MIDDLE EAST TECHNICAL UNIVERSITY

Department of Electrical and Electronics Engineering

EE464 Project-2 Report

Simulation and Design of the Hardware Project

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1- Introduction

In this report, simulations and the detailed design analysis of the chosen topology for the hardware project which is the Forward Converter 3 is examined. Simulation part includes the design schematics of the ideal and the non-ideal cases and their input/output voltages and inductor/load currents. The simulations are to observe the differences caused by the non-idealities added to the ideal cases. Later, the design process and the parameters of the transformer such as core material, its geometry, the turns ratio and the operating flux density are revealed. Then, capacitor and the inductor selection is included as well as the efficiency calculation. Furthermore, the conclusion chapter culminates the chapters before and all the relationships that are explained. The schematic of the converter can be seen in the Figure-1.

2- Results

Part-a

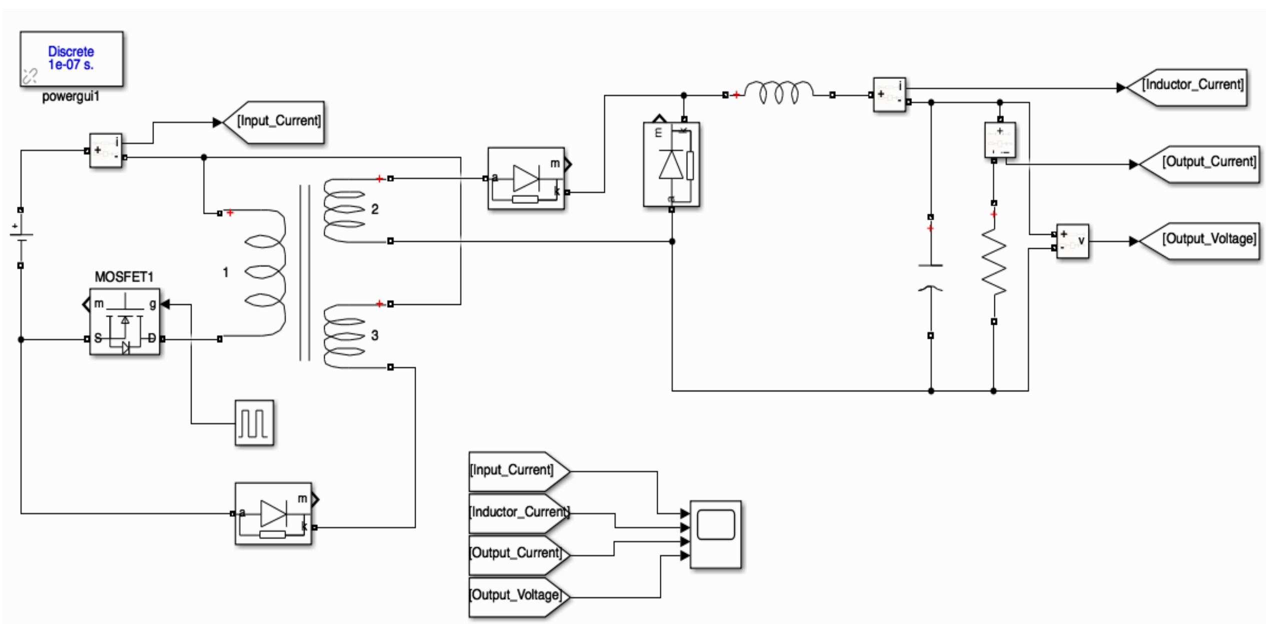

Figure 1: Schematic of the forward converter design.

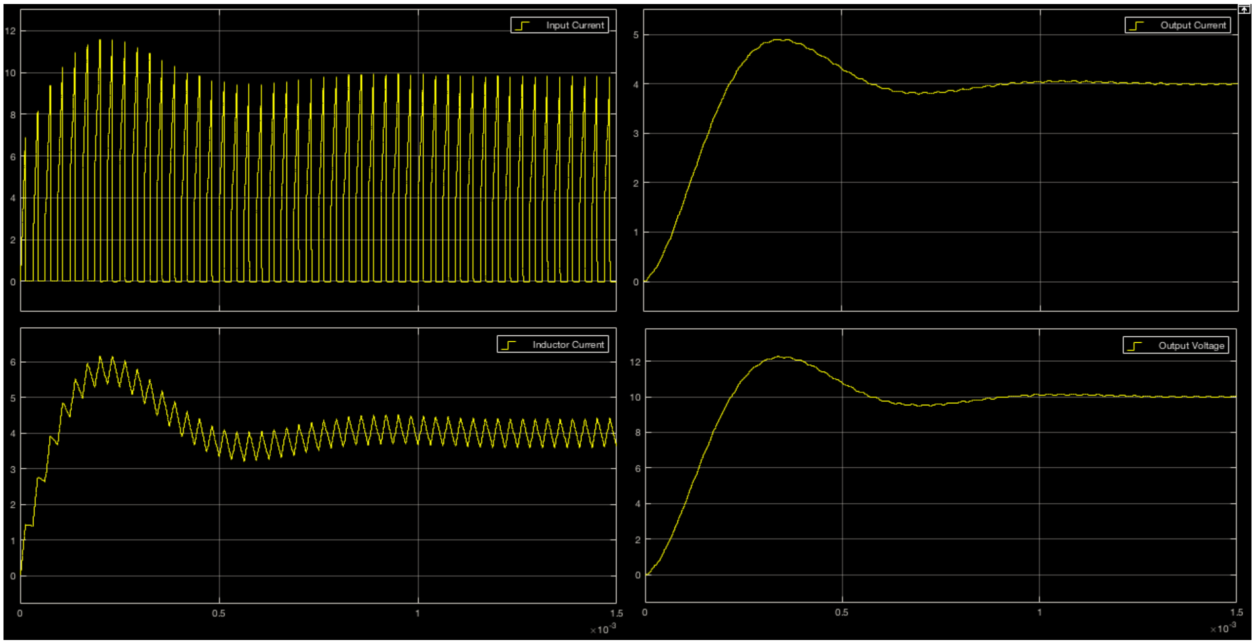

Figure 2: Graphs of the Forward converter design in the order of input current, inductor current output current and output voltage.

