MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICAL ENGINEERING

EE 464 – HW1

Magnetic Design of the Hardware Project

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INTRODUCTION

Magnetic design is an important aspect of the power electronics. Transformers and inductances have a wide usage in most of the converters and other topologies. So designing it correctly and getting all neccessary calculations is vital for building a power converter design.

In this report, our aim is to calculate important parameters for our DC-DC converter design through given questions. Firstly, we will select our converter topology for given wanted results. After that, we will design our transformer for our topology. Eventually, we will simulate our results to check accordingly.

A-

Firstly, topology is selected as Forward Converter. After that, from the equation of the V_{in} and V_{out}, required turns ratio is determined and maximum and minimum duty cycles are calculated.

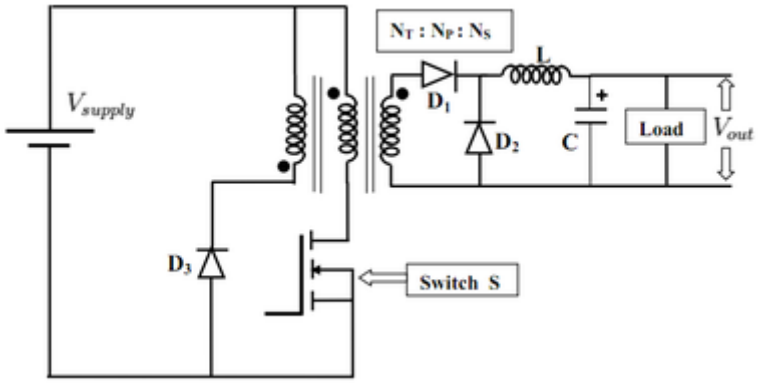

Figure 1. Forward Converter Topology

At the beginning, for the not saturated core and high core losses, duty cycle must be smaller than 0.5. Moreover, due to the non-idealities and some deviations, the most duty cycle value is taken as 0.45. After that, from the equation, $Vout = Vin * (N2/N1) * D$, required turns ratio at the 20 V input case is 1.33. After that, for simplicity and safety of the operation modes, turns ratio determined as 1.5. Then duty cycle is calculated for 40 V input voltage case. Value is calculated as 0.3. Finally, with the turn ratio is 1.5, required duty cycle at 20 V input voltage case calculated as the 0.4.

In conclusion, turns ratio determined as the 1.5 and duty cycle varies between 0.2 and 0.4.

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B-

1-

Firstly, core geometry is determined as the toroid. It has multiple advantages for project application, however, of course has many disadvantages. For example, it has higher efficiency, around 95 and 99%. For the perfect windings, no leakage flux occurred. Of course, design of the transformer will be not perfect, but this situation is very good specification. Moreover, due to effective containment of the magnetic flux, these cores shield adjacent components from EMI. It is very important for this project application because MOSFET's and inductors can be affected easily by the EMI. In addition, lower heat generation, no air gap and compact construction, toroid geometry will be more useful for us. If disadvantages are discussed, implication will be hard, higher inrush current, and cost should be taken into consideration. However, advantages outweigh the disadvantages.

Figure 2. Toroid Core

After selection of the core geometry, required core specifications are determined. From the searching about the transformer cores, core selection by Wa*Ac product is calculated. From the Formulation of this case, gives us some critical information about core. For the appropriate core, area product distribution used.

$$Wa * Ac = (P0 * Dcma)/(Kt * Bmax * f)$$

W_a: Window Area

A_c: Core Area

D_{cma}: Current Density

B_{max}: Flux Density

K_t: Topology Constant

From this formulation, required Wa*Ac product calculated as (60 * 750) / (3000 * 100 * 10^3 * 5 * 10^{-4}) = 0.3 cm^2. In addition, relative permeability and power charts gives us some critical points. So, core 0088894A7 ferrite core selected from the provided core list.

