MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE464 Simulation Project #2

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1 Introduction

For 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 design guide for project and simulation results for different cases.

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.

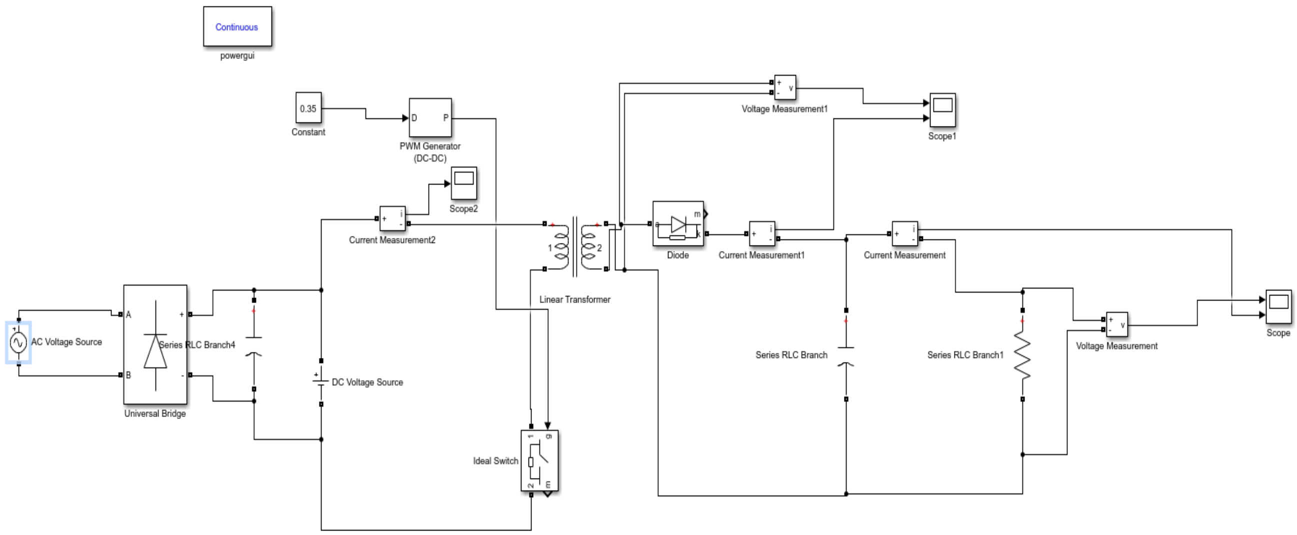

Figure 1: Flyback Converter Circuit Schematic

In flyback converter, in order to have an small magnetizing inductance value of the transformer for staying in continues conduction mode at normal operation, we decided the frequency of switch as 80 kHz. In other words, size of the transformer decreases as switching frequency increases. Moreover, with increasing switching frequency, all components such as filters, capacitors and inductors. However, when the switching frequency increases the switching loss increases as well.

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.

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

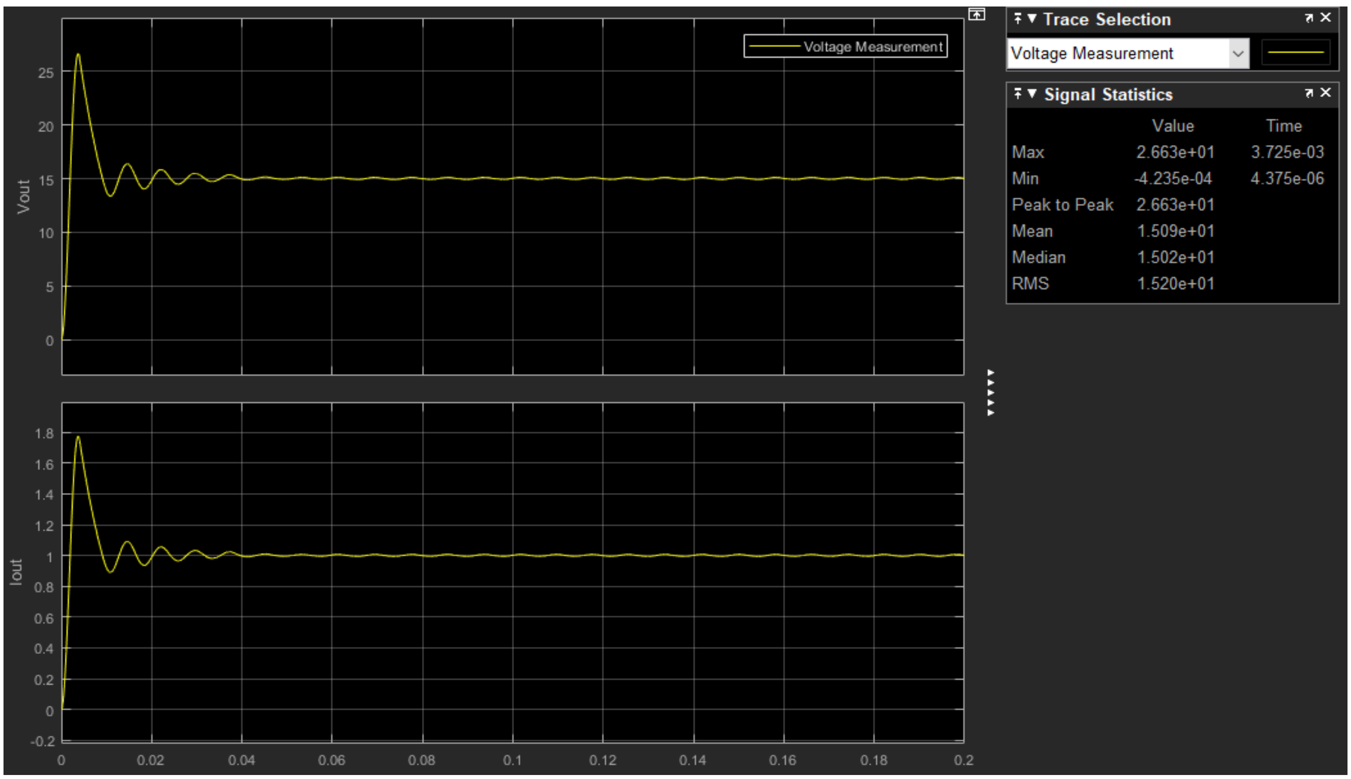

Figure 2: Output voltage and current graphs of the flyback converter.

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. With these calculated duty cycle and turns ratio we obtained the minimum magnetizing inductance value by using formula 4.

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

$$Lmin = \frac{(1-0.35)^2 \times 30}{2 \times 80kHz} . \frac{7}{1}^2 = 2.14mH$$

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 $B_{sat} valueis = 0.3T$. We found turns number as;

- $N_p = \frac{2.14mH \times 0.145}{25mm^2 \times 0.3T} \approx 42$
- $N_s = N_p/7 \approx 6$

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 7 (N1/N2), duty cycle is 0.35 (D) and switching frequency is 80 kHz (f).

$$Lmin = \frac{(0.65)^2 \times 30}{2 \times 80000} . \frac{7}{1}^2 = 2.14mH \tag{7}$$

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.

