MIDDLE EAST TECHNICAL UNIVERSITY

EE464- STATIC POWER CONVERSION-II

Hardware Project Simulation Report

Deniz Boran KARACA 2093987

Mert Yaşar AYDIN 2093334

Canberk DUMAN 2030450

Date: 23/03/2020

Table of Content

1 Introduction

This report is prepared to discuss design decisions, component selections and provide computer simulations of the regulated power supply for the EE464 hardware project.
There are mainly two different topologies and three different specs for each topology. In this report, both flyback and forward converters will be investigated with their advantages and disadvantages. The selection of topology and project design are explained with reasoning and simulation results.

2 Design Choices

2.1 Flyback Converter

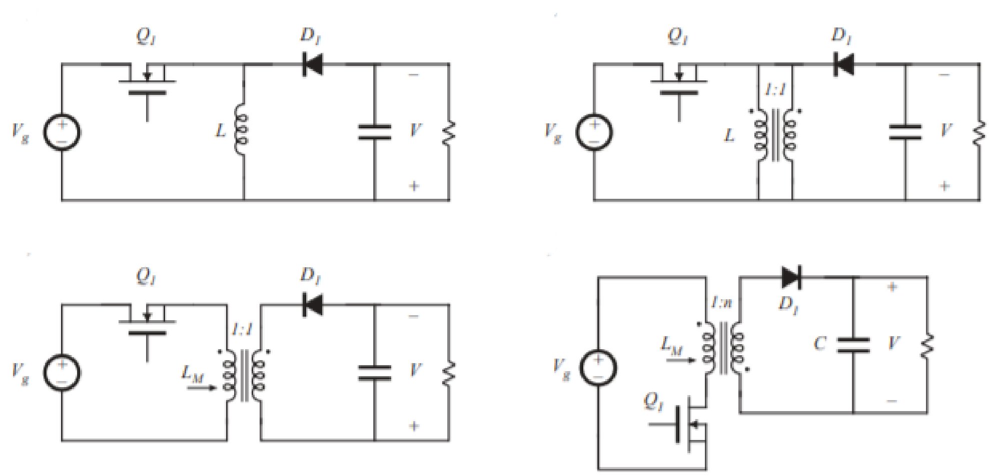

Figure 1: Derivation of the flyback converter.

The flyback converter can be described as the buck-boost converter with the isolated inductor wires, as seen in Figure 1. The isolation between primary and secondary sides is provided by a transformer. The transformer turns ratio depends on design specification and application, but mainly used to prevent results of possible internal failures on output and provide multiple outputs by adding more windings with a single input. They are generally used in the low to mid power range, less than 100 watts application. It also provides wide input voltage range.

Input output voltage relation of the flyback converter:

$$\frac{V_{out}}{V_{in}} = \frac{N_2}{N_1}\frac{D}{1-D}$$

There are also two different modifications of the flyback converter which are two-transistor and paralleling flyback converters, can be seen in Figure 2. These topologies can be answer of higher efficiency, lower cost or higher system reliability. Possible usage of these two modifications for our project will be discussed later.

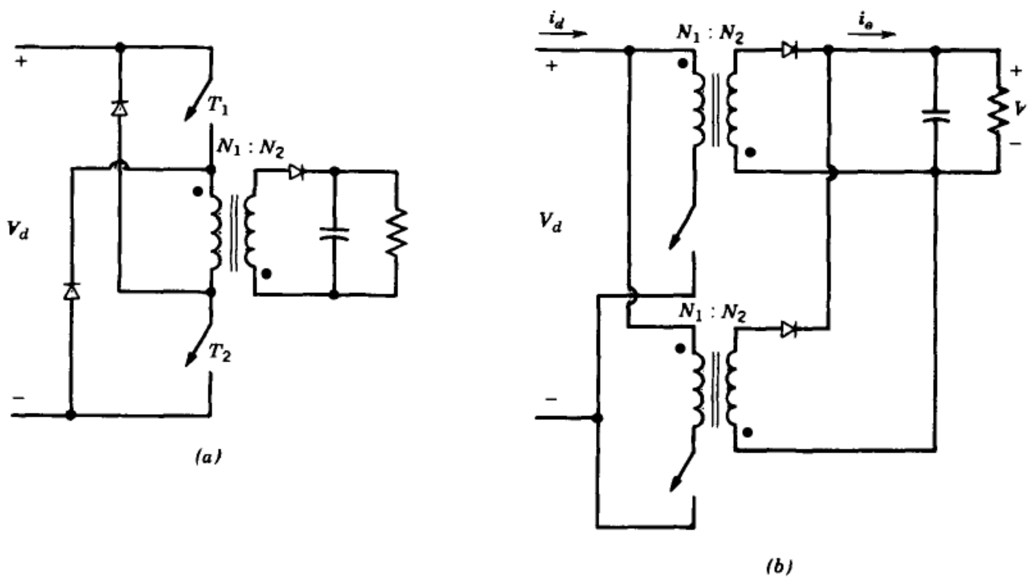

Figure 2: Two-transistor and paralleling flyback converters, respectively.

2.2 Forward Converter

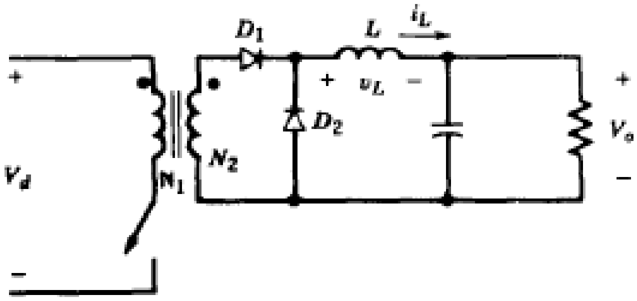

Figure 3: Practical forward converter.

