MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING

EE464 – STATIC POWER CONVERSION II

TERM PROJECT COMPLETE SIMULATION REPORT

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Introduction

A power supply is needed everywhere. Almost all electronic systems need a constant voltage supply. And a DC-DC converter is a circuit device to provide the DC power from a source to a load. In today's world, these converters are used to provide constant DC voltage or current to the circuits. For example, in electric cars, there are high voltage batteries, but the inner electronic circuits are powered with low voltage. Therefore, there are low voltage batteries that are charged by the high voltage battery. In this project, PL Electronics introduces a flyback converter (Buck-Boost) which is utilized to charge a 12 V battery from a 400 V high voltage battery. In the first part of this report, the topology of the converter will be discussed with the comparison of different topologies. The reason for the topology selection will be given in this part. In the second part, the circuit design and simulation results will be provided with the selected components. In the third part, the PCB design and cost analysis of the project will be provided. To conclude, our engineering skills in circuit design, simulations, and our project management skills will improve. Additionally, this project will give us an opportunity to implement the theoretical knowledge of us on EE464 lecture.

Topology Selection

As mentioned in the 'Introduction' section, the high voltage needs to be converted to low voltage to charge the low voltage battery. To achieve the conversion, there are lots of DC-DC converter topologies that can be used. In this project, PL Electronics decided to use quasi resonant flyback converter topology which is an isolated DC-DC converter that works as a buck - boost converter. The reason for this topology selection is the advantages of the flyback converter. These advantages are specified below:

- The primary side of the flyback converter is isolated from the output.
- The converter has the ability to operate on a wide range of input voltages.
- The converter uses very few components compared to other switching mode power supplies.
- There is no need for an additional inductor.
- Voltage rating for the components in the secondary side is low.

Quasi resonant flyback converter is a variant of flyback converter wherein it makes use of the parasitic elements to partially resemble a resonance action. Its basic operation is the same with a normal flyback converter. It stores energy in the primary during the switch on cycle and transfers the stored energy during the switch off cycle. It is designed for DCM operation. During the dead time period, there is no more energy. This results in a natural oscillation like a second order system. Magnetizing inductance in the circuit diagrams is used to store energy that is to be transferred to the load. The advantages of the quasi resonant flyback converter compared to the flyback converter are specified below;

- Lower switching losses when switching on the lowest valley point.
- EMI will be better since it can behave as partial resonance.
- The partial resonance action will be performed by parasitic elements thus no more added parts counts.
- Wider input range.
- Better transient response.
- Easier to compensate.

To implement the quasi resonant flyback converter, an integrated circuit component called LT8316, which is produced by Analog Devices, is used. This component is an IC that has a controller for duty cycle. The duty cycle is used to control the MOSFET which is the main control element of the flyback converter. Also, it is needed to design a transformer for the flyback converter. PL Electronic decided to design a suitable transformer itself by winding an E core with suitable cables.

Because of the pandemic conditions, we have no chance to work on the designed circuit physically in the laboratory. Therefore, we decided to design our circuit in an LTSpice to implement the real-life values of the components. In the following parts of the report, the simulation results for the LTSpice design will be given.

In short, PL Electronics chose a flyback converter with an integrated controller and a self-designed transformer. In the following section, the circuit will be examined in detail and the simulation results will be shown.

Circuit Analysis, Magnetic Design and Simulation Results

In this part of the report, analytical calculations, magnetic design, and simulation results will be demonstrated. After analytical calculations for the flyback converter, we will show the magnetic design according to analytical calculations. Lastly, we will provide the simulation results according to analytical calculation and magnetic design. We used LTSpice to simulate the circuit with the selected controller (LT 8316) and components.

