MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE464 Hardware Design Report

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1 Introduction

În EE464 (Static Power Conversion II) course hardware project has been announced. Our group "EMI Monster" selects flyback converter design with specified conditions given in Table 1.

Table 1: My caption

Project No	Vin (V)	Vout (V)	Pout (W)	Topology
9	230 AC	15	15	Flyback

We choose this project because flyback topology is more feasible to apply because of it does not require additional output inductance and third transformer winding to discharge magnetizing current. Moreover, our project needs to deal with high voltages but our load power is smaller than other projects therefore, overall design should require smaller components. In this report we have explained our hardware design for project, test results and component selection procedure.

2 Isolated Converter Design

2.1 Steady State Operation

In part a we were asked to implement the converter which converts 230 V_{rms} to 15 V output DC voltage. For this purpose, we implemented flyback converter. In flyback converter we used transformer and we adjusted the turns ratios of the transformer in order to have low voltage at the secondary side of the transformer. After that, by adjusting the duty cycle we obtained the 15 V output DC voltage. The circuit schematic of the flyback is in figure 1.

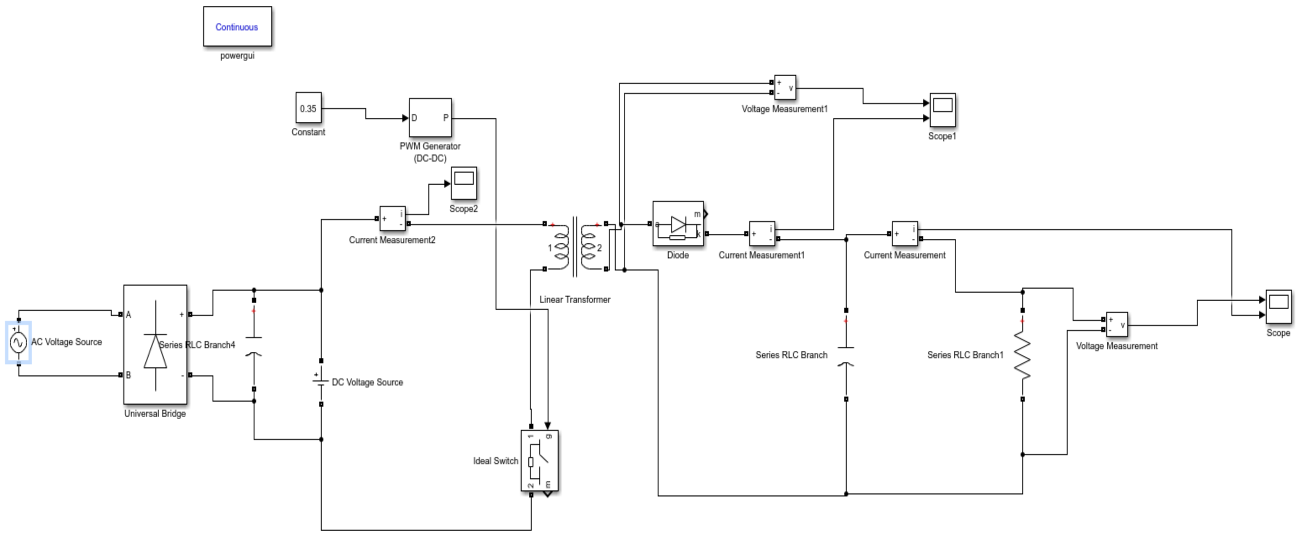

Figure 1: Flyback Converter Circuit Schematic

In flyback converter, in order to have an small magnetizing core size of the transformer,initially we decided the frequency of switch as 80 kHz. However our switching equipment turn on and turn off times are not suitable for this kind of high frequency switching, also switching losses are increased, so our switching frequency is reduced to 40 kHz. Moreover, with increasing switching frequency, all components size become smaller; such as filters, capacitors and inductors.

In order to obtain the proper duty cycle value we used the formula 1

$$[H]V_o = V_{in} \times \frac{N_s}{N_p} \times \frac{D}{1-D} \tag{1}$$

By using this formula we calculated the D value as 0.35. While calculating the duty cycle we used the turns ratio of the transformer as calculated in the section 2.2.

Moreover, we are using the full bridge rectifier and DC link capacitor in order to have the DC voltage at the input of the flyback converter. For this purpose we calculated the input voltage of the flyback converter by using the formula 2.

$$V_{dc} = 0.9 \times V_{rms} \tag{2}$$

By using the formula 2 the V_{in} voltage of the flyback converter is calculated as the 207 V.
However we couldn't consider the effect of rising DC Link voltage in the output. Since this hardware project has a small power output and high input voltage, primary current is really low. That's why capacitor can't discharge where sinusoidal waveform is crossing the zero

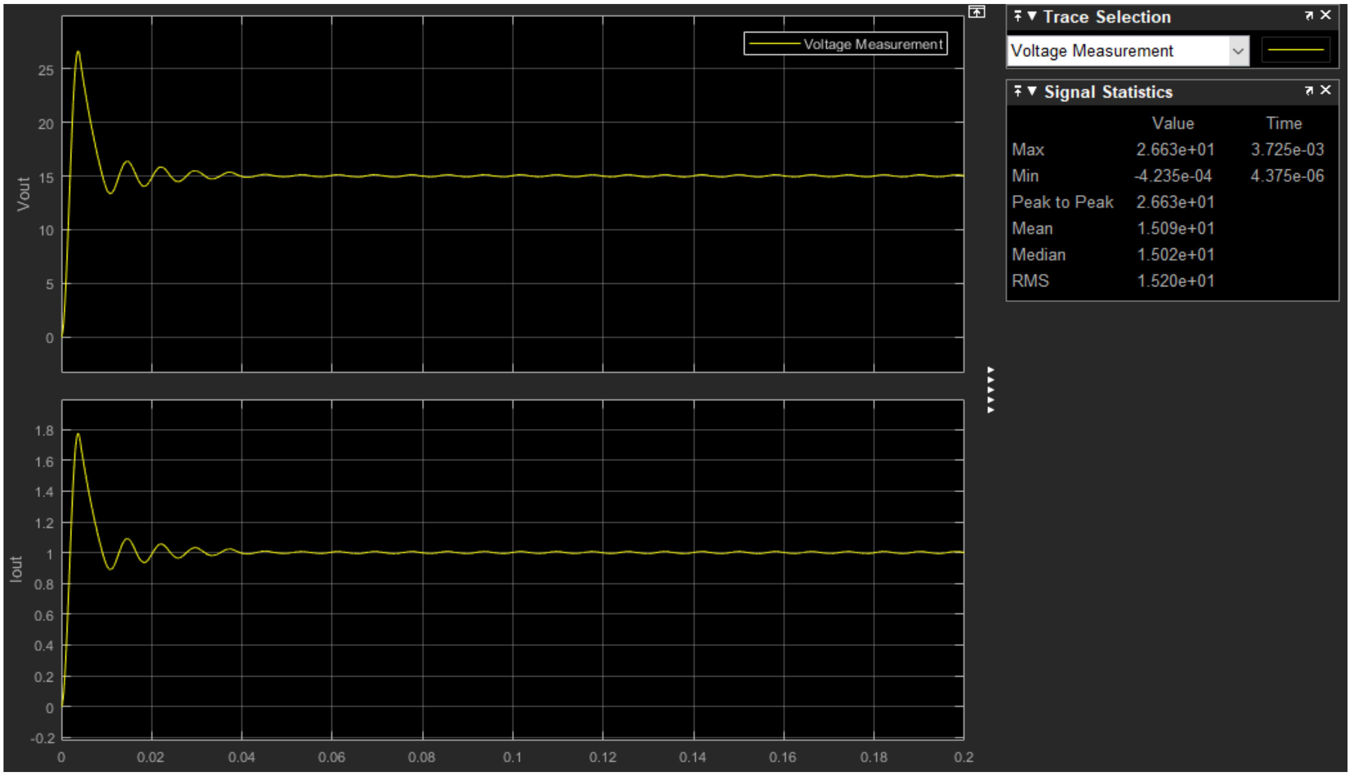

Figure 2: Output voltage and current graphs of the flyback converter.

point. Capacitor voltage can rise through the 325 V which is approximately equal to peak value of 230 V AC voltage.

The output voltage and output current graph of the flyback converter that we designed in the project is in figure 2.

2.2 Transformer Design

In this part we were asked to design a transformer. In order to design a transformer first we decided to geometry of the transformer and we selected the E shape core. After selecting the geometry of the transformer we decided to size of it. While deciding the shape of the transformer, we considered flyback switching frequency and the output power of the converter. Since our design has 15W power at the output at full load, we chose transformer which can operate well for 15W power. Chosen transformer is CF 139/E Core transformer. The transformer details are;

- Base Material of the transformer is MnZn
- Flux density at $25C^{\circ}$ is 490 mT
- Resistivity is 8 $m\Omega$

Also the data sheet of the transformer can be found in appendix section.

After choosing the transformer type, turns ratio of the transformer was decided. In order to finf the turns ratio we used the formula 3.

