MIDDLE EAST TECHNICAL UNIVERSITY

Department of Electrical and Electronics Engineering

EE464 Hardware Project Report

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Table of Contents

1- Introduction

In this report, Hardware Project, namely Forward Converter #3 for EE-464 course is documented. It explains the design process, material selection & cost analysis, obtained results, challenges faced during the project and includes a conclusion that summarizes the whole process. The specifications for the converter are explained in the Table-1. In order to get this input and output characteristics the PWM applied on the switches, which is done by an Arduino Nano module. As the input voltage increases PWM ratio decreases and vice versa. Also the line regulation is controlled by the controller algorithm as well. Other specifications such as output voltage peak to peak ripple is regulated through the choice of the inductor. All the problems that we have endured will be explained throughout this report as well as the design process, simulations, cost analysis and the outcome of the final implementation.

The whole schematic of the converter can be seen in the Figure-1.

Minimum Input Voltage (V)	Maximum Input Voltage (V)	Output Voltage (V)	Output Power (W)	Output Voltage Peak to Peak Ripple (%)	Line Regulation (%)	Load Regulation (%)
24	48	10	40	2	2	2

Table-1: Specifications of the forward converter design

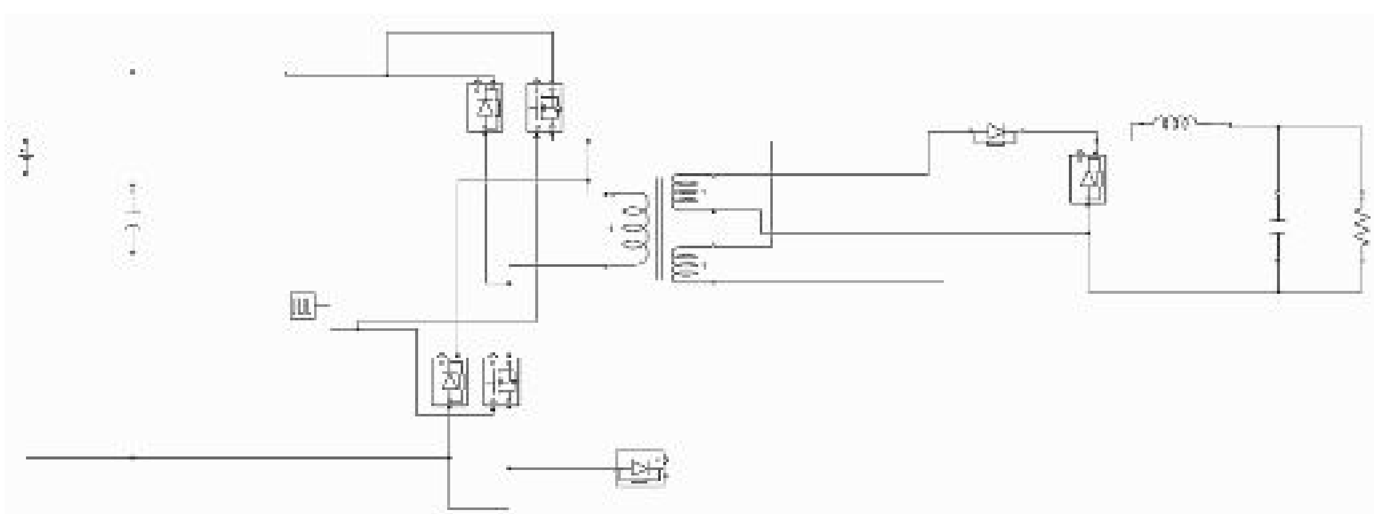

Figure-1: Whole circuit schematic of the double switch forward converter

2- Forward Converter Design and Component Selection

2.1 Transformer Design

Magnetic design is the most crucial part of the project. In the previous report, detailed transformer design process was explained. After the first test of the transformer, we realized that we did not consider the voltage drops on the diodes, so the output voltage of the converter did not reach the desired value. Therefore, we had to rearrange the turn ratio of the transformer. The new turn ratio is 16:20 for primary and secondary windings. Turn ratio of the primary and third windings is 16:16 as typical applications. This change did not affect the transformer core type because of the core size calculation formula as seen in the below equation.

$$A_p = A_w * A_e = \left[\frac{11.1 * P_{in}}{0.141 * \Delta B * f_s}\right]^{1.31} * 10^4 (mm^4)$$

where ΔB is the operating flux density change in each cycle, P_{in} is the input power and f_s is the switching frequency. A_w indicates the window area and A_e indicates the cross-sectional area of the core in mm^2 as shown in the Figure-2. This formula gives us the minimum size of the core. For safety, we selected the core whose A_p value is a bit more than the theoretically calculated one.

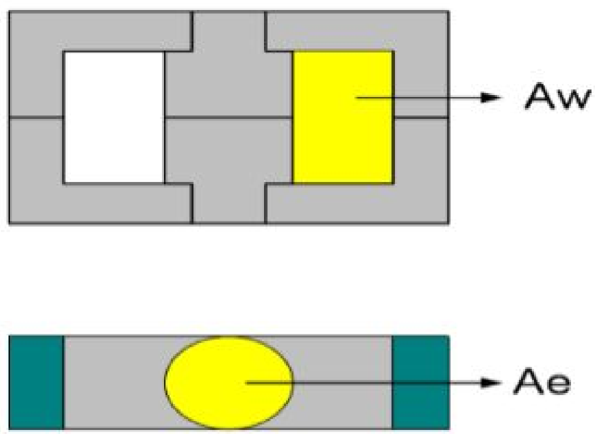

Figure-2: Window area and cross-sectional area of the core

In the above formula, we determined the input voltage by assuming that the converter has 70% efficiency and determined the flux density change by looking at the datasheet of the core as seen in the Figure-4 and selected the core with part number 00K4022E090. Its saturation flux value is 1 Tesla as seen in the Figure-3. Change of the flux density in each cycle is about 0.1 T in accordance with the Figure-5 which means that our transformer is far from being saturated. In the above formula, flux density change is unknown, and we determined the A_p value iteratively by comparing the results in each iteration.

	MPP	High Flux	Kool Mμ	XFlux	AmoFlux	Iron Powder
Permeability	14-550	14-160	26-125	26-60	60	10 -100
Saturation (B_{sat})	0.7 T	1.5 T	1.0 T	1.6 T	1.5	1.2-1.4 T
Max Temp (°C)	200	200	200	200	155	Variable

Figure-3: Specifications of the selected core

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00K4022E090

110 Delta Drive
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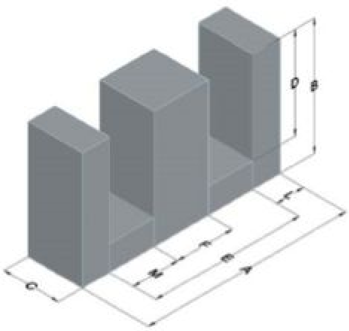

Kool Mμ Permeability (μ)	A_L (nH/T²)	Core Marking	
		Lot Number	Part number
90	281 ± 8%	XXXXXX	K4022E090

	Dimensions		Tolerance (±)			Packaging
	(mm)	(in)	(mm)	(in)		Box Qty= 168 pcs
A	42.85	1.687	0.635	0.025		
B	21.1	0.830	0.330	0.013		
C	20.0	0.788	0.254	0.010		
D	14.9	0.587	-	-	Min	**Available Hardware**
E	30.35	1.195	-	-	Min	**PCB4022N1**
F	11.9	0.468	0.254	0.010		
L	5.94	0.234	-	-	Nom	
M	9.27	0.365	-	-	Min	

