MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

EE464 Static Power Conversion-II
Hardware Project Report

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I. INTRODUCTION

This report presents the hardware project for the course EE464 Static Power Conversion-II. In this project, a regulated power supply is designed and implemented. Among the given projects, we chose Forward Converter 5 topology, whose specifications are given below in Table 1.

In this report, the designed forward converter is presented and the system description is made by all of its aspects. Firstly, the reasoning of the topology selection will be made. Then the circuit design will be presented with some simulations results in Simulink. After that, the magnetic design steps for both transformer and the inductor will be examined thoroughly. The component selection will explained and the behaviour of the implemented system will demonstrated with some test results. The controller used for the voltage regulation at the output is also described. Finally, a conclusion part which will highlight the key points will be included at the end. This report includes calculations, circuit schematics and simulation results for our forward converter design.

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Table 1. Forward Converter Specifications

	$Max\ V_{in}$	$Min\ V_{in}$	V_{out}	P_{out}	Output voltage ripple	Line Regulation	Load Regulation
FOR#5	48	24	12	50	2	2	2

II. FORWARD CONVERTER DESIGN

A. Topology Selection

Forward converter topology is chosen over flyback for a couple of reasons. First of all, forward converter topology has better transformer utilization since direct power transfer is made and there is no need for energy storage in the core. Moreover, since energy storage is not needed, a gapless core can be used. Finally, since there is an output filter output voltage ripple is way better compared to forward converter and output diode and inductor ensures continuous output current.

B. Magnetic Design

Like stated earlier, the forward converter topology is chosen for our design. It includes two magnetic components which are a transformer and an inductor. Their design process will be examined in the following sections.

1. Transformer

In our design, it is wanted to obtain 12 V at the output when voltages between 24-48 V given from the input. A transformer for this operation will be designed.

Besides the primary and secondary windings, there will also a third winding in order to provide a path for magnetizing current while the switch is open. The time passed during demagnetization, t_m, should be shorter than the off time for full demagnetization. Hence the maximum duty cycle of the operation becomes,

$$D_{max} = \frac{1}{1 + \frac{N_3}{N1}}$$

We chose N3 equal to N1, which yields a Dmax of 0.5. Duty cycle is chosen as 0.4 in order to give a safety margin. Afterwards, in order to find the necessary transformation ratio the following relation between the input and output of the forward converter is used.

$$\frac{V\,out}{V\,in} = \frac{N_2}{N1} \times D$$

$$\frac{12}{24} = \frac{N_2}{N1} \times 0.4$$

$\frac{N_2}{N1}$ is founded as 30/24 and we chose 32/24=4/3 as our winding ratio.

The core selection is made by looking at the power handling chart in the website of the manufacturer. Power handling chart can be found here. The power rating of the forward converter 5 topology is 50W. As the operating frequency, f_s, we have chosen 31.250 kHz.

By looking at the chart, it can be seen in Figure 1 that the core 0P43434EC is suitable for our application. Its datasheet can be found at this link.

Power in Watts 20 kHz	50 kHz	100 kHz	250 kHz	Pot, RS, DS	E Cores	RM, PQ, EP	UU, UI, UR	ETD, EER, EC	EFD, Planar	Toroid
70	110	157	306	43622 DS HS		43723 RM	42220 UU 42530 UU	42814 EER 42817 EER 43434 ETD		42508 TC 42908 TC 42712 TC

Figure 1 - Power handling chart

Forward converter design is made using the application note that can be found here.

Firstly the primary winding turn number is found by the following formula [1],

$$N_{p,\,min} = \frac{V_{DC,\,min} \times D_{max}}{A_e \times f_s \times \Delta B}$$

$A_e = 97.11\ mm^2$ for our selected core, which is obtained from the datasheet.

Operating frequency is $31.250\ kHz$

Flux density at this operating point is approximately $0.2\ T$ at 31kHz, which is obtained from the graph below in Figure 2.

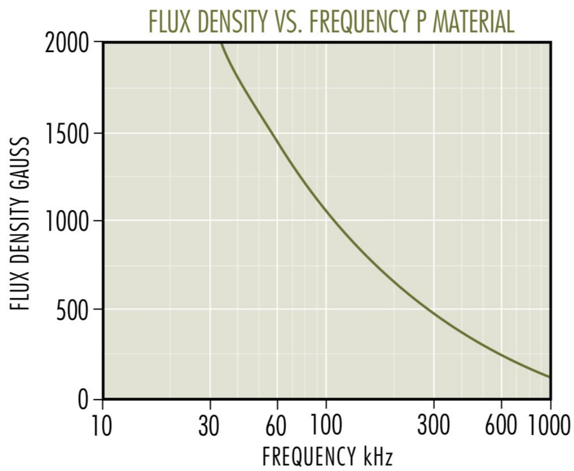


Figure 2 – Flux density vs Frequency characteristics of core material [2]

We found $N_{p,\,min} = 15.8$, hence 15 is chosen as the primary turn number. From the turns ratio, secondary winding turn number can also be found.

$$N_p = 15$$

$$N_s = \frac{N_2}{N_1} = 20$$

After finding the turn number, magnetizing inductance can be found with the following formula [1],

$$L_m = A_L \times N_p^2 \times 10^{-9} = 0.66\ mH$$

Reset and secondary currents can also be calculated by the below formulas [1].

$$I_{reset} = \frac{V_{DC,\,min} \times D_{max}}{L_m \times f_s} \times \sqrt{\frac{D_{max}}{3}} = 0.15\ A = 150\ mA$$

$$I_{secondary} = I_o \times \sqrt{\left(3 + K_{RF}^2\right) \times \frac{D_{max}}{3}} = 2.16\ A$$

K_{RF} is taken as 0.1 for practical design purposes[1].

$I_o = \frac{50}{12} = 4.16\ A$

Once the number of turns and the magnetic core of the transformer is determined, wire selection and resistance calculations can be made.

While choosing the cable, skin effect and current density are two factors that are considered. Skin effect at our operating frequency can be calculated by the following formula:

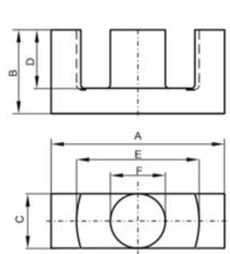
$$\sigma = \sqrt{\frac{2\times\rho}{\mu\times\omega}} = \sqrt{\frac{2\times\rho}{\mu\times2\times\pi\times f}}$$

$$\sigma = \sqrt{\frac{2\times1.72\times10^{-8}}{1.256629\times10^{-6}\times2\times\pi\times31250}} = 0.373\ mm$$

The diameter of the wire should be chosen considering the skin effect. When the AWG table is examined, **AWG-21** is found suitable for the wire of the transformer which has a diameter of 0.723 mm and wire area of 0.484 mm^2 .

The current RMS at the first winding of the transformer is 4.2A and at the second winding of the transformer is 2.8A. We chose our current density to be around 4 A/mm^2 . However, with a cable of the size AWG-21, our current density at the primary side is became 8.67 A/mm^2 . In order to prevent higher density and decrease the copper resistance, we paralleled the primary and the secondary side windings. This way, the current density and the resistance is halved.