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \times \frac{N_2}{N-1} \tag{3}$$

Before using the formula 3, we chose the duty cycle as 0.35. In that way we found the turns ratio as "7:1" for the flyback converter.However rising DC voltage forces us to change the turns ratio to 13.33. With these calculated duty cycle and turns ratio we obtained the minimum magnetizing inductance value by using formula 4.

$$Lmin = \frac{(1-D)^2 \times R}{2 \times f} . \frac{N1}{N2}^2 \tag{4}$$

$$Lmin = \frac{(1-0.35)^2 \times 30}{2 \times 40kHz} . \frac{13.33}{1}^2 = 0.59mH$$

Also, in order to find how much we wind the primary and secondary windings of transformer we used the formula 5.

$$N_p > \frac{L_p \times I_{p,max}}{B_{sat} \times A_e} \tag{5}$$

Since our core's $A_e = 125mm^2$ and $B_{sat} value is = 0.3T$. We found turns number as;

- $N_p = \frac{0.59mH \times 0.145}{25mm^2 \times 0.3T} \approx 200$
- $N_s = N_p/13.33 \approx 6$

After all calculations we obtained the equivalent circuit parameters of the transformer. In other words, we are able to make an other calculations by considering those parameters.

2.3 Discontinuous Mode Calculations

Discontinuous mode is defined for flyback converter as; magnetizing current of transformer drops to zero in one cycle period. This condition is directly related to duty cycle of switching and inductance of the magnetizing branch. Magnetizing inductance can be found from the number of turns in the primary winding. This magnetizing inductance is calculated in 8.

$$Lmin = \frac{(1-D)^2 \times R}{2 \times f} . \frac{N1}{N2}^2 \tag{6}$$

We have designed our converter to operate at continuous mode when loading is 50%. Our nominal load is 15 Ohm. In our minimum magnetizing inductance calculation we calculated with 30 Ohm. As stated before our turns ratio is 13.33 (N1/N2), duty cycle is 0.35 (D) and switching frequency is 40 kHz (f).

$$Lmin = \frac{(0.65)^2 \times 30}{2 \times 40000} . \frac{13.33^2}{1} = 0.59mH \tag{7}$$

We expect to observe discontinuous mode of operation at higher resistances/ lower load currents than %50 loading case. Minimum current of magnetizing branch can be calculated in equation . Naturally at the edge of discontinuous minimum magnetizing current should be zero.

$$Imin = I_{lm} - \frac{\Delta Ilm}{2} \tag{8}$$

$$Imin = \frac{V_s \times D}{(1-D)^2 \times R} \times (\frac{N1}{N2})^2 - \frac{V_s \times D \times T_s}{2 \times L_m} \tag{9}$$

Using equation 9 we calculated the R value as:

$$R = \frac{2 \times L_m}{(1-D)^2 \times Ts} \times (\frac{N1}{N2})^2 = 29.98\Omega \tag{10}$$

This resulted is expected. In figure 3 one can find the simulation results for 30 Ohm load in secondary side of the transformer. In 30 Ohm load our minimum current for continuous operation is 0.5 A . In figure 4 shows the load current and voltage.

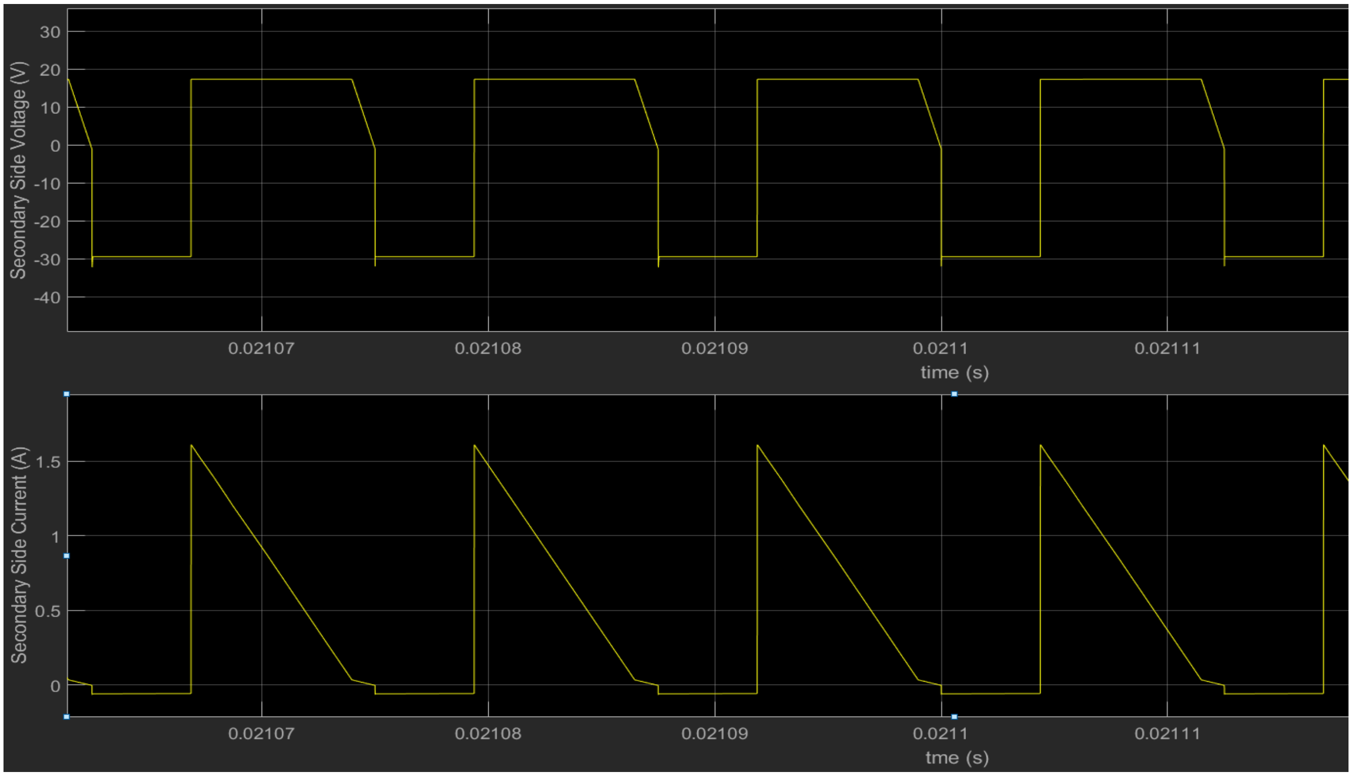

Figure 3: Transformer Secondary Side Voltage and Current Waveform

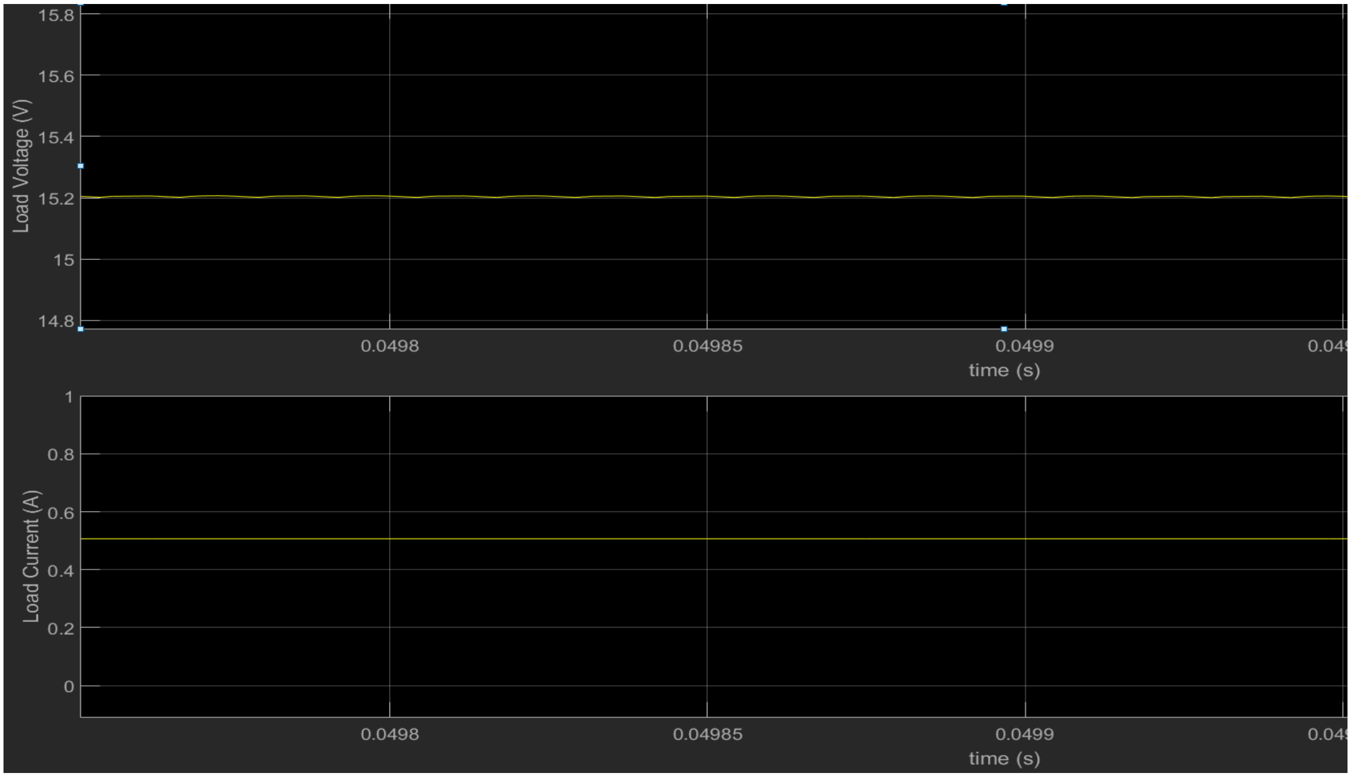

Figure 4: Load Voltage and Current Waveform at the Edge of Discontinuous

Our normal operation is shown in section 2.1. When we increased the load resistance 1 Ohm more we observed sudden voltage drop at the secondary terminals while switch is still operating at off condition. This kind of operation is not desired using a controller can solve this issue since our design is capable to compensate the increment in duty cycle up to 0.5 approximately.