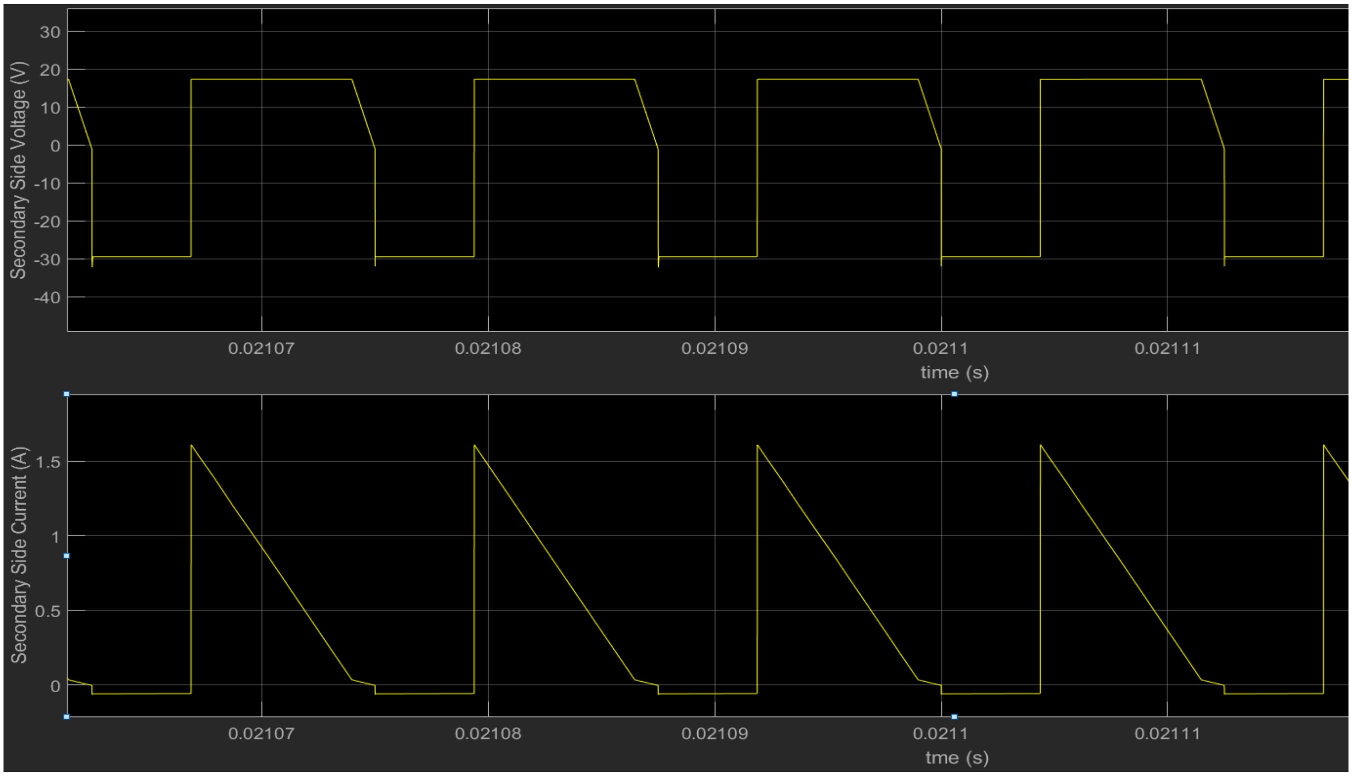

Figure 3: Transformer Secondary Side Voltage and Current Waveform

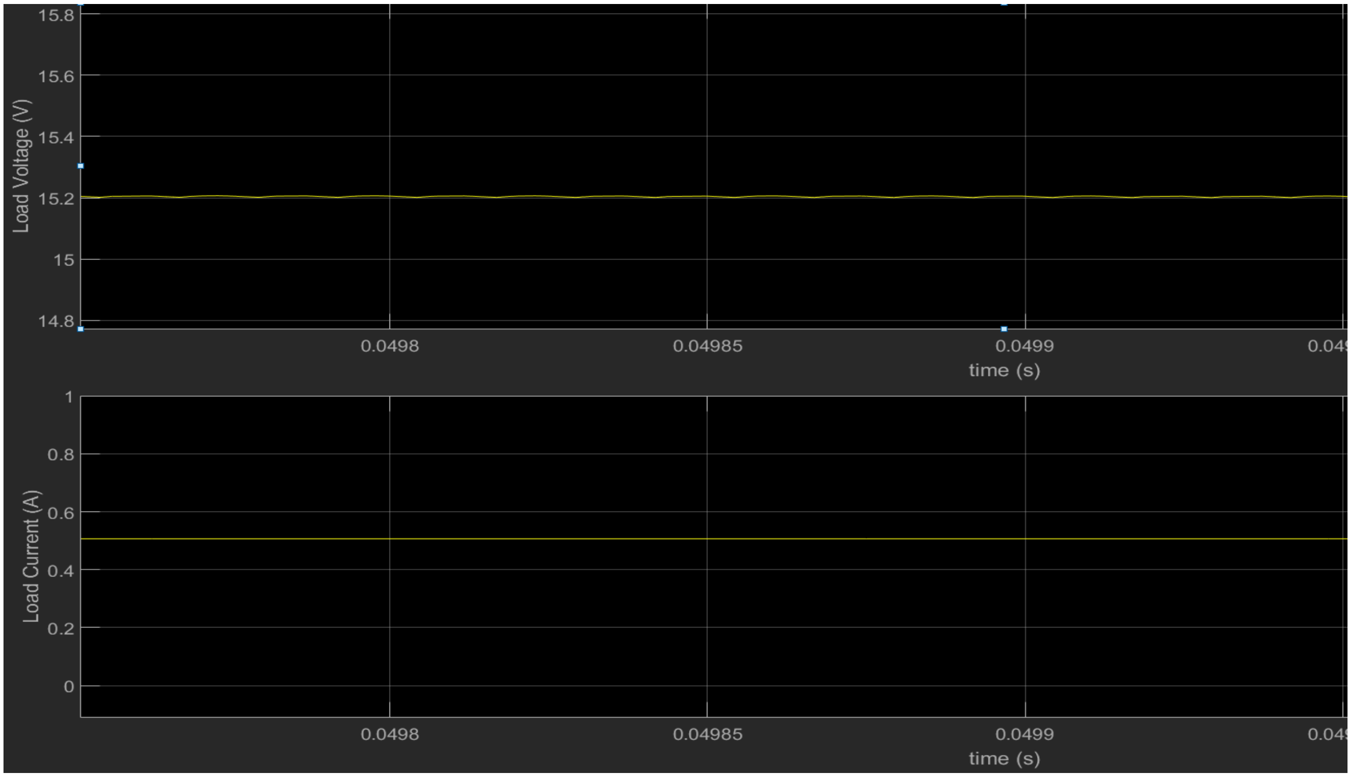

Figure 4: Load Voltage and Current Waveform at the Edge of Discontinuous

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.

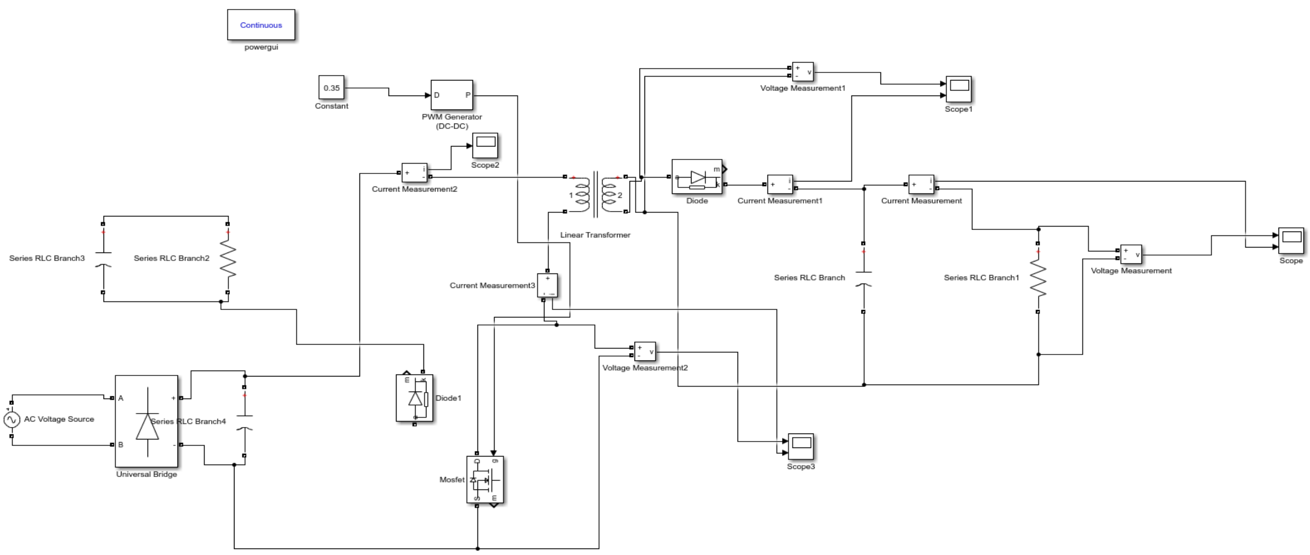

Figure 5: The circuit schematic with non ideal switches and without snubber circuit.

The switch voltage and current graph is in figure 6.

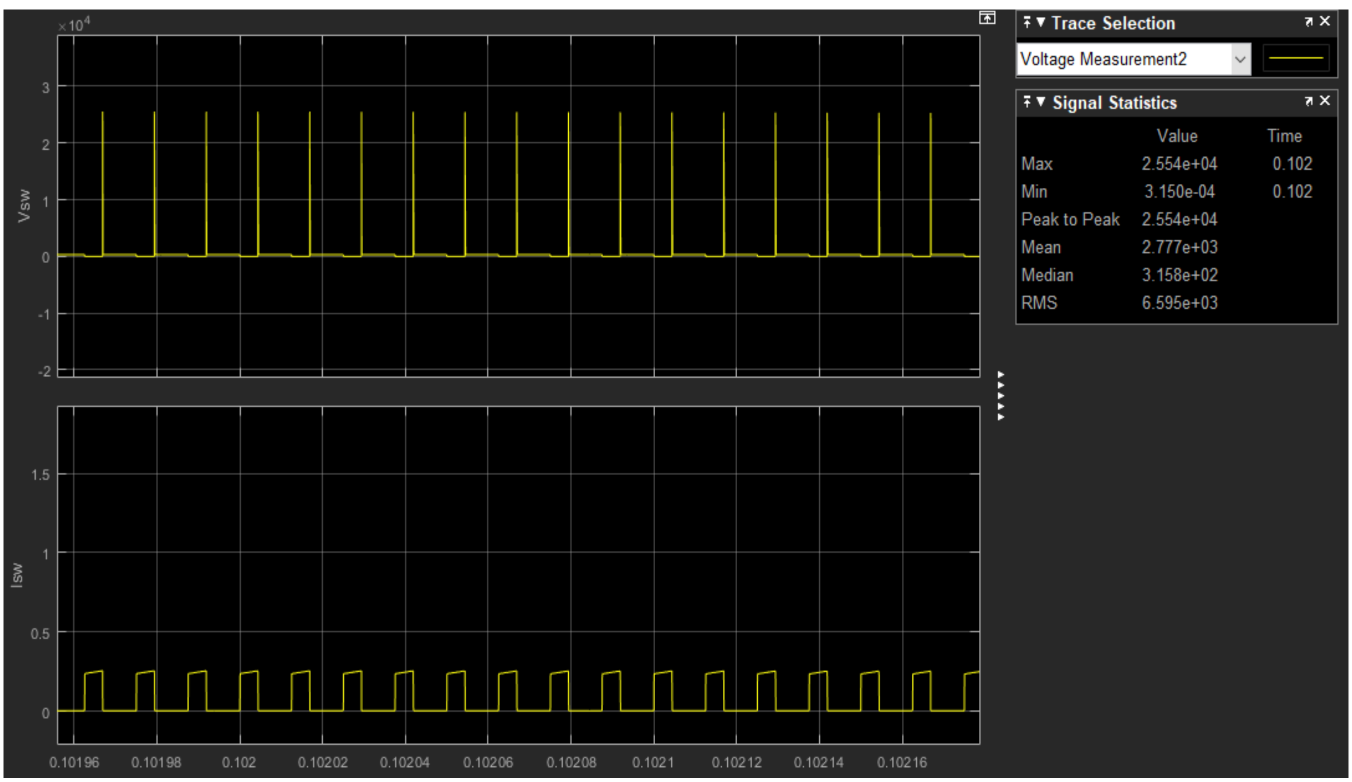

Figure 6: The switch voltage and switch current graph of the flyback converter.