To calculate the wire resistances, the wire lengths should be found first. From the datasheet of the chosen magnetic core, the dimensions of the core are obtained and can be seen in the following figure.



(mm)	Nominal:	Tol. min.:	Tol. max.:
A	35.0	-1.6	0.0
B	17.3	-0.2	+ 0.2
C	11.1	-0.6	0.0
D	11.8	0.0	+ 0.6
E	25.6	0.0	+ 1.4
F	11.1	-0.6	0.0

Eff. Parameters

Ae mm ^{2}	Amin mm ^{2}	le mm	Ve mm ^{3}
97.1	91.6	78.6	7640

Figure 3– The dimensions of the E – Core 0P43434EC.

The circumference of the part F must be calculated first. It is calculated as,

$$\pi \times R = 34.87\ mm$$

where R = 11.1 mm as highlighted in Figure 3.

The number of turns for the primary winding is 15. Thus, the total wire length at the primary winding is equal to:

$$15 \times 34.87\ = 0.523\ m$$

From the AWG table, the resistance/length constant is found as 42 mΩ/m. Resistance of the wire in the primary winding is calculated as:

$$R_p = 0.523\ \times 42 = 0.0219\ \Omega$$

The secondary winding will be winded on the primary winding which increases the circumference of the surface. New circumference can be found as:

$$\pi \times R = 39.41\ mm$$

where R = 11.1 + 0.723 × 2 = 12.54 mm

The number of turns for the secondary winding is 20. Thus, the total wire length at the primary winding is equal to:

$$20 \times 39.41 = 0.788\ m$$

Resistance of the wire in the secondary winding is calculated as:

$$R_s = 0.788 \times 42 = 0.033\ \Omega$$

2. Inductor

Forward converter topology has an output inductor unlike the flyback topology. Hence another magnetic design for this inductor is necessary. In our design, output inductor design is made using the design guide that can be found here.

Our output current is 4.16 A and our inductance value is chosen as 100 μH. So, LI^2 product becomes,

$$LI^2 = 0.15\ mH \times 4.16^2 = 2.59$$

After that the LI^2 product is located on the core selector chart that can be seen in Figure 4.

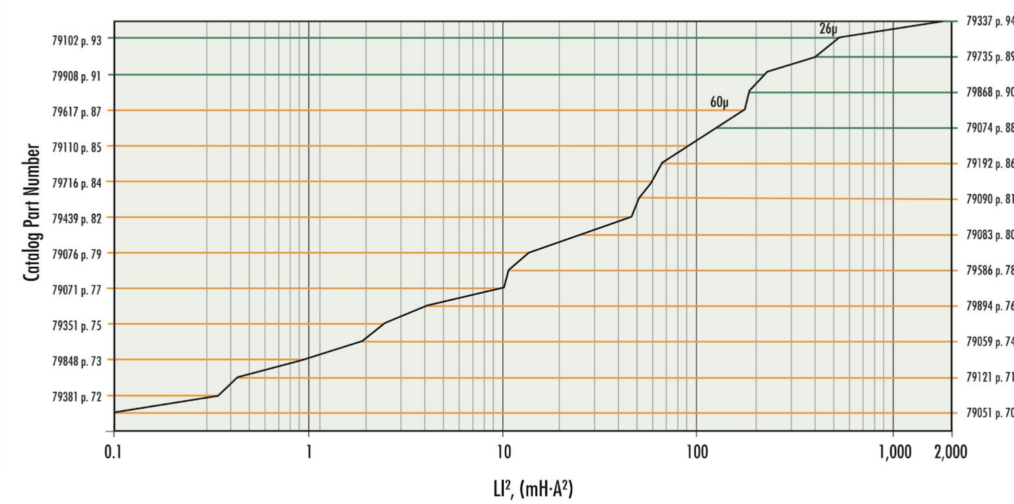


Figure 4 - Core selector chart [3]

The core number corresponds to the first intersection is the smallest core size that can be used. Hence, the core 79083A7 is chosen which lay down the conditions mentioned.

The datasheet of the toroid core can be found at this link. Its material is Kool Mμ MAX with a permeability of 60μ.

Once the inductance, core size and permeability are known, number of turns can be calculated.

First of all, the inductance factor A_L for the core is obtained from the core data sheet. It has a value of 81 nH/T^2 for the chosen toroid core. Then, the number of turns needed to obtain required inductance can be found by using the following formula:

$$N = \sqrt{\frac{L \times 10^3}{A_L}} \simeq 43$$

Hence, 50 is chosen for the number of turns of the inductor.

After determining the core and turn number, the wire size is determined. The Current that will flow through the inductor will be maximum 4.16 A. For this current rating and the switching frequency, AWG 21 is chosen which has a cross section area of 0.00484 cm^2. Total wire area then becomes, $N \times 0.00484 = 0.242\ cm^2$.

The window area of the chosen toroid is 427 mm^2. So, the winding factor of the design can be found as:

$$Winding\ Factor = \frac{Total\ Wire\ Area}{Core\ Window\ Area} = \frac{0.242}{4.27} = 0.0566$$

C. Controller

The switching of the MOSFET will be done by a PWM signal that is created by a closed loop digital controller. As the microcontroller, we used an Arduino UNO board. For the control method, we preferred hysteresis control because of its good dynamic response and easy implementation.

The voltage feedback is taken from the output via a voltage division by resistors. The maximum acceptable voltage level of the Arduino pins is 5V. Hence, output voltage is reduced almost to its one tenth in order not to damage Arduino.

The voltage feedback is then compared with a predefined reference value in Arduino and the duty cycle of the PWM signal increased or decreased accordingly. The Arduino code for the controller can be found in the APPENDIX.

The obtained PWM signal with varying duty cycle is fed to the mosfet gate for proper switching. However, since arduino operate at low voltage levels while our converter operates at much higher voltages. Hence isolation between high and low voltage side is essential in this situation. We preferred to use an optocoupler chip as the isolator.

D. Simulation Results

After determining the design parameters of our forward converter design, we simulated the circuit using MATLAB Simulink in order to observe the performance of our design and see whether it complies with the specifications given in the project definition.

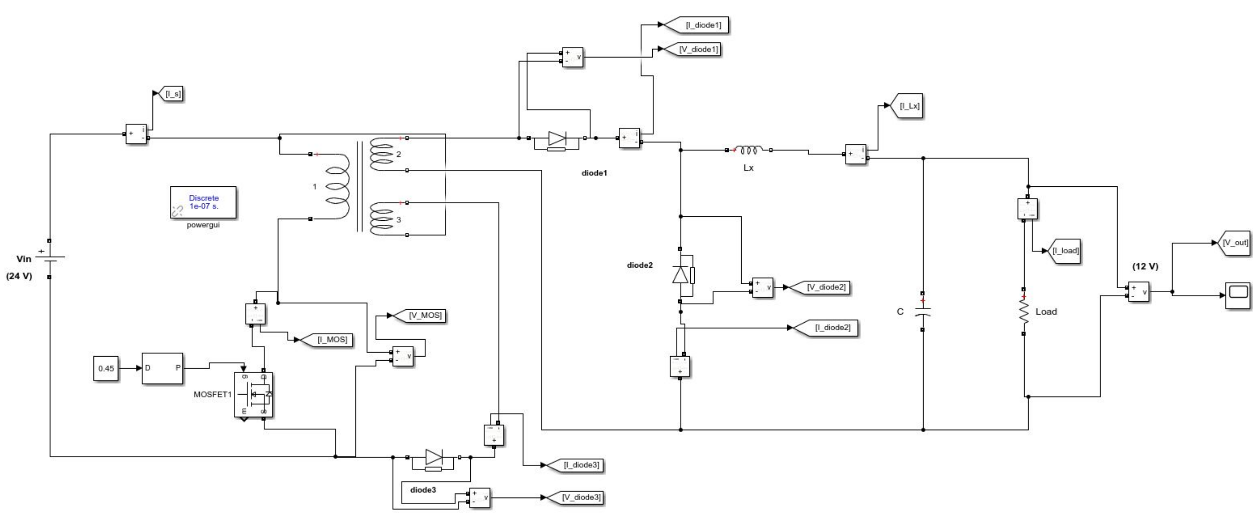


Figure 5 - The simulink model of the forward converter

Simulation results can be seen in Figure 6 below.