From the Figure-2, it can be shown that the output is oscillatory which means the system is underdamped and as the time goes the system reaches its steady state where output voltage is 10V as desired (9.98-10.06). However, it should be noted that the steady state is a sinusoidal voltage of 32kHz with a DC component. The envelope around the output is the one that dies out. Which is something to be expected since without AC the transformer would not work in the first place.

Part-b

We had to determine an average efficiency, turn ratio and duty cycle to specify some parameters that help to choose the transformer core. We determined the efficiency of the converter as 70%, turn ratio as one and duty cycle of the PWM signal as 10/24. According to these values, we started to calculate the current passing through each sides and minimum number of turns of the each sides. In order to calculate that, firstl we needed to calculate the ripple factor, K_{RF}.

$$K_{RF} = \frac{\Delta I}{2I_o}$$

where I_o is the maximum output current. We have 2% current ripple and 4 amper output current, so $K_{RF} = 0{,}01$. Peak current and rms current of the switching component are obtained as:

$$I_{ds}^{peak} = I_{EDC}(1 + K_{RF})$$

$$I_{ds}^{rms} = I_{EDC}\sqrt{(3 + {K_{RF}}^2)\frac{D_{max}}{3}}$$

where $I_{EDC} = \frac{P_{in}}{V_{DC}^{min} * D_{max}}$. Our I_{ds}^{peak} and I_{ds}^{rms} values are 5,77 and 3,69 amps respectively.

After that, we determined the size of the E-core. While selecting the core, there are two important parameters. 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-3.

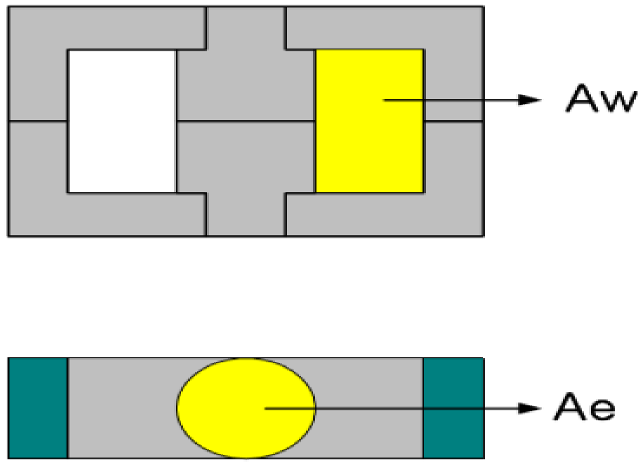

Figure 3: Window area and cross sectional area of the E-core

$$A_p = A_W * A_e = \left[\frac{11.1 * P_{in}}{0,141 * \Delta B * f_s}\right]^{1,31} * 10^4 (mm^4)$$

where ΔB is operating flux density and f_s is switching frequency. This is the minimum value of the core. Our A_p value is approximately 15600 when ΔB is about 0,1 T in accordance with the Figure-4. According to that value, we chose the E-core with part number 00K4022E090. Window area of this core is 276 $mm^2$and cross section area is 237 mm^2. A_p value of the core is much higher than our minimum value, but it is the smallest core we could chose. The advantage of the big core is that operating flux density is smaller than the small sized cores. The disadvantage of biger core is its higher price.