The forward converter is derived from the buck converter employs a transformer for isolation between input and output sides, can be seen in Figure 3. It is possible to provide both higher and lower output voltages like the flyback converter. Even the forward converter looks like the flyback converter, it works in a different way. The forward converter passes energy directly to output by transformer, in contrast to the flyback converter which stores energy during conduction period and pass during non-conducting period. Moreover, since energy is not stored, gap-less core can be used.The forward converter is commonly used in the power range below 200 W.

Input output voltage relation of the forward converter:

$$\frac{V_{out}}{V_{in}} = \frac{N_2}{N_1} D$$

In a practical forward converter, the transformer magnetizing current should be considered for a proper operation. To feed back the magnetizing energy to input supply which refers the higher efficiency, a third magnetizing winding is necessary.
There are also two different modifications of the forward converter which are two-transistor and paralleling forward converters like flyback, can be seen in Figure 4.

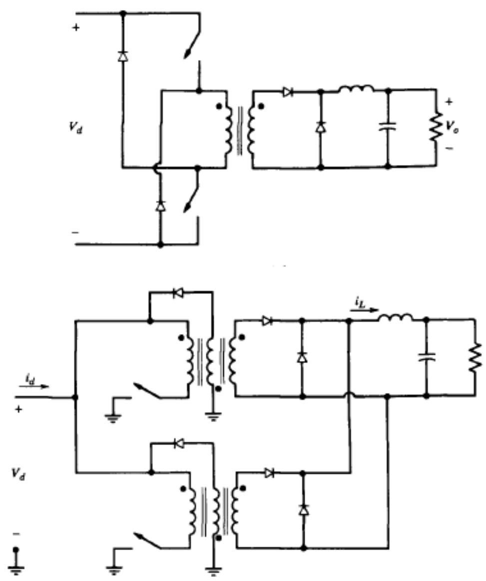

Figure 4: Two-transistor and paralleling forward converters, respectively.

2.3 Flyback vs Forward

Table 1: Advantages and disadvantages of flyback and forward converters.

Flyback Converter	Forward Converter
+ Less component + Lower cost + Wide input voltage range + Regulate multiple outputs with a single controller - Bulky output capacitor is needed -High current stress in the power switch -Airgap and eddy current losses	+ Direct power transfer/better utilization of power + Continuous output current + Gapless core/ less ripple + Lower copper losses -Gain changes in DCM -Higher voltage requirement for Mosfet -Higher conduction losses

The main advantages and disadvantages of two topologies are discussed in Table 1. In hardware project, wide input voltage range is a important factor to reach stable and desired output voltage. In this respect, the flyback converter is better option. In addition to that, simplicity of less components and lower cost advantages of it are the main reasons to choose flyback converter topology. Compact design and high power density is another benefits of the flyback converter. Moreover, the flyback converter offers higher efficiency in low voltage range. The Fly 1 is preferred by taking all of these into account.

3 Design Process

Design specifications of the converter are very important during the design procedure. They are provided in Figure 5.

FLYBACK	Minimum Input Voltage (V)	24
	Maximum Input Voltage (V)	48
	Output Voltage (V)	15
	Output Power (W)	60
	Output Volt. Peak-to-Peak Ripple (%)	4
	Line Regulation (%)	2
	Load Regulation (%)	2

Figure 5: Design Specifications of the Flyback 1 Converter

Design procedure is explained step by step below. This procedure is simplified a bit. The more accurate design is made via the excel sheet prepared. That excel sheet is added to Github.

3.1 Step 1: Choosing Operating Condition

The first step is choosing the proper operating condition according to specifications. Flyback converters are used in continuous (CCM) or discontinuous (DCM) conduction mode. In order to ease the selection of operating condition, a helpful comparison shown in Table 2.

Table 2: DCM and CCM comparisons of the flyback converter.

Discontinuous Conduction Mode	Continuous Conduction Mode
Easy to stabilize(no RHP zeros)	Stability problems
Generally smaller transformer	Generally larger transformer
Larger component ratings due to higher peak currents	Lower component ratings due to lower peak currents
Soft switching	Soft switching is not available
Small switching losses	Larger switching losses
Larger conduction losses due to higher RMS currents	Smaller conduction losses due to lower RMS currents
Bigger output capacitor	Smaller output capacitor

Note that CCM operation is mostly used high power and large output current applications. For that application, DCM is selected due to relatively low 4 A output current and 60 W output power. It provides stable operation. However, efficiency is important for that design. Therefore, three major implementations are considered in order to compensate the conduction loss of the DCM operation. Firstly, MOSFET having lower ON resistance is chosen. Secondly, a schottky diode is used. Lastly, resistance of the cables are lowered by using bigger ones, and fewer turns are used in transformer.

3.2 Step 2: Choosing Switching Frequency

There is a simple switching frequency trade-off. Higher switching frequency means higher switching loss and smaller components. Since an efficient converter wanted to be designed, a relatively small 40 kHz switching frequency is chosen.

3.3 Step 3: Choosing Controller:

First stage

Initially, since we are new in the converter control techniques and integrated circuits we are planning to use simpler controller while starting the project. For that purpose, we choose the "FAN 6604" IC. It has 6 pins and various features like built in soft-starting and current mode control. Also, its pwm frequency is very close to the one that we determined before therefore, we can use the all of out ratings with that controller.
FB pin still needs compensation network to determine performance of the controller. Gate pin is the output of that controller which is connected to "gate" of the power mosfet. Also, from the "SENSE" input we can give peak current feedback from the output of the converter and by this way the current mode control can be done. Additionally, HV pin provides soft starting by keeping PWM at very low values until its internal charges become full.

Second stage

In order to regulate the output voltage we need to implement some kind of feedback. In order to implement controller, if we are successful at first stage,we

are planning to use “UCC28780” integrated circuit .Beside providing PWM control feature for regulation purposes, it has multiple features that satisfy the requirements of the project. For example,it provides synchronous switching for active clamp snubber configuration which reverse the energy of the leakage winding to the source.
In order implement this operation pin 4 and pin 5 should be connected to the high side and low side gate drivers of the mosfets. Also, it can provide soft starting through the current sense input (pin 7). And another important feature of it is current mode control.