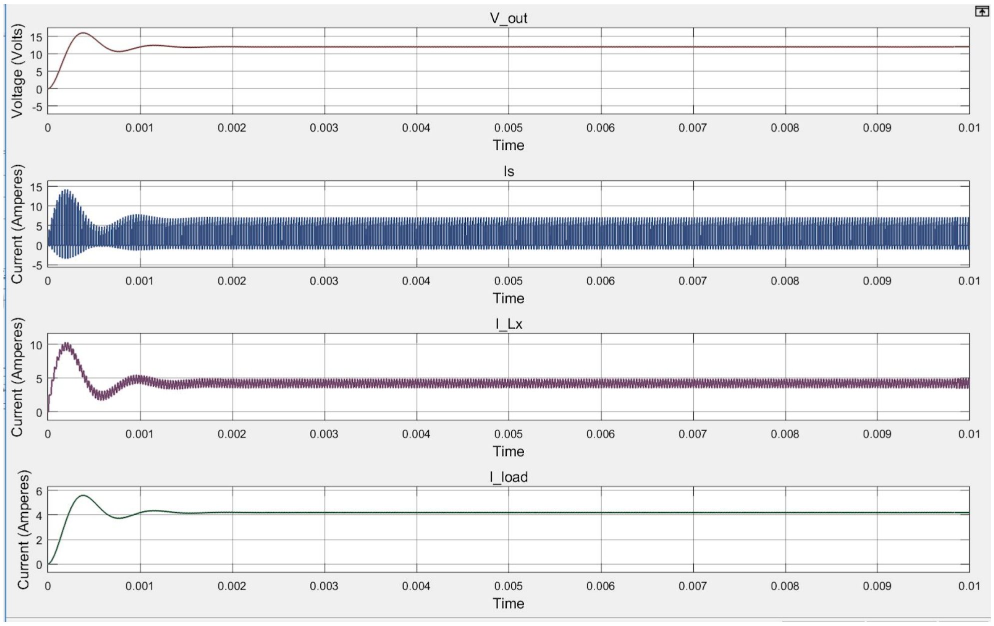


Figure 6 – Output voltage, Input, Output and Inductor current waveforms of the ideal forward converter.

Output voltage characteristics of our forward converter design can be seen in Figure 7 and Figure 8.

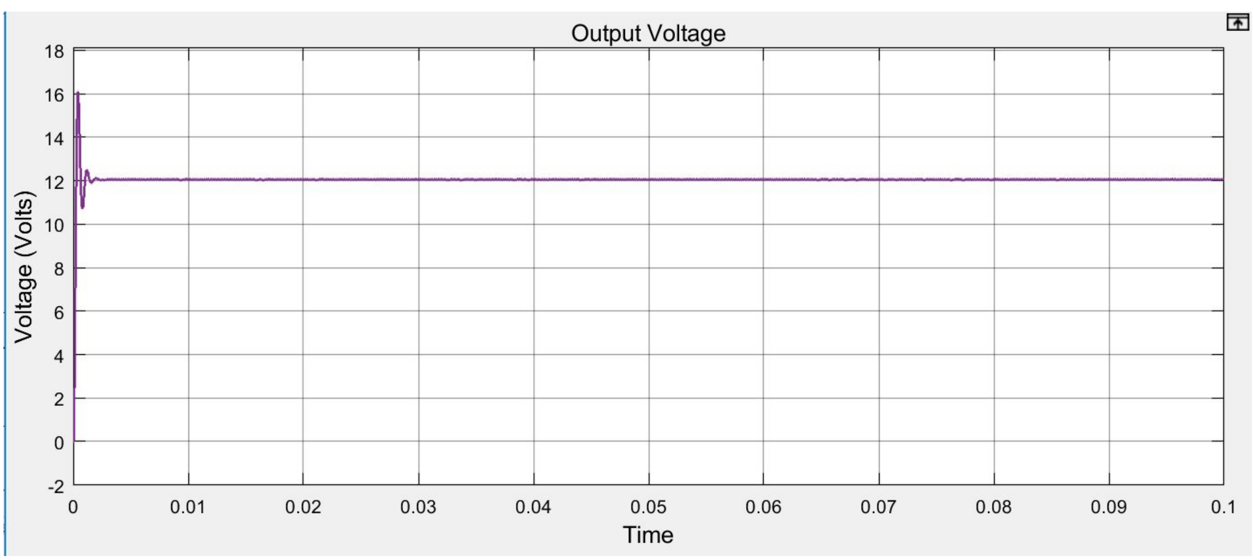


Figure 7 - Output Voltage Waveform

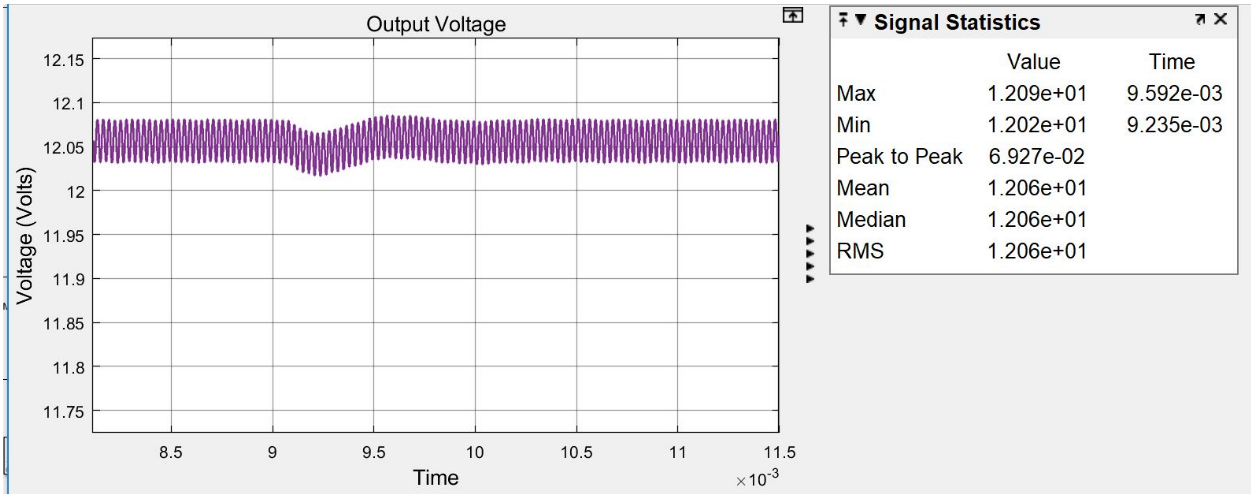


Figure 8 – Output Voltage ripple

As one can see from Figure 8, output voltage ripple is around 0.069 volts which is better than enough for the 2% ripple constraint.