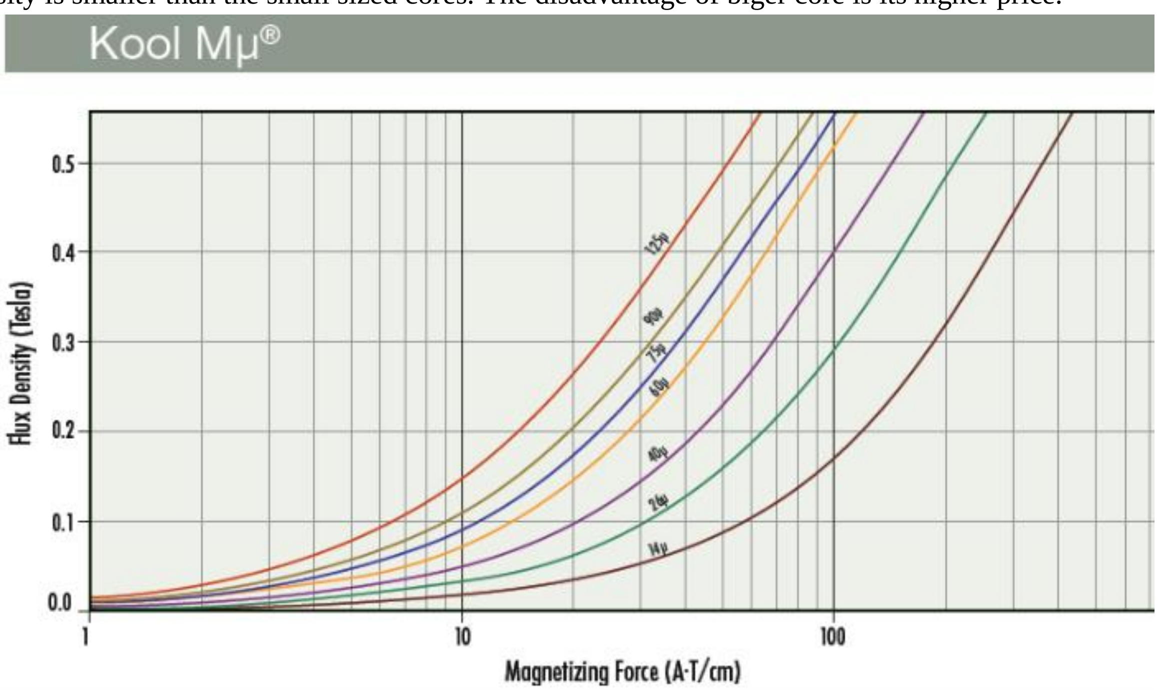

Figure 4: Flux density versus magnetizing force graph of the E-core

Minimum number of the primary turn is calculated as the following formula:

$$N_p^{min} = \frac{V_{DC}^{min} * D_{max}}{A_e * f_s * \Delta B} * 10^6 \ (turns)$$

which is 13.18 for our design. We decided to make our turn numbers as 15. Then, we calculated the magnetizing inductance, L_m.

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

where A_L is the inductor factor and for our core its value is 265 $^{nH}/_{T^2}$. L_m is equal to 596 µH.

The currents passing through the secondary and reset winding were found by using the following formula:

$$I_{sec}^{rms} = I_{o,sec} * \sqrt{(3 + {K_{RF}}^2)\frac{D_{max}}{3}}$$

$$I_{reset}^{rms} = \frac{V_{DC}^{min} * D_{max}}{L_m * f_s}\sqrt{\frac{D_{max}}{3}}$$

which are 2.6 and 1.95 amps respectively. We picked size of the cables according to these current values.

We calculated leakage inductance of the transformer according to this formula:

$$L_{leakage} = \frac{292 * N^{1,065} * A_e}{10^6 * l_e}$$

where l_e is path length of the core and its value is 98,4mm.Primary leakage inductance is equal to secondary leakage inductance because of the unit turn ratio and its value is about 13 µH.

We needed to determine the core loss for simulation. Again, we checked the core characteristics. According to the Figure-5, our core loss density is about 200 $^{mW}/_{cm^3}$. The core volüme is 23,3 cm^3, so the core loss is 4,66 watts.