3.4 Step 4: Choosing Reflected Voltage

Making reflected voltage larger causes larger drain source voltage and lower peak current of the primary side MOSFET, and lower voltage stress on diode. Moreover, it also affects the maximum duty cycle of the converter. Maximum duty cycle generally has to be less than 65% due to possibility of transient problems. Reflected voltage is chosen as 31 V by considering all. Reflected voltage is symbolized as $V_R$for the rest of the design steps.

3.5 Step 5: Choosing Expected Efficiency

Choosing expected efficiency between%70-80 is reasonable. It is chosen as 80% since the output voltage is relatively higher, and an efficient flyback wanted to be designed.

$$P_{in,max} = \frac{P_{out}}{\eta} = \frac{60}{0.8} = 75W$$
$$V_{Mosfet(on)} = \frac{V_{in,min} + V_R}{1 + \frac{V_{in,min} * V_R}{P_{in,max} * R_{DS(on)}}}$$

Assuming on state resistance of a MOSFET having low ON resistance is 0.05 ohm:

$$V_{Mosfet(on)} = 0.275V$$
$$D_{max} = \frac{V_R}{(V_{in,min} - V_{Mosfet(on)}) + V_R}$$
$$D_{max} = 0.566$$

Primary side peak current:

$$I_{pri(peak)} = \frac{P_{in}}{V_{in,min} - V_{Mosfet(on)}} \frac{2}{D_{max}}$$
$$I_{pri(peak)} = 11.17A$$

3.6 Step 6: Transformer Design

Firstly, maximum primary inductance value provides converter operate in DCM is found.

$$L_{pri,max} = \frac{V_{in,min} * D_{max}}{I_{pri(peak)} * f_{sw}}$$

$$L_{pri,max} = 30.1\mu H$$

Increasing primary inductance over the maximum value can make converter operate in CCM for high duty cycle values. In other words, if the maximum value is chosen converter is in the boundary between DCM and CCM for minimum input voltage value.

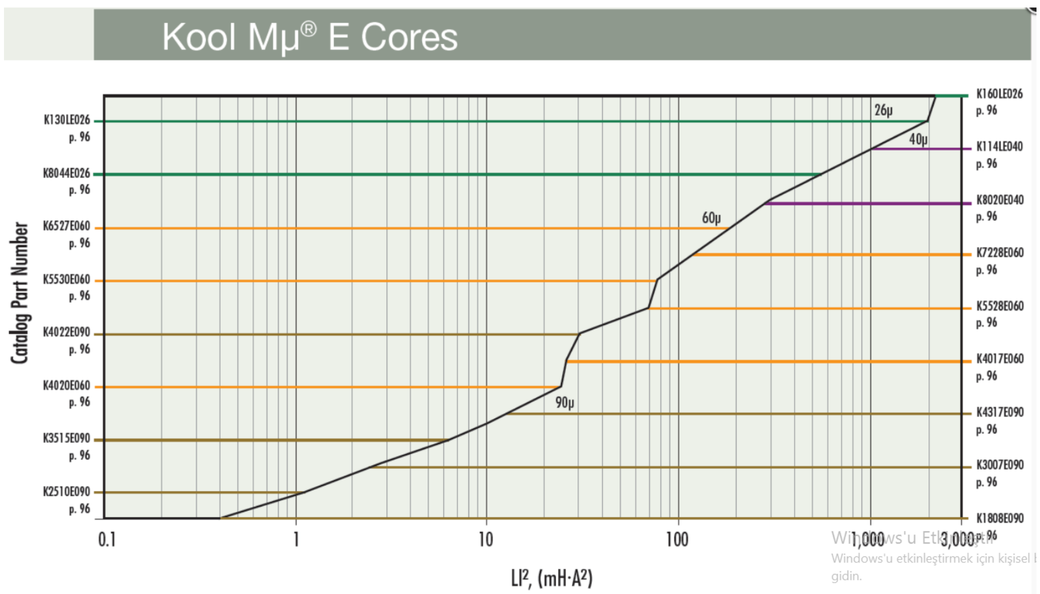

Figure 6: LI^2 Characteristics of Kool Mu E Cores [1]

In order to select the proper core, the graph in the Figure 6 is investigated.

$$L_{pri,max} * I_{pri(peak)}^2 = 3.75mH.A^2$$

K3515E090 core can be used from 0.1 to $7mH.A^2$. Since it is small and capable for that operation, it is chosen as the transformer core.
Turn ratio is simply:

$$n = \frac{V_R}{V_{out} + V_D}$$

where V_D is the diode forward voltage and generally around 0.5 V for schottky diodes. Therefore,

$$n = 2$$

Then, minimum primary turns are found with two different equations as follows:

$$N_{pri,min} = \frac{L_{pri} * I_{pri(peak)}}{B_{max} * A_e}$$
$$N_{pri,min} = 4turns$$

Note that A_e can be found from core datasheet [2], and saturation flux density is shown in Figure 7.

Material	Alloy Composition	DC Bias	Core Loss	Relative Cost	Saturation Flux Density (Tesla)	Curie Temperature	Operating Temp. Range	60µ µ flat to...
XFLUX®	FeSi	Highest	High	Low	1.6	700°C	-55 to 200°C	500 kHz
High Flux	FeNi	Highest	Moderate	High	1.5	500°C	-55 to 200°C	1 MHz
75-Series	FeSiAl	High	Moderate	Low	1.5	700°C	-55 to 200°C	500 kHz
Kool Mµ® MAX	**FeSiAl**	**High**	**Very Low**	**Medium**	**1.0**	**500°C**	**-55 to 200°C**	**900 kHz**
MPP	FeNiMo	High	Very Low	Highest	0.8	460°C	-55 to 200°C	2 MHz
Kool Mµ®	FeSiAl	Moderate	Low	Low	1.0	500°C	-55 to 200°C	900 kHz
Iron Powder	Fe	Moderate	Highest	Lowest	1.2 - 1.5	770°C	-30 to 75°C	500 kHz
Ferrite	Ceramic	Low	Lowest	Lowest	0.45	100 - 250°C	Variable	Variable

Figure 7: Material Properties of Kool Mu [3].