In the flyback converter, the relation between output voltage and input voltage is:

$$V_{out} = V_{in} \cdot \left(\frac{D}{1-D}\right) \cdot \left(\frac{N_2}{N_1}\right) \tag{1}$$

As we will examine in magnetic design part, we found turn ratio secondary to primary $\frac{N_2}{N_1}$ =3/36, iteratively. Putting this turn ratio, output voltage and input voltage at boundaries (220 V and 400 V), we obtained following duty ratios:

$$V_{in} = 220\,V \rightarrow D = 0.395 \qquad and \qquad V_{in} = 400\,V \rightarrow D = 0.265 \tag{2}$$

Output capacitor is found by Equation 3 to be suitable for the project ripple specification (max peak to peak ripple is 4%). For this calculation, the worst case (D is maximum) took into consideration. Also, ripple depends on switching frequency which we take 100 kHz because the controller LT8316 operates at 100 kHz with 220 V - 400 V input range.

$$\Delta V_o = \frac{\Delta Q}{C} = \frac{V_o \cdot D}{f_s \cdot R \cdot C} \quad and \quad \frac{\Delta V_o}{V_o} \leq 0.04 \quad \rightarrow \quad C \geq 68.5\,\mu F \tag{3}$$

After these analytical calculations, we have done magnetic design. Since, the controller samples the output voltage from the isolated flyback waveform appearing across a third winding on the transformer, a transformer with three windings has been designed. To decide the primary to secondary turn ratio, we did some iterative calculations on Matlab.

The transformer primary L_p and secondary L_s side inductances for the flyback converter to operate in the worst case is found by Equation 4.

$$L_p = \frac{V_{in-min} \cdot D_{max} \cdot (1-D_{max}) \cdot \frac{N_1}{N_2}}{f_s \cdot 2I_{out-avg}} \simeq 380\ \mu H \qquad \rightarrow \qquad L_s = L_p \cdot \left(\frac{N_2}{N_1}\right)^2 \simeq 2.63\ \mu H \qquad (4)$$

Also, peak current in the secondary and primary side is found:

$$I_{s-peak} = \frac{2 \cdot I_{out-max}}{1-D_{max}} = 27.53\ A \qquad \rightarrow \qquad I_{p-peak} = \frac{I_{s-peak}}{N_1/N_2} = 2.29\ A$$

(5)

After these calculations, we decided which core we will use. As a result of iterative calculations, we have decided to use 0P44721EC core. This core length is sufficient to get desired primary and secondary inductances. The properties of the selected core is shown table below.

Table-1

Core	Effective Cross-Sectional Area (Ae) (mm2)	Maximum Magnetic Flux Density (T)	AL Value (with air-gap) (nH/T^2)
0F43517EC	84.3	0.3	295

With the chosen core, the minimum number of turns for the transformer primary side to avoid the core saturation is found:

$$N_1 = \frac{L_p \cdot I_{p-peak}}{Ae \cdot B} = 34.4 \qquad \rightarrow \qquad N_1 \geq 34.4 \qquad (6)$$

$$N_1 = \sqrt{\frac{L_p}{AL}} = 35.89 \qquad \rightarrow \qquad N_1 = 36 \qquad and \qquad N_2 = 3 \qquad (7)$$

To calculate fill factor, size of selected core and cables are needed.

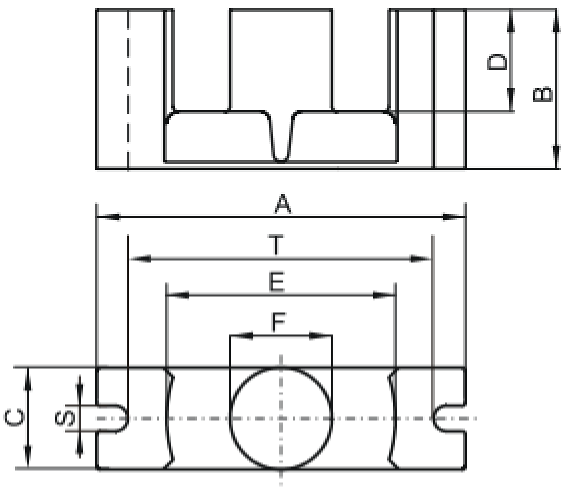

Figure 1: Dimensions of selected core

In the figure above; D,E and F are 12.3, 22.75 and 9.5, respectively.Therefore window area as found:

$$A_{window} = (E - F)D = 162.975\, mm2 \qquad (8)$$

Our selected cables can be seen in the table below.