Electrical Characteristics			Physical Characteristics						
Watt Loss @ 100 kHz, 100mT max(mW/cm^3)	DC Bias min (A·T/cm)		Voltage Breakdown wire to wire min (V_{AC})	Break Strength min (kg)	Window Area W_A(mm^2)	Cross Section A_e (mm^2)	Path Length L_e (mm)	Volume V_e (mm^3)	Weight (g)
	80%	50%							
1000	47.7	95.4	1000	48	156	65.4	63.5	4,150	26

Figure 3. Physical Characteristics of the Selected Core

Used formulations and datasheet of the selected core can be found in our GitHub repository.

2-

For the number of turns at primary side, some design reports are researched, and many applications are found. According to forward converter design application of Dr. J. K. Watson, number of turns calculated as

$$N_p = \frac{V_{in(\min)} D_{(\max)} \left(10^4\right)}{f A_c \Delta B}, \quad [\text{turns}]$$

Figure 4. Formulation of Number of Turn at Primary Side

From this equation, required number of turns at primary side calculated as N > (20 * 0.4 * 10^4) / (100 * 10^3 * 0.65 * 0.1) = 12.3. So, number of turns at primary side determined as 20 and secondary side is determined as 30.

Then for the calculation of the magnetizing inductance, typical DC bias performance chart is examined.

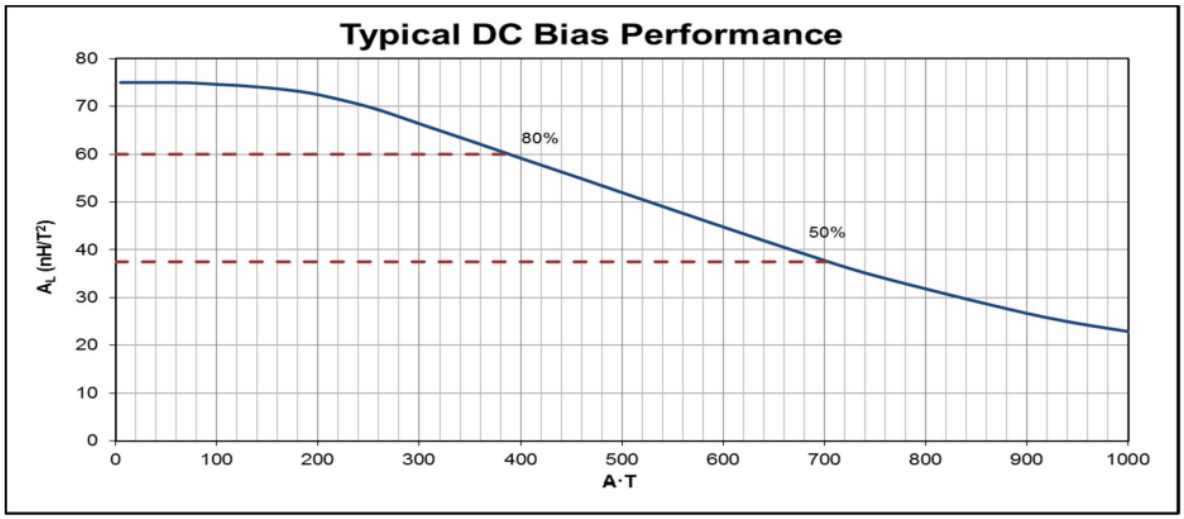

*Figure 5. A_L vs A*T Graph*

From this graph, when A * T = 120, expected current at minimum voltage is around (12 * 5) / 20 = 3, at this point A_L value is around 75. So, from the equation of the A_L, inductance value can be calculated as (A_L * N^2) / 10^9 = 30.04 µH.