To avoid magnetic saturation, second equation is:

$$N_{pri,min} = \sqrt{\frac{L_{pri}}{A_L}} = \sqrt{\frac{30.1 * 10^{-6}}{146 * 10^{-9}}} = 14.36turns$$

A_L value is found from core datasheet. Primary side turn number is selected as 16 turns considering both equations. Therefore N_sec becomes 8 turns.
Then, required minimum airgap to get desired primary inductance value is calculated as follows:

$$L_{gap} = \mu_0 A_e \frac{N_{pri}^2}{L_{pri}} - \frac{I_c}{\mu_r} = 0.126mm$$

l_c is core magnetic path length and μ_r is the relative permeability. They are found from core datasheet.

Step 6: Choosing Wire Size

Choosing a proper wire for transformer windings is very crucial since the wires need to carry such primary and secondary side currents. First step for wire size selection is estimating total transformer loss.

$$P_{tot} = \frac{\Delta T}{R_{th(core)}}$$
$$\Delta T = T_{max} - T_{amb}$$

By limiting T to 100 °, and assuming ambient temperature is 25°:

$$\Delta T = 75C^{\circ} \tag{1}$$

Moreover, $R_{th(core)}$ can be estimated as:

$$R_{th(core)} = 23 * AP^{(-0.37)}$$
$$AP = W_A A_e = 12.7cm^4$$

Window area is also found from core datasheet.

$$P_{tot} = 8.3W$$

Secondly, actual flux swing is found as follows:

$$\Delta B = \frac{I_{pri(peak)} L_p ri}{N_{pri} A_e} 10^4$$
$$\Delta B = 0.25T$$

By neglecting the core losses, primary and secondary side resistances are:

$$R_{pri} = \frac{P_{tot}}{2I^2_{pri(RMS)}}$$
$$I_{pri(RMS)} = I_{pri(peak)} \sqrt{\frac{D_{max}}{3}} = 4.822A$$
$$R_{pri} = 0.178\Omega$$
$$R_{sec} = \frac{P_{tot}}{2I^2_{sec(RMS)}}$$
$$I_{sec(peak)} = I_{pri(peak)} \frac{N_{pri}}{N_{sec}} = 22.32A$$
$$I_{sec(RMS)} = I_{sec(peak)} \sqrt{\frac{1 - D_{max}}{3}} = 8.55A$$
$$R_{sec} = 0.083\Omega$$

Minimum primary and secondary side wire cross sectional area:

$$A_{pri,min} = \frac{p_{100} N_{pri} L_t}{R_{pri}}$$
$$A_{sec,min} = \frac{p_{100} N_{sec} L_t}{R_{sec}}$$

L_t is the turn length and depends on the bobbin used, and it can be assumed as 50 mm for that core. p_{100} is the limited temperature copper resistivity, and $2.303 * 10^{-6} \Omega cm$ for 100 C°. Therefore,

$$A_{pri,min} = 1.03mm^2$$
$$A_{sec,min} = 1.1mm^2$$

Before going further, considering skin effect is very important. For a reliable operation, the radius of conductor is smaller than skin effect.

$$skindepth = \sqrt{\frac{p_{100}}{\pi * f_{sw} \mu_{copper}}}$$
$$skindepth = 3.26mm$$

Lastly, proper wire size is determined according to chart in Figure 8. AWG 16 cable is selected for now. However, cable size can be enlarged in order to decrease the conduction losses later. AWG 16 cable is also appropriate for skin effect consideration.

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Conductor cross section in mm^2	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper	Breaking force Soft Annealed Cu 37000 PSI
0000	0.46	11.684	107	0.049	0.16072	380	302	125 Hz	6120 lbs
000	0.4096	10.40384	84.9	0.0618	0.202704	328	239	160 Hz	4860 lbs
00	0.3648	9.26592	67.4	0.0779	0.255512	283	190	200 Hz	3860 lbs
0	0.3249	8.25246	53.5	0.0983	0.322424	245	150	250 Hz	3060 lbs
1	0.2893	7.34822	42.4	0.1239	0.406392	211	119	325 Hz	2430 lbs
2	0.2576	6.54304	33.6	0.1563	0.512664	181	94	410 Hz	1930 lbs
3	0.2294	5.82676	26.7	0.197	0.64616	158	75	500 Hz	1530 lbs
4	0.2043	5.18922	21.1	0.2485	0.81508	135	60	650 Hz	1210 lbs
5	0.1819	4.62026	16.8	0.3133	1.027624	118	47	810 Hz	960 lbs
6	0.162	4.1148	13.3	0.3951	1.295928	101	37	1100 Hz	760 lbs
7	0.1443	3.66522	10.6	0.4982	1.634096	89	30	1300 Hz	605 lbs
8	0.1285	3.2639	8.37	0.6282	2.060496	73	24	1650 Hz	480 lbs
9	0.1144	2.90576	6.63	0.7921	2.598088	64	19	2050 Hz	380 lbs
10	0.1019	2.58826	5.26	0.9989	3.276392	55	15	2600 Hz	314 lbs
11	0.0907	2.30378	4.17	1.26	4.1328	47	12	3200 Hz	249 lbs
12	0.0808	2.05232	3.31	1.588	5.20864	41	9.3	4150 Hz	197 lbs
13	0.072	1.8288	2.63	2.003	6.56984	35	7.4	5300 Hz	150 lbs
14	0.0641	1.62814	2.08	2.525	8.282	32	5.9	6700 Hz	119 lbs
15	0.0571	1.45034	1.65	3.184	10.44352	28	4.7	8250 Hz	94 lbs
16	0.0508	1.29032	1.31	4.016	13.17248	22	3.7	11 k Hz	75 lbs
17	0.0453	1.15062	1.04	5.064	16.60992	19	2.9	13 k Hz	59 lbs
18	0.0403	1.02362	0.823	6.385	20.9428	16	2.3	17 kHz	47 lbs
19	0.0359	0.91186	0.653	8.051	26.40728	14	1.8	21 kHz	37 lbs
20	0.032	0.8128	0.519	10.15	33.292	11	1.5	27 kHz	29 lbs
21	0.0285	0.7239	0.412	12.8	41.984	9	1.2	33 kHz	23 lbs
22	0.0253	0.64516	0.327	16.14	52.9392	7	0.92	42 kHz	18 lbs

