiency results when Vin=24V case. Corresponding input power is 100.8W as can be inferred from Figure 21, and the output power is 71.92W has not changed significantly as expected and shown in Figure 22. The resulting efficiency becomes 71% which is lower Vin=48V case, nevertheless satisfying our requirements.

Figure 21- Measured Vs and Is values (Vin=24V)

Figure 22- Measured Vo and Io values with Pout included (Vin=24V)

Now, let us give the output voltage and current waveforms corresponding to Vin=48V case. Note that it would be the same when Vin=24V, hence it is enough to give only Vin=48V case's results.

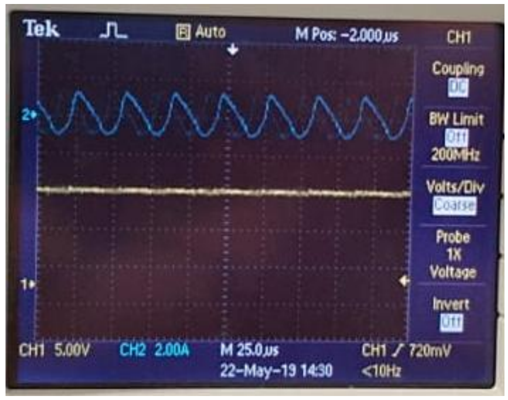

Figure 23- Output current waveform

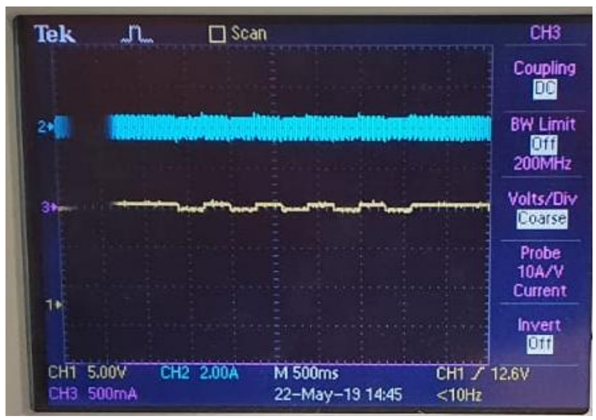

Figure 24- Output voltage waveform

As can be seen in Figure 23, the average value of the output current is 5,86 A which matches the previous calculations. However, it oscillates because of the applied modulation technique i.e. bang-bang control. Output voltage waveform is available in Figure 24. As can be seen from this figure, output voltage waveform seem a little like square because of the imperfect performance of the controller. In other words, controller is slower than it needs to be, because of small incremental value of the duty cycle applied in the controller algorithm, and this slow response makes the output voltage look like in Figure 24. Nevertheless, oscillations take place very near to 12V hence the ripple value is very small. Thus, we did not need to calibrate our controller algorithm further.

The final analysis includes the thermal measurements which plays crucial role in the long-lasting performance of the converter. As can be seen in Figure 25, input capacitor (due to being very close to transformer), transformer core and snubber resistances (due to discharging the snubber capacitor) are the hottest components. Whereas, output diode and the MOSFET are not hot at all indicating the satisfying performance of the heat-sinks coupled. Also note that; although snubber diode is not coupled to any heat-sink, it does not heat up significantly which is thanks to the low value of leakage inductance of our transformer.

Figure 25- Thermal measurements

VI) Conclusion

By completing such a project, we got experienced about the practical aspects of implementing an isolated power supply as well as designing it from scratch. In other words, we have learnt the process while making a magnetic design and also the related challenges. In addition, we had the chance to operate a closed loop control for the first time. Moreover, we further experienced in choosing components by paying attention to a number of critical points such as voltage, current and wattage ratings, non-ideal factors and efficiency concerns. Regarding our implementation process, we made some changes in our design i.e. we changed our core and decreased number of turns as the previous one was not satisfying efficiency limitation because of large leakage inductance, we calibrated our controller PWM increments to maintain a better switching process since larger increments is a burden on switching device and causes it to break down. Additionally, we modified our snubber topology and changed our resistors with sand-stone resistors in order to withstand large amount of power dissipated on snubber. Lastly, we increased the number of parallel output capacitors for a better efficiency. To sum up, we satisfied the requirements -power, voltage, output voltage ripple and efficiency- of our topology i.e. have obtained an efficiency of 71%, around 12V output voltage corresponding to both 24V and 48V of input with an output voltage ripple of 0.8%, output power of 72W by maintaining the isolation between primary and secondary sides which is the main purpose of utilizing such a topology called “Flyback”.

VII) Appendices

Controlling Arduino Code:

```
float pwm=20;
void setup() {
 pinMode(3, OUTPUT);
TCCR2B = TCCR2B & B11111000 | B00000001; // for PWM frequency of 31372.55 Hz
Serial.begin(9600);
}
void loop() {

 int voltage = analogRead(A0);
 Serial.print ("voltage");
 voltage = map(voltage, 0 , 1023 , 0 , 100);

 Serial.println (voltage);
  if (voltage==0){
  pwm=20;
  Serial.print ("sabit pwm=");
  Serial.print(pwm);
  analogWrite(3,map(pwm,0,100,0, 255));
   }
 else if (voltage<=64) {

  pwm=pwm+0.2;

  if(pwm<0){
   pwm=0;
   }
  if (pwm>60){
   pwm=60;
   }
  Serial.print ("artıyor pwm=");
```

```
    Serial.print(pwm);

    analogWrite(3,map(pwm,0,100,0, 255));

    }


  else if (voltage>64) {

    pwm=pwm-0.2;


    if(pwm<0){

      pwm=0;

      }

    if (pwm>60){

      pwm=60;

      }

    Serial.print ("azalıyor pwm=");

    Serial.print(pwm);


    analogWrite(3,map(pwm,0,100,0, 255));

    }

   delay(300);


}
```

VIII) References

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