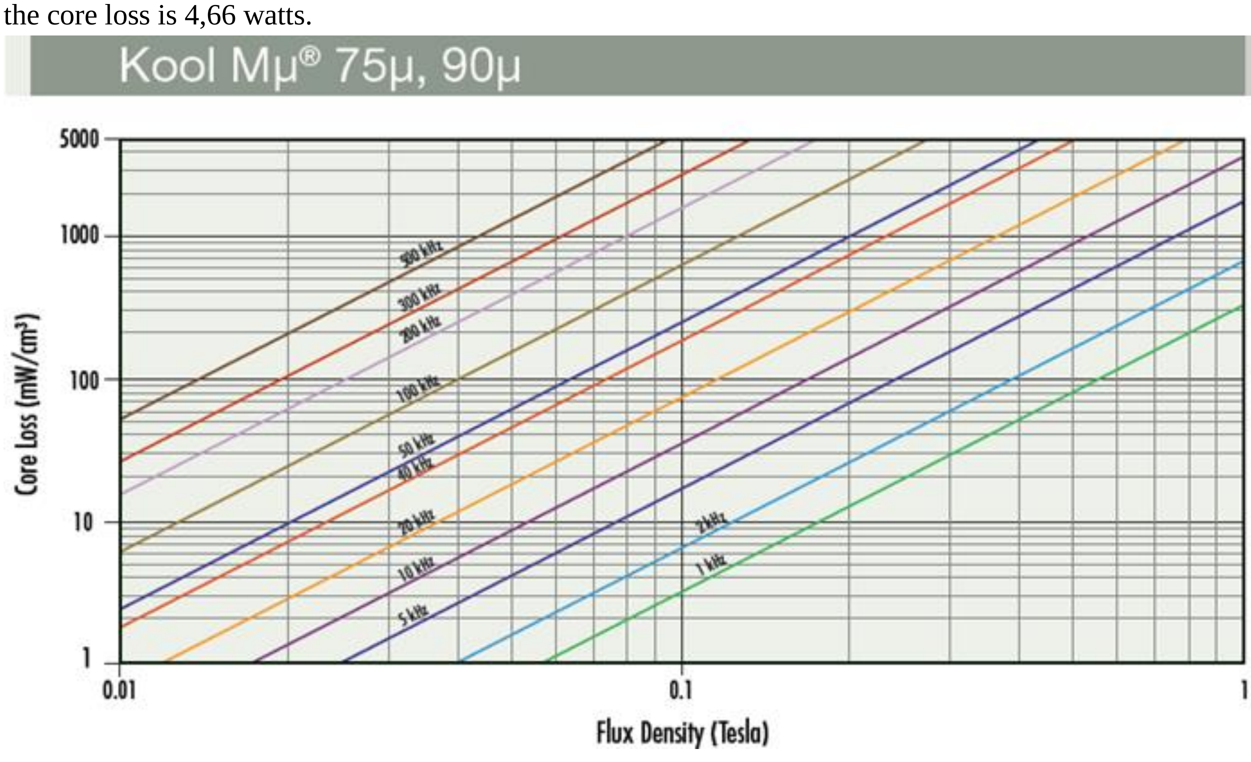

Figure 5: Core loss density versus flux density graph of the E-core

Part-c

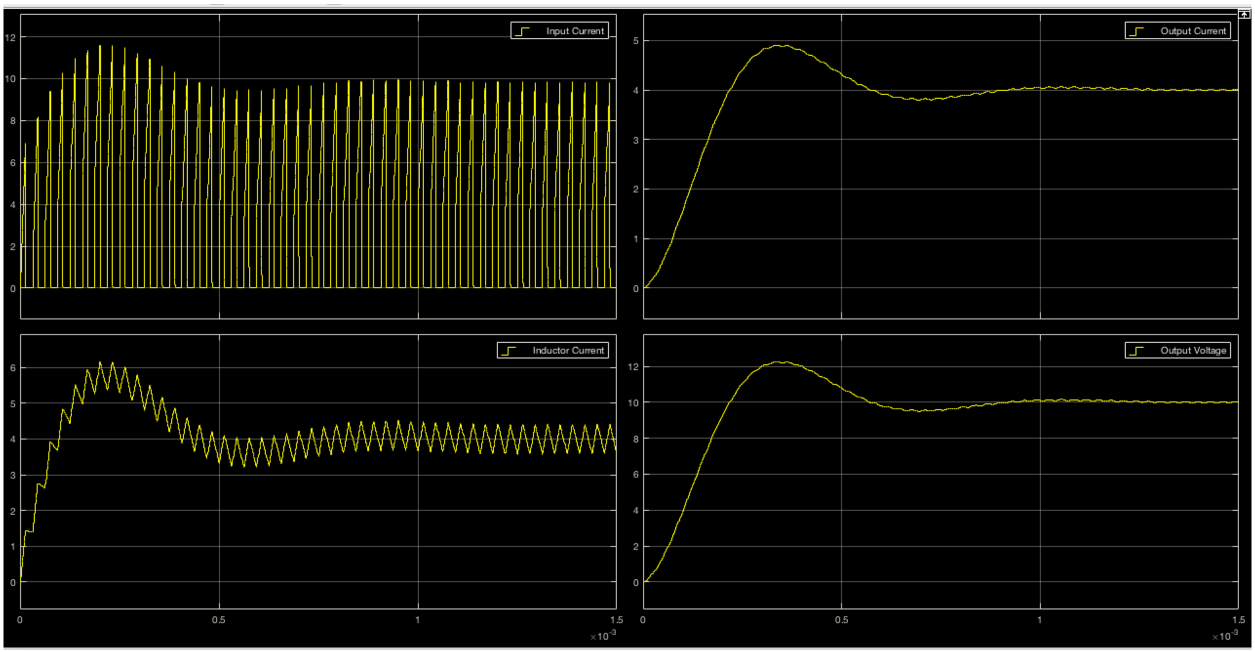

Figure 6: Graphs of the Forward converter design with ideal switch in the order of input current, inductor current output current and output voltage.

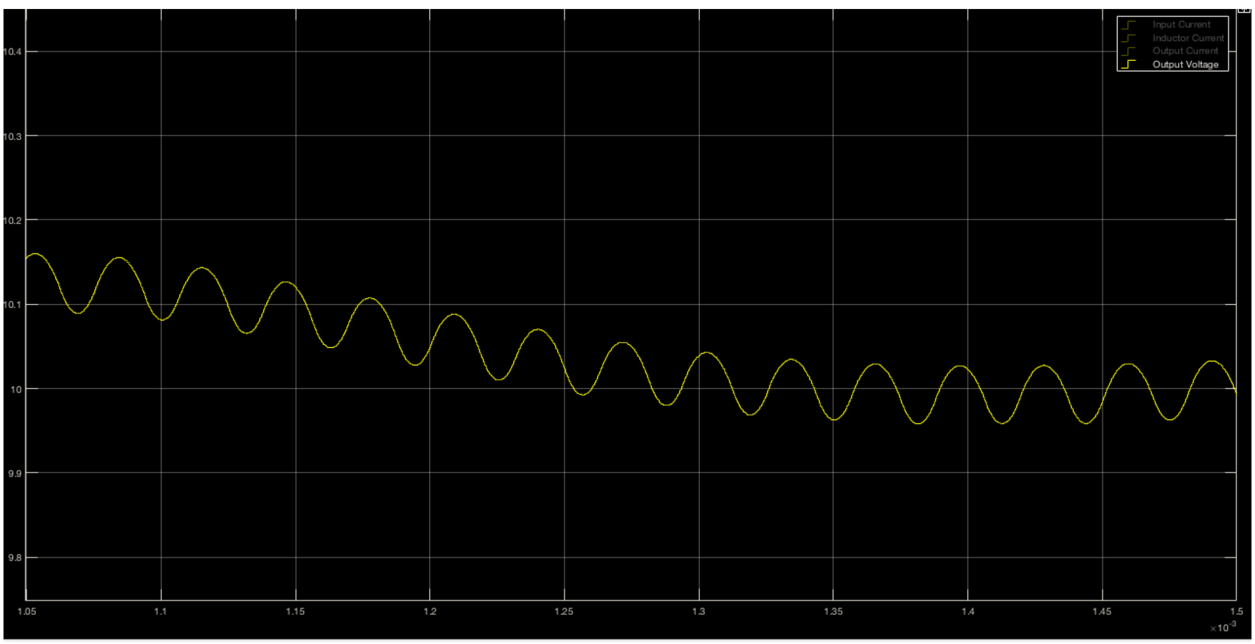

Figure 7: Grapf of the output voltage ripple of the Forward converter with ideal switch.