Figure 8: AWG Copper Chart

Step 7: Choosing MOSFET

As mentioned before, since rectifier operates in DCM switching losses are small. In order to reduce the conduction losses, a MOSFET having small ON resistance is selected.

Maximum current flowing through the MOSFET is primary side peak current. Although considering RMS current is pretty enough during component selection, peak currents provides some margin and more reliable operation. Therefore,

$$I_{rated(Mosfet)} > I_{pri(peak)} = 11.6A$$

Voltage rating of the MOSFET is calculated as follows:

$$V_{rated(Mosfet)} = V_{in,max} + V_R + V_{spike}$$

Assuming expected maximum spike voltage is 30 % of maximum input voltage. Note that that spikes are decreased with a clamp circuit.

$$V_{rated(Mosfet)} = 48 + 31 + 14.4 = 93.4V$$

For that purpose, 100V 33A 0.044 ohm IRF540NSPbF [4] MOSFET is selected.

3.7 Step 8: Choosing Diode

Similarly, in order to decrease the conduction losses, a schottky diode is chosen.

$$V_{rated(diode)} = V_{out} + V_{in,max}\frac{N_{sec}}{N_{pri}} = 39V$$

$$I_{rated(diode)} > I_{sec(peak)} = 22.32A$$

Secondary peak current is considered due to more reliable operation. Moreover, 30% margin is added to voltage rating. At the end, a schottky diode whose ratings are over 50V and 22.32 A is selected. For this purpose, 80 V 30 A VT3080S [5] is chosen. It's forward voltage drop is typically 0.5-0.6 V.

3.8 Step 9: Choosing Output Capacitor

Since rectifier is operating on DCM, and higher peak currents flow through the components, ESR of the capacitor becomes important.

$$C_{cap} >> \frac{I_{out}D_{max}}{f_{sw}V_{ripple}}$$

N_{cp} is a value between 10-20, and allowable maximum ripple for that case is 0.6 V. Taking it as 10,

$$C_{min} = 9.3\mu F$$

Calculating maximum ESR:

$$ESR_{max} = \frac{V_{ripple}}{I_{sec(peak)}} = 0.0268\Omega$$

$$V_{rated(cap)} = V_{out} = 15V$$

At the end, 50 V 330 μF 23 mΩ aluminium electrolytic capacitor [6] is chosen.

3.9 Step 10: RCD Clamp Circuit Design

During the off time, high voltages may occur due to leakage inductance of the transformer and they may damage the MOSFET. Therefore, a clamping circuit shown in Figure 9 is designed. The components of that circuit depends on the primary leakage inductance, so they may be changed after measuring the leakage inductance in practice. For theoretical calculations, leakage inductance is taken as 3% of the primary inductance.
Note that there are different type of clamping techniques, and the selected topology may be changed since it may decrease the efficiency in a considerable amount. For now, a simple RCD snubber is functional enough.

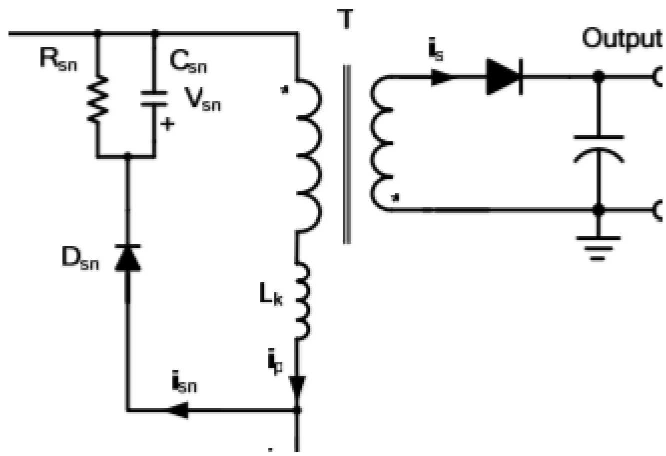

Figure 9: RCD Snubber Topology [7]

In that topology, higher R value causes low power loss but high voltage spike. Moreover, lower R value causes more oscillations. Components will be chosen according to simulation results considering the MOSFET ratings.
Note that ratings of all of these selected components will be ensured with simulation results. If there is a discrepancy between theoretical and simulation results, selected components will be changed. Moreover, different application notes of different companies are investigated before starting to design that converter. Their information is mixed and used.