2.4 Non Ideal Simulation

In this circuit we were asked to implement the same flyback converter with using the non ideal switches. The circuit schematic is in figure 5.

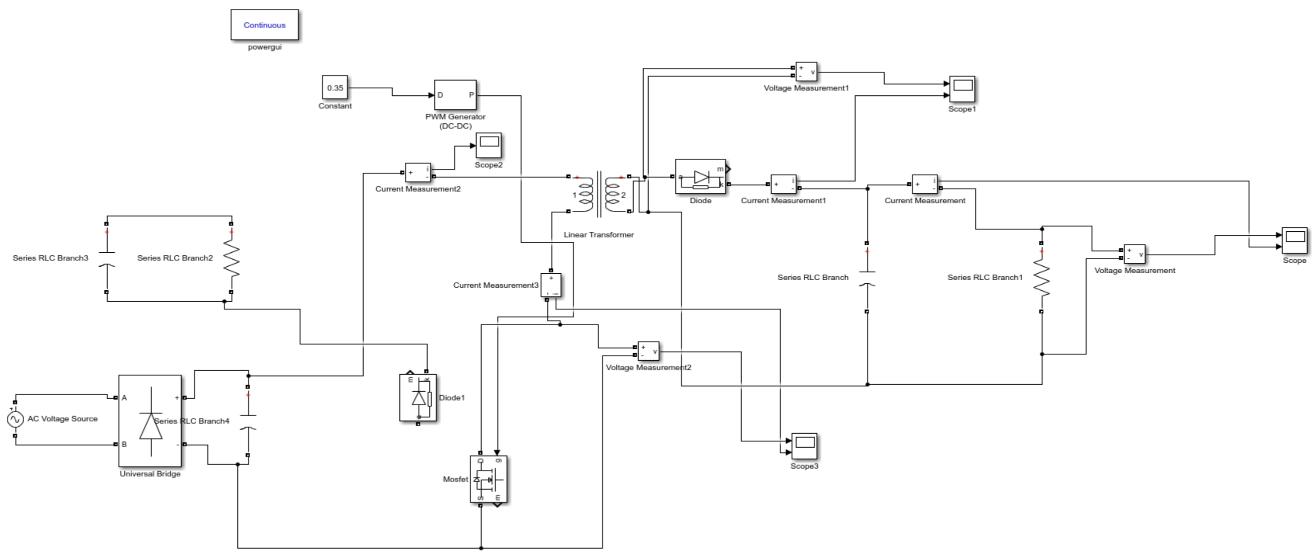

Figure 5: The circuit schematic with non ideal switches and without snubber circuit.

The switch voltage and current graph is in figure 6.

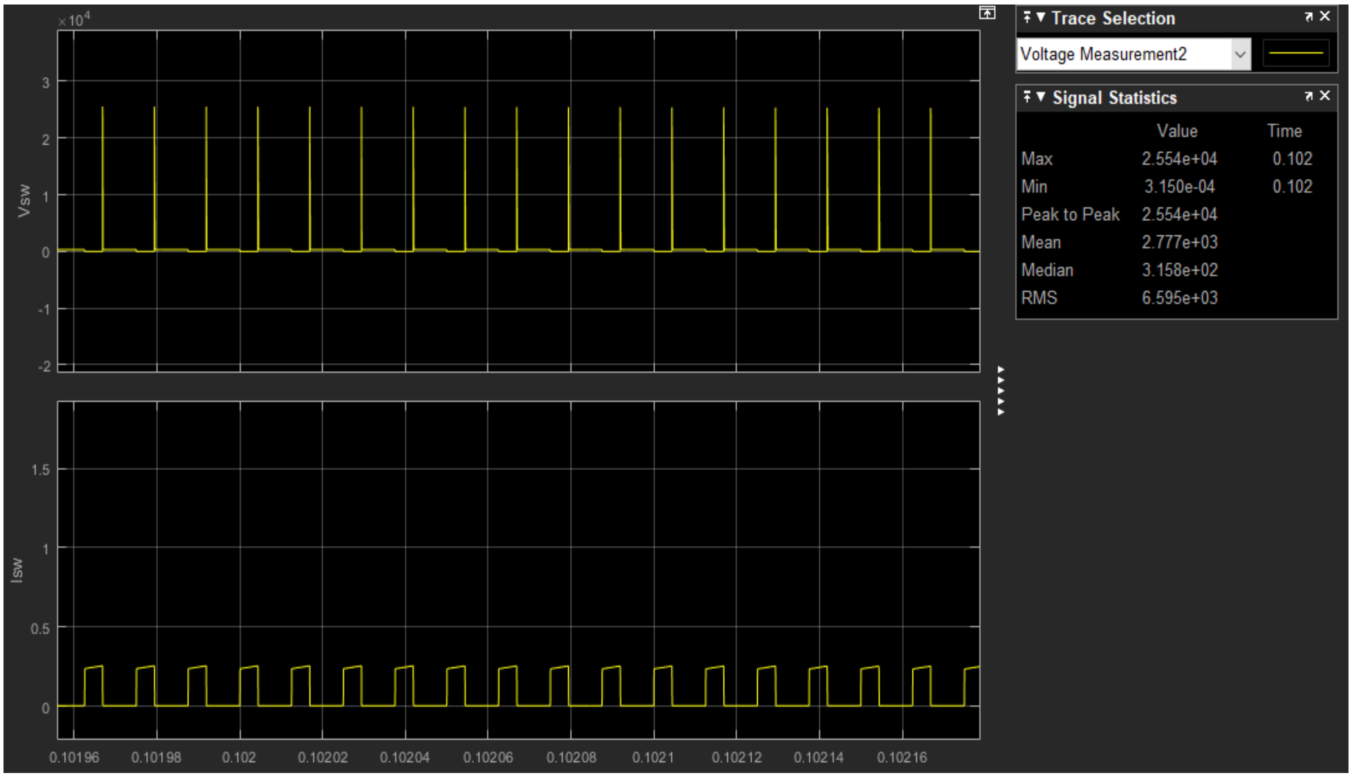

Figure 6: The switch voltage and switch current graph of the flyback converter.

As it seen from the figure 6 when we use the non ideal switch and not using the snubber circuit, voltage is increasing to $2.5444 * e + 04$. It is serious problem for the switch component since it sees very high voltage when the switch is off. Therefore, we need the snubber circuit for protect the switch from high voltages.

The flyback converter with the snubber circuit is in figure 7.

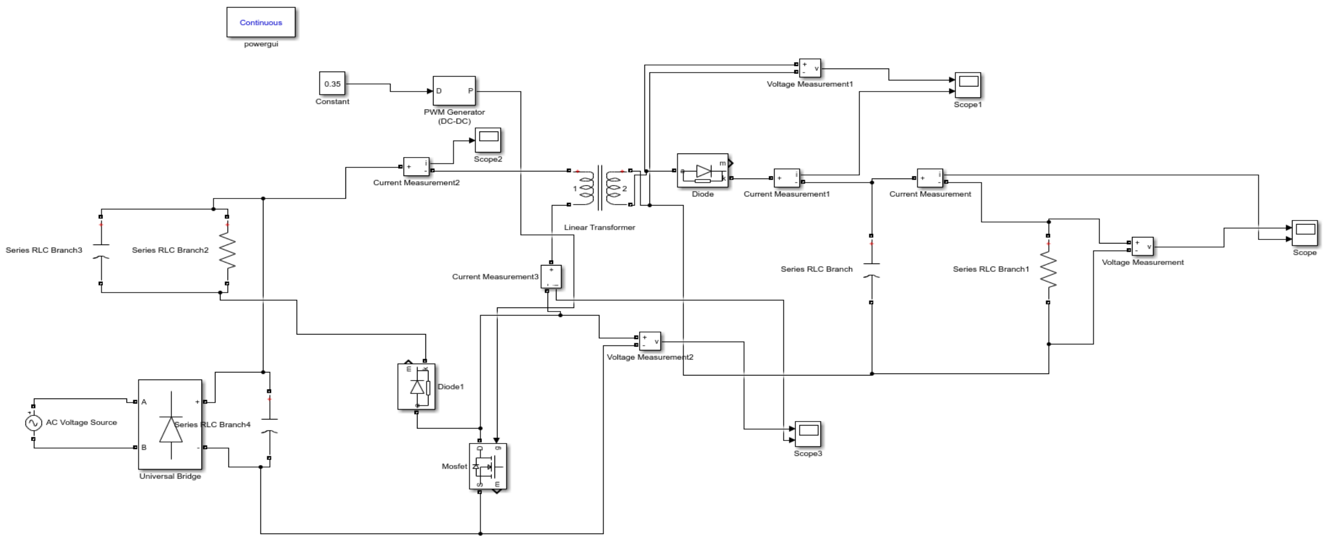

Figure 7: The flyback converter with snubber circuit.