Electrical Characteristics		Physical Characteristics					
Watt Loss @ 100 kHz, 100mT max(mW/cm³)	DC Bias min (A·T/cm)	Break Strength min (kg)	Window Area W_A(mm²)	Cross Section A_e (mm²)	Path Length L_e (mm)	Volume V_e (mm³)	Weight (Ea. Piece) (g)
902	80% 18.1	23	276	237	98.4	23,300	69

Notes:	Temperature Rating
	Curie Temp: 500°C

Figure-4: The selected core parameters

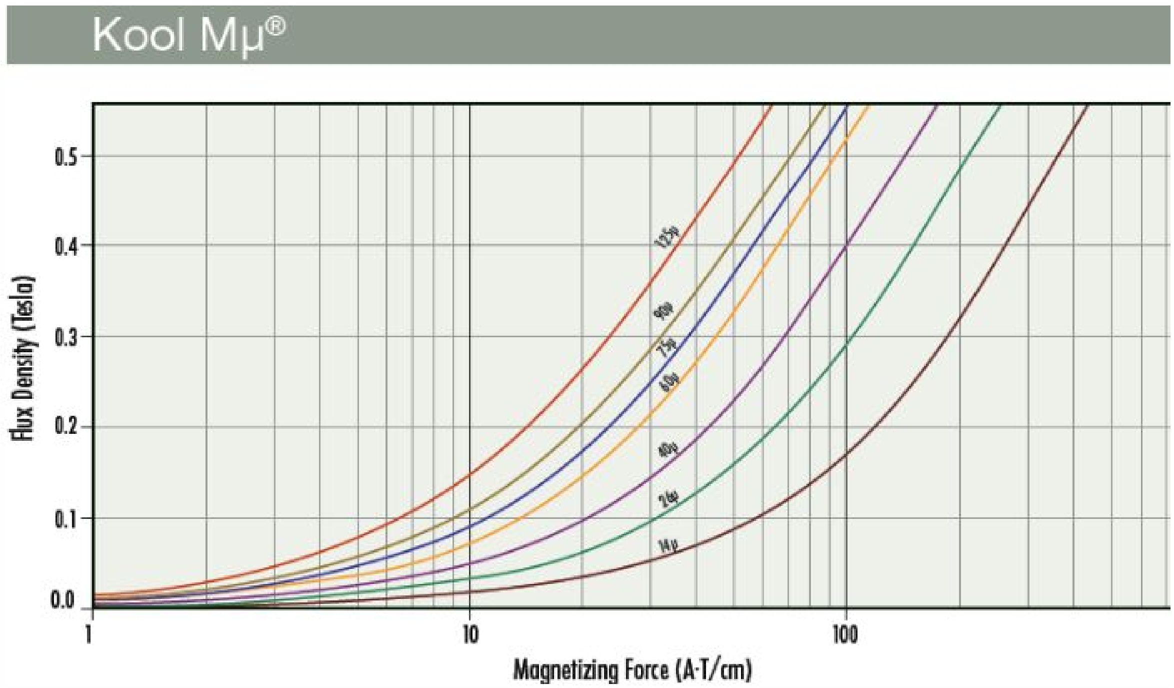

Figure-5: Flux density vs magnetizing force graph of the selected E-core

In the previous report, we have made a mistake by calculating the magnetizing inductance of the core. The magnetizing inductance can be calculated by using the following formula:

$$L_m = A_L * N^2 * 10^{-9}(H)$$

where A_L is the inductor factor which is change by DC bias and N is the number of turns. Considering the DC bias and different number of turns between primary and secondary sides, magnetizing inductance is calculated approximately 75 μH. The real value of the magnetizing inductance was found by using RLC meter as 71.2 μH and leakage inductance is 2% of the magnetizing inductance. Secondary side leakage inductance is a bit more than the primary side value.

After calculating the required parameters, we calculated the core loss on the transformer by looking at the graph as seen in the Figure-6. The operating flux density is about 0.1 T and the switching frequency is 32 kHz, so core loss density is about 110 mW/ cm^3. The core volume is 23.3 cm^3 ,so the approximate core loss is 2.5 Watts.

We used framework to simplify the winding. Thus, we considered the proximity effect and we made interleaving windings. At the end of the project, our transformer is the best working part of the converter. Its losses and temperature rising were very less.

We made double switch topology, so 3rd winding is unnecessary, but we did not sure to run double switch topology, so we designed the transformer for both topology; single switch and double switch.

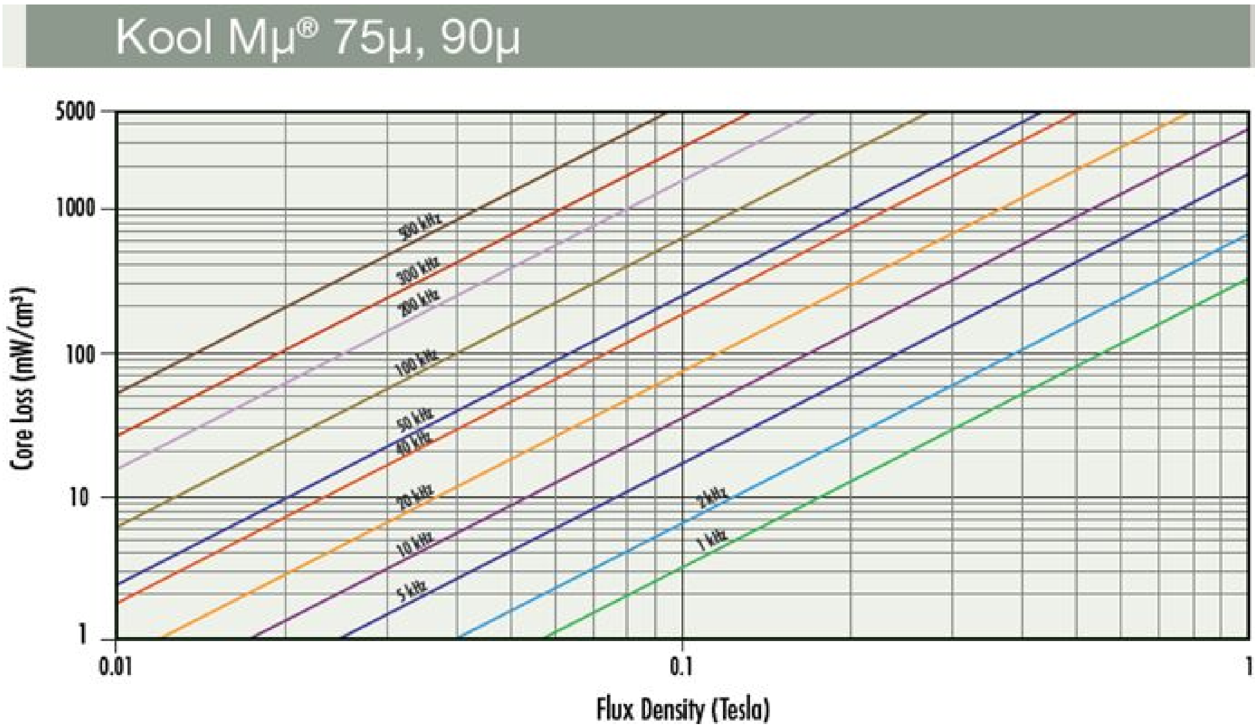

Figure-6: Core loss density vs flux density graph of the core

2.2 Inductor Design

In the previous report, we designed an output inductor as 220 μH. After that, we changed the inductor value to minimize the output voltage ripple. We did not find a toroid core in the lab, so we used E-core for inductor as seen in the Figure-7. While selecting a core, we paid attention to inductor factor and core losses of the core. Higher inductor factor means a smaller number of turns, so less copper loss. Inductance of the inductor was determined by using the following formula:

$$L = A_L * N^2$$

We could not find the DC bias characteristics of the core, so we arrange the number of turns by trial and error. We will mention the experimental results of the inductance in test results section.