Load current characteristics of our forward converter design can be seen below in Figure 9.

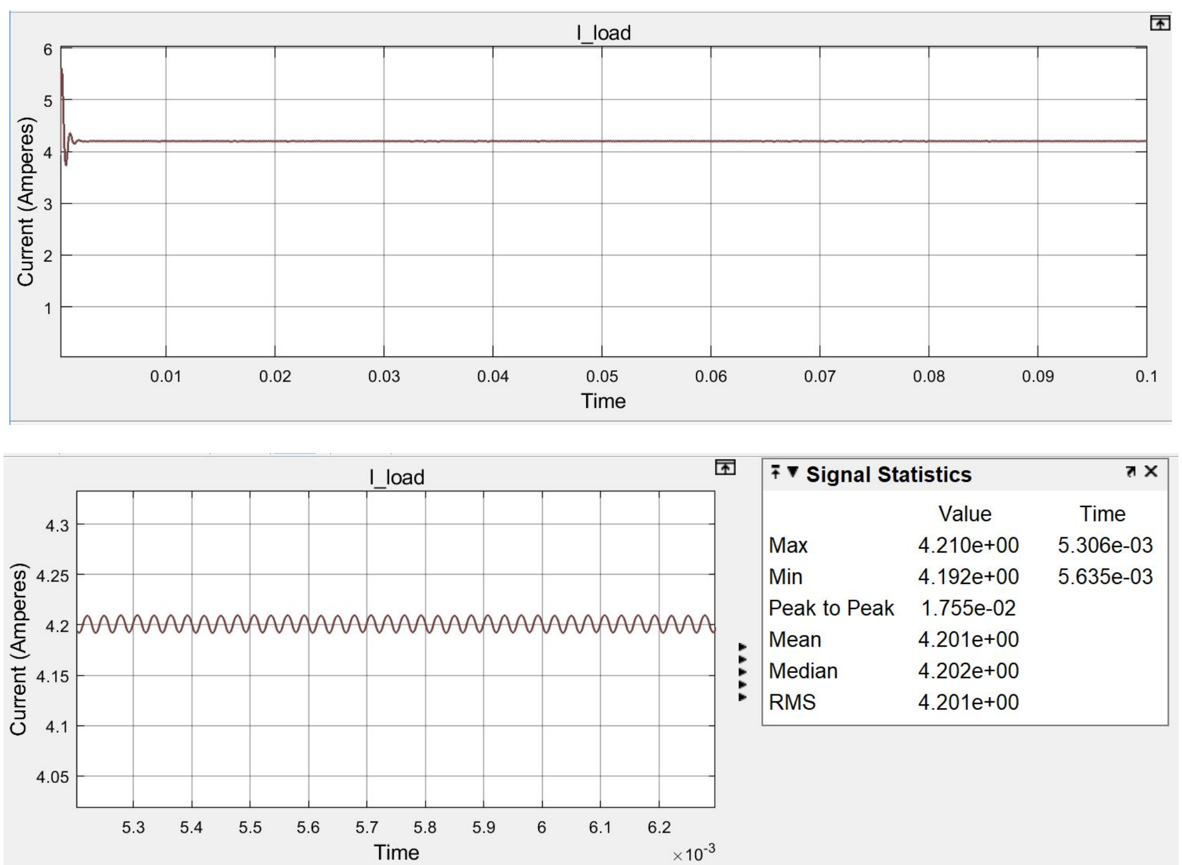


Figure 9 – Output Current characteristics

E. Component Selection

The component selection for the forward converter includes selecting an switching MOSFET, diodes for both primary and secondary sides, output filter capacitor and an optocoupler. All selections were made according to the voltage and current which components having.

We selected PJZ22NA50A-To as MOSFET. This type of MOSFET has a Gate-Source voltage of 500V and has 22A continuous output current according to datasheet. As seen in Figure 10, in our design, MOSFET has voltage of 120V and almost 7A current, then this type satisfies our desired voltage and current limits.

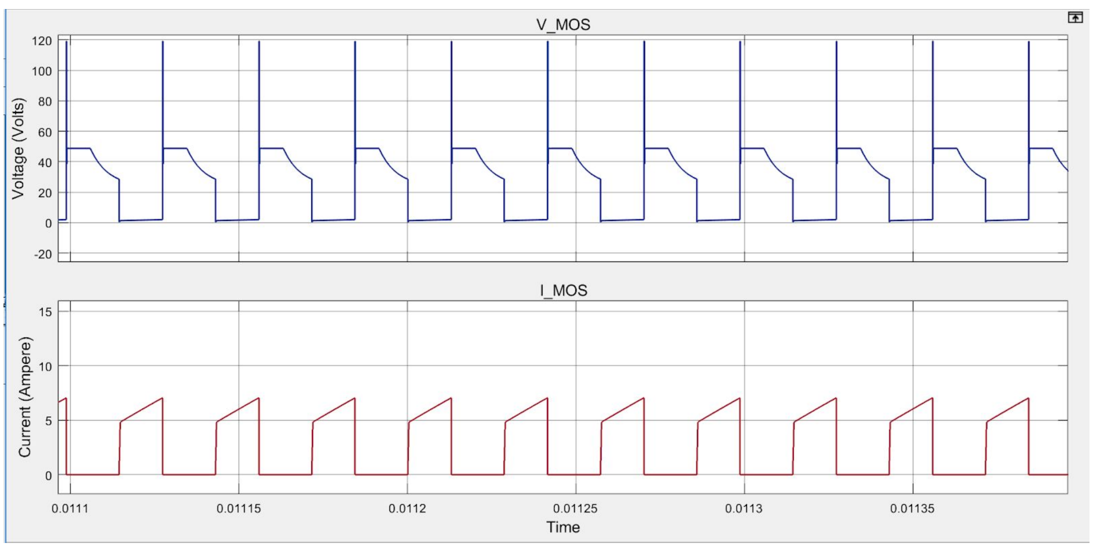


Figure 10 - The voltage and current waveform for MOSFET

We used STTH1602CT as diode1 and diode2. This diode is dual center tap (as seen in Figure 11) rectifier suited for switch mode power supplies and high frequency DC to DC converters.

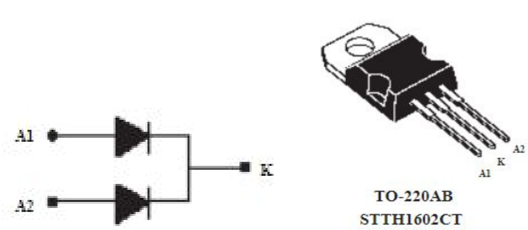


Figure 11 - The circuit schematic of dual center tap diode STTH1602CT

Diode has maximum limits which are forward current of 20A and repetitive reverse voltage of 200V according to its datasheet. As seen in Figure 12, diode1 has forward current of 5A and voltage of almost 30V. Diode2 has also same characteristics with diode1. Then, our selected diode satisfies these current and voltage limits. It has also low forward and reverse recovery times, and low losses.