The voltage and current of the switch graph is in figure 8.

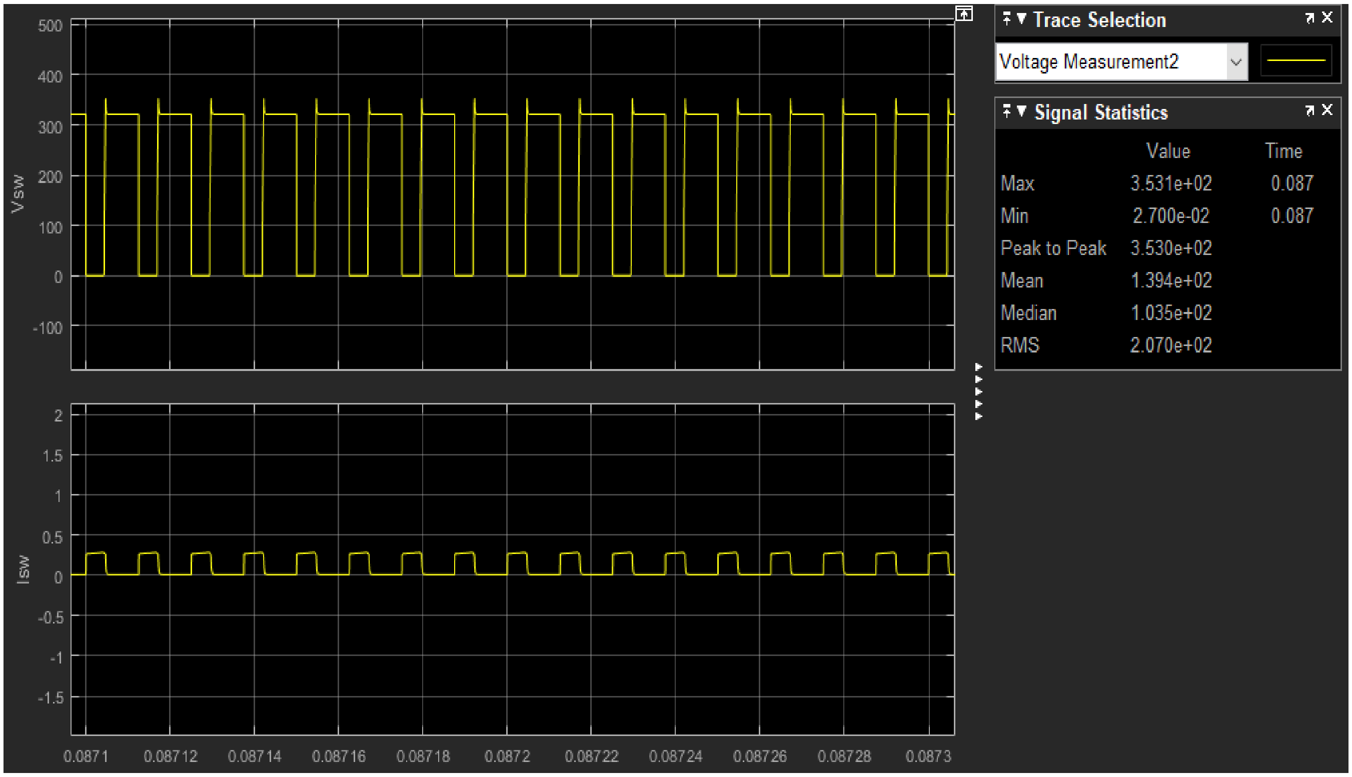

Figure 8: The voltage and current graph of the switch.

As is seen from the figure 6 and 8 there is quite difference for voltage being seen at the switch. Therefore, we built a snubber circuit for reducing the overshoots for switch voltages. In order to have a proper snubber circuit we used some equations which are 11, 12.

$$C > \frac{V_{clamp}}{V_{ripple} \times f_{sw} \times R} \tag{11}$$

$$R < 2 \times V_{clamp} \times \frac{V_{clamp} - V_{OR}}{L_{leak} \times I_p^2 \times f_{sw}} \tag{12}$$

By using these 11 and 12 formulas we obtained the resistance value as 33 $k\Omega$ and capacitance value as 220 pF.

2.5 Efficiency

In this section we were asked to calculate the efficiency of the flyback converter that we designed during the project. In order to calculate the efficiency we used the formula 13.

$$\delta = \frac{V_o \times I_o}{V_{in} \times I_{in}} \tag{13}$$

By using voltage and current graph we calculate the efficienct. The voltage and current graph for full load is in 9, 75% load is in 10, 50 % load is in 11, 25 % load is in 12.

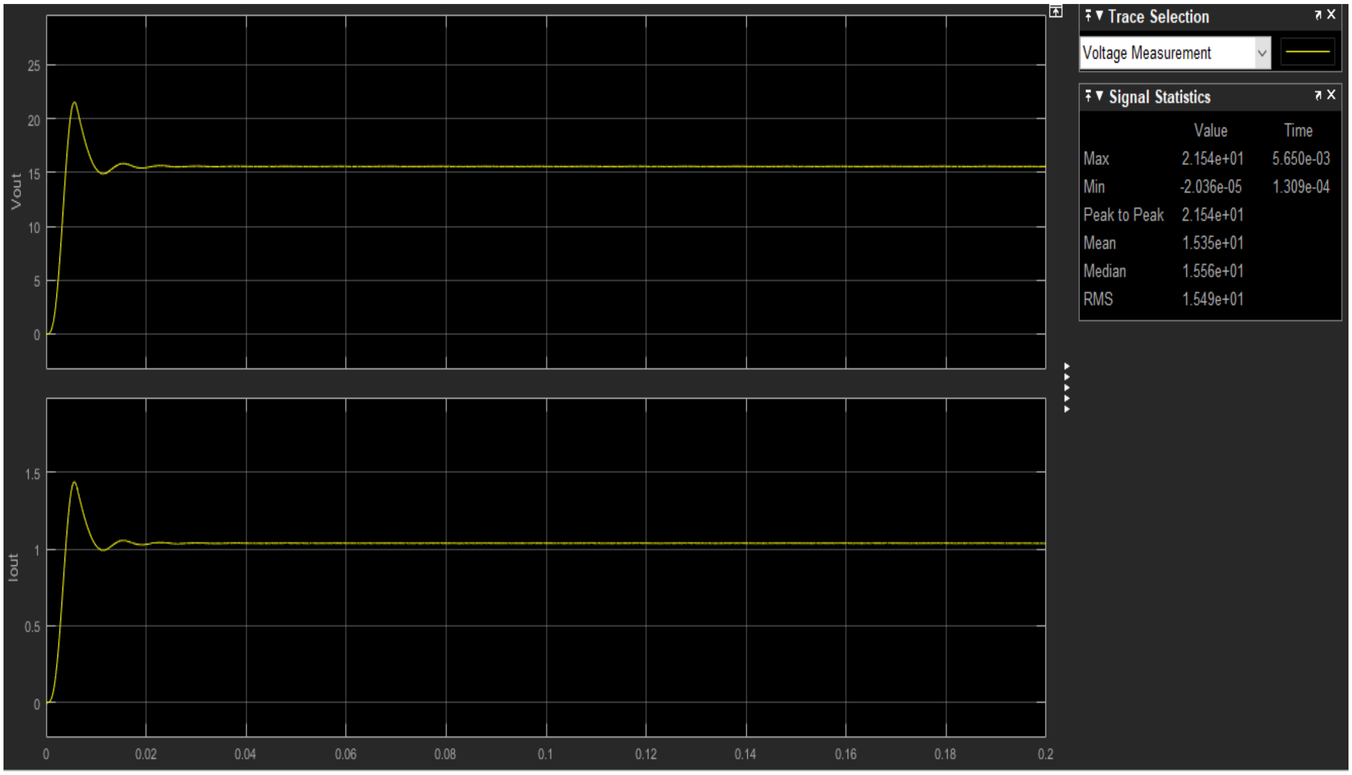

Figure 9: The voltage and current graph of the full load.