Table-2

Wire	Cross section in mm2
AWG14	2.08
AWG20	0.519
AWG40	0.00487

To calculate fill factor, we have found cable area:

$$A_{cable} = AWG14 \cdot N_2 + AWG20 \cdot N_1 + AWG\,40 \cdot N_3 = 76.45\, mm2 \qquad (9)$$

$$Fill\, factor = \frac{A_{cable}}{A_{window}} = 0.47 \qquad (10)$$

Also, the length of each cable can be seen in the Table below.

Table-3

Wire	Length (m)

AWG14	0.12
AWG20	1.42
AWG40	0.12

Then we simulate the circuit according to values we have found analytically and our magnetic design. In the figure below, overall circuit design can be seen.

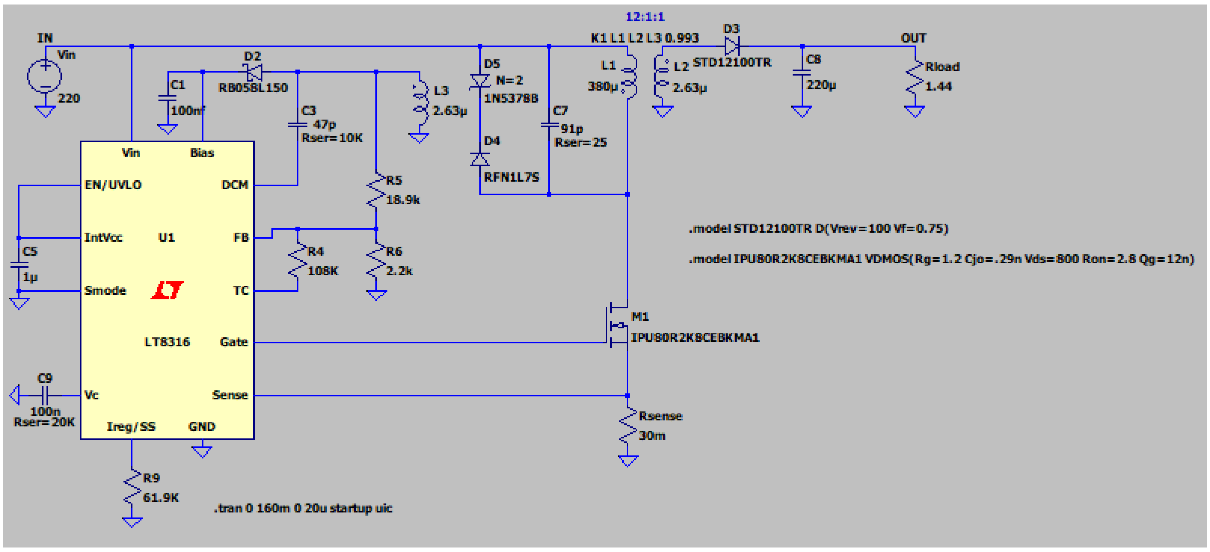

Figure 2: The overall circuit design

Feedback resistors R_{FB1} and R_{FB2} for the controller are found:

$$V_{out} = 1.22 \cdot \left(1 + \frac{R_{FB2}}{R_{FB1}}\right) \quad \rightarrow \quad \frac{R_{FB2}}{R_{FB1}} = 9.45 \qquad (11)$$

Since it is recommended to keep R_{FB1} between 1kΩ and 10kΩ in order to preserve the resistor divider's dynamic response, we chose R_{FB1}=2k Ohm and R_{FB2}=18.9k Ohm.