3-

With our operation frequency 100 kHz, from the AWG table, cable 26 is chosen. Also, currents in each winding calculated. For the primary side winding, current at each winding calculated as Pin / (Vin(min) * $Dmax^{0.5}$), so at the primary side, current on each winding 60 / ((0.63) * 20) = 4.54 amps. At the secondary side, it is calculated as 5 / 1.41 = 3.55. Then Ku factor selected as 0.4. After this selection current densities of the wire is

$$J = (2 * Pin * Dmax\text{^}0.5 * 10\text{^}4) / (f * dB * Ac * Wa * Ku)$$

Which is equal to 194.46. Then required area for the carrying current at primary side is calculated as 4.54 / 194.46 = 0.023, number of primary strands calculated as 0.023 / 0.00128 = 17. Required area for the carrying current at secondary side is calculated as 3.55 / 194.46 = 0.018, number of primary strands calculated as 0.018 / 0.00128 = 14.

4-

For the fill factor, firstly total copper area is calculated. As we use N1 = 20 and N2 = 30. Copper area of the AWG 26 cable is 0.128, so total used area is 97.28 mm^2, window area is 156.54, so fill factor is 97.28/156.54 **= 0.6214**. It is nearly good value; however bigger core can be selected.

For the high frequency, AC and DC resistances' ratio of the core can be taken as 1. Winding length per turn at 60% winding factor is 48.8. At the primary side, we have 20 turns, so total winding length can be calculated as 48.8 * 20 = 976 mm. On the other hand, at the secondary side, total winding length can be calculated as 48.8 * 30 = 1464 mm. From the datasheet of the AWG 26 cable resistance per km is 133.85. So, resistance per mm can be calculated as 1.33 * 10^{-4}. Then the resistance at the primary side is 1.33 * 10^{-4} * 976 = 0.13 Ω and secondary side is 1.33 * 10^{-4} * 1464 = 0.194 Ω. Total copper loss can be calculated as 4.54^2 * 0.13 + 3.55^2 * 0.194 = 5.124 W.

5-

Core loss can be calculated with watt loss constant in datasheet of the core. Bmax is taken as 0.3 tesla and volume of the core can found in datasheet as 0.00415 cm^3.

$$\frac{\text{Watt Loss @ 100 kHz, 100mT max(mW/cm}^3\text{)}}{1000}$$

Figure 6. Core Loss Constant in the Datasheet

Core Loss = 3 * 1 * 4.15 = 12.45 W. If we compare with copper loss, it nearly twice of the copper loss. Total loss at transformer is Copper Loss + Core Loss = 17.56 W. It is nearly high, because of the losses at this stage, duty cycle or transformer ratio can be changed. It will be determined again physical applications.