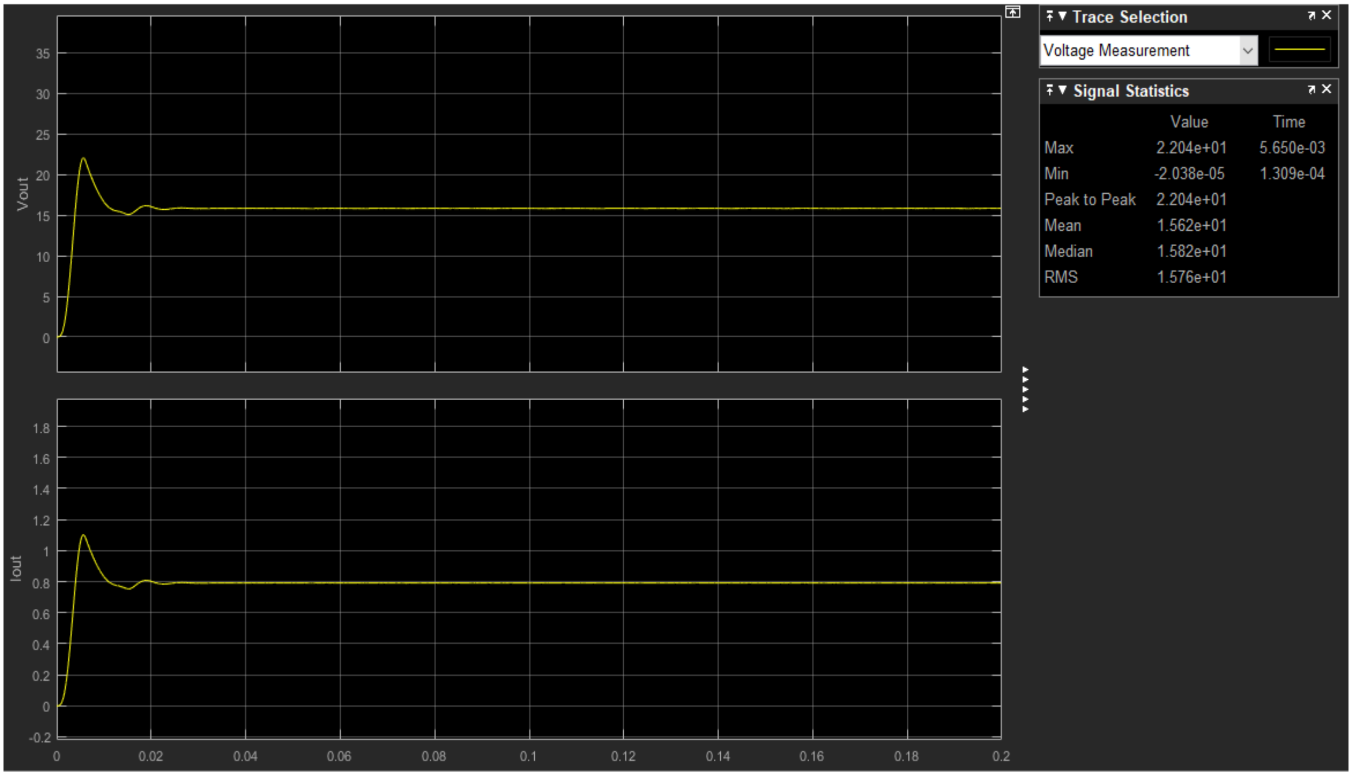

Figure 10: The voltage and current graph of the 75 % load.

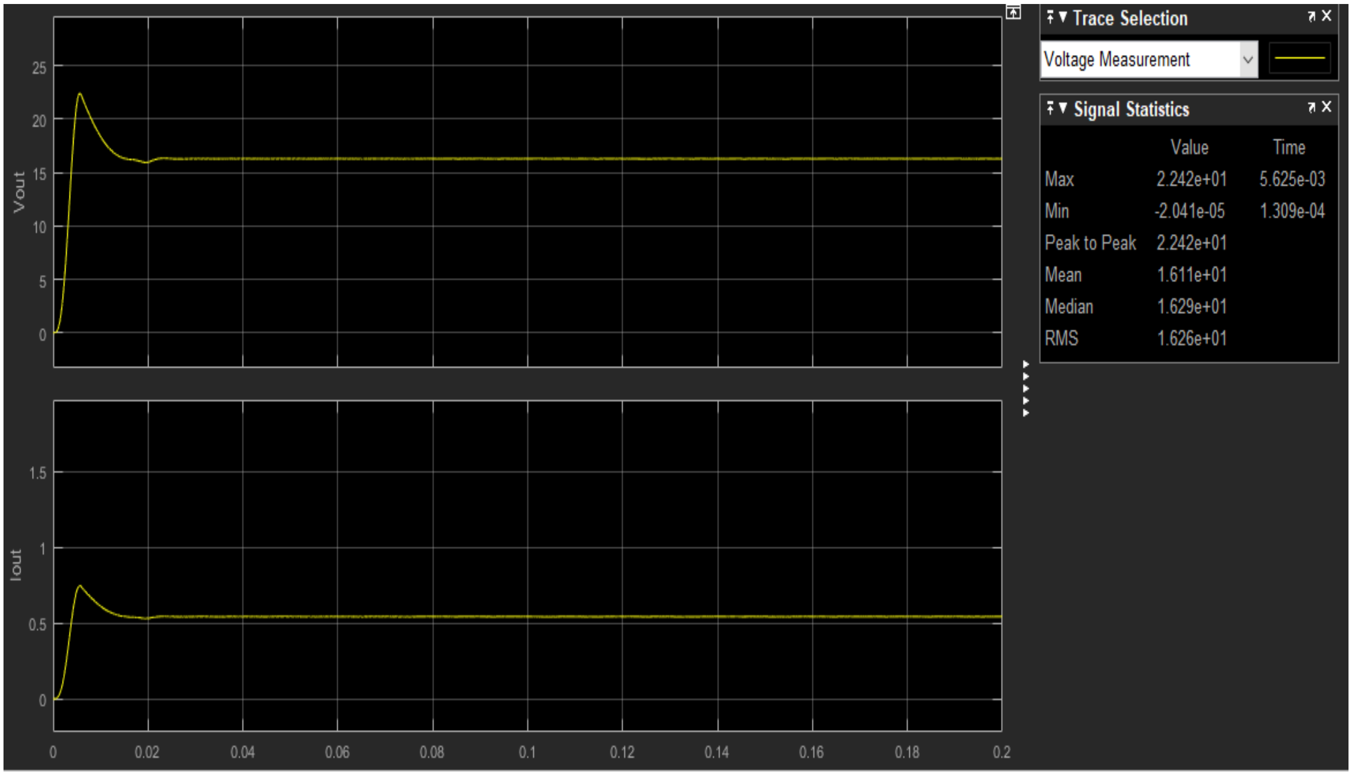

Figure 11: The voltage and current graph of the 50 % load.

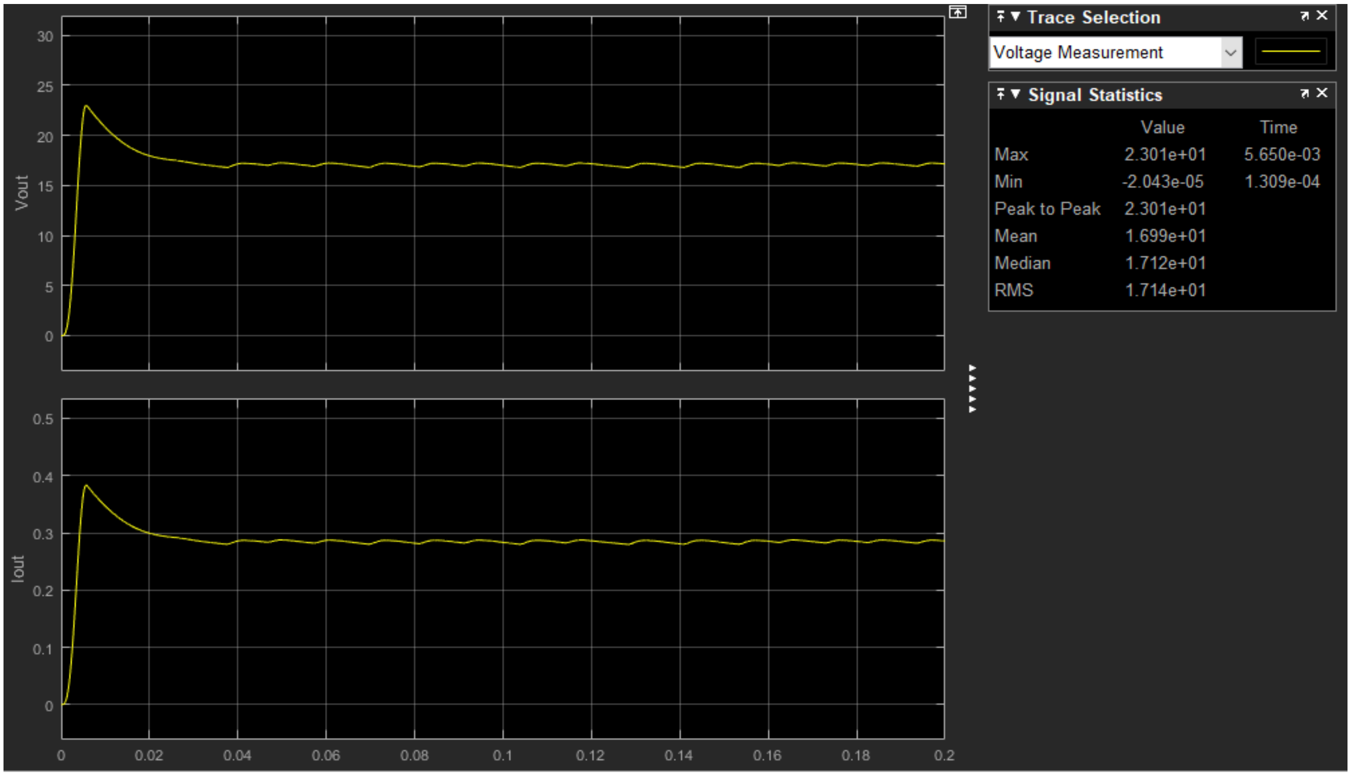

Figure 12: The voltage and current graph of the 25 % load.