The advantage of using E-core is that it has high inductor factor. The disadvantage of using E-core instead of toroid is that its bigger size.

We tried to wind the core firmly, but we did not as successful as winding the transformer. In the operation, sometimes its windings were vibrating and made noise.

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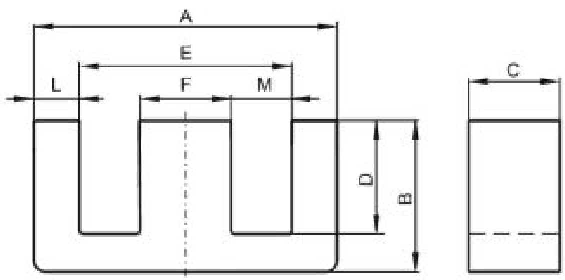
DIMENSIONS



(mm)	Nominal:	Tol. min.:	Tol. max.:
A	43.0	-1.7	0.0
B	21.0	-0.2	+ 0.2
C	20.0	-0.8	0.0
D	14.8	0.0	+ 0.6
E	29.5	0.0	+ 1.4
F	12.2	-0.5	0.0
L	6.75 Nom.		
M	8.65 Nom.		
Eff. Parameters			
Ae mm^2	Amin mm^2	le mm	Ve mm^3
233.0	233.0	97.0	22700

INDUCTANCE

AL value (nH)	Test conditions
Nom: 6013 Min.: 4510	10 kHz, < 0.5 mT, 25 ℃

MARKING

0P44022EC PXXXXX

CORE LOSSES

P_l max	Test conditions
128 mW/cm^3 (2.9 W/set)	100 kHz, 100 mT, 100 ℃

Figure-7: The selected core parameters

2.3 Output Filter Design

The main consideration with the output capacitor is that is should withstand tho output voltage. Since we have 10 volts for output, we do not really need a particularly expensive or bulky capacitor. We picked a 16 V 47 uF capacitor.

In order to have 2% ripple on the output, we have used the formula below to figure out the output inductor:

$$\Delta i_{Lo} = \left(\frac{n_3}{n_1} \cdot V_i - V_o \right) \cdot \frac{1}{L_o} \cdot t_{on}$$

⇨ Lo = 2.2 mH

The final value of the inductance of the inductor is 2.6 mH which will be mentioned in the test results section. Core selection part were told in the previous section.

2.4 Diodes

At first, we did not spend a lot of time thinking about the diodes and we were thinking “All we need is a diode that can withstand our maximum voltages and currents, what could possibly go wrong?”. However, we figured out the hard way that when you buy random diodes off Konya Sokak, they might not do the job well. The first ones that we bought were considered “slow diodes”. They were heating up a lot and they were causing a lot off loss on the system. After this incident, we figured that we needed fast diodes to reduce the loss.

After buying the fast diodes, their operation was smooth and relatively low loss.

2.5 Mosfets

The bane of our existence was the switches. The first MOSFETs that we bought off Konya Sokak were complete trash, and it took a lot of time for us to figure out that we they were both slow and high resistance.

After buying the new ones(IRF640), the performance improved, however, they were heating up a lot. Later we figured out that the gate resistor was quite important as well. The resistance amount was directly affecting the losses on the MOSFETs. Firstly, we were using 1k gate resistance. As expected, this was rubbish because it was causing a lot of losses. Then we tried 10 ohms, however, we could not get the MOSFETs to work with this resistance value. Lastly, we used 47 ohms, which apparently was doing the job.

2.6 Snubbers

At the earlier design steps, we actually decided to go with a single switch and a reset winding. After winding the transformer with a reset winding, with the incentive provided from Ozan Hoca saying that it wasn’t that hard to implement two switches, we decided to spice things up by making the converter double-switched. We kept the reset winding, so that we could go even higher duty cycles than %50 if we felt the need.

When we built the whole circuit for the first time, we didn’t really thoroughly and we used a single optocoupler for both of the MOSFET’s gates. Of course, this didn’t work and when we figured out that we actually needed two optocouplers and two external power supplies for optocouplers, we realized that having two switches was easier said than done.

At first, one might think that “Hey, it’s a double-switch forward converter, it’s silly to have snubbers installed parallel to the MOSFETs.” We have had the same train of thought, but when we saw that the MOSFETs were hitting 200 degrees celsius, we figured that we needed to do something about it. When we could not get the two-switch to work, we decided to go one switch since we had a reset winding. We prepared a snubber with 100-ohm resistor and 100 nF and observed that it was somehow working. When we saw that the converter was working, we decided to go one step further and implement two snubbers at two MOSFETs.

For testing purposes, we didn’t implement the same resistance for each snubber. First snubber had 100 ohms and 100 nF, the other one had 200 ohms and 200 nF. Later we figured out that both were working fine, and we were really scared if we played any more with the circuit, we might have had screwed things up and we let the snubbers be uneven.

2.7 DC-link Capacitor

The power supply that we used for the demonstration is unable to take power back, so double switch converter has lost its meaning. We used DC-link capacitor, so we supplied power to the capacitor instead of power supply. The DC-link capacitor stores the charges that we were trying to pump back into the source and sending them back to the circuit on the next cycle. We picked a 100V 330 uF capacitor.

3- Non-Ideal Simulation Results

We used the following circuit to figure out the voltage ripples and potential losses of the circuit.