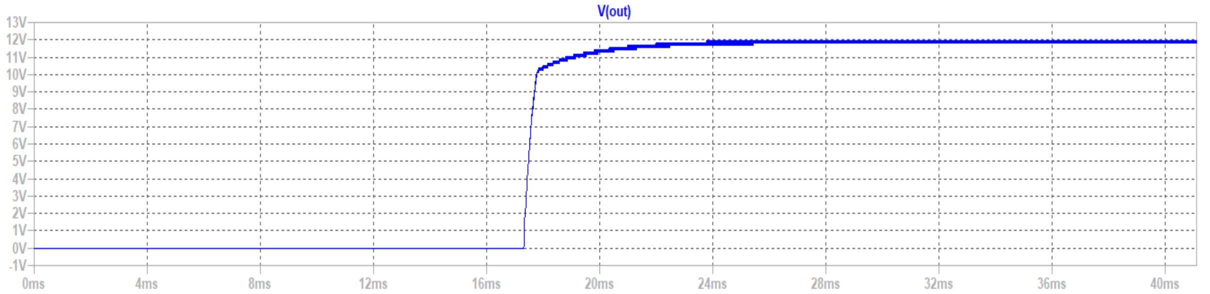

Figure 3: Output Voltage Waveform for 220 V input

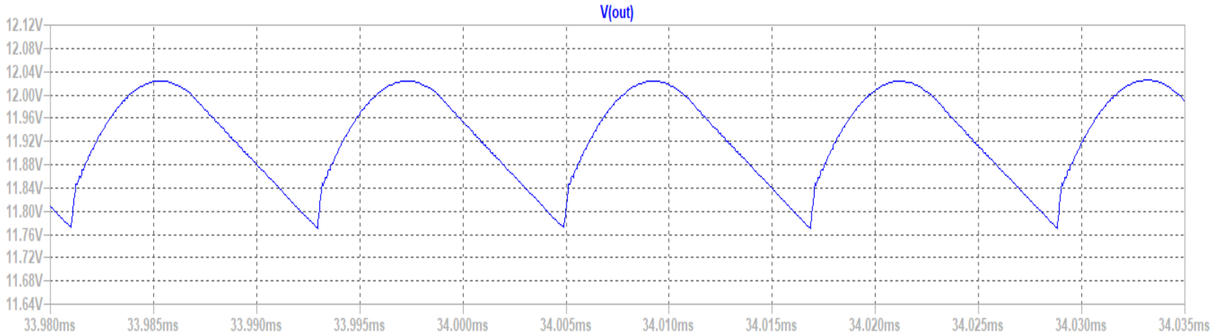

Figure 4: Output voltage ripple for 220 V input

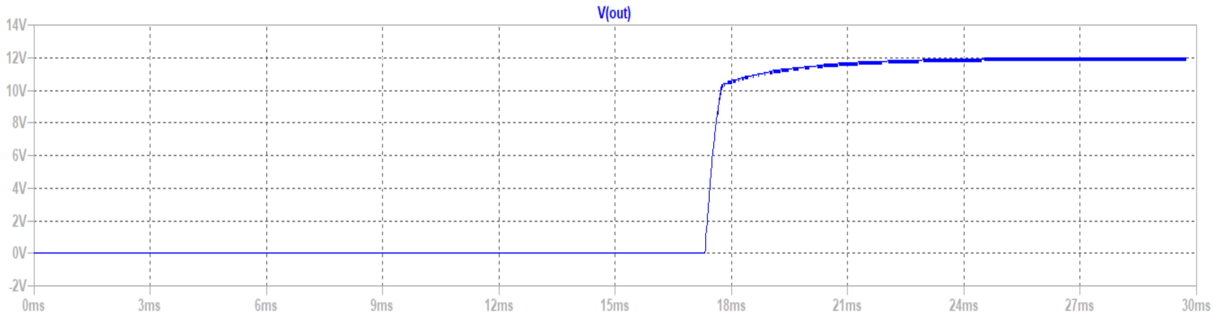

Figure 5: Output Voltage Waveform for 400 V input

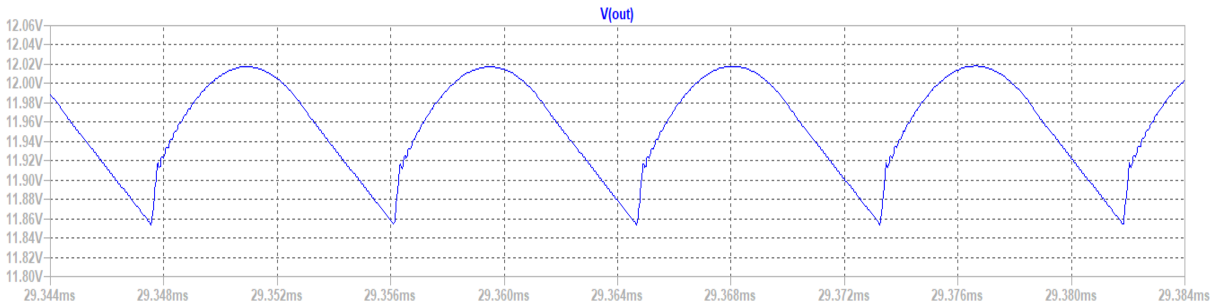

Figure 6: Output voltage ripple for 400 V input

As seen in the figures above, output voltage is 12 V for input voltage is 220 V and 400 V. It is not affected by varying input voltage between 220 V and 400 V.

Component Selection

Table-4

	Component	Manufacturer	Digi-Key Part Number
Mosfet	SIHB24N80AE-GE3	Vishay Siliconix	742-SIHB24N80AE-GE3-ND
Diode	STD12100TR	SMC Diode Solutions	STD12100TRSMC-ND - Tape & Reel (TR)
Output Capacitor	EEU-FK1E271B	Panasonic Electronic Components	EEU-FK1E271B-ND - Tape & Box (TB)
Transformer Core	0F43517EC	Magnetics	
RFB1	WR04X202 JTL	Walsin Technology Corporation	1292-WR04X202JTLTR-ND - Tape & Reel (TR)
RFB2	MCT06030C1892DP500	Vishay Byschlag/Draloric/BC Components	MCT06030C1892DP500-ND - Tape & Reel (TR)
RTC	CR205402F	Meritek	2997-CR205402FTR-ND - Tape & Reel (TR)