The efficiency values are;

$$\delta_{full_load} = \frac{15 \times 1}{207 \times 0.81} = \%40$$
$$\delta_{\%75load} = \frac{15 \times 0.75}{207 \times 0.14} = \%38$$
$$\delta_{\%50load} = \frac{15 \times 0.5}{207 \times 0.11} = \%32$$
$$\delta_{\%25load} = \frac{15 \times 0.25}{207 \times 0.058} = \%31$$

2.6 Component Selection

For this project we add every component a safety margin with all those margins our component list has been found at table **??** . All of these components have already been bought, on the other hand if unexpected situations are encountered we could change our components during the implementation part of the project.

2.6.1 Transformer

Transformer design is the most important part of this project. We have already calculated the core size, turns ratio and primary turn number in transformer design section. This calculations are made on power ratings and magnetizing current rate. Since our transformer should capable of transferring 15 Watts of power, we selected ferrite CF139 E core. Details of core is explained in section 2.2, related data sheet can be found in appendix.

2.6.2 Capacitor

We need two different capacitor for primary and secondary side of the transformer. At the exit of of 1 phase diode rectifier we need a DC Link capacitor in order to obtain ripple free DC voltage. For secondary side we need low pass filter capacitor. In table **??**, one can find the specifications of the capacitors.

Table 2: Capacitor Information

Component	Model	I rated (A)	Vrated (V)	Value
Capacitor	CD60	-	330	600 uF
Film Capacitor	-	-	450	220 pF

2.6.3 Diode

For flyback converter diode roles as a blocker for the period duty on, current rating and blockage voltage rating should be similar to output characteristics. In table 3, one can find the diode information and in appendix A one can find the related data sheet. We choose fast diode in order to work at high frequencies.

Table 3: Diode Data

Component	Model	I forward (A)	Vblockage (V)
Diode	BYT 08P 1000	16	1000

2.6.4 Switching Equipment

Since we implement our design at working under high frequencies, the best switching device could be IGBT for this kind of operation. IXGH20N120Bis selected for our design and this decision is made based on voltage rating, low switching loses and simple gate driver. In table 4 one can find the related information about our design. Snubber circuit is a compulsory for switching transformers magnetizing branch over-voltages to protect switching equipment.

Table 4: Switching Equipment Data

Component	Model	Id (A)	Vds (V)	ton+toff (ns)
IGBT	IXGH20N120B	40	1200	150

2.6.5 Rectifier Bridge

For supply we are using 230 V AC from grid. For flyback converter we rectify this signal with using full bridge diode rectifier. Ratings of rectifier is simple and it does not require any additional calculations. For this purpose we bought B80-C800 bridge rectifier.

Table 5: My caption

Component	Model	If (A)	Vdc (V)
Bridge Rectifier	B80-C5000	1.5	200

3 Test Results

In this section, results of the converter will be discussed. Results section covers how we wound the primary and secondary side of the transformer, how loads are affecting the output voltage and current (efficiency), what kind of obstacles that we experienced, etc.

3.1 Overall Design

Overall design can be seen in figure 13.

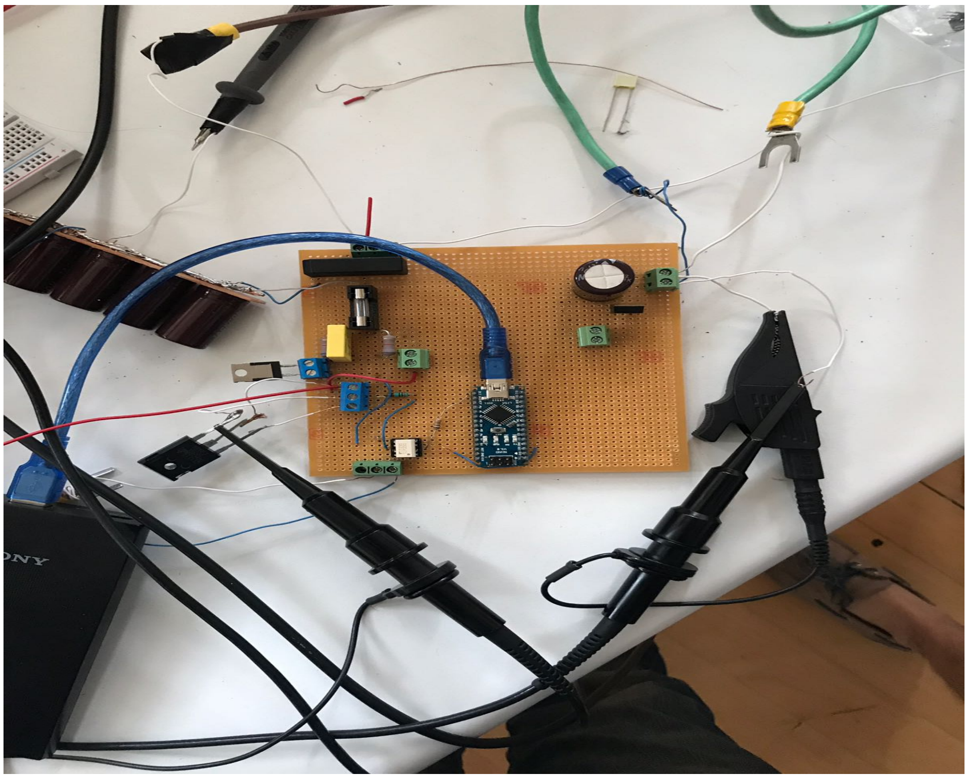

Figure 13: Overall fly-back converter design.

3.2 Transformer Results

In designing section, primary winding turns number was calculated as 42 turn. However, we saw that when we wind the primary as 42 turn, inductance of the winding becomes smaller, therefore, we could not obtain the proper output voltage. Therefore, primary winding turn was selected as 200 turn. In this way, Lm increased and converter starts to normal operation. The transformer that we used in the flyback converter is in figure 14.

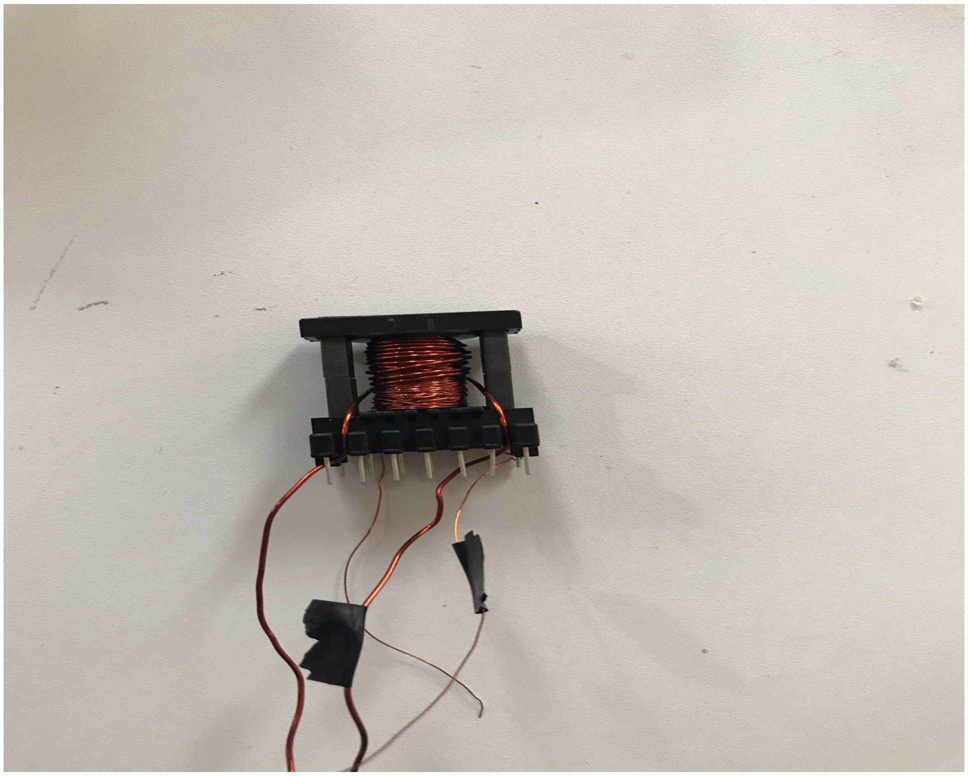

Figure 14: Transformer with 200 primary turn and 15 secondary turn.