Part-d

If the inductor current gets to 0, the device will go into DCM. When the switch is off,

$$L * \frac{dIl}{dt} = Vl = Vout = 10 = 220 * 10^{-6} * \frac{dIl}{dt} => \frac{dIl}{dt} = 45454.5\ A/s$$

For our frequency, one period is 1/32000 sec, and the off duration is 1/32000 * 0.42 =1.3*10^-5 sec. Therefore, if the device enters DCM, at the best case, the current will fluctate between 1.3*10^-5*45454.5 = 0.592 A and 0 A. If we take the average, the average fringe current that will put us in the DCM is 0.296 A. Tranformer current is calculated before in part b.

Part-e

When we put a mosfet for a switch, we have seen that voltage stress over the switch was enormous.

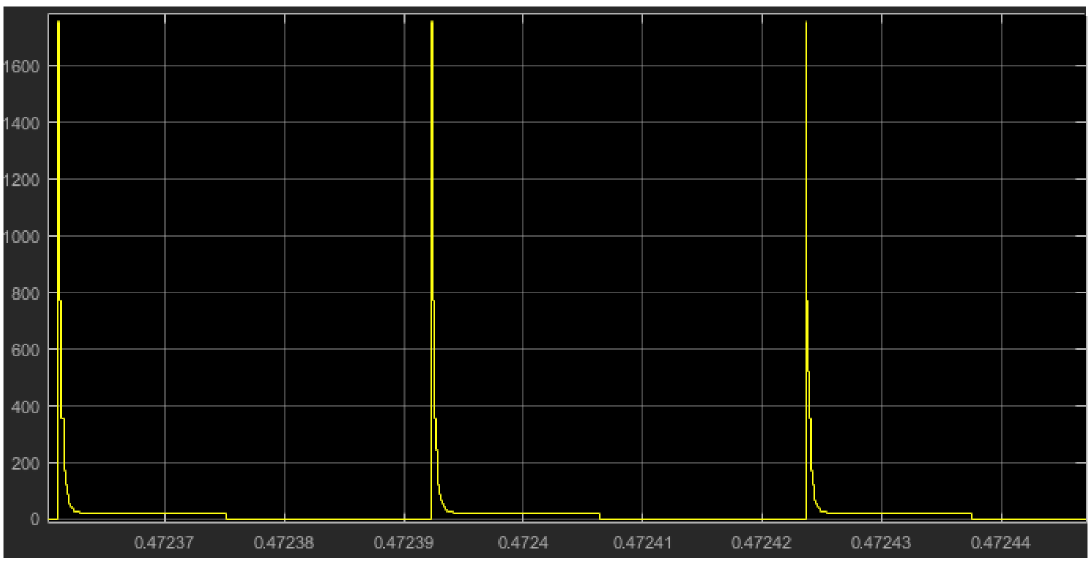

Figure 8: The switch stress when there is no snubber circuit

Let’s design a snubber circuit:

R = 2*pi*f*Lm = 12 ohm

C = 1/(2*pi*f*R) = 0.414 uF

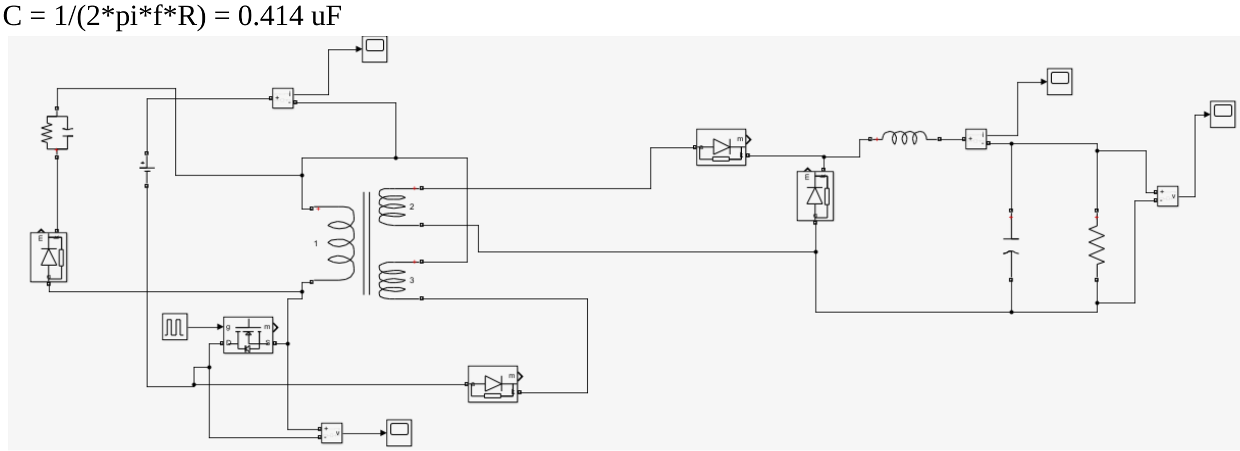

Figure 9: The new circuit with an added snubber circuit

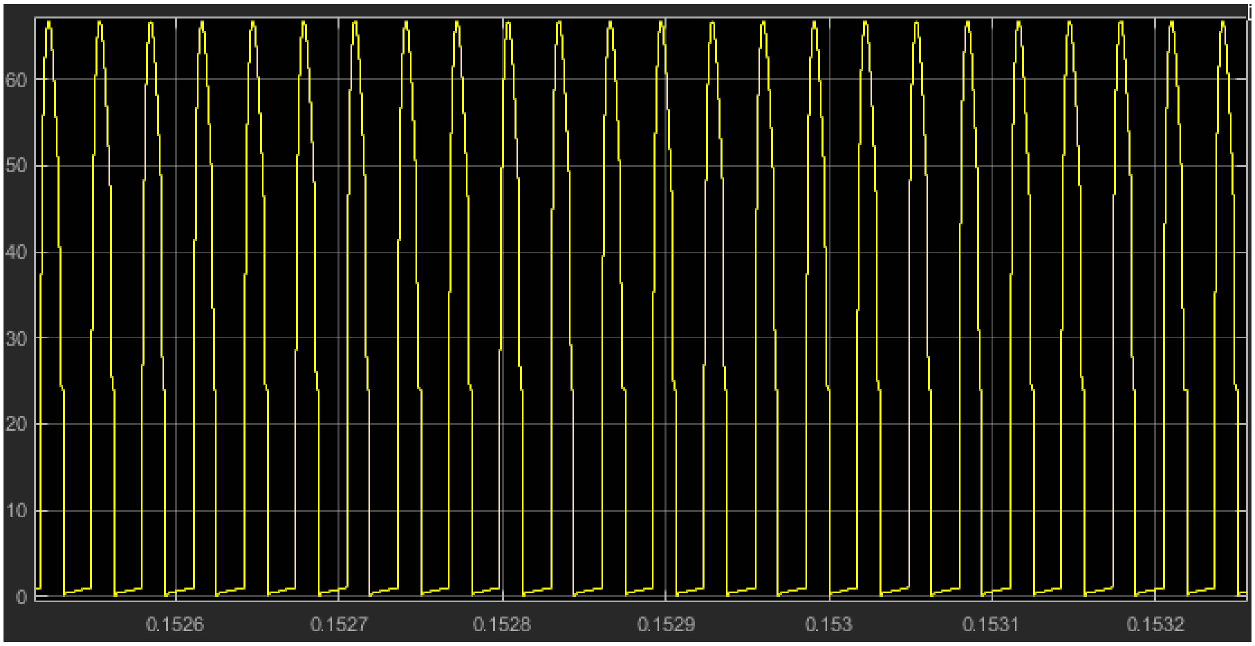

Figure 10: When we use the snubber given in the circuit, this is the new stress on the switch, which is much more manageable

Part-f

At full load:

Transformer current is 3.69 amperes and transformer copper resistance is 0.0259 ohm.

Transformer copper loss primary side = 3.69^2*0.0259 = 0.35 W

Transformer copper loss secondary side = 2.6^2*0.0259 =0.175 W

Reset windig copper loss = 1.95^2*0.0259 = 0.1 W

For switching loss, let’s pick a power mosfet, IRF540NSPbF

Trise = Tfall = 35*10^-9

Vds= 75 V

Coss= 250 * 10 ^-12 F

Crss = 40 *10^-12 F

$Switching\ loss = (Coss + Crss) * Vds^2 * f = 290 * 10^{-12} * 60^2 * 32000 = 0.033\ W$

Conduction loss = 3.69 ^2 * 44 *10^-3 = 0.6 W

Transformer core loss = 4.66 W

- ⇨ Efficiency = Pout/Pin = 40/(40 + 0.35 +0.6 + 0.033 + 4.66 + 0.175 + 0.1) => n = 88%

As the load reduces, the losses also get lower.