Rsense	WK73S2HTTE29L4F	KOA Speer Electronics, Inc.	2019-WK73S2HTTE29L4FTR-ND - Tape & Reel (TR)
R_l_reg	WR04X6192FTL	Walsin Technology Corporation	1292-WR04X6192FTLTR-ND - Tape & Reel (TR)
R_load	WR04W1R43FTL	Walsin Technology Corporation	1292-WR04W1R43FTLTR-ND - Tape & Reel (TR)
R_ser(C7)	CR2025R0F	Meritek	2997-CR2025R0FTR-ND - Tape & Reel (TR)
R_ser(C9)	WR04X203 JTL	Walsin Technology Corporation	1292-WR04X203JTLTR-ND - Tape & Reel (TR)
C7	GRM0335C1H910JA01D	Murata Electronics	GRM0335C1H910JA01D-ND - Tape & Reel (TR)
R_ser(C3)	CR20103J	Meritek	2997-CR20103JTR-ND - Tape & Reel (TR)

C3	GMC04CG470J16NT	CAL-CHIP ELECTRONICS, INC.	2571-GMC04CG470J16NTTR-ND - Tape & Reel (TR)
C1	CL10A475KQ8NNNL	Samsung Electro-Mechanics	CL10A475KQ8NNNL-ND - Tape & Reel (TR)
C5	CL05A105KQ5NNND	Samsung Electro-Mechanics	CL05A105KQ5NNND-ND - Tape & Reel (TR)
C8	EDK227M025S9MAA	KEMET	EDK227M025S9MAA-ND
C9	CL05A104KA5NNND	Samsung Electro-Mechanics	CL05A104KA5NNND-ND - Tape & Reel (TR)
D2	BAT54WSTR	SMC Diode Solutions	BAT54WSTRSMC-ND
R-Pot	3314G-1-103G	Bourns Inc.	3314G-1-103G-ND
D5	SMBJ5386B-TP	Micro Commercial Co	SMBJ5386B-TPMSTR-ND
D4	M7L	Diotec Semiconductor	2796-M7LTR-ND