C-

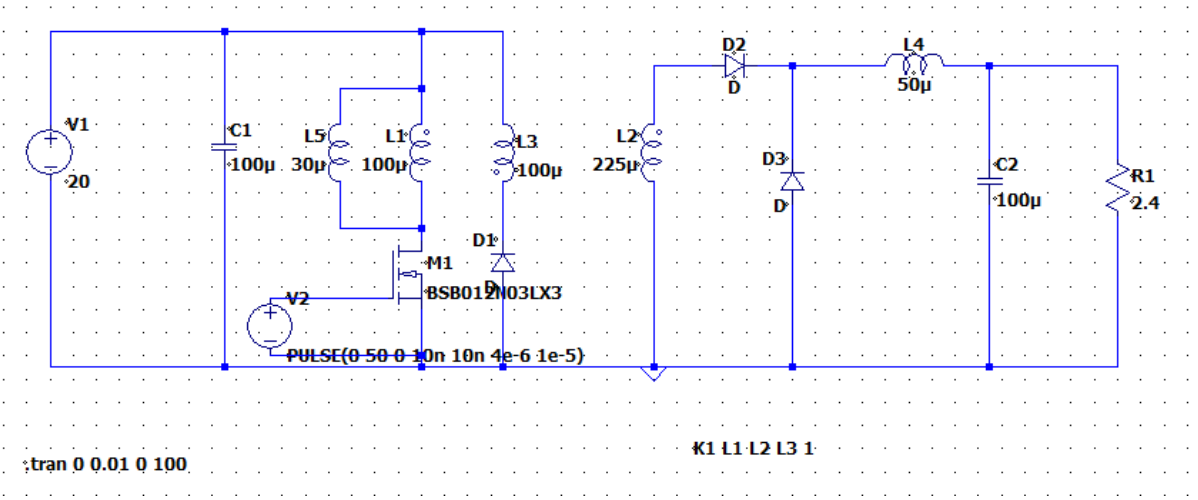

Figure 7. Simulation Schematic of the Selected Topology

In Figure 7, designed topology can be seen. Magnetizing inductance is 30 µH, turn ratio is put as 1.5. Input voltage is 20 V and duty cycle is 0.4 as calculated. Switch selected randomly model in LTSpice. Inductor and capacitor value are selected according to some design tools. Load is put as 2.4 for getting 5 A output and output voltage is 12 V.

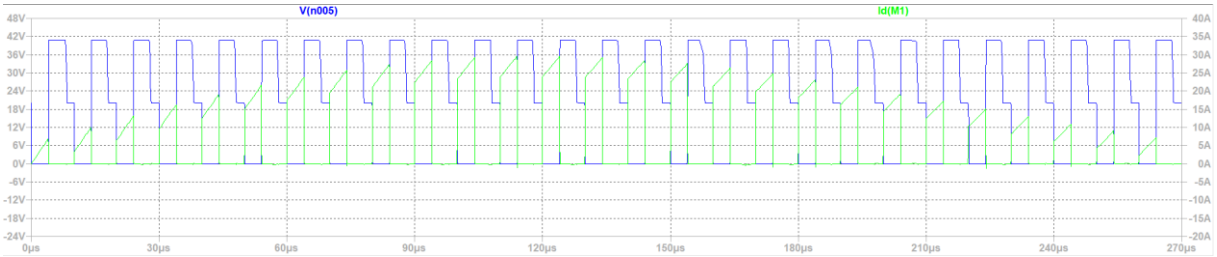

Figure 8. MOSFET Ratings at Transient State

From the Figure 8, transient response of the MOSFET can be analyzed. Maximum voltage at MOSFET is nearly 42 V and maximum current is around 30 A.

Figure 9. MOSFET Ratings at Steady State

At steady state, current varies between 6 and 11 A and voltage rating is around 42 V. According to these datas, required MOSFET will be selected and used.

Figure 10. D1 Characteristics

D1 voltage and current waveforms can be seen in Figure 10. Voltage level is around 42 V and current spikes can be 4.2 A. These values are important for selection of diode.

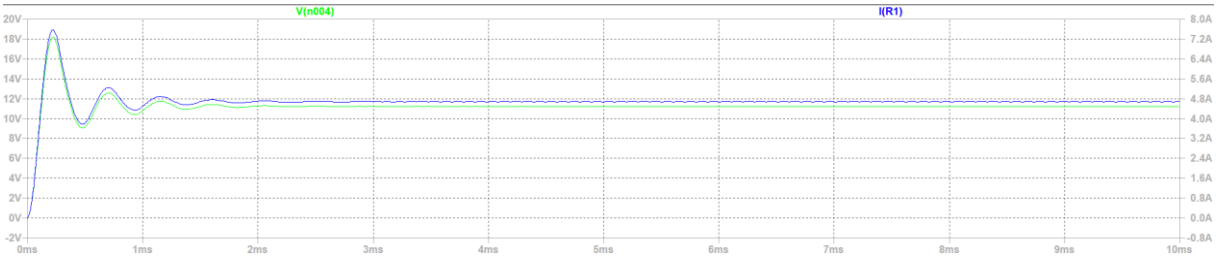

Figure 11. Load Characteristics

At the load side, output voltage and current can be seen. Load is going to steady state in nearly 1.5 ms. So, designed transformer and selected duty cycle are suitable for our DC/DC converter.