4 Simulation Results

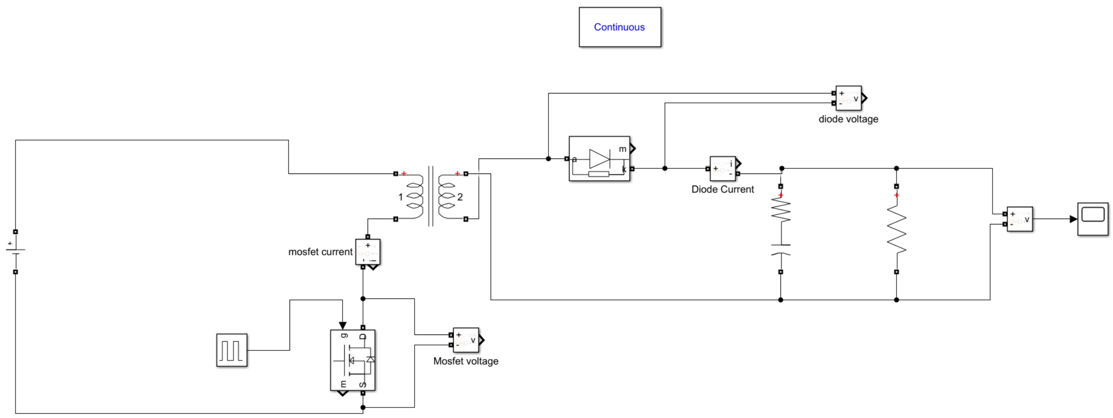

Figure 10: Circuit diagram of the project.

4.1 Output voltage verification

In order to observer how much the duty cycle is deviated from the ideal case to compansate non linearities.

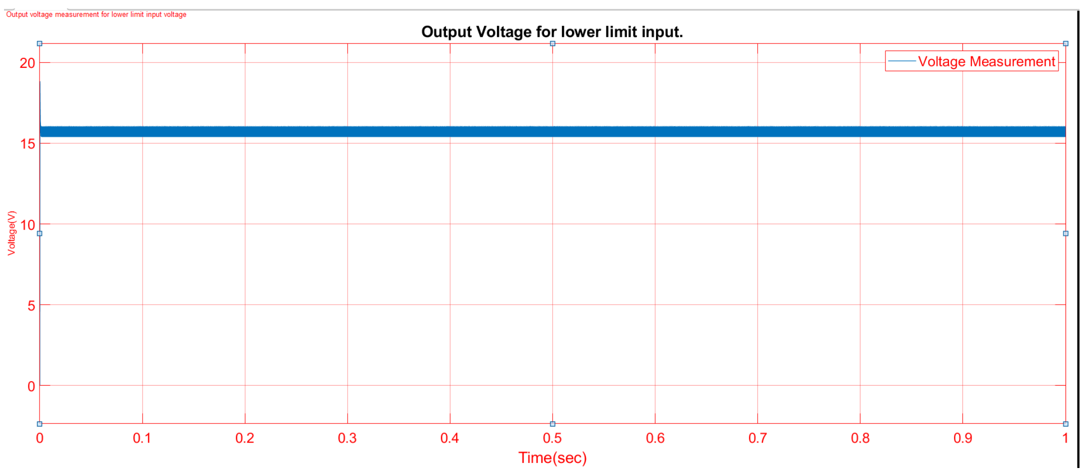

Figure 11: Output voltage verification.

4.2 Diode ratings

This simulation is done such that the duty cycle is the value that creates most voltage stress on the diode and also highest current.

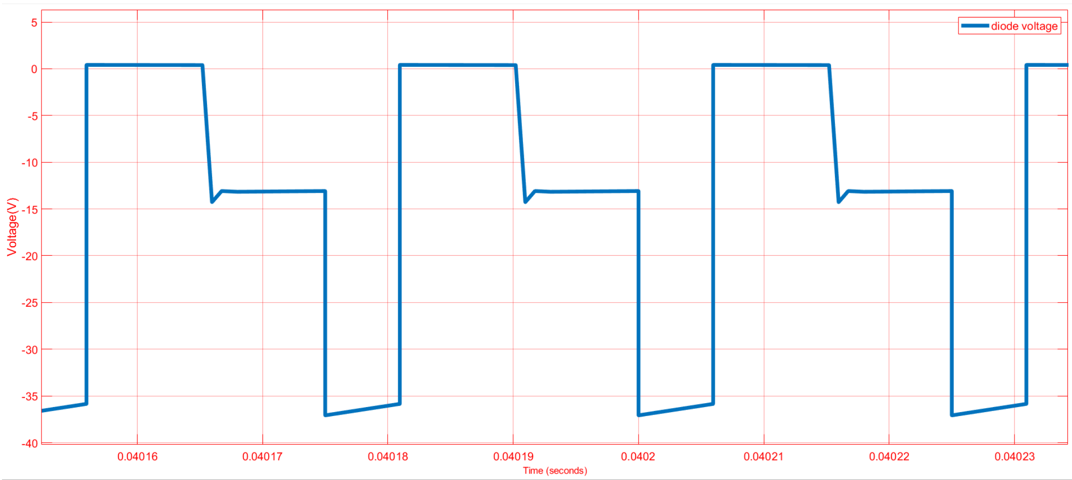

Figure 12: Voltage stress on the diode.

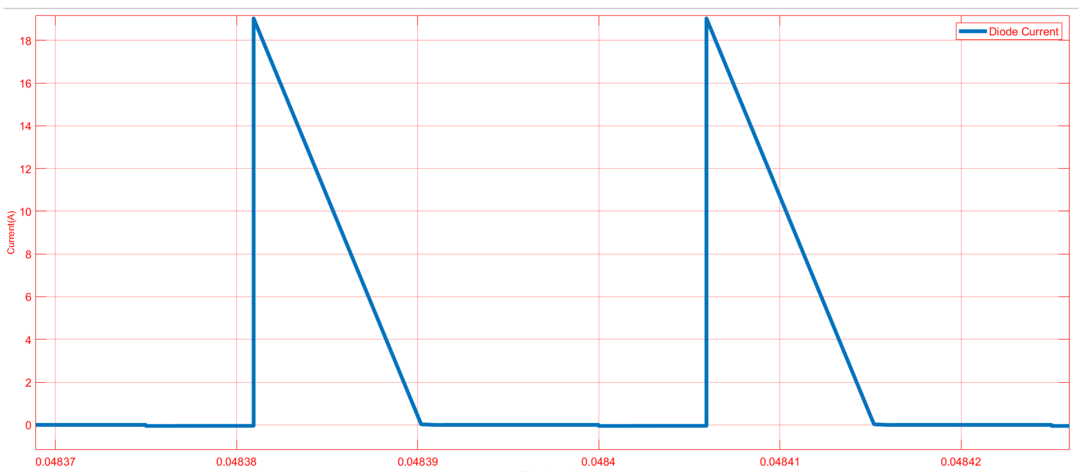

Figure 13: Current stress on the diode.