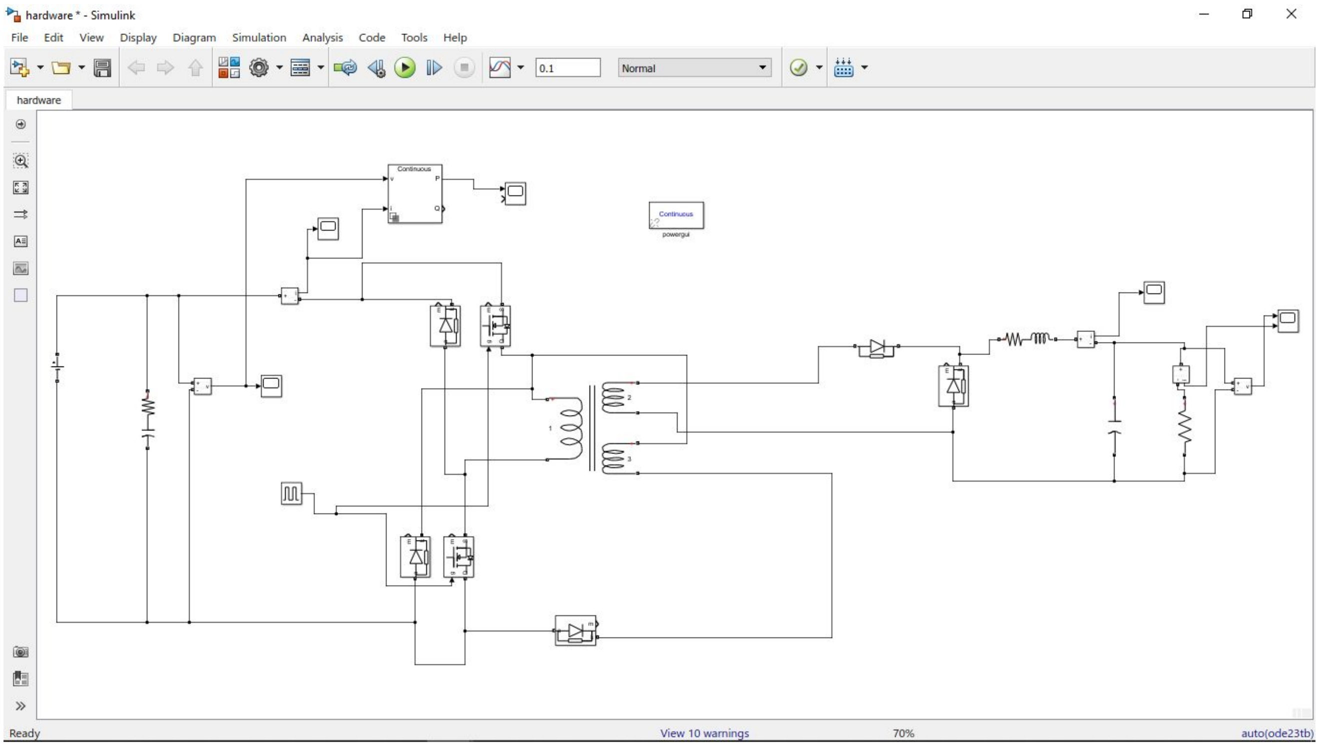


Figure-8: Test circuit of the non-ideal converter

When we inspect the input current, we see that it was able to pump the charges back to the source. The input current waveform is shown in the following figure.

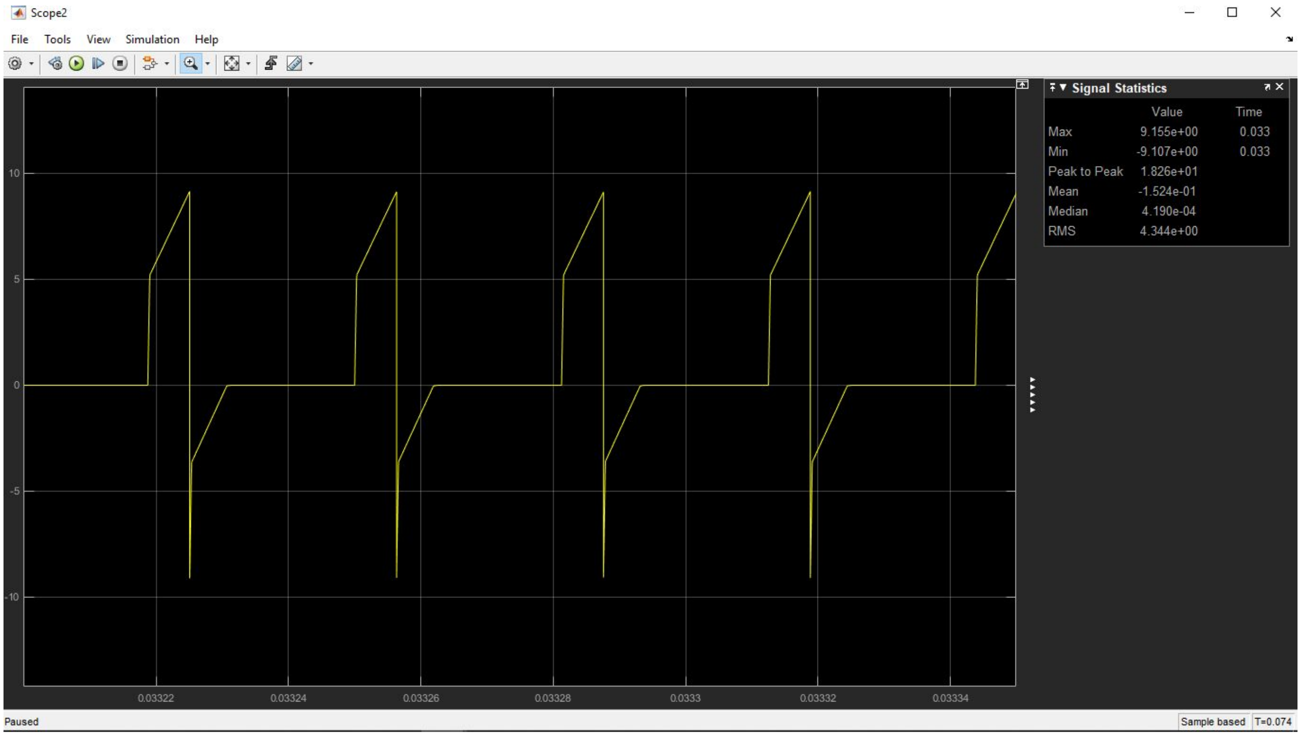


Figure-9: Input current waveform of the converter

We have checked if the system corresponds to the power requirement of the project. Input and output power of the simulation are shown in the Figure-10, Figure-11, and Figure-12.