We used the same diode for just two legs, namely one diode part inside original diode. According to our simulation results(as seen in Figure 13) for diode3, it has almost 1A and 50V. Then, our selected component is proper for this case.

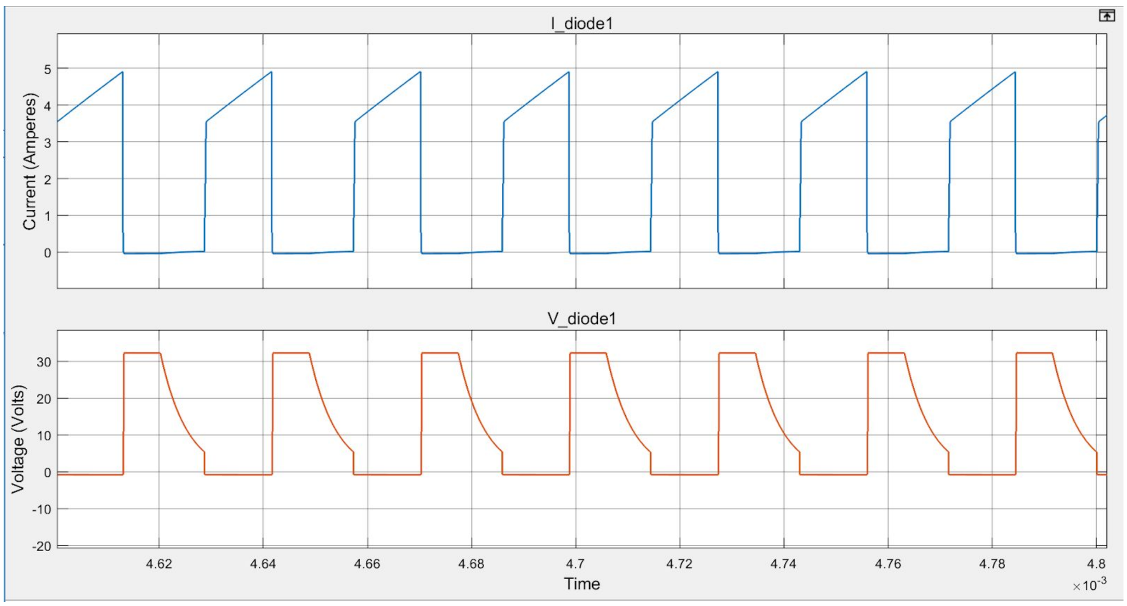


Figure 12 - The current and voltage waveform of Diode1

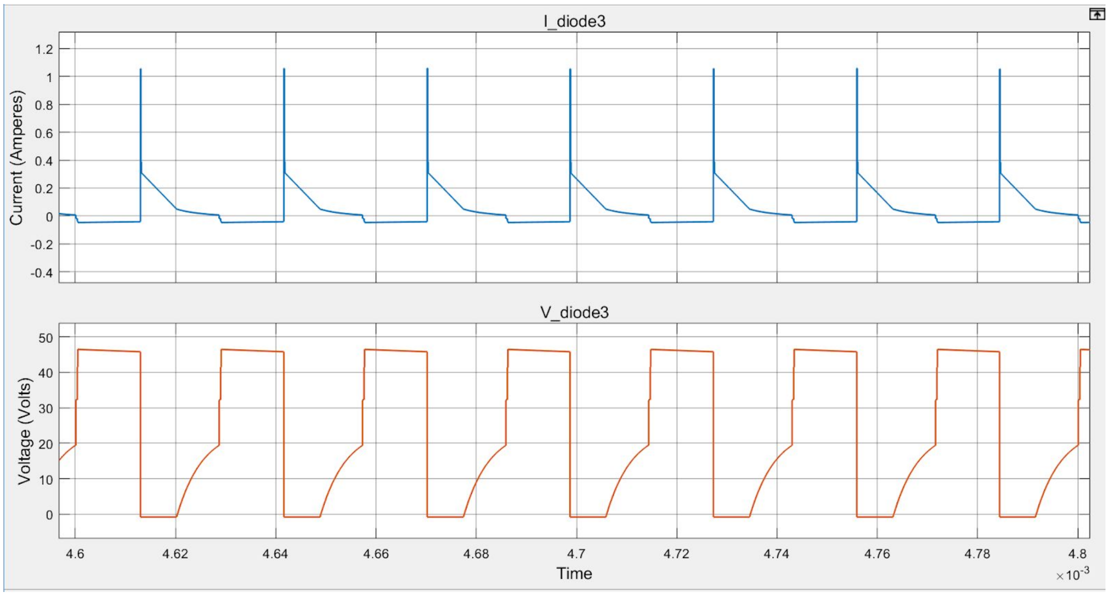


Figure 13 - The current and voltage waveform of Diode3

We also used an optocoupler chip TLP250 to make isolation between arduino and converter for controller part because arduino operates in low voltage level, but our designed converter operates at higher voltage level. While connecting the optocoupler to arduino and converter we set the circuit as seen in Figure 14 by using datasheet of TLP250. We used Rl = 10 Ω because the output resistance which connecting to MOSFET must be low to provide low loss.

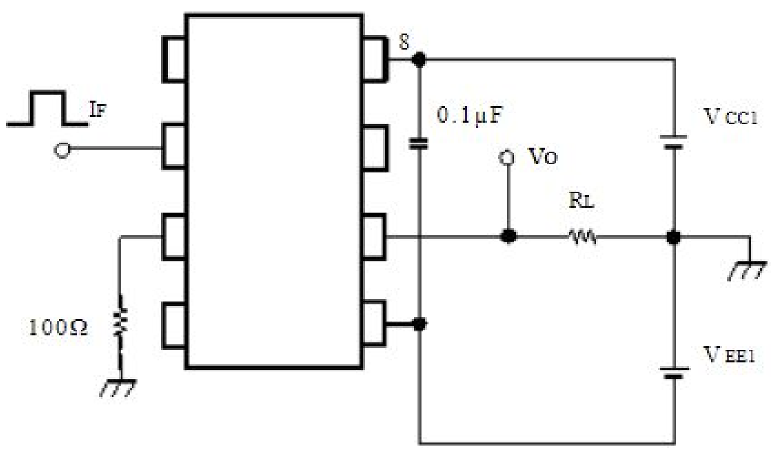


Figure 14 - The circuit schenatic of TLP250

We also used GT128-5.0-02P-14-05AH green golten connector while connecting diodes and MOSFET.

III. TEST RESULTS

In this section, the test results performed with the implemented forward converter topology are shown and the practical results are compared with the theoretical expectations. The design is examined under various conditions (load regulation, line regulation etc.) and the results are discussed.

A. The Overall Design

The overall implemented design is illustrated at Figure 15 . The digital controller, Arduino UNO, is not shown in the Figure.