By increasing the number of turns in both primary and secondary circuit we have increased the equivalent inductance seen by the circuit. First effect of this situation is high voltage stress on our IGBT. In average switching equipment has same voltage value as DC Link voltage. For peak voltages it can reach up to double of DC Link voltage.

3.3 RLC Measurement

In order to find the primary winding inductance of the transformer, we used the RLC meter in the laboratory. First of all, we connected the primary sides of the transformer to props and we open circuited the secondary side of the transformer. By this way we obtain the primary side inductance value as it seen from the figure 16. After that, we short circuited the secondary side of the transformer and we measured the inductance again. This time, we obtained the mutual inductance of the transformer's primary winding, as it seen from the figure 15. In order to calculate the leakage inductance value we subtract these two values. After at all, we found inductance values as ;

- Primary winding inductance = 32.665 mH
- Leakage inductance $= 71.470mH - 32.665mH \approx 38.800mH$

The pictures of the RLC meter measurements are in below;

Figure 15: Primary winding inductance.

Figure 16: Total inductance with primary leakage inductance and mutual inductance.

3.4 Output Voltage and Current

For output voltage, we were asked to implement the 15 V output voltage at 15 W power rating. For this purpose we used the 15 Ω resistor as load at the output. At first, when we implemented the flyback converter we saw ringing at output voltage. This issue occurs because the transformer is not wrapped properly and leakage inductance is very high. Therefore, we wrapped another transformer, which has less leakage inductance. After that, we obtained desired output voltage. The output voltage and current graph is in figure 17 and used load is in figure 18

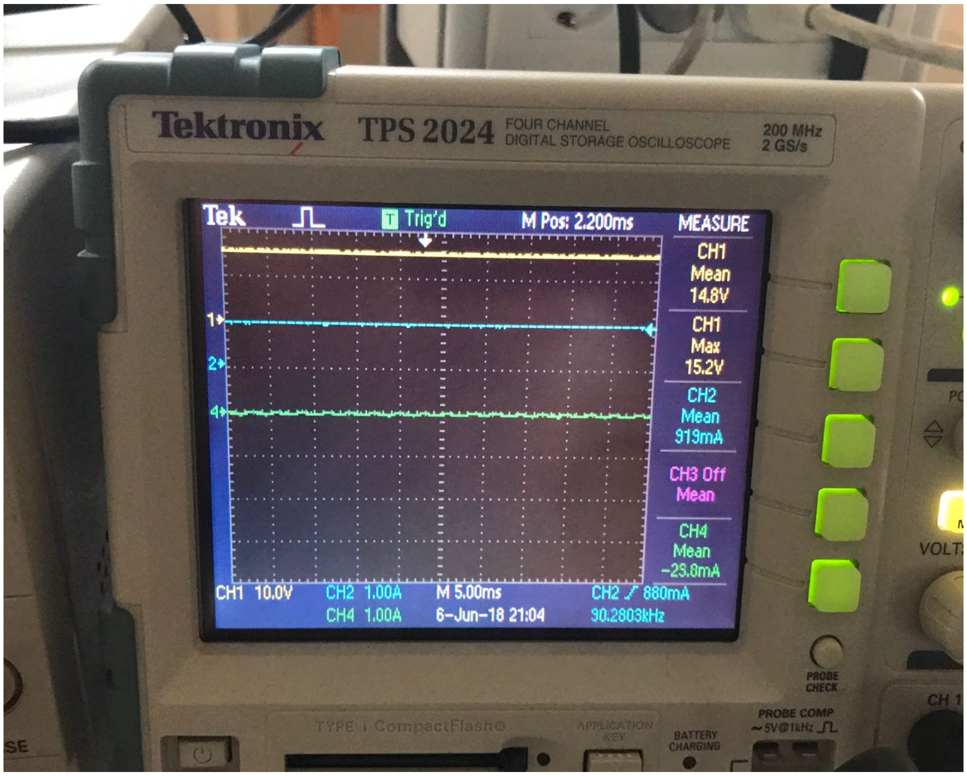

Figure 17: Output voltage and current values of the fly-back converter.

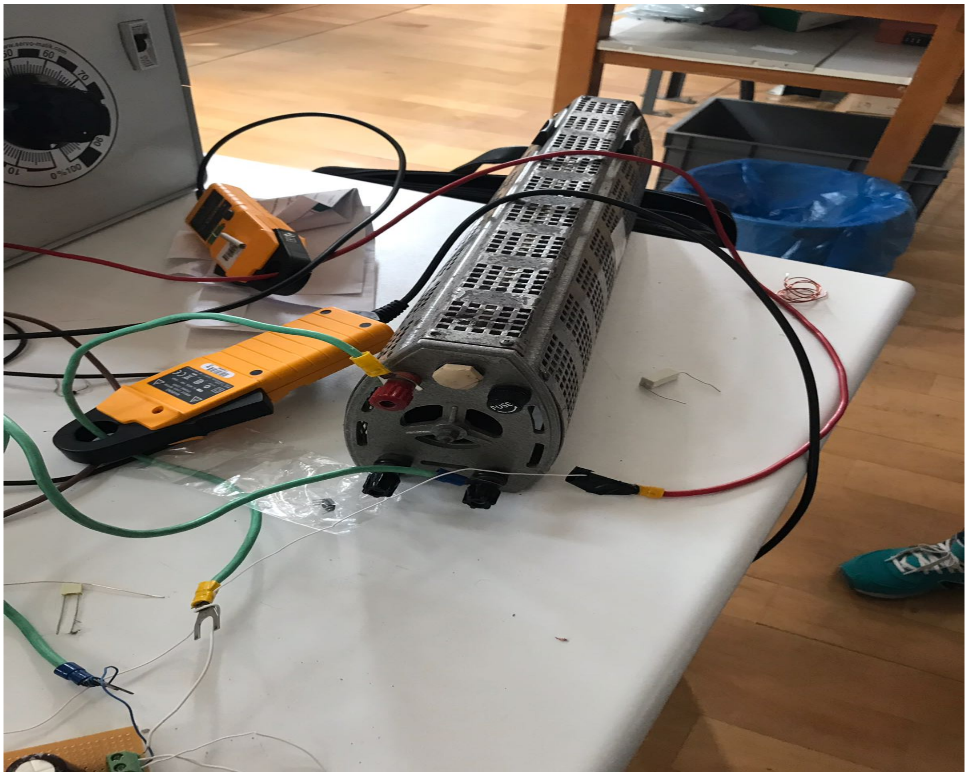

Figure 18: 15 Ω load.

As is seen from the figure 17 the mean of the output voltage is 14.8V and the mean of the output current is around 1 A. By this way we obtained the 15 W output. The power of the output is in figure 19.

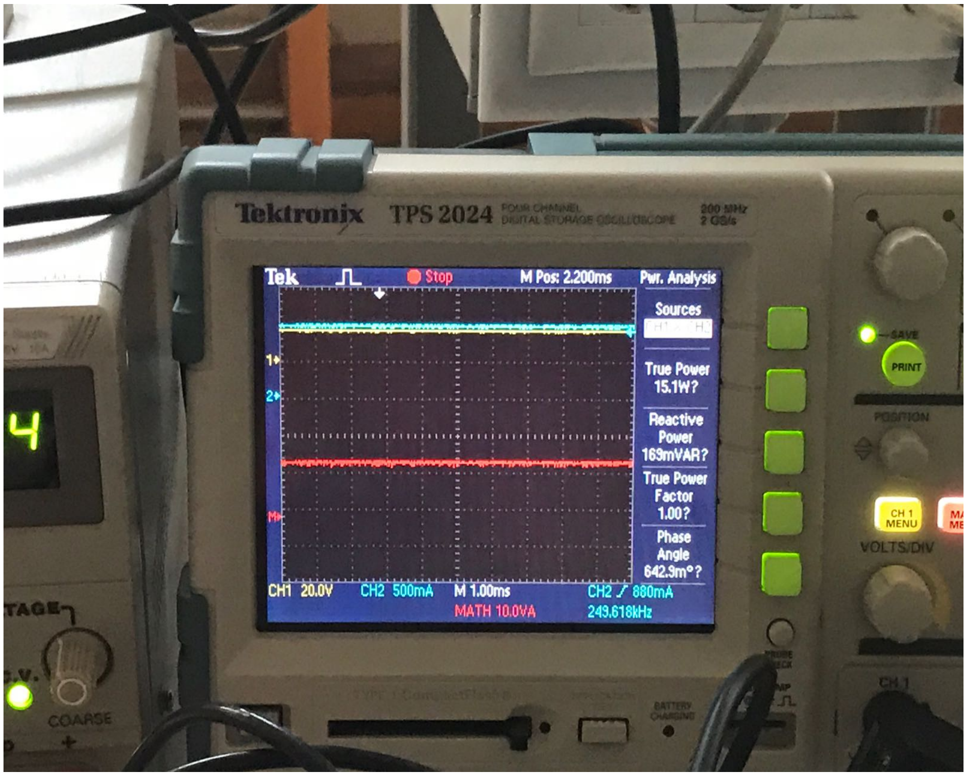

Figure 19: The output power of the fly-back converter.