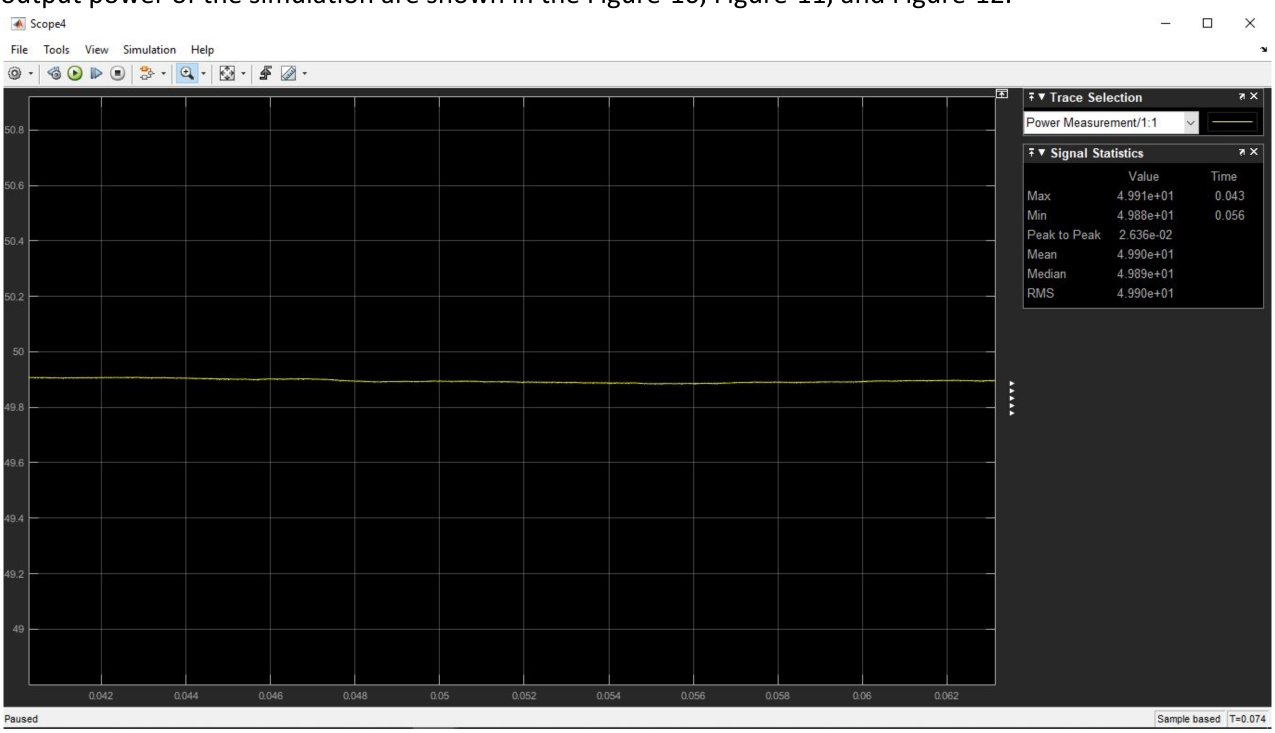


Figure-10: Input power of the converter

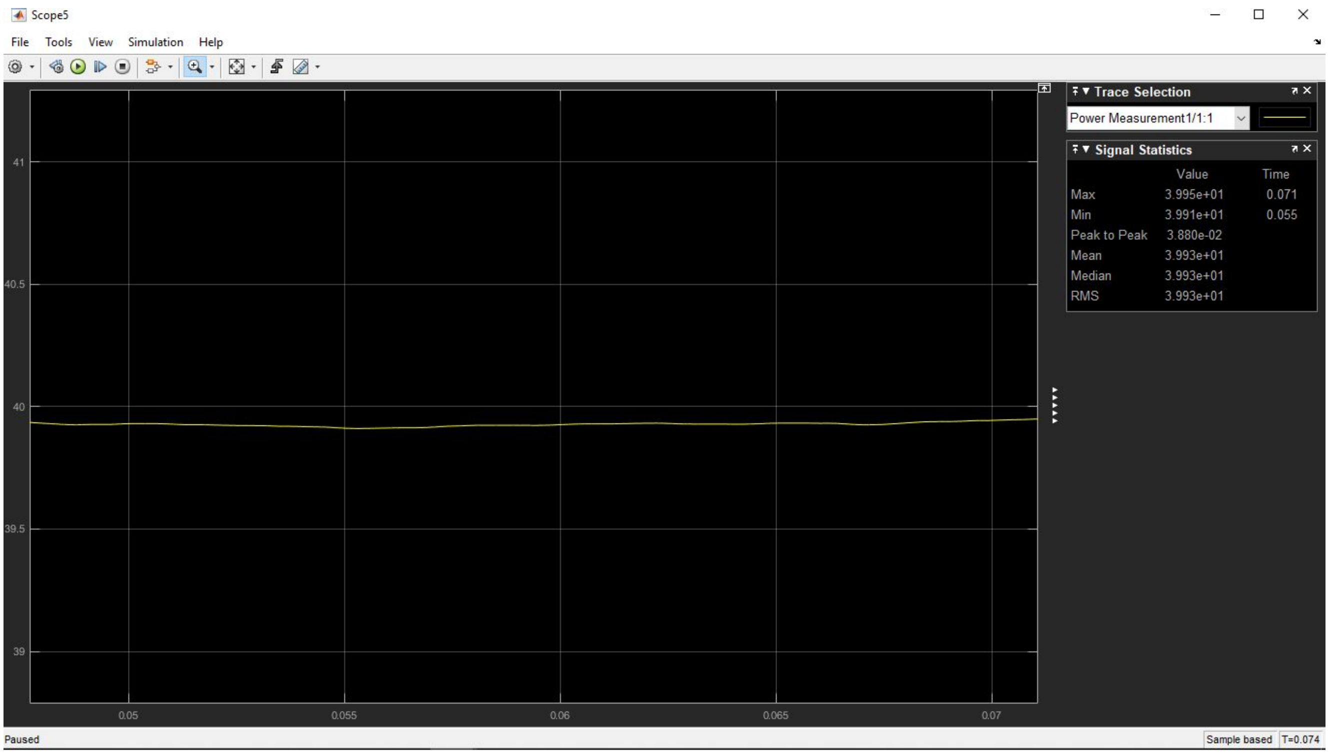


Figure-11: Output power of the converter

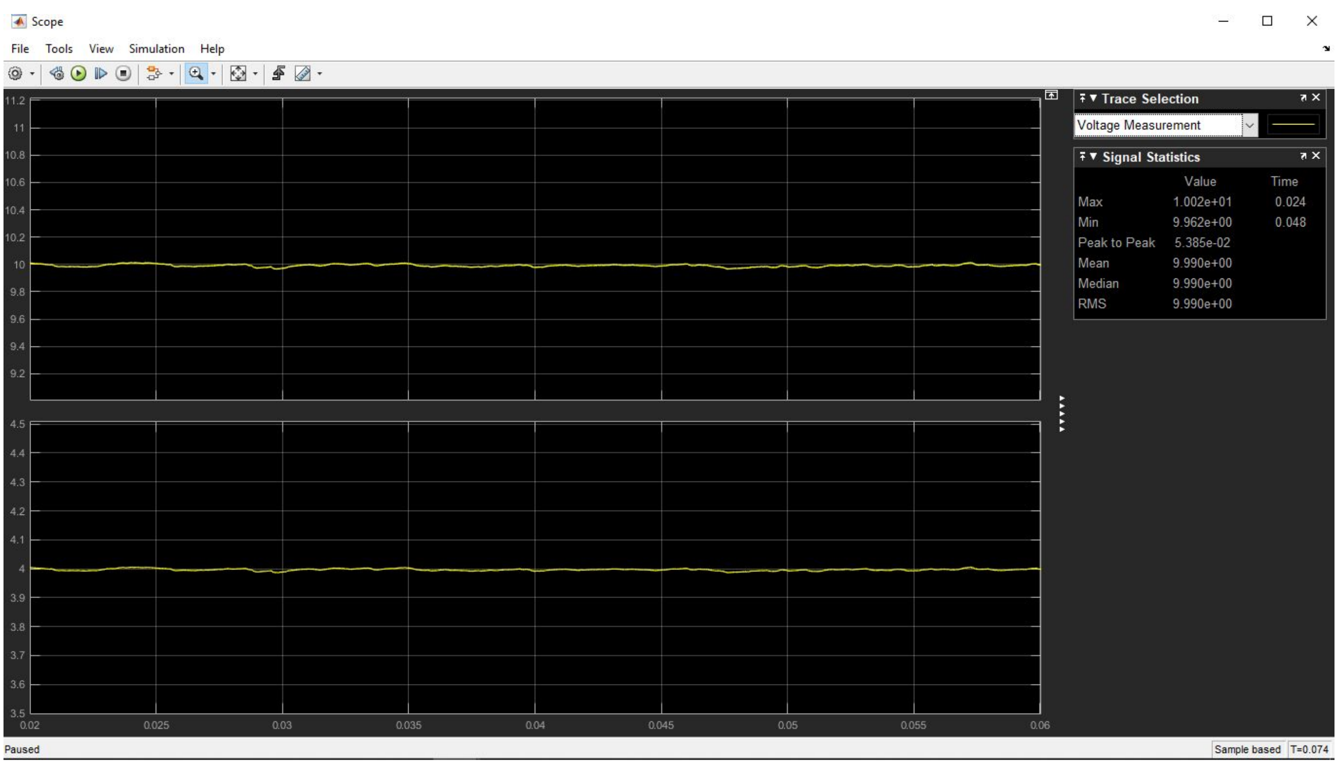


Figure-12: Output voltage and current waveforms of the converter

Upon inspecting the output, everything is normal and as we wanted. The efficiency is around %80, and life is good. However, when we snap back to reality, our converter's efficiency was around %60. One of the reasons behind this was our snubbers were found with trial and error and is far from optimal. Also, the 47 ohm resistor at the gate of the MOSFET's were quite high, and that was causing us to have a lot of switching losses on them. Lastly, even though we had the capacitor on the input, it is not an optimal solution and causing us some losses.