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.

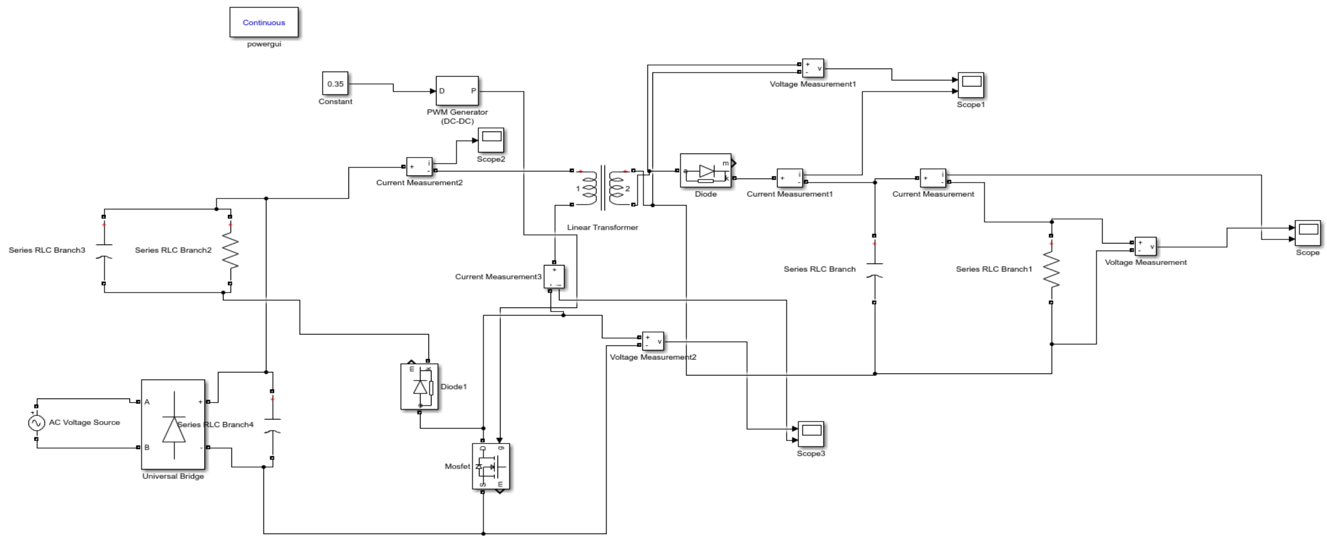

Figure 7: The flyback converter with snubber circuit.

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

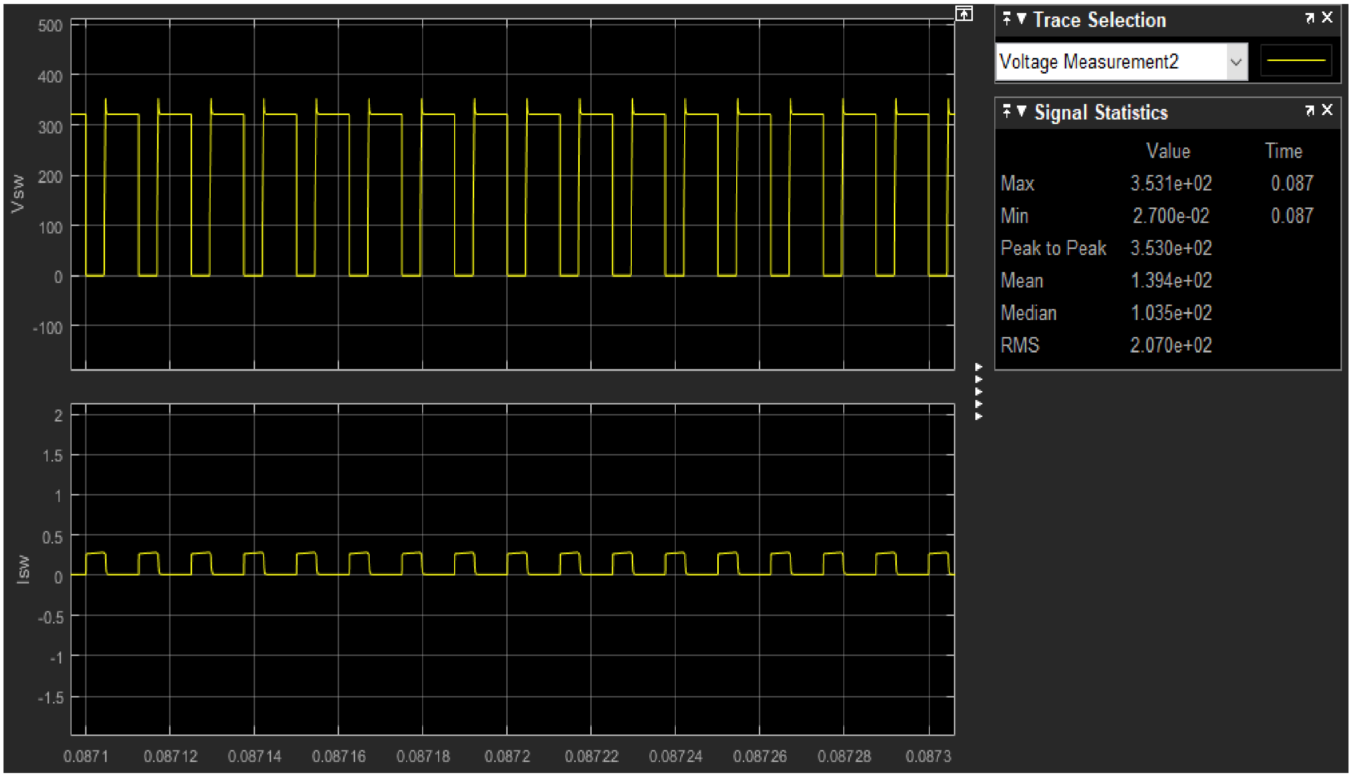

Figure 8: The voltage and current graph of the switch.

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 75 $k\Omega$ and capacitance value as 330 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.

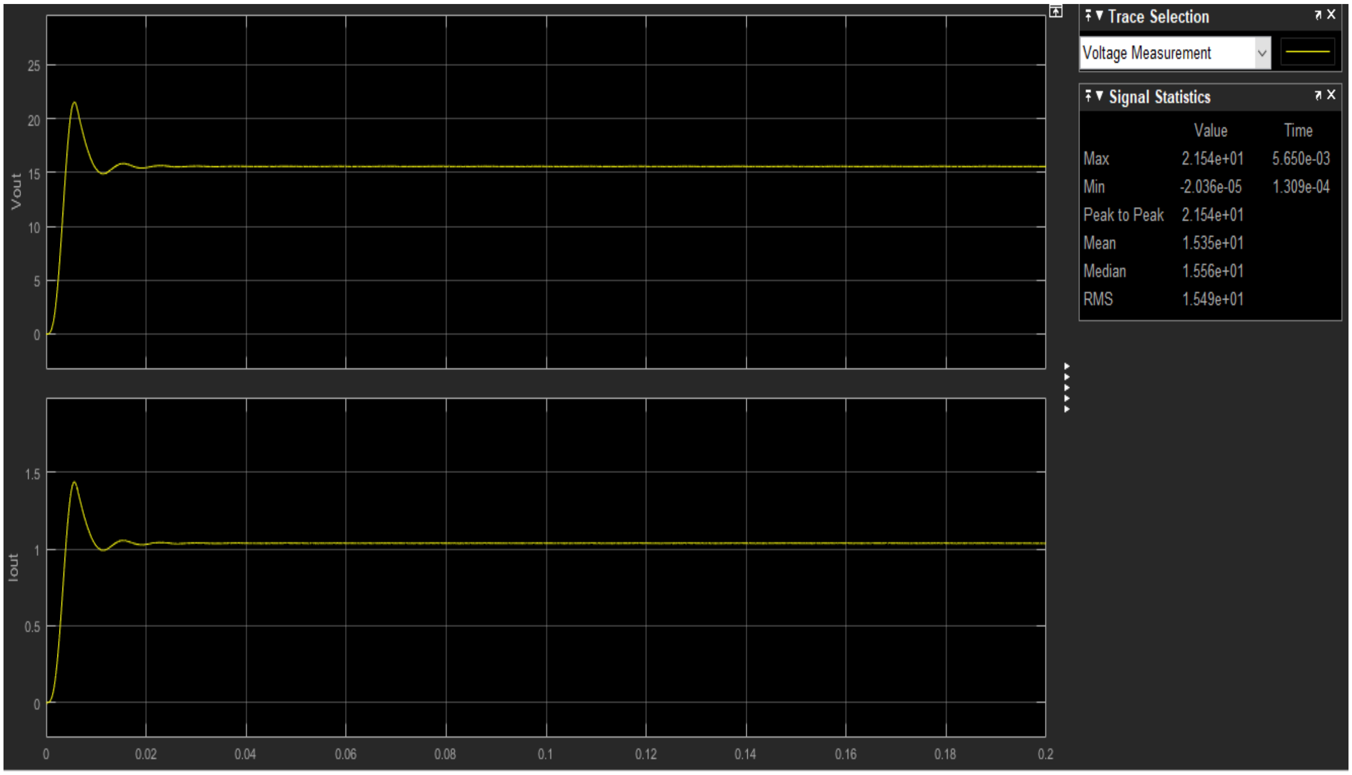

Figure 9: The voltage and current graph of the full load.