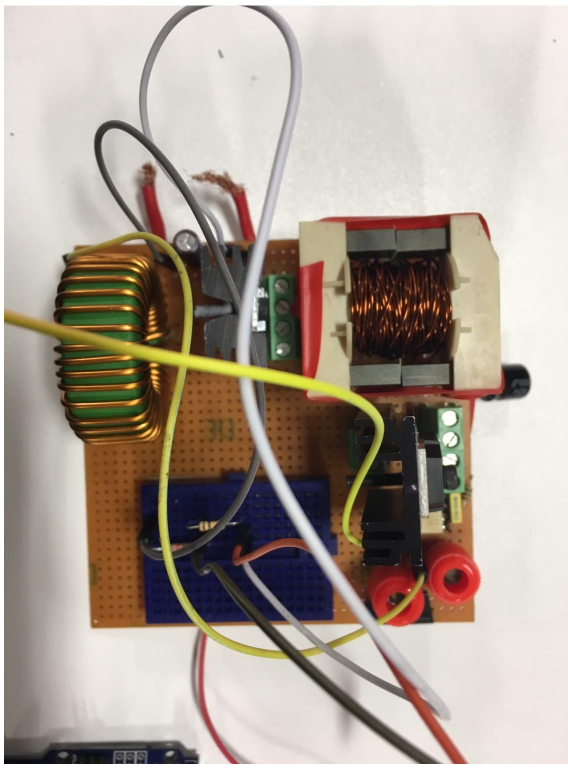


Figure 15 - The overall forward converter design.

B. Transformer Analysis with RLC Meter

The magnetic design of the transformer is explained in the previous parts. The primary turn number N_p is found as 15 and the secondary turn number N_s is calculated as 20. While winding the transformer, the interleaving winding approach is performed. This is used in order to reduce the proximity effect and the leakage. There are a number of interleaving winding applications that is feasible with our design. We chose the application mentioned in Dr. Ozan Keysan's magnetic design lecture notes [4]. The winding technique is illustrated at Figure 16.

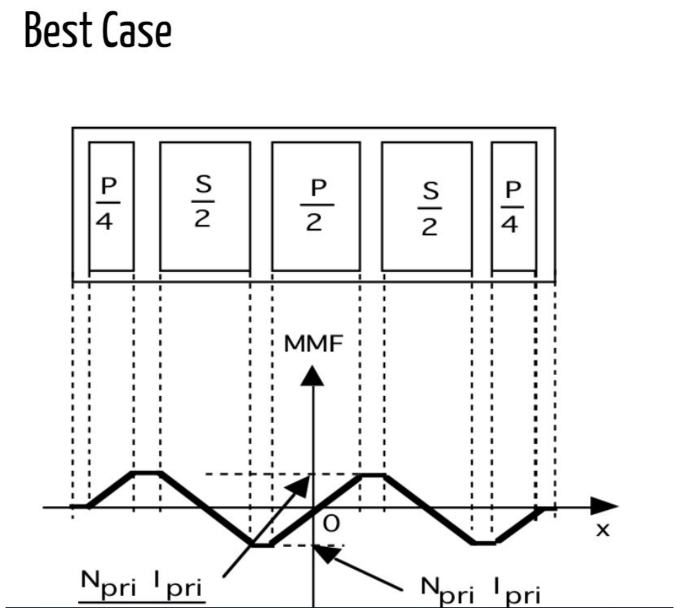


Figure 16 – The winding technique applied in the transformer design.

The sequence of the windings can be given as:
Primary 4 T, Secondary 10 T, Primary 8 T, Secondary 10 T, Primary 4 T.
The third winding is then winded 15 Turns upon the other windings.

After completing the windings of the transformer, we used the RLC meter at the laboratory in order to check if the transformer meets the specifications of our magnetic design or not. The magnetizing inductance and the leakage inductance parameters are measured and observed through the RLC meter.

Firstly, in order to measure the magnetizing inductance of the primary side, secondary side is open circuited and the probes are connected to the primary winding. The magnetizing inductance of the primary side and the secondary side is measured with the same way. The LC meter readings of the transformation ratios for N1:N2 and N1:N3 can be seen below in Figure 17.

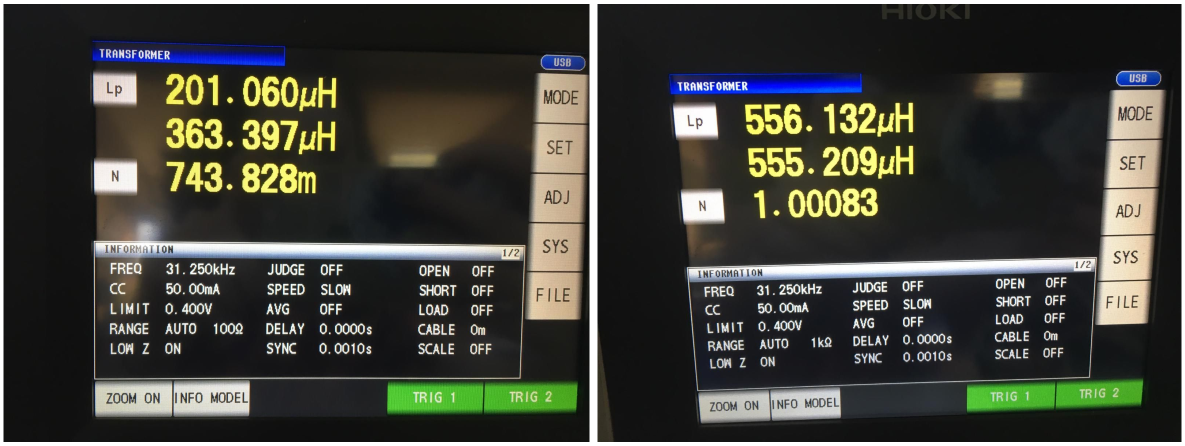


Figure 17– LC meter readings for the transformation ratios

The magnetizing inductance ratios give the overall turns ratio and as can be see from the figures, the ratios obtained are consistent with the design values which are N1:N2=0.75 and N1:N3 =1 . The primary side magnetizing inductances seems to be different in Figure 17. The difference stems from the variation of the air gap between the cores while taking the measurements.

In order to measure the leakage inductance of the primary winding, the secondary side is short circuited and the probes are connected to the primary side. For the leakage of the secondary side, the operation is repeated vice versa. The measurement results are illustrated at Figure 18. The figure on the left side is from the RLC meter readings from the primary side and the figure on the right side is from the RLC meter readings from the secondary side.