4.3 Mosfet ratings

This simulation has been done under the conditions where the mosfet current and voltage at its highest value.

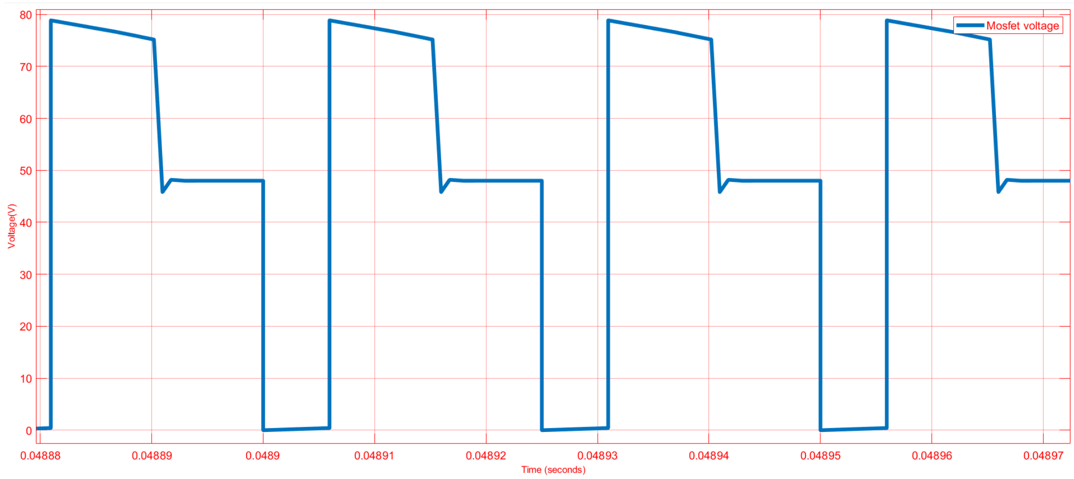

Figure 14: Voltage stress on the mosfet.

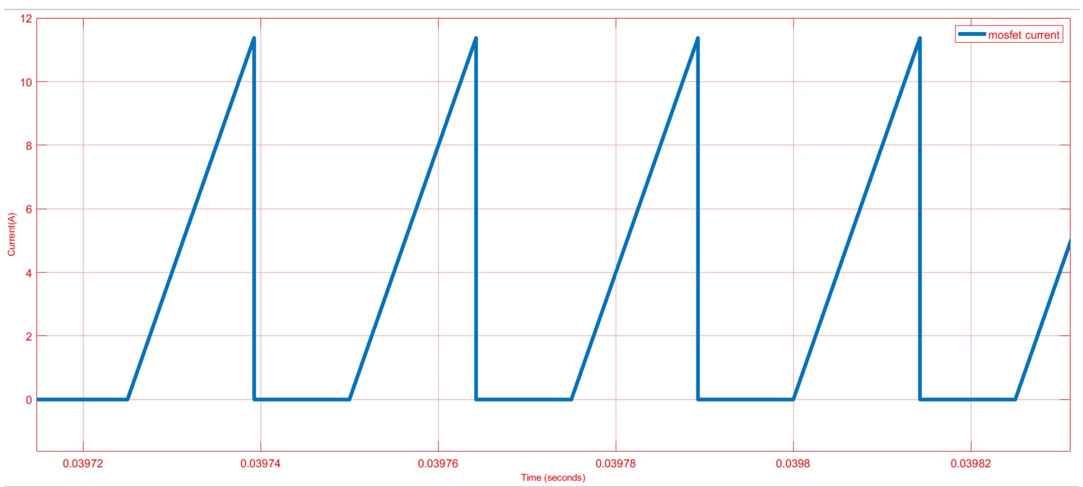

Figure 15: Current stress on the mosfet.

4.4 Output ripple

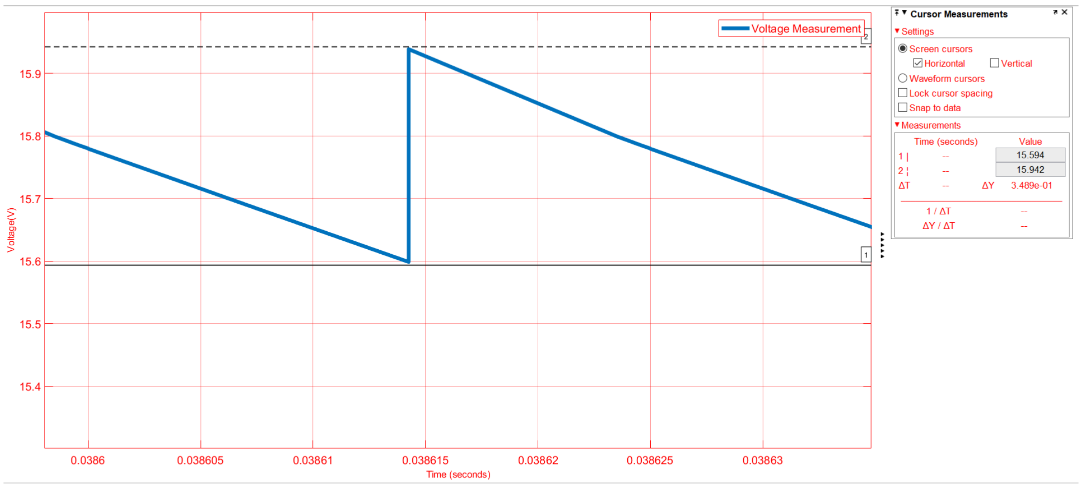

Figure 16: Output ripple.