Lastly, we checked the drain-source voltage of the mosfets as seen in the Figure-13.

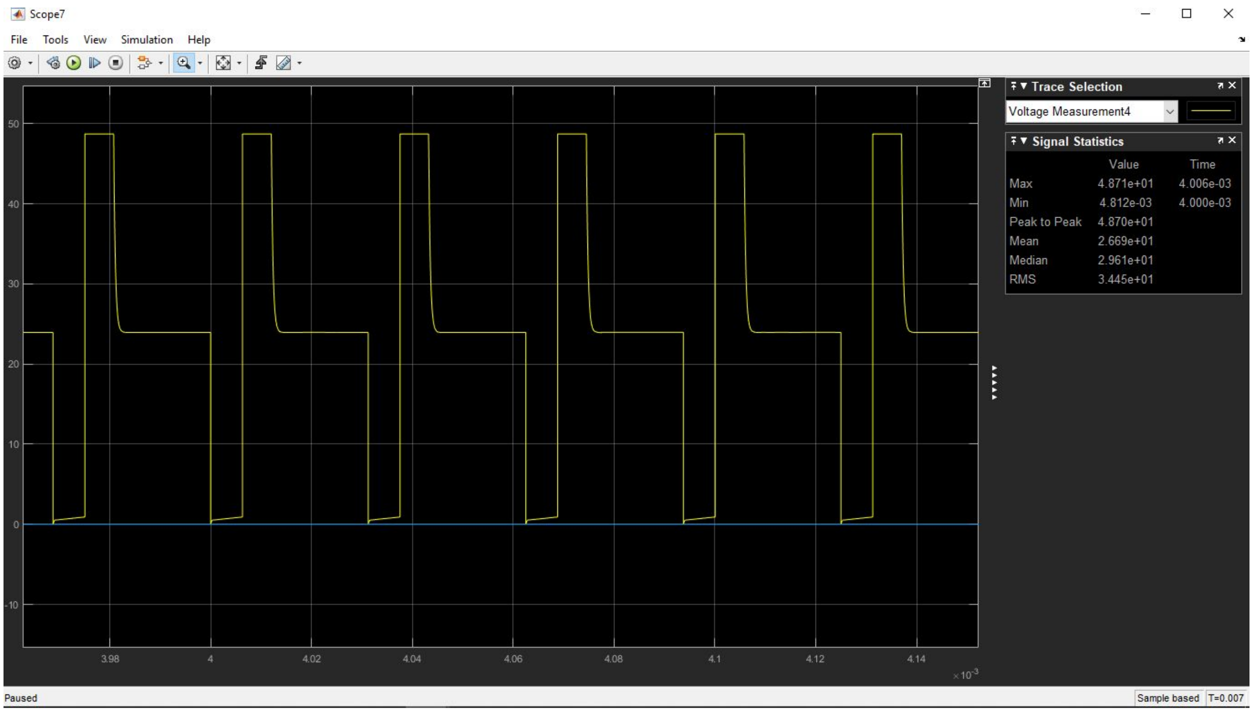


Figure-13: Drain-source voltage waveforms of the mosfets

4- Control Algorithm

The algorithm that we used is a simple Arduino code that compares the feedback from the output voltage with the reference voltage. In the table below, the Arduino code that we used can be seen.

```
 void setup() {
 Serial.begin(9600);
 pinMode(Vcontrol, INPUT);
 pinMode(feedback, INPUT);
 pinMode(PWM, OUTPUT);
 TCCR2B = TCCR2B & B11111000 | B00000001;    // pin 3 and 11 PWM frequency of 31372.55 Hz
}

void loop() {
 int cont = analogRead(Vcontrol);
 int output  = analogRead(feedback);
 dummy = pwm;

   if (output > cont)
    {
     if (pwm < 60)
     {
    pwm = dummy -0.5;
    pwm = constrain(pwm, 1, 127);
     } else
     {
      pwm = dummy-1;
      pwm = constrain(pwm, 1, 127);
     }
   }
   if (cont > output)
   {
    if (pwm < 60)
     {
    pwm = dummy+0.5;

    pwm = constrain(pwm, 1, 153);
     } else
     {
      pwm = dummy + 1;
      pwm = constrain(pwm, 1, 153);
     }
   }
  analogWrite(PWM,pwm);
  Serial.print(" PWM = ");
  Serial.print(pwm);
  Serial.print(" , Feedbac: ");
  Serial.print(output);
  Serial.print(" , control: ");
  Serial.println(cont);
 }
```

Table-2: Arduino code that we used in the demonstration

As it is obvious from this code that if the output voltage is smaller than the reference voltage, generated duty cycle must increase and if the situation is the other way around the generated duty must decrease while having a limit on the output as below 60%.

Also another notable feature of this code is that it employs a soft starting technique as it increases the duty cycle 0.32 percent (100*0.5/153) per cycle.

5- Materials and Cost Analysis

Used materials in the project and their costs are listed in the Table-3.

Name of the Component	***Number used and the cost***
Arduino Nano	1x30 =30 TL
Pertinax	1x15 = 15 TL
DC-link capacitor	1x13.5 = 13.5 TL
Inductor (leased only)	1x0 =0 TL
Transformer (leased only)	1x0 = 0 TL
Diodes	5x7.5 = 37.5 TL
MOSFET	2x5 =10 TL
TLP250	2x6.95 =13.9 TL
Input & Output sockets	4x1= 4TL
AWG 21 cable (in 1m unit)	6x1 = 6 TL
Total	129.9 TL

Table-3: Components of the converter and their costs

6- Test Results

In this section, some test results of the converter will be published and discussed.

6.1 Overall Design

We have built the circuit on stripboard. The size of the converter is bigger than the other projects because double switch topology has more components than other topologies and our inductor core is not toroid. The overall design can be seen in the Figure-14.