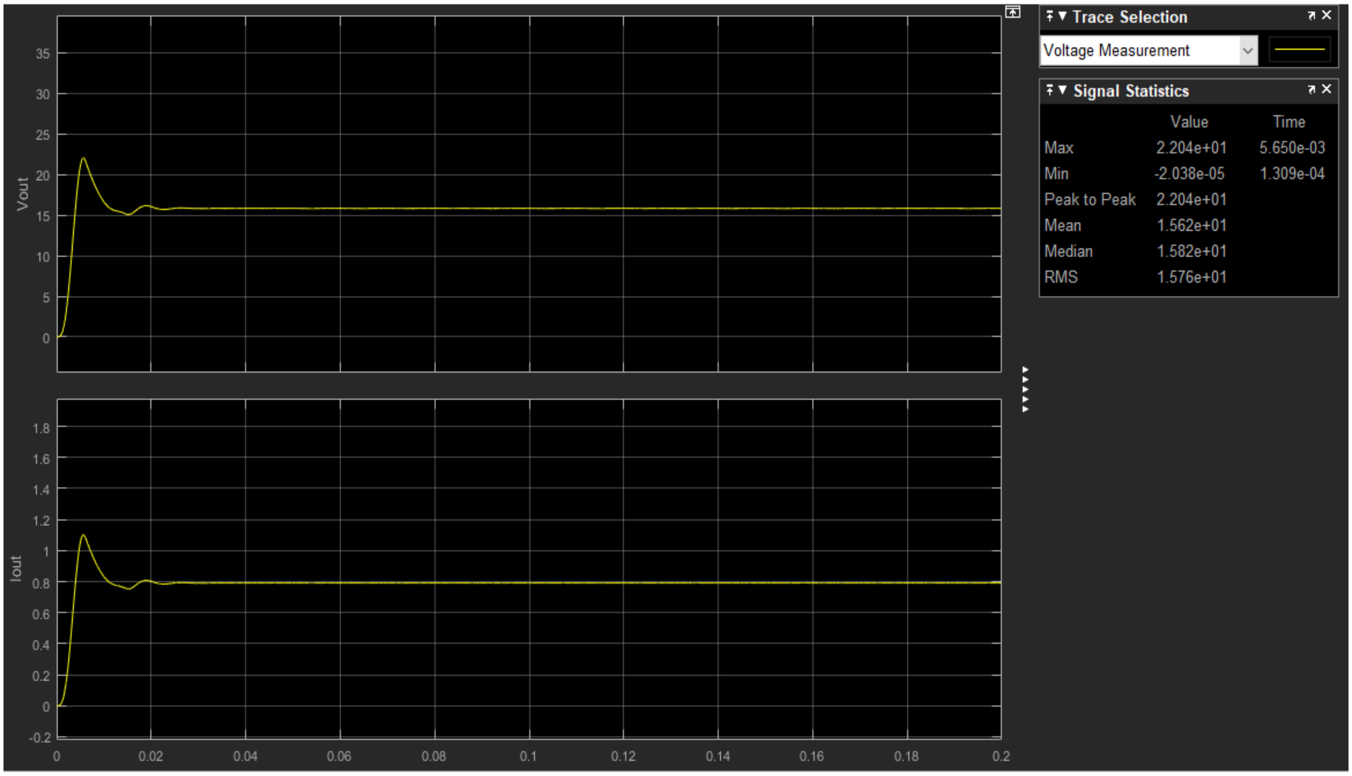

Figure 10: The voltage and current graph of the 75 % load.

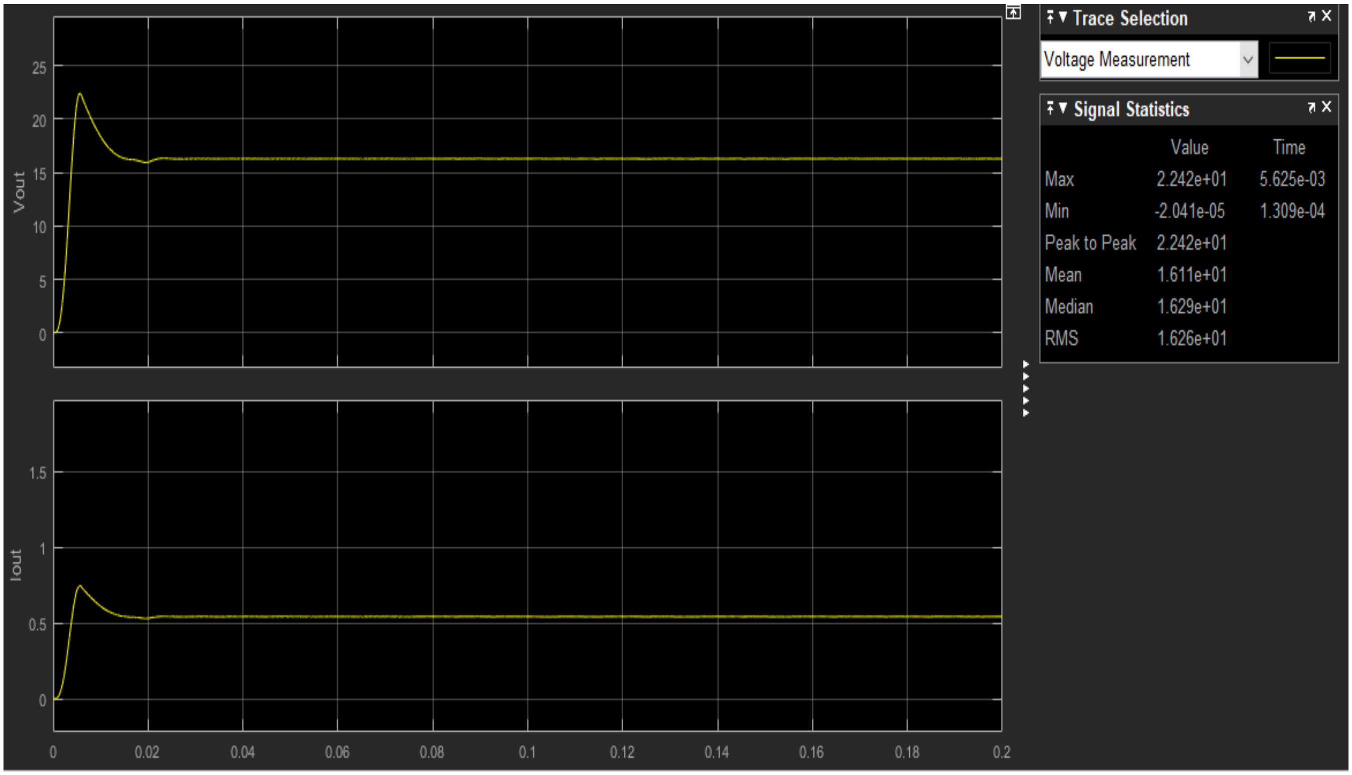

Figure 11: The voltage and current graph of the 50 % load.

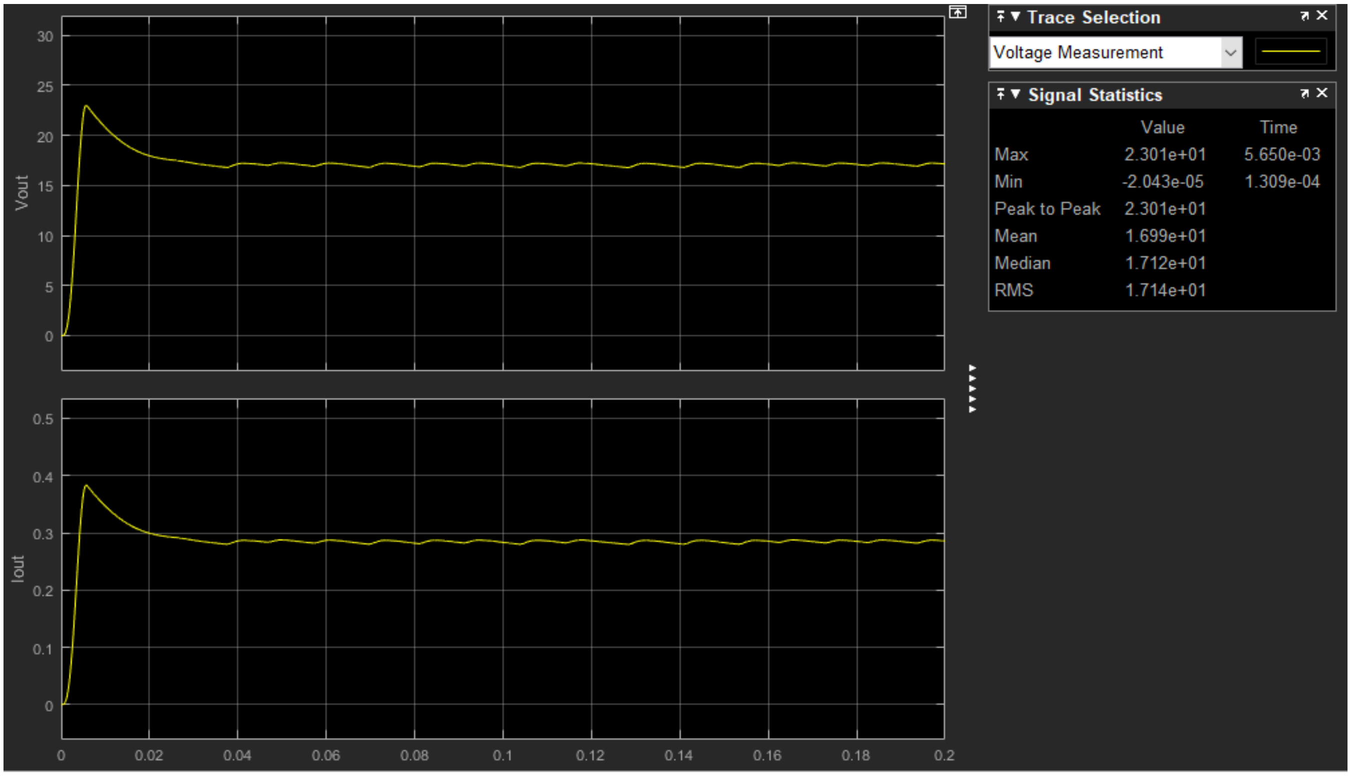

Figure 12: The voltage and current graph of the 25 % load.