3.5 Input voltage

In our design, since we were asked to convert 230 V AC to 15 V DC voltage, we used the rectifier circuit as well with the fly-back converter. In rectifier circuit we had 400 V DC link capacitor. At DC link capacitor, we expected 330 V as explained before, current ratings of primary is so low that results a voltage rise in DC Link. This 325-330 V DC is approximately equal to peak value of 50 Hz AC signal.One can see the voltage measurement taken by voltmeter in figure 20

Figure 20: DC link capacitor voltage.

3.6 IGBT Results

For this project, in order to make the fly-back converter, we designed the gate driver circuit for the IGBT. For gate driver circuit, we used arduino and opto-coupler. Arduino nano was used for the PWM generation and opto-coupler was used for the isolating fly-back converter from controller circuit. Moreover, we generated PWM at 40 kHz since at higher frequencies we know that, inductor and capacitor sizes decreases and also at higher frequencies transformer size also decreases. In other words, we selected 40 kHz switching frequency in order to obtain the compact size converter. The output graph of the gate driver circuit is in figure 21.

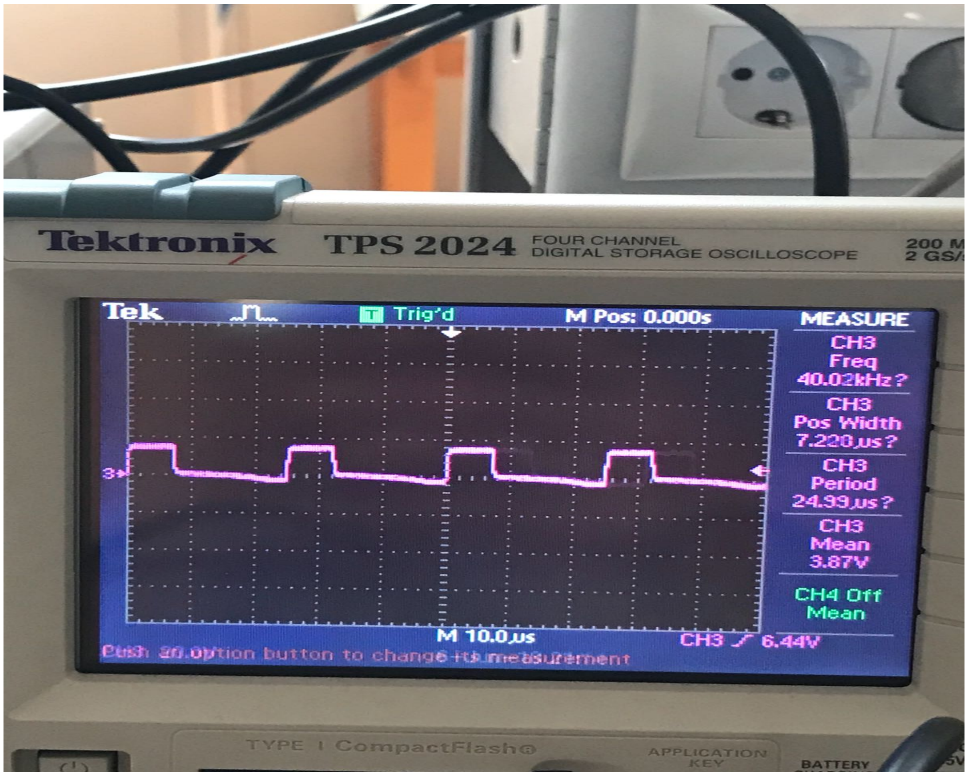

Figure 21: The output waveform of the gate driver circuit.

As it seen from the figure 21 the frequency is 40 kHz and the duty cycle is $\frac{PosWidth}{Period} \approx \%30$. We used %30 duty cycle because, in designing part we calculated the duty cycle as around %35.This decrease in duty cycle decision is made because of more feasible operation and has a range to adjust the voltage level if power rating of load is changed.

Moreover, after gate driver circuit, we measured the voltage between collector and emitter of the IGBT. The output graph is in figure 22.

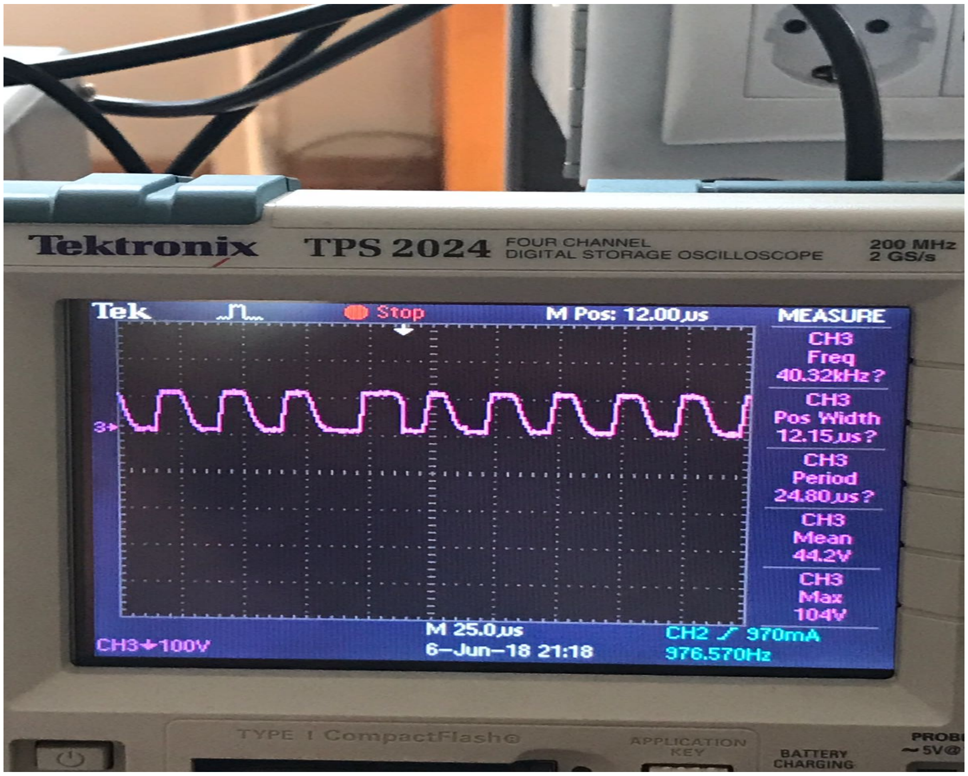

Figure 22: V_{CE} of the IGBT.

As it seen from the figure 22 the PWM signal is not pure square wave. This issue occurs since, IGBT has own internal capacitance and turn on-off times inside it. Since we are working at 40 kHz IGBT can not operate well. In order to eliminate this issue, faster IGBT or MOSFET can be used. However, we couldn't find faster IGBT and since the wave form is good enough to work with, we continued with the chosen IGBT. The figure 22 shows the V_{CE} at low voltages. We observed linear relationship between input voltage and IGBT voltage. Effect of transformer nearly doubles the voltage seen by IGBT terminals. This is the main reason why we changed our equipment. This double is seen with snubber circuit. Without snubber nearly 4 times of input voltage is seen by the peak of Collector Emitter voltage.

4 Conclusion

In this report we have explained our design guideline for fly-back converter for EE464 Hardware project. First we take simulations for steady state operation and estimate the turns ratio of transformer and duty cycle of switch. After that we designed a transformer for proper conditions and select a suitable transformer core. Also discontinuous mode is investigated and we found the point where magnetizing current becomes discontinuous. Non ideal components are investigated and effects of over voltage and losses are observed. Using all of this analysis we selected our suitable components for our design. However in real life when we implement the flyback converter with selected components we have faced off unpredicted problems due to non-ideality of components such as parasitic capacitance and inductance. These kind of problems make us to change some of the components in our first design. However in overall we have accomplished a successful project with satisfies the requirements and has high efficiency without any heating problem. During implementation period we used our theoretical approach in a real life application and design a DC-DC converter according to project requirements.

5 Appendix-A

Appendix A contains related data sheets of selected equipments in EE 464 Hardware project.
Mosfet: https://www.vishay.com/docs/91059/91059.pdf
Capacitor: http://pdf1.alldatasheet.com/datasheet-pdf/view/340635/SUNTAN/TS13D3-CD60.html
http://www.ersinelektronik.com/class/INNOVAEditor/assets/Datasheets/Elektrolitik-Radial.pdf
Diode Bridge: https://www.digchip.com/datasheets/parts/datasheet/139/B80-C1500R-pdf.php
Diode: http://pdf.datasheetcatalog.com/datasheet/SGSThomsonMicroelectronics/mXruyqv.pdf
Transformer Core: http://www.cosmoferrites.com/Downloads/Alnh/CF139.pdf