Part-g

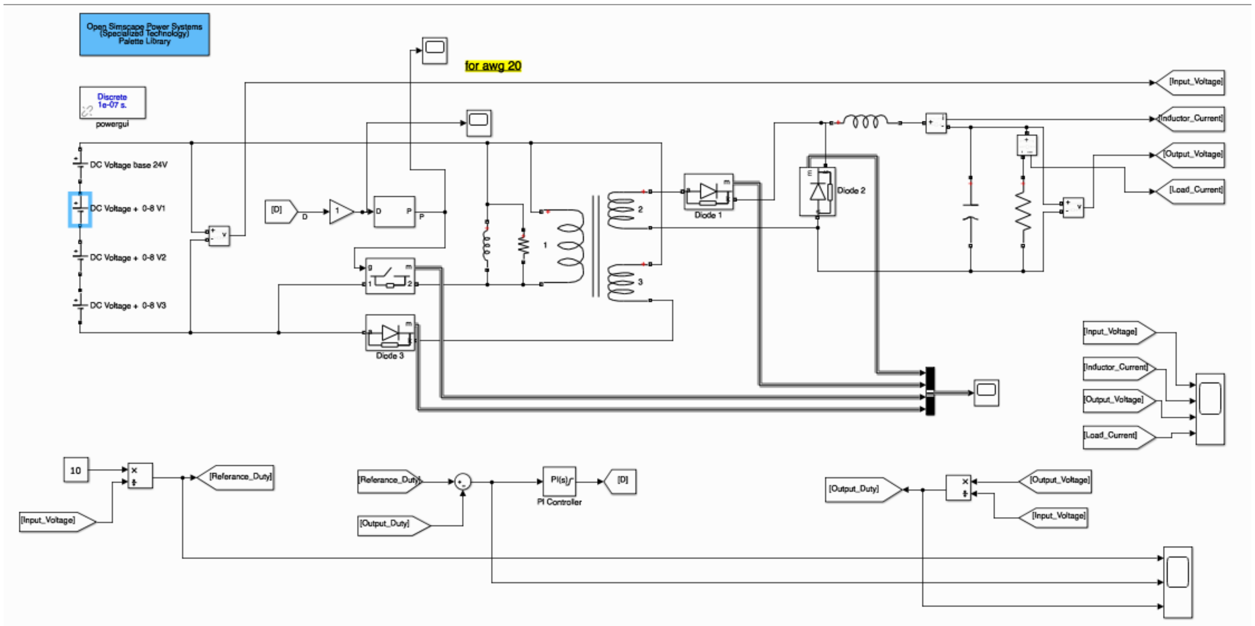

Figure 11: Schematics of the Forward converter design with the controller.

Controller operation

The controller that we have designed is a PI controller that adjusts the duty cycle of the switch according to the input and output data which is the desired duty cycle ration coming from the input side as the reference signal and the actual duty cycle ratio coming from the output side as the feedback signal. The difference between them which is the error converges to zero as the PI controller works. In figure 11, the operation of the controller can be seen. As the input voltage increased 8 volts per step, the output does not change which can be seen in figure 12.

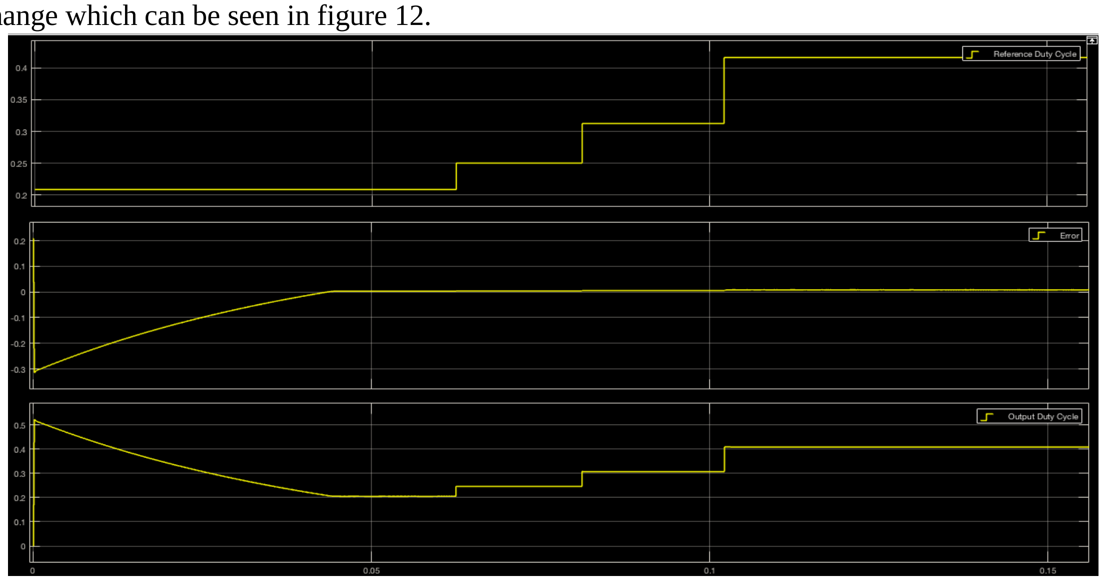

Figure 12: Graphs of the controller of the Forward converter design in the order of input duty ratio, error between input and output duty ratios and the output duty ratio.

In figure 13, the effect of the input value change can be seen. First the converter reaches its steady state for the input of 24 volts. As the input voltage is increased by 8 volts in each time the output voltage is readjusted to its new value which is still around 10 volts. In figure 14, the ripples in the inductor current can be seen.