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
Capacitor	CD110X	-	35	100 uF

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 Mosfet for this kind of operation. IRF820 is 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)
Mosfet	IRF820	2.5	500	41

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

2.6.6 Analog Controller

Since this kind of converters should work under various loads we need a controller circuit to adjust the duty cycle of switching equipment. For this purpose we will use analog PID controller UC38448. This is a current sensing control device additional circuitry is required. Operation principle of this kind of controllers are described in detail in Section 3.

3 Controller Design Using Buck Converter Topology

3.1 Analytic Transfer Function Calculations

To calculate the transfer function analytically, we used linearization with state space averaging technique. Considering both modes of operation (switch ON and OFF periods), we obtained two state space systems and calculated the weighted average with respect to duty cycle. Obtained state-space system is as follows:

$$x = \begin{bmatrix} v_C \\ i_L \end{bmatrix}$$

$$\dot{x} = \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \frac{D}{L} \end{bmatrix} V_{in}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} x$$

Hence, the transfer function is obtained from this state space system as:

$$H(s) = \frac{\frac{D}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}}$$

Replacing the values $C = 100\mu F, L = 0.1mH, R = 15\Omega, D = 0.075$, H(s) becomes:

$$H(s) = \frac{7.510^6}{s^2 + 666.7s + 10^8}$$

Bode plot of this transfer function is shown in Figure 13

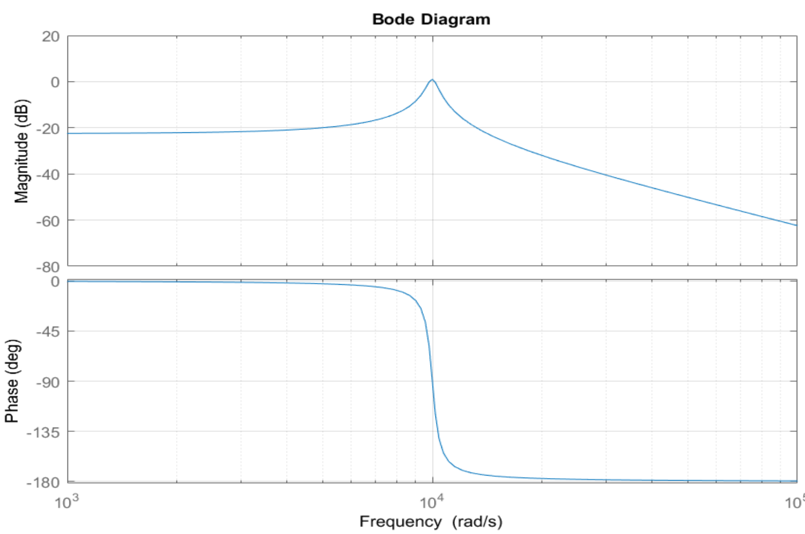

Figure 13: Bode Plot of Analytically Calculated Transfer Function

Obviously, the system is close to be unstable, as its phase margin decay rate is too large around 10 krad/s.

3.2 Simulations

Schematic of the uncontrolled buck converter system and its output voltage waveforms are present in Figures 14 and 15, respectively.

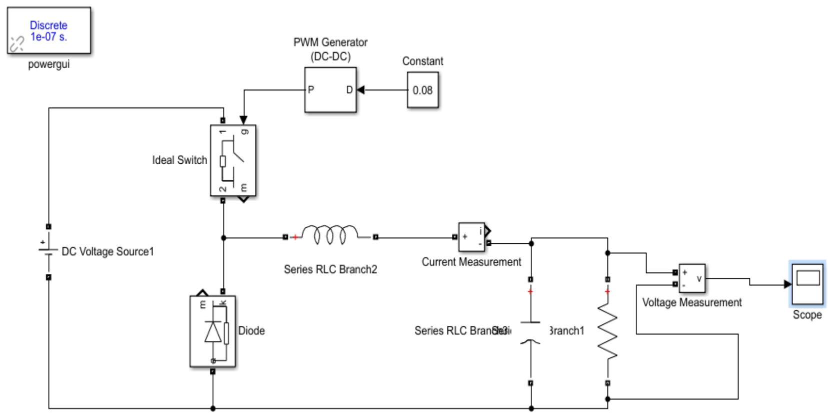

Figure 14: Buck Converter

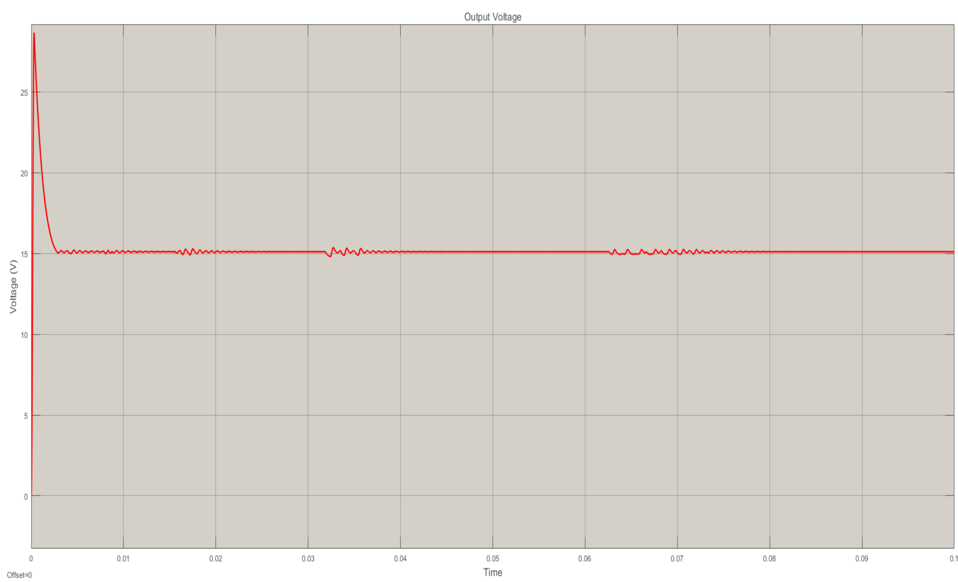

Figure 15: Output Voltage of Uncontrolled System

To obtain the frequency response characteristics of the system (i.e. the transfer function), we used System Identification toolbox of MATLAB. We chose the transfer function that is the most compatible with the actual one among transfer functions with different numbers of poles and zeros.

Bode plot of the estimated transfer function is given in Figure 16. As it can be seen, the phase margin is only 5 degrees, which implies that the system itself is very close to be unstable.

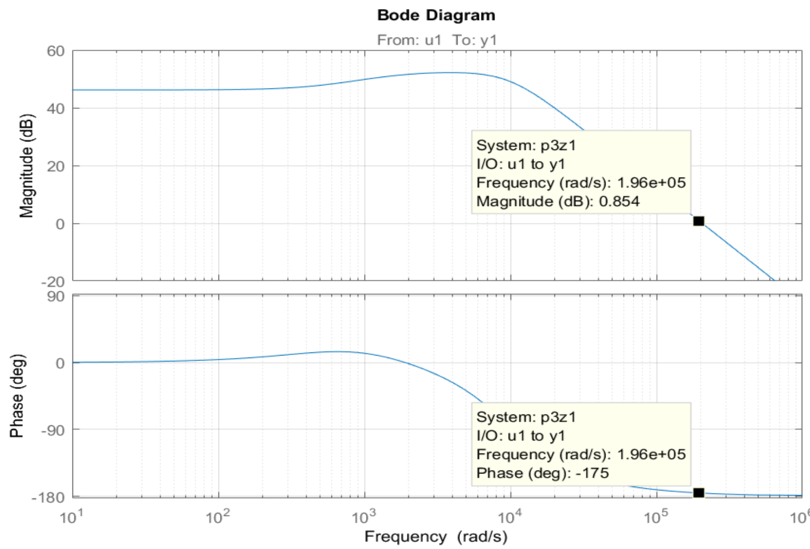

Figure 16: Bode Plot of Transfer Function Obtained with System Identification

3.3 Type II Controller

For the system whose Bode plot is given in Figure 16, above, the controller to be designed should have one pole, one zero and one integrator, in order to increase the phase margin around the operating frequency. One appropriate option may be:

$$C(s) = \frac{s + 10^4}{s^2 + 10^5 s}$$

Bode plot of the proposed controller is given in Figure 17.

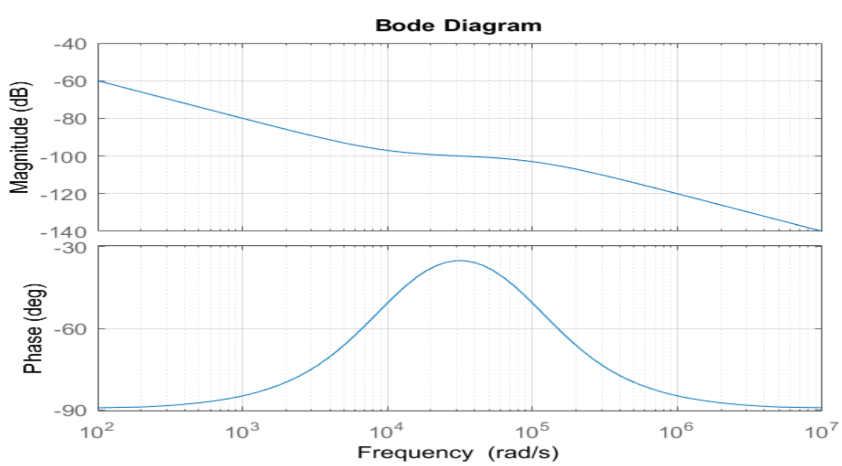

Figure 17: Bode Plot of Designed Controller

3.4 Performance Analysis

Having simulated the closed loop system, we observed that the controller designed with respect to the estimated model fits the actual one, substantially (For closed loop system and its output voltage, see Figures 18 and 19.).