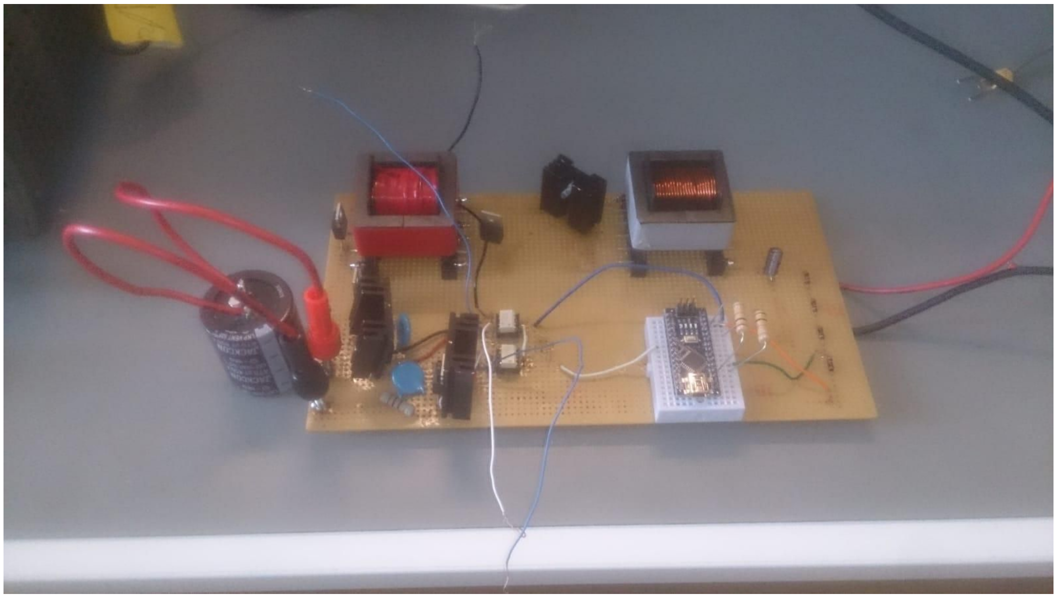


Figure-14: Overall design of the double switch forward converter

6.2 Gate Driver

We have looked and tested the output of the optocoupler. The output of the optocoupler is PWM signal with different duty cycles, so accuracy of the output of the optocoupler is very important to drive the switching element correctly. We add small resistance at the end of the optocoupler output to arrange the time constant of the PWM signal. We used small resistance because we want small time constant for fast response. Thus, the switching loss on the mosfet can be minimized. We tried different resistance values like 10 ohm and 47 ohms. The biggest mistake we made in this project was that we could not find the right value of the resistance and mosfet which is fast enough. For this reason, there was a lot of switching loss. In the thermal analysis, we also observed a lot of loss on the mosfet. An example of the optocoupler output is shown below.

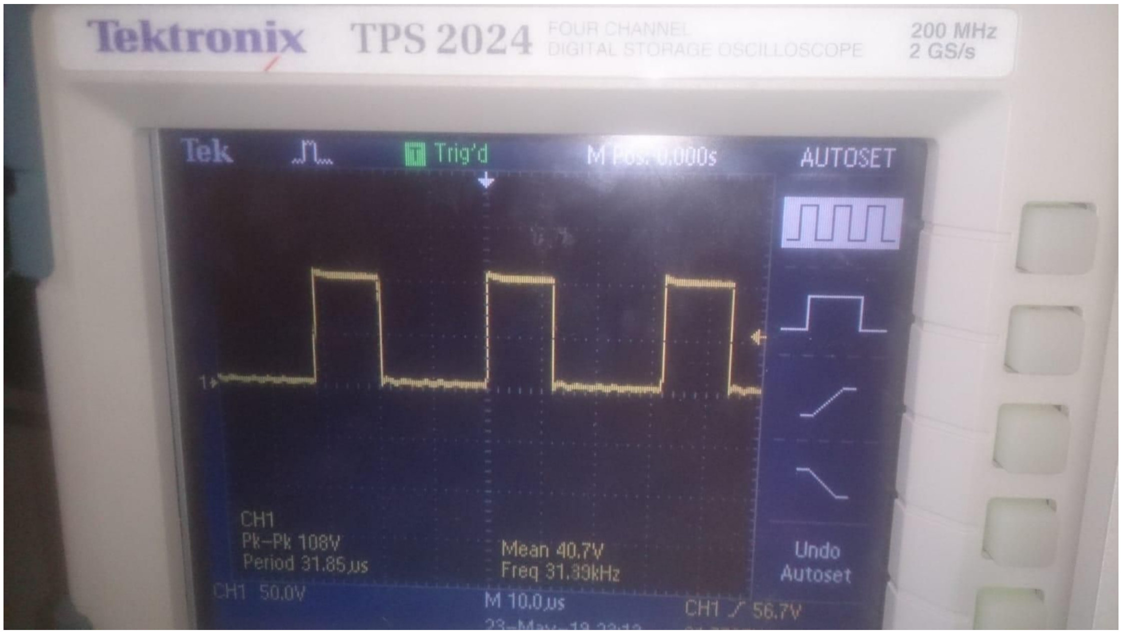


Figure-15: Output waveform of the optocoupler

6.3 RLC Measurement

Transformer and inductor inductances were calculated by using RLC meter. We used 3 measurement to obtain leakage inductances and magnetizing inductance. We connected the probs to the primary side of the transformer and open circuit to the secondary side. In this way, we measured the total inductance seen from the primary side. After that, we short circuited to the secondary side and measured the magnetizing inductance of the transformer. We found the leakage inductance of the primary side by subtracting the second measurement from the first measurement. The magnetizing inductance is 71.2 μH, primary side leakage inductance is 1.5 μH, and secondary side leakage inductance is 1.8 μH.

As mentioned in the inductor design part, we found inductance of the inductor experimentally. In the first effort, we winded 30 turns, and we measured 4.74 mH as seen in the Figure-16. Then, we checked the datasheet of the core and realized that core might be saturated. After that, we winded 22 turns, and measured 2.6 mH as seen in the Figure-17. This inductance value is suitable for saving the core from saturation.

Figure-16: Inductance of the 30 turns inductor

Figure-17: Inductance of the 22 turns inductor

6.4 Thermal Analysis

As we mentioned previous parts, the transformer and the inductor are well designed, so their losses are minimized. Their temperatures were not reached high values. The main problem of the converter was switching loss. Thus, most heated parts were mosfets and their snubber circuits as seen in the Figure-18. As a precaution, we mounted heat sink to the mosfets and secondary side diodes with thermal paste. With the heat sink, secondary side diodes were not a problem for us about thermal consideration. We had a backup plan as adding a fan to cool the mosfets and their snubber circuits, but there was no need to do that. The temperature value was not critical enough to damage the converter.

Figure-18: Thermal analysis of the converter

6.5 Output Characteristics of the Converter

The controller provided a constant 10 volts output voltage whether there was full load or half load. In the full load condition, 2.5 ohm, constant 4 amps flows the secondary side of the converter as seen in the Figure-19. Also, the Figure-20 shows that output voltage waveform (yellow one) and the reverse capacitor current waveform (blue one).