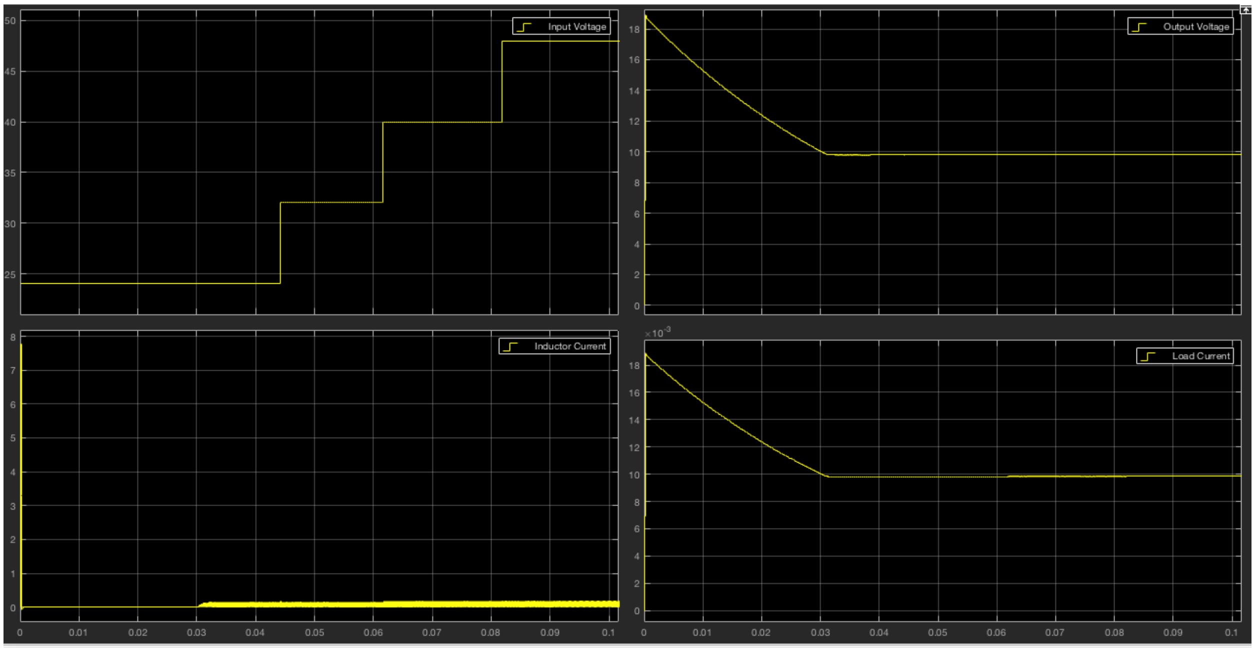

Figure 13: Graphs of the input/output voltages and inductor/load currents of the Forward converter.

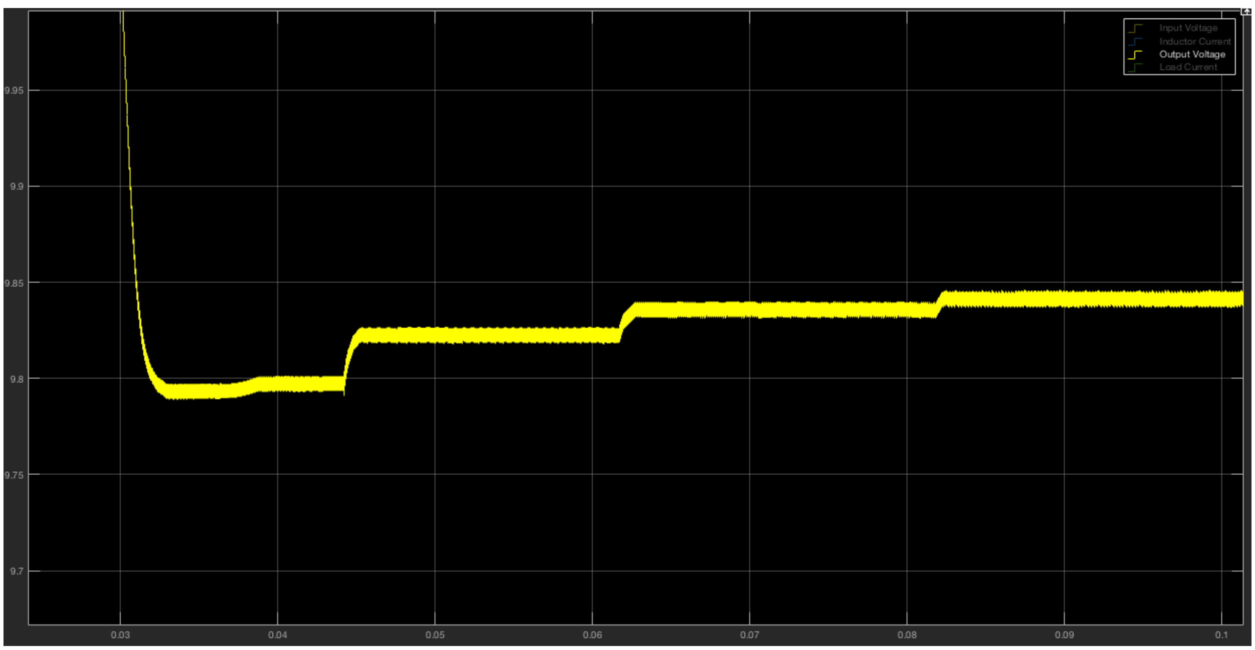

Figure 14: Graphs of the output voltage of the Forward converter.

As it is evident from this graph, the steady state voltage ripple is less than 0.1 percent. As another important fact is there is no oscillations in the outputs for the input changes. This could be related to the controller dynamics where the controller factors K and Ki creates damping to the system.

Part-h.

We specified the transformer components in the previous parts. The manual that we refer to is shown in the appendices. Also, we indicated the switching component in the previous parts. The datasheet of the mosfet and the diode can be seen in the appendices. We will design the inductor by ourselves. Finally, we picked the filter capacitor as seen in the appendices. When selecting these components, we paid attention to their current and voltages level. Also, we considered their usage areas. As seen in the simulations, there is no problem with the components.

4- Conclusion

In this project, we tried to design and analyze different parts of the forward converter as a switching mode power supply. We designed and simulated a simple version of the converter. Then, we added to parasitic components like core loss, leakage inductance and copper losses. Also, we designed a transformer. According to this transformer parameter, we selected different parts of the converter like transformer cable and filter of the secondary side. In the end, we designed a controller. We decided to use a digital controller because of its simple implementation. This is the beginning phase of the hardware project and we have completed a large part of the project theoretically. We have made some mistakes like efficiency calculation, but we will correct our mistakes in the second phase of the project.

5- Appendices

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

http://pdf1.alldatasheet.com/datasheet-pdf/view/227556/IRF/IRF540NSPBF.html

https://www.mouser.com.tr/datasheet/2/427/rgl34a-279712.pdf

https://www.mouser.com.tr/ProductDetail/United-Chemi-Con/KTD101B476M99A0B00?qs=sGAEpiMZZMuMW9TJLBQkXmnrInYFHsnYAZNIiqP33cs%3D