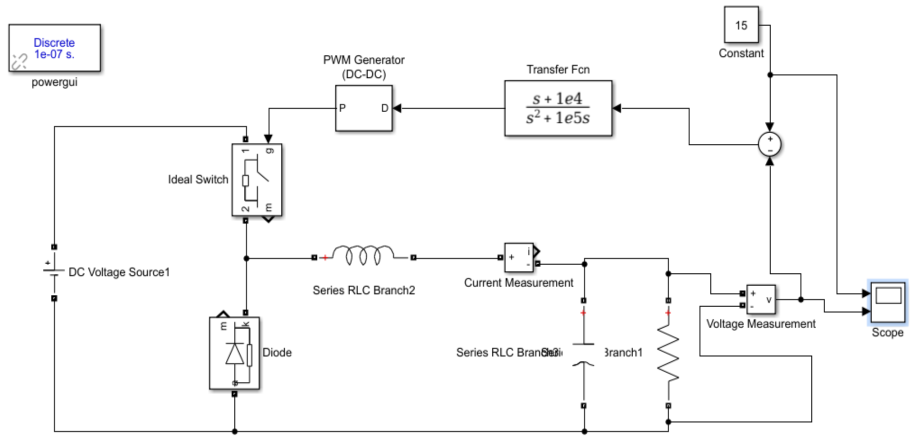

Figure 18: Controlled Buck Converter

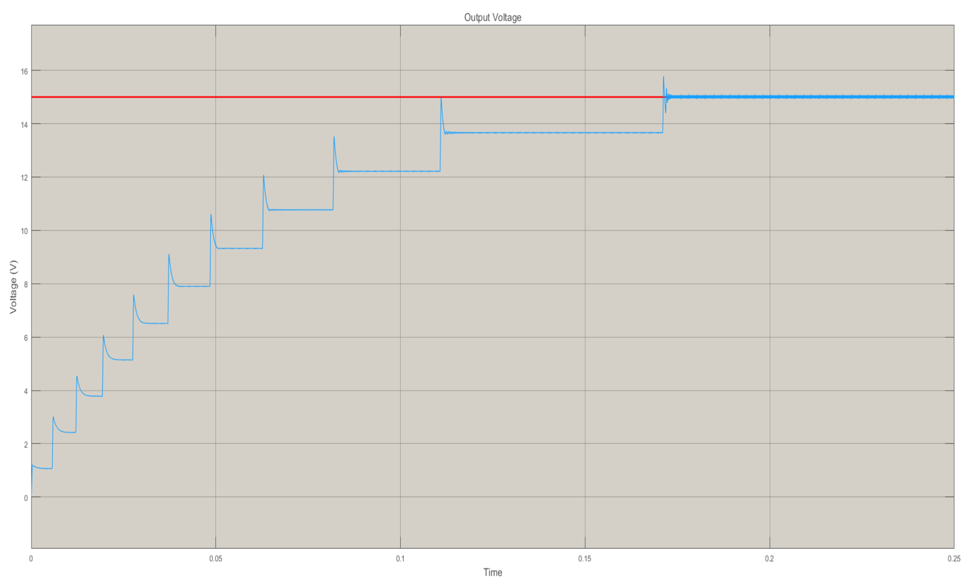

Figure 19: Output Voltage of Controlled System

To check the controller stability, we halved the load at a time instant t=0.2. Halving the load increases the oscillations at the output, however the system continues operating in a proper manner also in that condition. Further, we increased the input voltage to 230 V. Also for this case, the system preserved its stability. These simulation results are given in Figures 20 and 21, respectively.

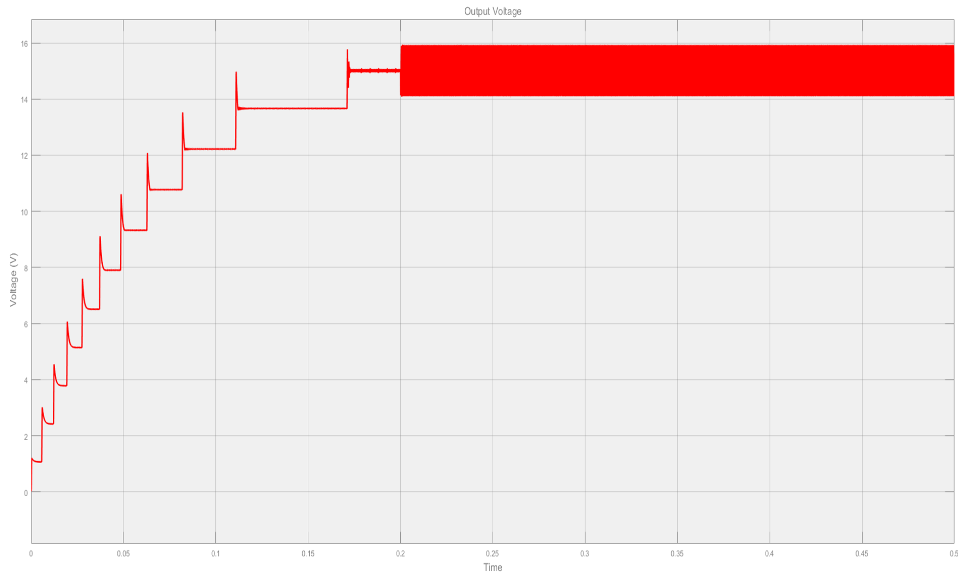

Figure 20: Full to Half Load Test for Type-2 Controlled System (Switching Time: 0.2)

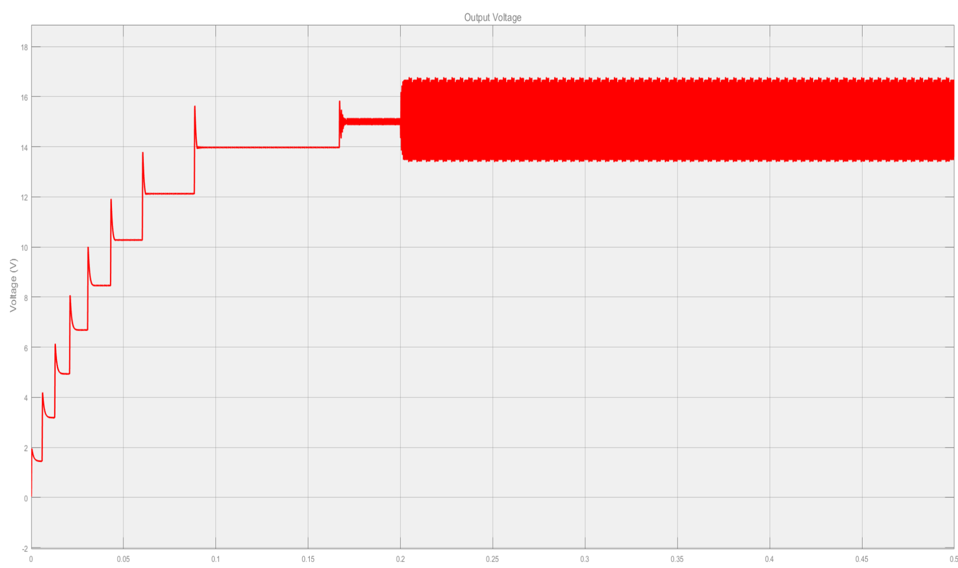

Figure 21: Overvoltage Test for Type-2 Controlled System

3.5 Comments

Without the controller, steady state response of the system is better. However as it reaches high voltage levels in transient period, it is necessary to use a carefully designed Type 2 controller. One other drawback of controller is the elongation of the time constant of the system. Closed loop system reaches the steady state after a longer period.

Further, we have seen that estimation of the transfer function analytically is not as reliable as using a simulation software. Nevertheless, by considering the Bode plots of two models, we can say that our analytical estimation is not very different from the simulation estimation.

4 Controller Design Using Flyback Converter Topology

4.1 Analytic Transfer Function Calculations

For analytical calculation of the transfer function of the flyback topology, we used linearization with state space averaging technique, again. Having obtained the state space matrices with respect to two states, we calculated the transfer function using MATLAB. State space matrices are as follows:

$$x = \begin{bmatrix} v_C \\ i_L \end{bmatrix}$$

$$\dot{x_1} = \begin{bmatrix} \frac{-1}{RC} & 0 \\ 0 & 0 \end{bmatrix} x_1 + \begin{bmatrix} 0 \\ \frac{D}{L} \end{bmatrix} V_{in}$$

$$\dot{x_2} = \begin{bmatrix} \frac{-1}{RC} & \frac{7}{C} \\ \frac{-7}{L} & 0 \end{bmatrix} x_2 + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in}$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} x$$

Replacing the values $C = 600\mu F, L = 3.8mH, R = 15\Omega, D = 0.35$, H(s) becomes:

$$H(s) = \frac{-2333s^3 + 2.11 * 10^8 s^2 + 2.317 * 10^9 s + 1.921 * 10^15}{s^4 + 222.2s^3 + 1.817 * 10^7 s^2 + 2.018 * 10^9 s + 8.245 * 10^13}$$

Bode plot of this transfer function is shown in Figure 22

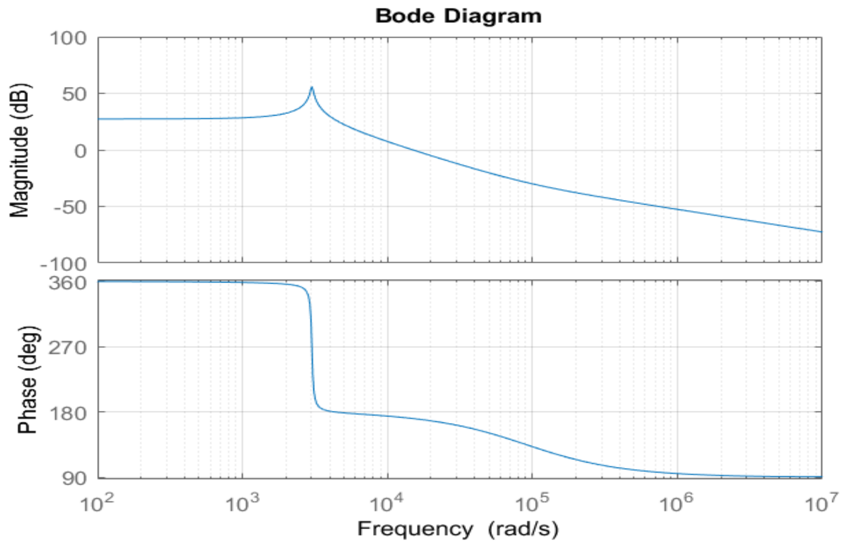

Figure 22: Bode Plot of Analytically Calculated Transfer Function

4.2 Simulations

Schematic of the uncontrolled flyback converter system and its output voltage and current waveforms are present in Figures 23 and 24, respectively.