Figure-19: Output characteristics of the converter

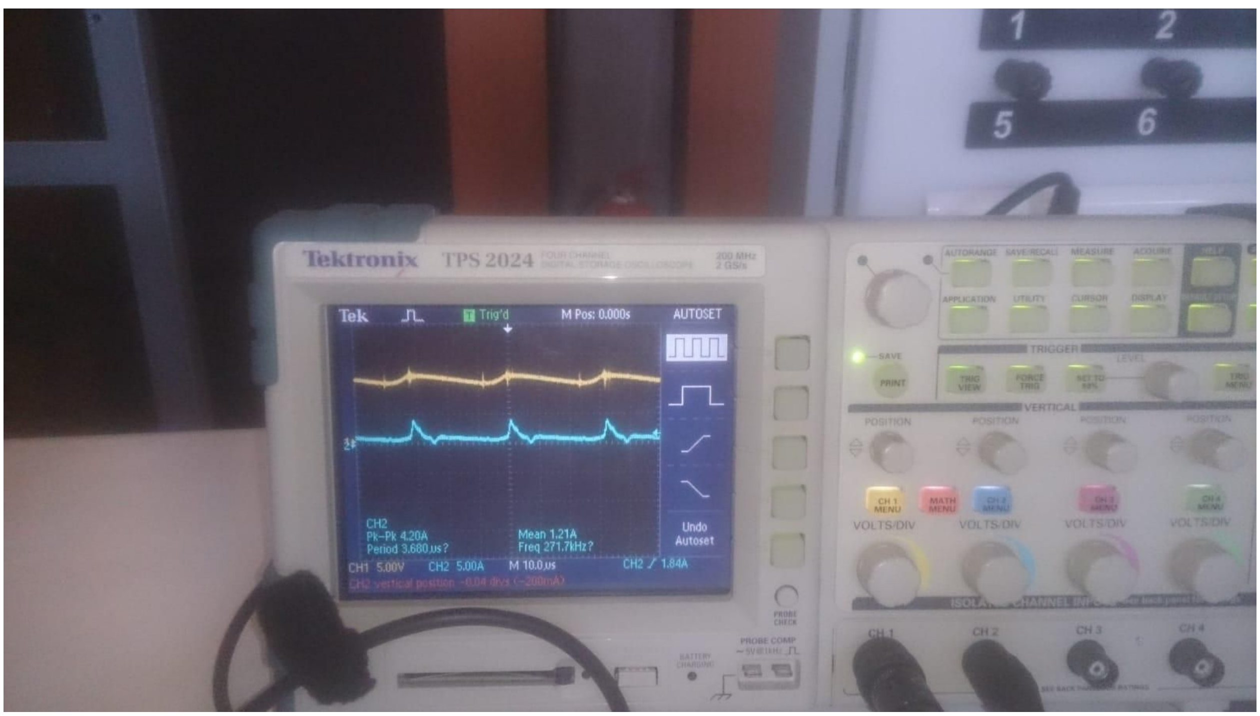


Figure-20: Output voltage waveform (yellow one) and reverse capacitor current waveform (blue one)

This double switch topology enabled us to supply power to the input capacitor instead of losses as heat. This feature is the main reason why we chose the double switch topology. In the next figure, oscilloscope probs were connected to the capacitor to observe the supplying power. Negative current value means that converter supply power to the capacitor.

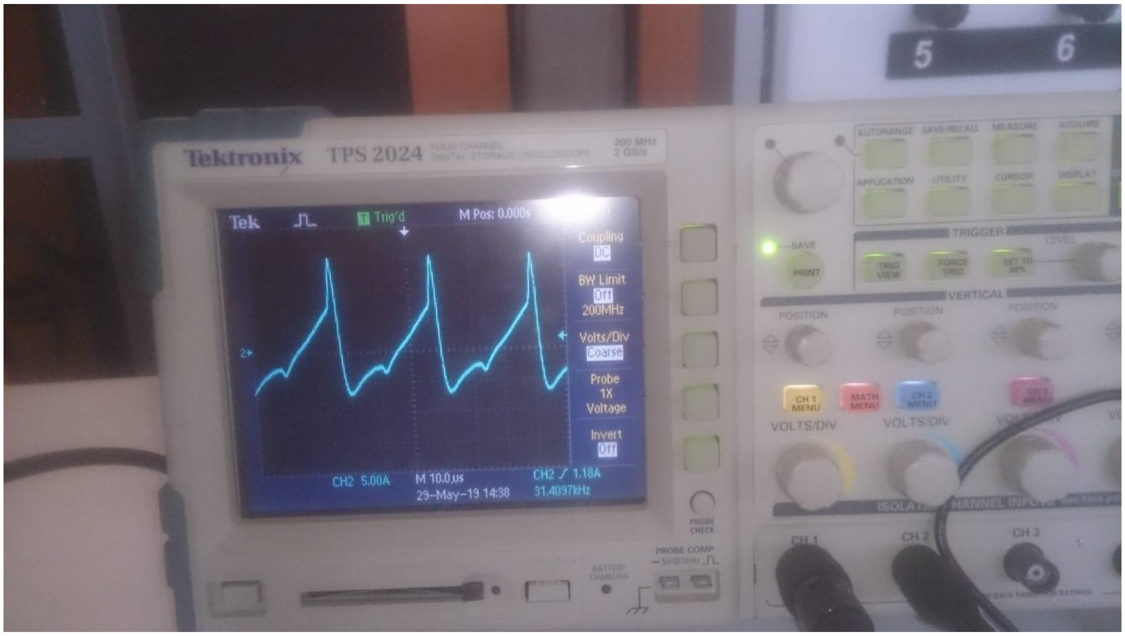


Figure-21: Capacitor current characteristic

6.6 Load Regulation Test

Load regulation is the capability of the supply to maintain constant voltage or current level on the output despite changes the load condition. A well-designed converter should have this feature. Thanks to the controller, our converter can respond to change in the load as seen in the Figure-22.

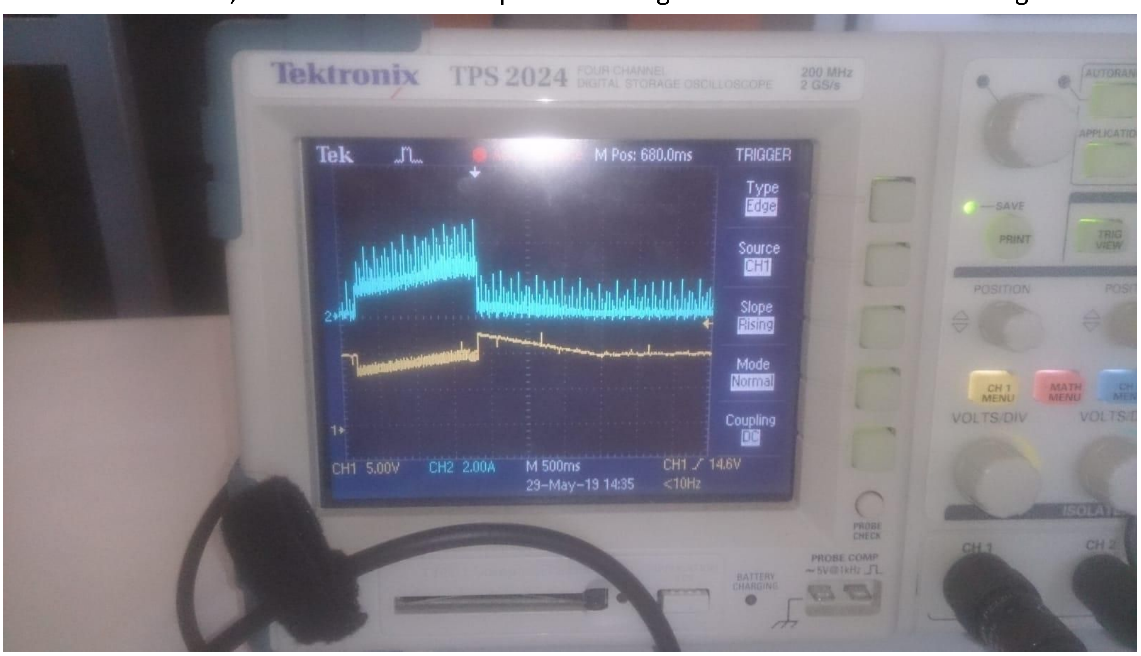


Figure-22: Load regulation test of the converter

7- Conclusion

In this report, all the design stages and implementation process are documented. It began by addressing the design specifications and continues with design stages such as the transformer design, inductor design, output filter design, diode selection, mosfet selection, snubber design, DC-link capacitor inclusion. Also, it includes the non-ideal simulation results. Later, it proceeds with the control algorithm, materials and cost analysis and the test results such as overall design gate driver RLC measurement, thermal analysis, output characteristics of the converter and the load regulation test.

Throughout this project, we made a great deal on how to implement a hand made, commercially applicable, isolated DC-DC converters. We learned the delicacies of hardware setup such as good soldering, choosing the right components and plan of action when it comes to implementing a design on a physical body maybe more so than the previous semester’s hardware project.