Output voltage ripple is approximately %2.5 according to the simulation result.

4.5 Snubber

Snubber is designed not to exceed our mosfet voltage limit and also providing enough time to dissipate the energy on the leakage inductances.

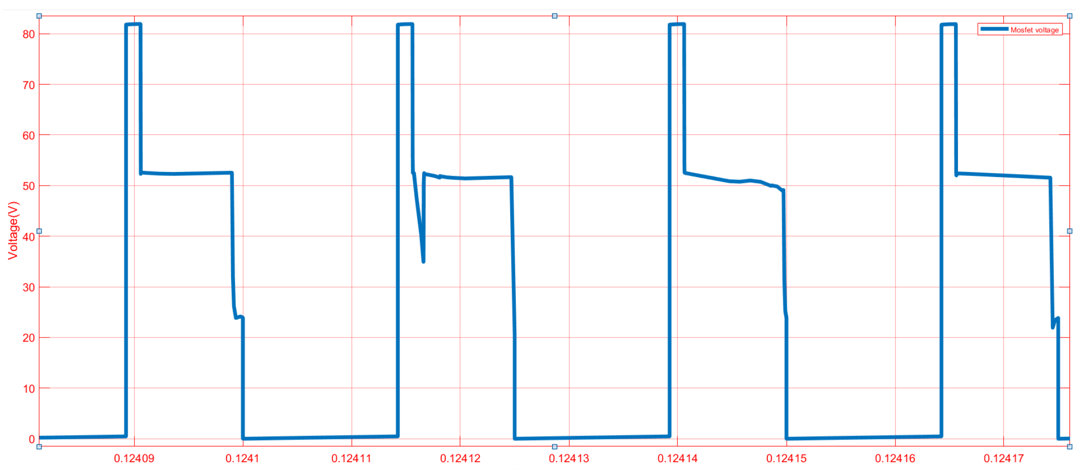

Figure 17: Voltage stress on the mosfet with snubber.

4.6 Efficiency

Efficiency is calculated with same schematic. It is found as 0.85 for maximum duty cycle value as shown in Figure 18.

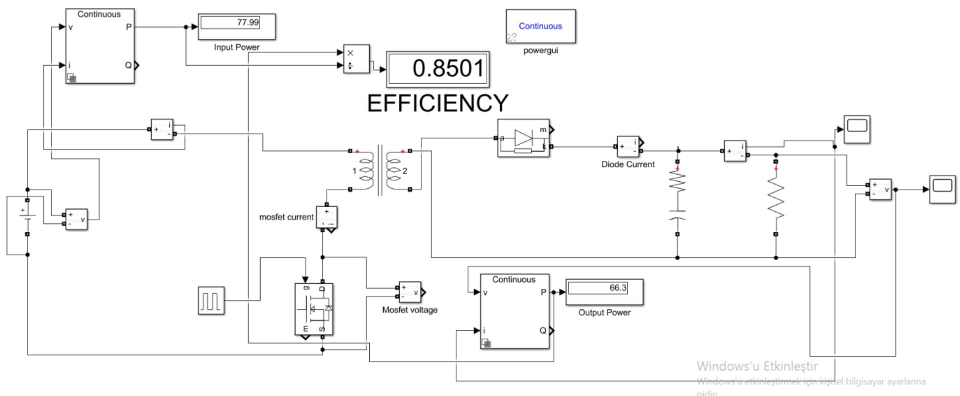

Figure 18: Schematic for efficiency calculation.

With these simulation results, it is proven that components selected in design steps are appropriate for that operation.

5 Conclusion

In that project, a flyback converter with certain specifications is designed. Before starting to the design process, a very comprehensive research is made. All necessary points of the design is considered, and the best solution is tried to develop between countless tradeoffs. Actually, these points are not just conceptual ideas but also the design arguments that are supported by very detailed simulation results.Also, An excel sheet is formed to understand the tradeoffs of the system better. In the comparison part, we explain why we chose that topology to forward converter and in the design part, we have followed some design steps to reach and finalize every detail of the project. That part has very solid calculations and promising decisions about the components of the project additionally not just components itselves but the way we use them is explained at there , Finally, we have shown that our design decisions are very much correct by using simulink design tool in the simulation result part At the end, a functional solution is developed for that purpose. All necessary points of the design process and simulation results are stated in that report. That project is very beneficial since it helps students to become engineers. Considering a variety of pros and cons prepares them to the professional career. It is a very good contribution to the students practical knowledge. Even if theoretical knowledge of them is enough, facing with real life problems is very crucial in power electronics to develop themselves. Converter was designed easily on the paper. However, as expected, there will be much bigger problems during the implementation but these problems will be overcome again as always.

6 References

[1]= Kool M® Material Curves. (n.d.). Retrieved from https://www.mag-inc.com/Products/Powder-Cores/Kool-Mu-Cores/Kool-Mu-Material-Curves
[2]= (n.d.). Retrieved from https://www.mag-inc.com/Media/Magnetics/Datasheets/00K3515E090.pdf
[3]= (n.d.). Retrieved from https://www.mag-inc.com/Media/Magnetics/File-Library/Product
[4]= (n.d.). Retrieved from https://pdf.direnc.net/upload/irf540nspbf-datasheet.pdf
[5]= (n.d.). Retrieved from http://www.vishay.com/docs/89242/vt3080s.pdf
[6]= (n.d.). Retrieved from https://www.mouser.com.tr/datasheet/2/315/ABA0000C1255-1128316.pdf
[7]=(n.d.). Retrieved from https://www.monolithicpower.com/en/documentview/productdocument/index/vers