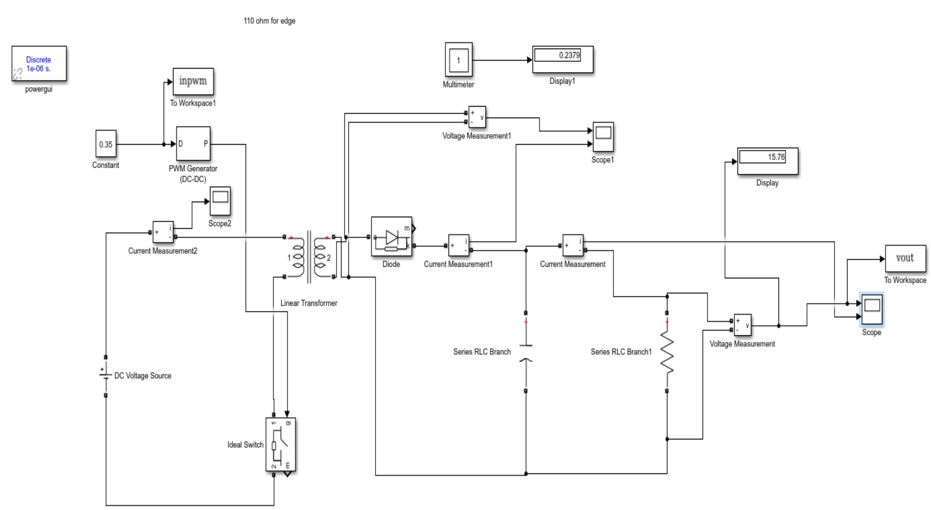

Figure 23: Flyback Converter

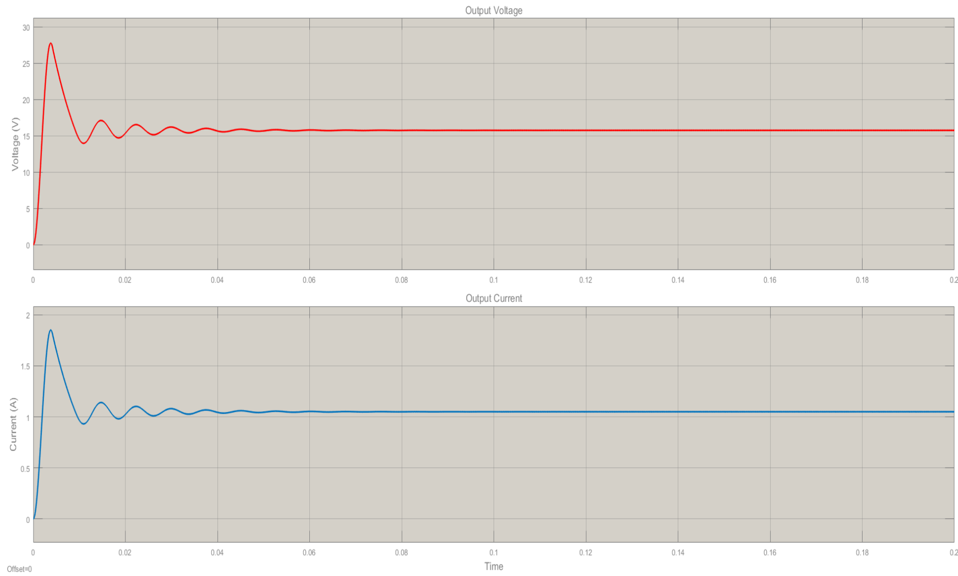

Figure 24: Output Voltage of Uncontrolled System

Similar to the buck converter analysis, here, we also used the System Identification toolbox of MATLAB and chose a model that is more compatible with the actual system. Its bode plot is present in Figure 25

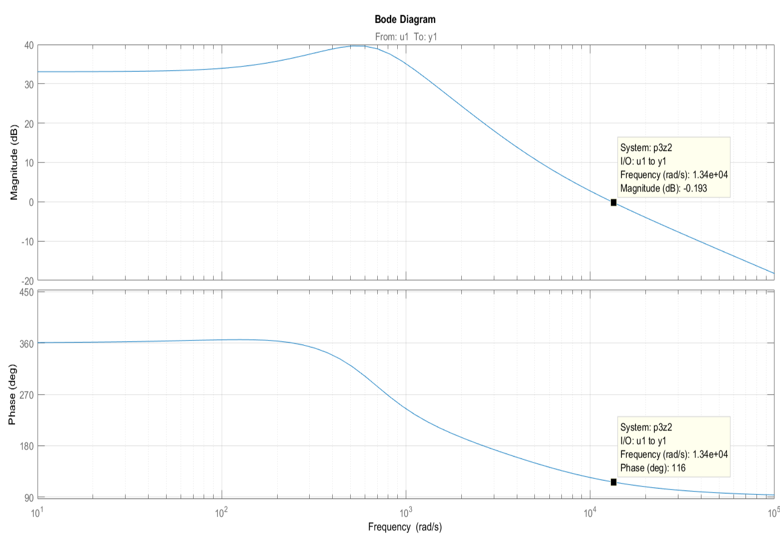

Figure 25: Bode Plot of Transfer Function Obtained with System Identification

4.3 Controller Design

For the system representing the Flyback converter, we designed one Type II (one pole, one zero, one integrator) and one PI (one zero, one integrator) controller, in order to be able to compare the performances of these two type of controllers. Their transfer functions and bode plots are present in next subsections, on Figures 26 and 27.

- Type II Controller

$$C(s) = \frac{s + 2 * 10^3}{s^2 + 2 * 10^4 s}$$

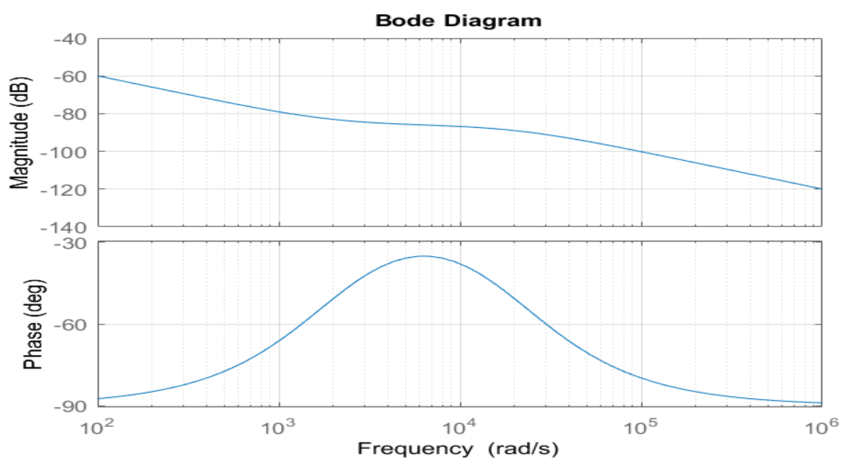

Figure 26: Bode Plot of Designed Type II Controller

- PI Controller

$$C(s) = 0.025 + \frac{1.5}{s}$$

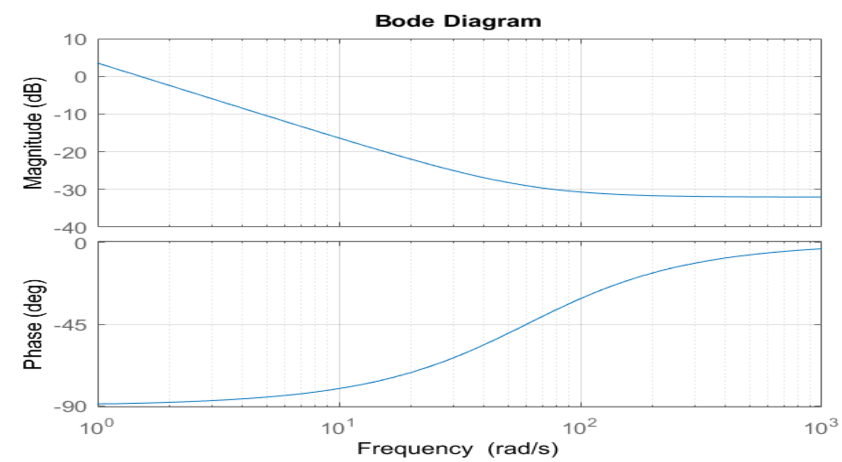

Figure 27: Bode Plot of Designed PI Controller

4.4 Performance Analysis

Having simulated the closed loop system, we observed that the type II controller designed with respect to the estimated model is not quite convenient for the actual one, however using a PI controller provides a more stable steady state output with less oscillations. (For closed loop system and output voltage of Type 2 and PI controlled systems, see Figures 28, 29 and 30.).