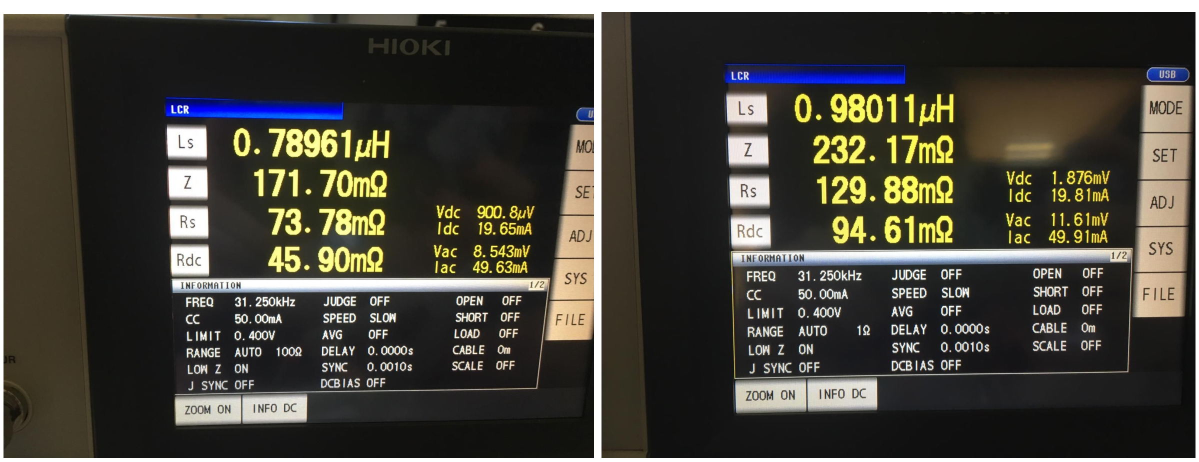


Figure 18 – RLC meter readings for the transformation leakage parameters.

The leakage inductances don't exceed 1 uH, which is an acceptable value for our application since the losses from the transformer will be negligible.

C. Output Voltage and Current

For the forward converter topology #5, it is expected to have a 12V constant output voltage and the output power is 50 W. While testing our design at the lab, we used a load of 2.7 Ohms in order to satisfy the current and the power requirement. However, we were not be able to satisfy the voltage requirement at the beginning. We found out that the transformer was saturating and this limited our output voltage to 8-9 V. Despite the fact that in a forward converter design an air gap between the E cores is not necessary, we needed to put a small air gap between the cores so that the hysteresis curve's slope is reduced and the core won't saturate any more.

However, putting an air gap between the cores also reduces the magnetizing inductances of the windings too. Hence, we tried to adjust the air gap so that the loss is kept minimum. After doing that, we were able to increase the output voltage to 11.5 V at 80% load.

At full-load condition, the core still saturated and the output voltage was around 11 V.

The test results at the demo setup is illustrated at Figure 19 and Figure 20.

The input side DC source and the wattmeter is illustrated at Figure 19.

Firstly, we performed our demo at low load conditions and the output is shown in Figure 20. While testing the design at the power lab before the demo day, we were observing 11.5V output voltage at low load conditions. We observed some additional losses on the demo day and the output voltage is decreased to 10.5 V at the demo setup. The reason behind that is the long cables coming from the input side and the going to the wattmeter. Stray inductances and the resistance of the long cables have reduced the output voltage. Yet, when the circuit reached to its steady state, we observed approximately 11V at the oscilloscope screen. It can be deducted that there is a certain amount of loss while the output is transferred to the wattmeter.

Secondly, we performed a full-load condition test at the demo setup and the results are measured in a wattmeter and illustrated at Figure 21. Since the core saturated, we couldn't observe 12V output voltage. The output voltage was around 10.7V and the output power was 40W. The efficiency requirement is not satisfied totally because of the lower output voltage.

The output voltage ripple meets the requirements of the design with the help of the LC filter at the forward converter topology.

Figure 19 – The input side DC voltage generator and wattmeter.

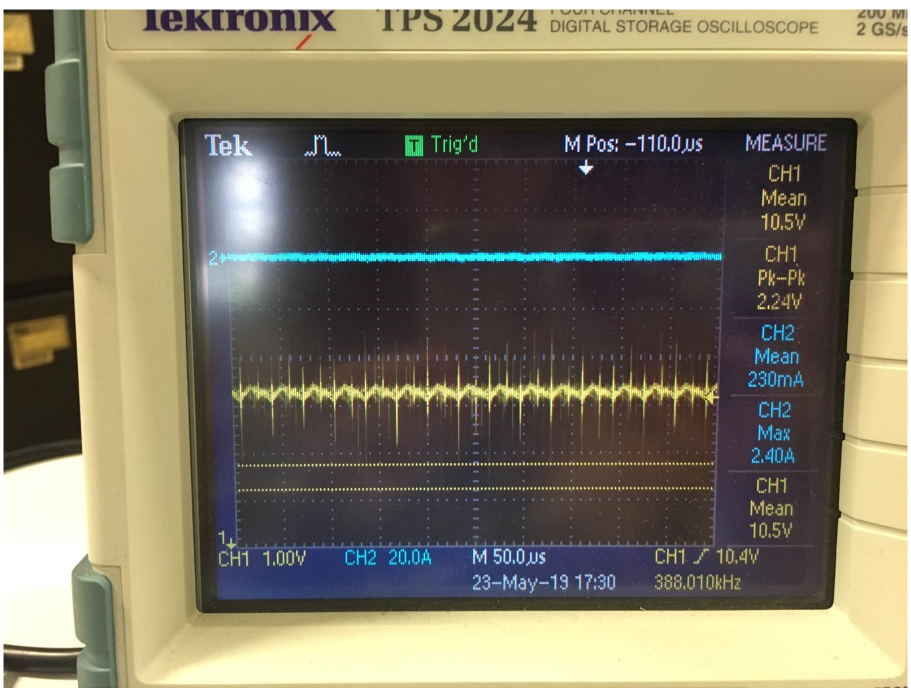


Figure 20 – The output voltage waveform at load low condition.

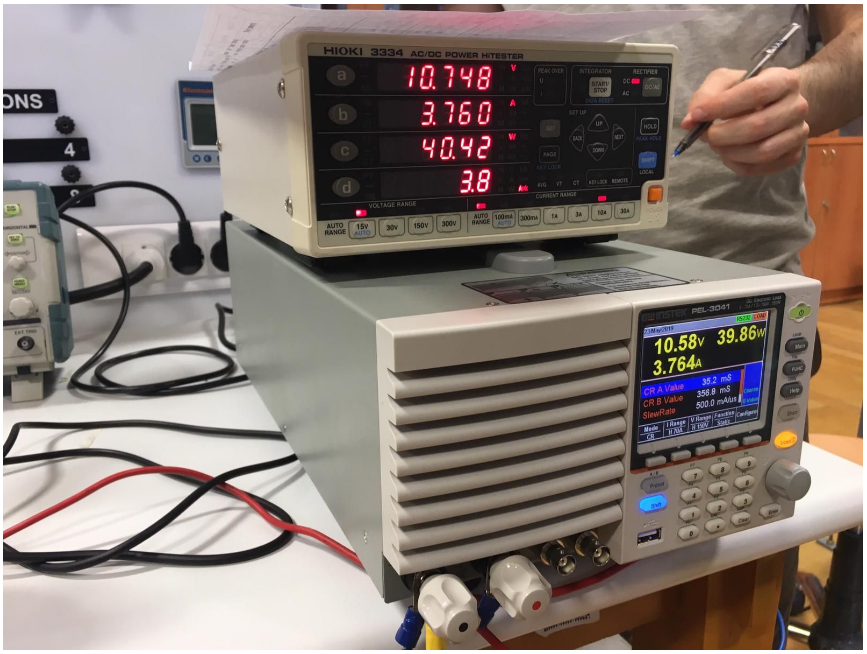


Figure 21 – The output voltage, current and total output power shown in wattmeter for full-load condition.