Figure 12. MOSFET Characteristics at 40 V Input Voltage

From the Figure 12, transient response of the MOSFET can be analyzed at 40 V input case. Maximum voltage at MOSFET is nearly 80 V and maximum current is around 30 A.

Figure 13. MOSFET Ratings at Steady State 40 V

At steady state, current varies between 6 and 13 A and voltage rating is around 80 V. According to these data, required MOSFET will be selected and used.

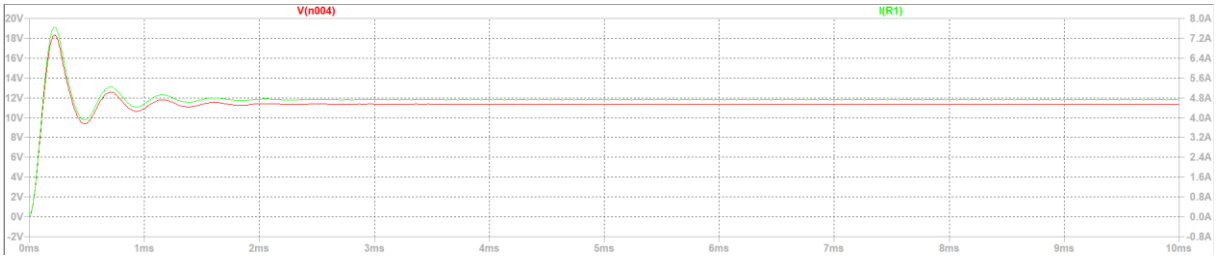

Figure 14. Load Characteristics at 40 V Input Voltage

In conclusion, from the simulation results of our selected topology, designed transformer, and determined duty cycle are suitable for our project. Of course, with some deviation's voltage level is lower very little. These deviations will be evaluated in simulation report.

D-

From the schematic of the forward converter topology, inductance at load side is selected as 100 µH, at the maximum input voltage case, duty cycle is nearly 0.2. From these values, at the off state, discharging amount of the inductor can be calculated as $dI = Vout * dT/L$ = 12 * 10^{-5} * 0.8 / 100 * 10^{-6} = 0.96 A. These value goes from 0.96 A to 0 A for finding smallest load current. So, average of this current is around 0.48 A. In conclusion, minimum load current is calculated as getting 100 µH inductor at the load side and for not a DCM operation, minimum load current should be 0.48 A.

E-

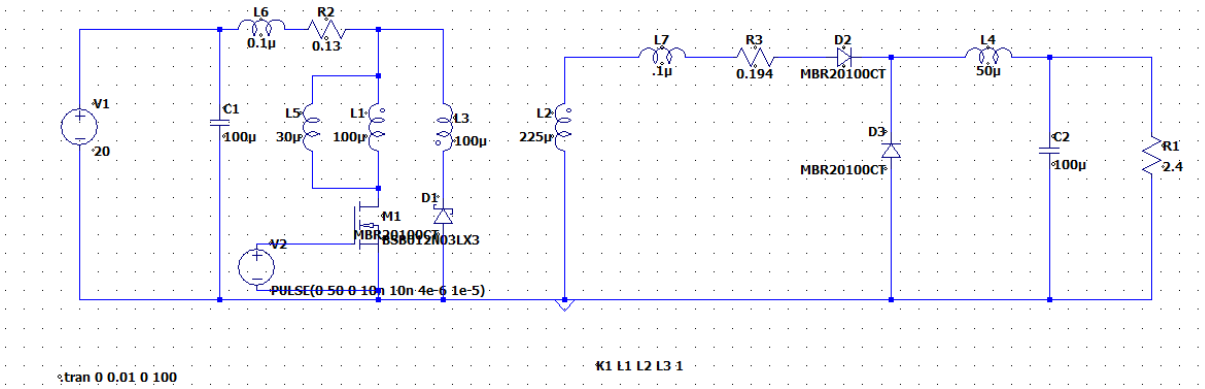

Figure 15. Converter Schematic with Parasitic Components

From the practical design of the transformer, leakage inductances are took as 0.1 µH. After the LCR tests, real value of the leakage inductances will be determined. Then, R1 and R2 values are used as found in part B. After that, MBR20100CT diode are used in order to ideal diodes. Its rating are suitable for our project. After these determinations, simulations are done. Then waveforms of Vds and Id MOSFET are observed.