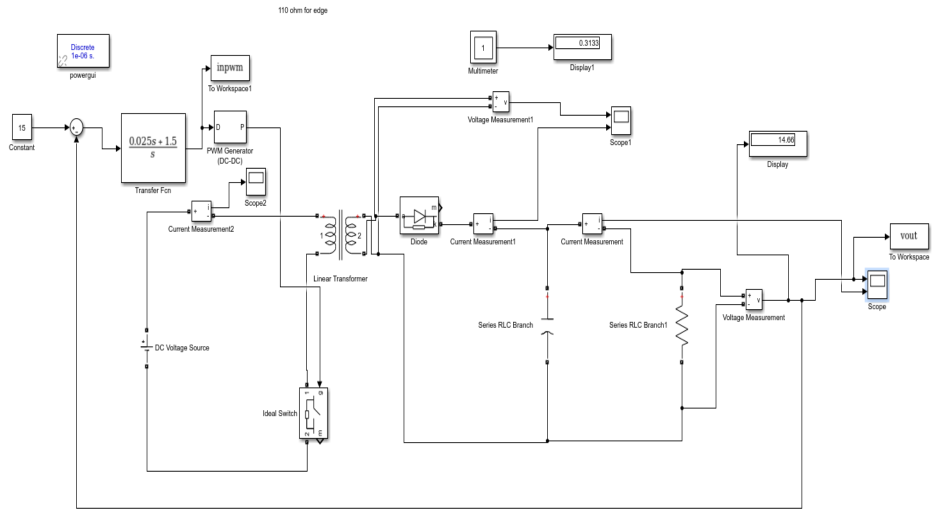

Figure 28: Controlled Flyback Converter

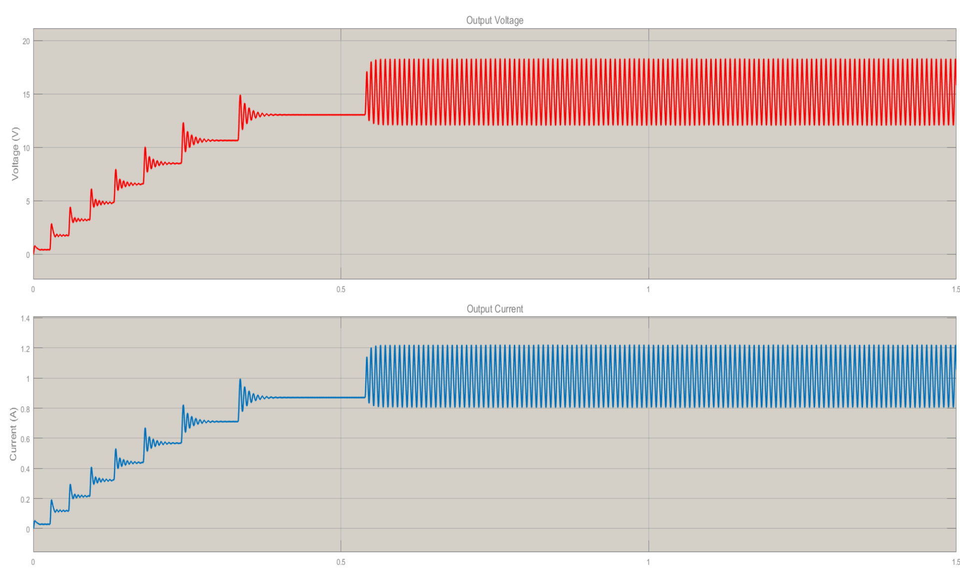

Figure 29: Output Voltage of Type 2 Controlled System

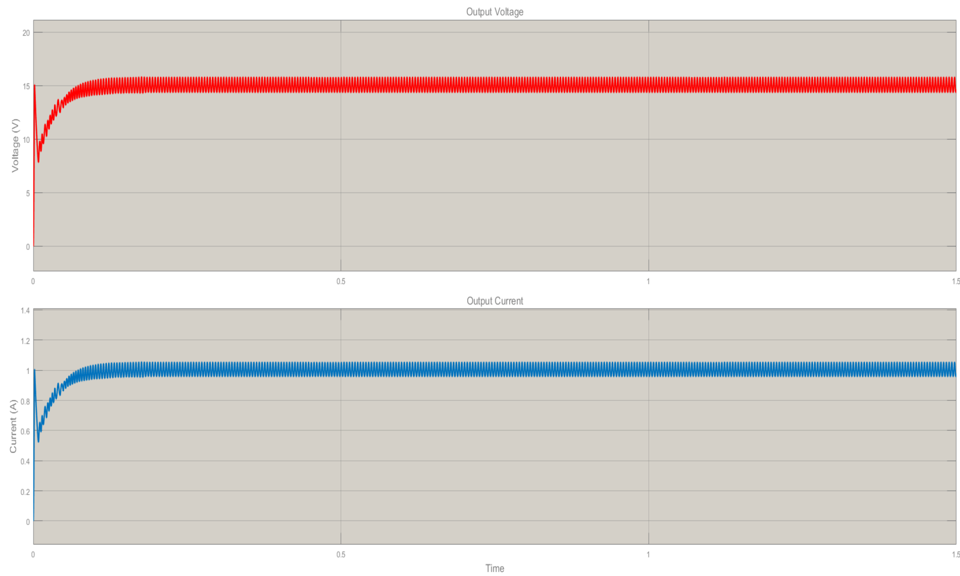

Figure 30: Output Voltage of PI Controlled System

To check the PI controller stability , we halved the load at a time instant t=0.2. Halving the load increases the oscillations at the output, however the system continues operating in a proper manner also in that condition. Further, we increased the input voltage to 230 V. Also for this case, the system preserved its stability. These simulation results are given in Figures 31 and 32, respectively. We did not perform these tests on Type 2 controlled system, as it is not really stable already.

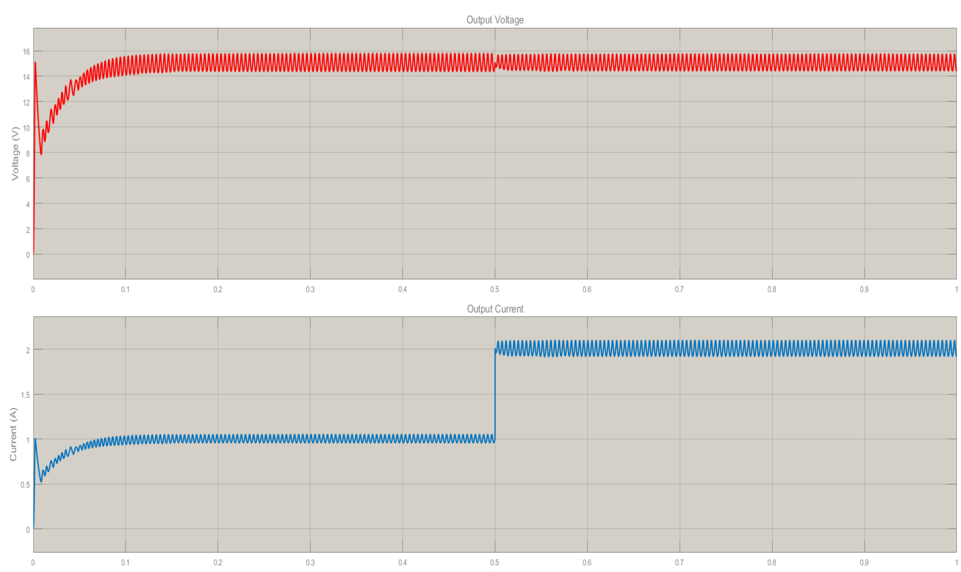

Figure 31: Full to Half Load Test for PI Controlled System (Switching Time: 0.2)

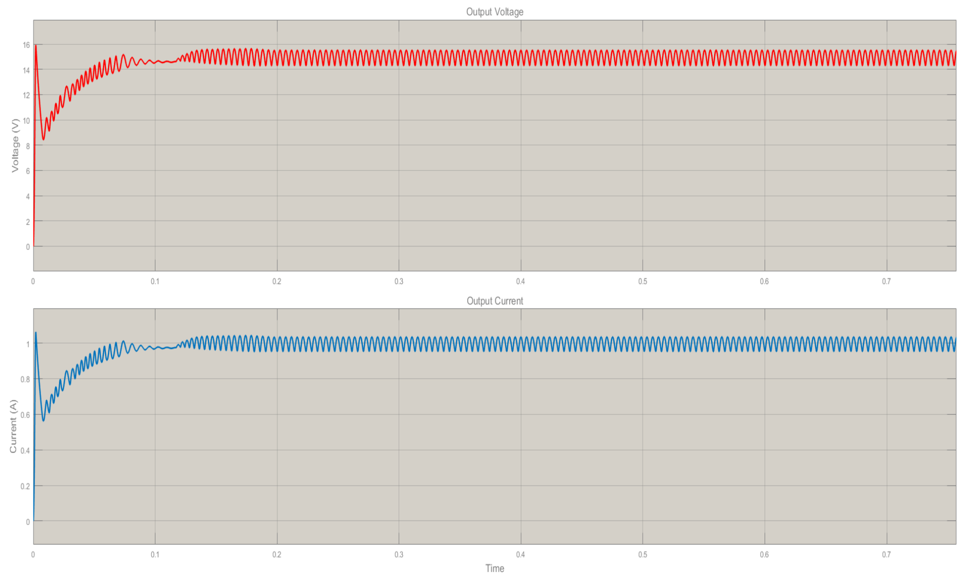

Figure 32: Overvoltage Test for PI Controlled System

4.5 Comments

Analytic estimation of the transfer function of a flyback converter is quite challenging, since the transfer function has a nonlinear element, changing with each value of duty cycle. For that reason, analytic calculations and transfer function estimation with system identification do not hold with the actual system. As a result, designed Type 2 controller could not provide a stable steady state operation for the closed loop system. Nevertheless, with intuitively estimated PI controller, we could observe stable steady state operation.

5 Conclusion

In this report we have explained our design guideline for flyback 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 overvoltage and losses are observed. Using all of this analysis we selected our suitable components for our design. After that we have done a control analysis for our flyback converter. Controller design process for a DC-DC converter may be a challenging process, since the analytical calculations and estimated results by the simulation software for the transfer function may not hold for 100% cases. However, having obtained rough estimations that gives us an idea about the general behavior of the system, we can design and tune a controller with at least one integrator and one zero (optionally additional one pole). For this kind of applications, these type of controllers (Type 2 and PI) are suitable.

6 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