D. Discrepancies Between Simulation and Experimental Results

- As previously mentioned in Part C, according to the magnetic design of the core we were expecting the transformer to work perfectly. However, at the full-load condition we observed the core gets saturated even the input voltage is around half of the rated input voltage which is 12V. The magnetic flux density coefficient was chosen according to the application notes of the Magnetics the power handling chart was also checked to see if the chosen core satisfies the requirements. It was highly unexpected to observe the Hysteresis curve reaches to the saturation point too easily. This problem is solved by adding an air gap between the cores, despite the fact that normally in a forward converter topology gapless cores are used.
- Another discrepancy we observed at the experiment is that the snubber topology which consists of a RC circuit didn't have an effect on reducing the stress on the MOSFET. At the simulation results, adding the snubber circuit reduced the voltage peaks on the MOSFET significantly.
- The overall efficiency of the system was way lower in the experiment results than the simulation results. Many things can be the cause of this difference. For instance, the

switching losses at the MOSFET was at quite big. We were not expecting such great losses at the MOSFET because we performed the simulations with all the internal parameters set with respect to the datasheets. In addition to that, there were also losses due to the very long cables connecting the circuit to the load and the wattmeter. We observed that wattmeter readings are a little smaller than the oscilloscope reading. Hence, we concluded that there are additional losses on the way to the wattmeter.

- At the simulations, the load regulation couldn't be tested at the Simulink and we thought it would work well when the load condition is changed from half-load to full-load. However, the MOSFET couldn't handle the voltage peaks and the current peaks. The load regulation failed the MOSFET.

E. Thermal Results

The thermal analysis of the project is observed through the thermal camera and the results are illustrated in Figure 22 and Figure 23. When the system is approximately at half-load condition the power semiconductor devices don't overheat. The MOSFET , which is the most heated component in our circuit stayed at the range of 40-60 °C under half-load condition. However, when the load condition is at full-load, the MOSFET started to heat. The MOSFET could dissipate the heat to some level with the help of the heatsink. After operating at full-load condition for 4-5 minutes, we observed that the MOSFET heated up to 150 °C. The primary side diode didn't have a heatsink and it didn't heat up much. The diode on the secondary side had a heatsink and the heatsink was enough for the diode to dissipate its heat. The temperature of the diode on the secondary side stayed at the range of 30-45 °C.

At the last part of the demo, the load regulation is tested on our circuit. When the load condition is changed instantaneously from half-load to full-load, the MOSFET is heated up to 200°C in a short while and exceeded the maximum junction temperature limit. As a result, the MOSFET failed.

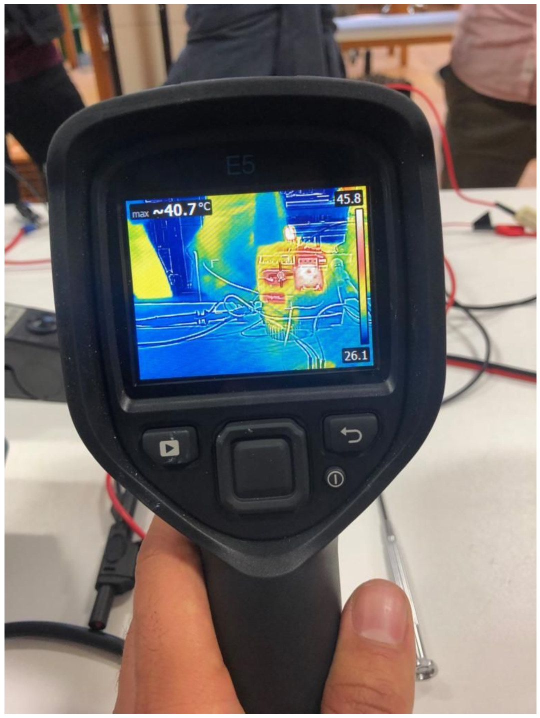


Figure 22 – RLC meter readings for the transformation leakage parameters.

Figure 23 – RLC meter readings for the transformation leakage parameters.

IV. COST ANALYSIS

The total cost of the components are calculated as 14.5 $ and given in the Table 2. Not all the components listed in the Table are used in the overall design. Considering the price of the components only used in the circuit, the total cost becomes 6.4 $.

Table 2 - Total Cost of the Project

Unit Name	**Price**
MOSFET (4)	6 $
Diode (3)	1.14 $
Electrolytic Capacitor (20)	0.46 $
Ferrite Core	3 $
Connectors (10)	0.9 $
Optocoupler (3)	3 $
TOTAL COST	**14.5 $**

V. CONCLUSION

In this project, we designed and implement a regulated power supply. We chose Forward Converter 5 topology whose specifications are given in the Introduction part. In the beginning, we designed the circuit of the converter in Simulink according to desired parameters. Then, we designed the magnetic materials which are transformer and inductor. While doing this, we made a core and wire selection according to desired operation. After completing of all design process, we chose the components which we will use according to their current and voltage limits etc. and we built a transformer and inductor. One of the main benefits of this project is the practical application of magnetic materials.

We designed a controller because the switching of the MOSFET will be done by a PWM signal that is created by a closed loop digital controller. Then, we demonstrated the implemented system and get some test results which are explained in detail in this report. To sum up, we learned a lot of practical application information while doing this project. We struggled with many problems in the process of demonstrate. For example, detecting and solving core saturation problem of transformer, providing isolation between the input and output voltage levels to implement a controller by using Arduino, and implementing closed loop circuit by giving feedback from output. All these process gave us many important experiences for our engineering career. As a result, this project improved us in power electronic area thanks to its special experiences.

VI. REFERENCES

[1] https://www.onsemi.com/pub/Collateral/AN-4134.PDF

[2]https://www.mag-inc.com/Design/Design-Guides/Transformer-Design-with-Magnetics-Ferrite-Cores

[3]https://www.mag-inc.com/getattachment/Design/Design-Guides/Inductor-Design-with-Magnetics-Powder-Cores/CoreSelectionChart2017.pdf?lang=en-US

[4]http://keysan.me/presentations/ee464_magnetic_design.html#1

VII. APPENDIX

```
int Duty = 18;
int PWM = 5;
void setup() {
  Serial.begin(9600);
  pinMode(5, OUTPUT);
  TCCR2B = TCCR2B & B11111000 | B00000001;
}
void loop() {
  int Volt = analogRead(A1);
  Volt = map(Volt, 0 , 1023 , 0 , 100);
  if (Volt == 0) {
    Duty = 18;
    analogWrite(PWM, map(Duty, 0, 100, 0, 255));
  }
else if (Volt <= 58) {
  Duty = Duty + 0.25;
  if (Duty < 0) {
    Duty = 0;
  }
  if (Duty > 45) {
    Duty = 45;
  }
  analogWrite(PWM, map(Duty, 0, 100, 0, 255));
}
else if (Volt > 58) {
  Duty = Duty - 0.25;
  if (Duty < 0) {
    Duty = 0;
  }
  if (Duty > 45) {
    Duty = 45;
  }
  analogWrite(PWM, map(Duty, 0, 100, 0, 255));
}
delay(250);
```

Figure 24 – Arduino code written for the PWM generation of the digital controller.