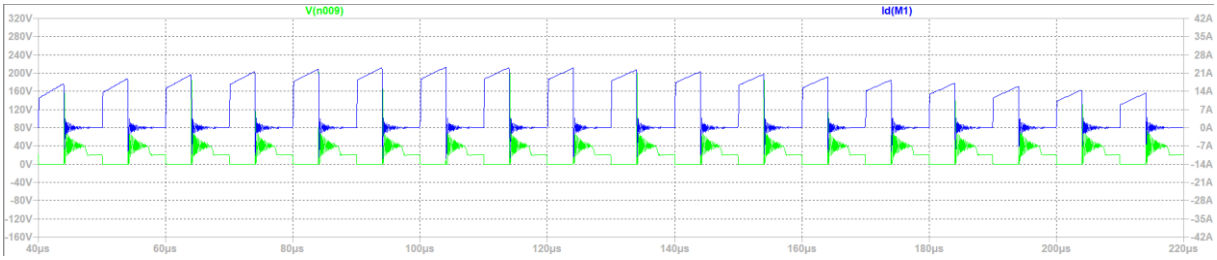

Figure 16. Waveforms of the MOSFET at Transient Response at 20 V Input

Figure 17. Waveforms of the MOSFET at Steady State Response at 20 V Input

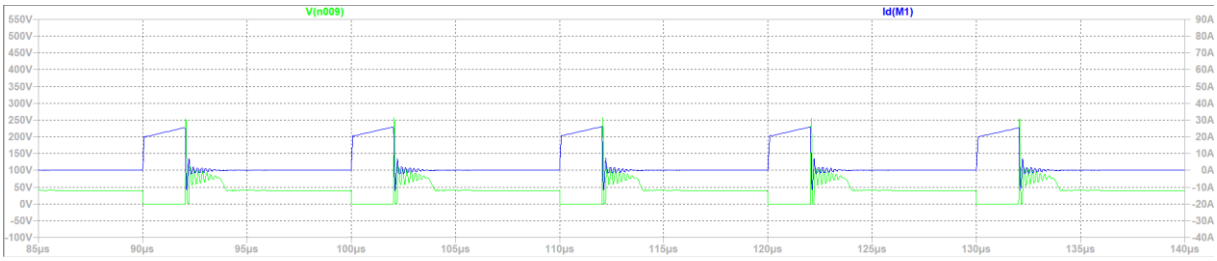

Figure 18. Waveforms of the MOSFET at Transient State Response at 40 V Input

Figure 19. Waveforms of the MOSFET at Steady State Response at 40 V Input

From these waveforms, oscillations can be observed. This situation affects our topology badly. Decrease the efficiency and cause EMI problems. Stresses on the MOSFET may be harmful for the selected MOSFET. So, snubber circuits should be designed and implemented to circuit. Design of the snubber will be done in next weeks.

F-

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}$$

For 20V

- At 100% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = 0.9049$$

- At 50% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = 0.95$$

- At 25% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = 0.974$$

For 40V

- At 100% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = \ 0.8963$$

- At 50% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = 0.9407$$

- At 25% load

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} = 0.9623$$

Note: This efficiency does not cover the semiconductor losses.

CONCLUSION

In this report, our aim was to calculate important parameters for our DC-DC converter design Firstly, we selected our converter topology for given wanted results as Forward Converter. After that, we designed our transformer for our Forward Converter. Eventually, we simulated our results to check any unwanted results.

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Our observations was getting a snubber circuit and drawing a PCB is must since high EMI problems seen in the grapghs. We will focus these on the simulaion report and try to find a solution.