Table-5

Voltage Protection circuit			
Mosfet	IXTA10P50P	IXYS	IXTA10P50P-ND
PNP Transistor	PBHV9050ZF	Nexperia USA Inc.	PBHV9050ZF-ND
Zener	BZT52-C51X	Nexperia USA Inc.	2156-BZT52-C51X-NEX-ND
C1	MC12KTB501104	Viking Tech	2577-MC12KTB501104TR-ND

PCB Design

PL Electronics decided to design a 2-layer PCB for quasi resonant flyback circuit. Schematic for the PCB design and 3D view for the PCB design is given below;

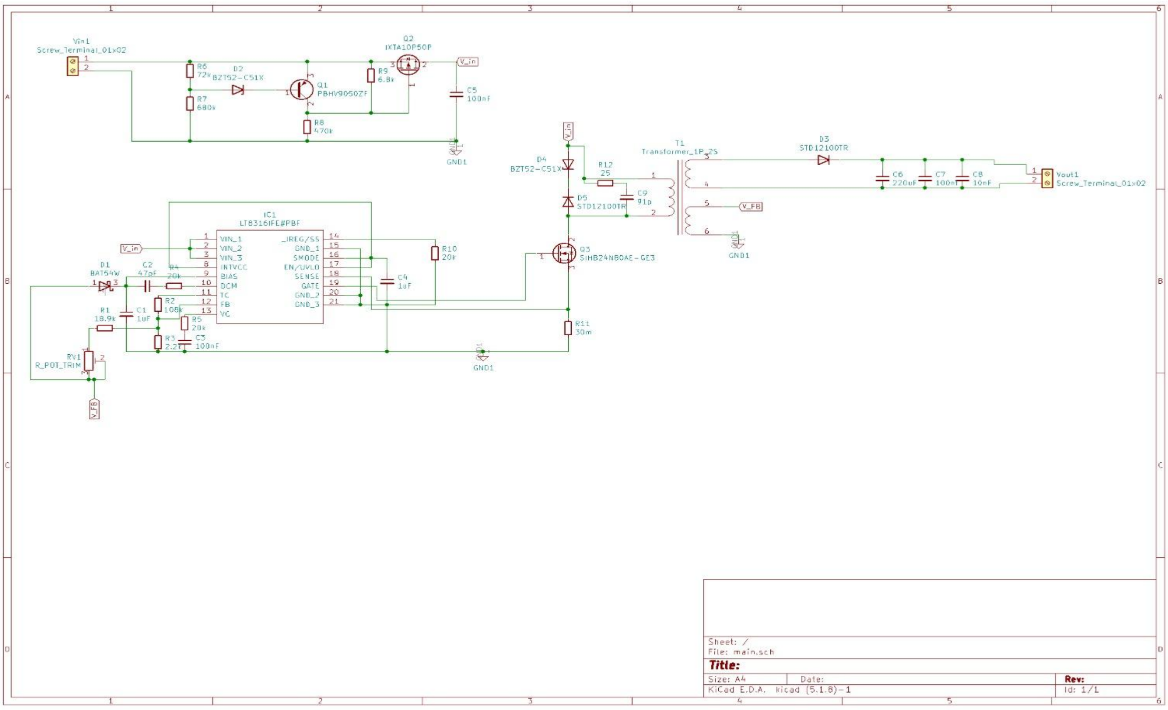

Figure 7: Schematic of the PCB Design

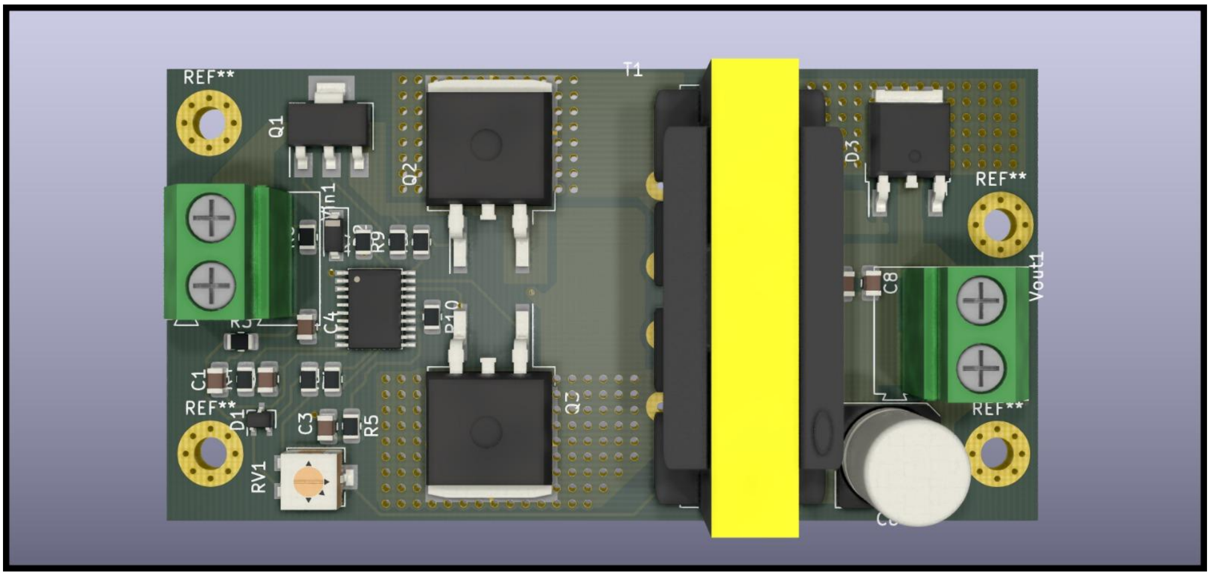

Figure 8: Top View of the PCB Design

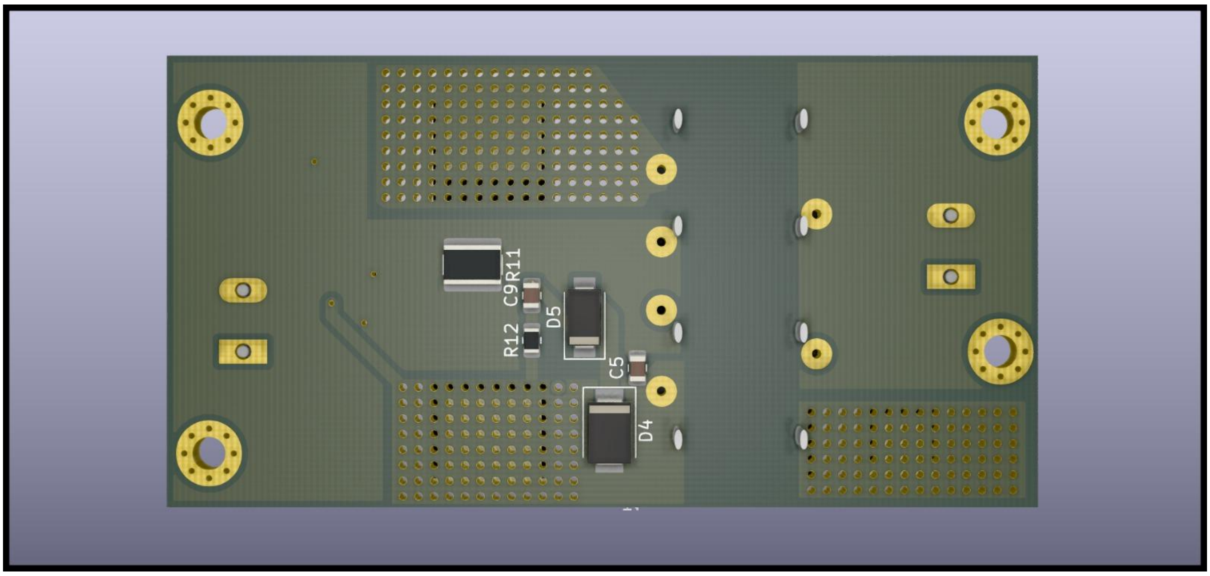

Figure 9: Bottom View of the PCB Design

Cost Analysis

Table-6

Component	Cost
Mosfet	$3,39000
Diode	$0,20000
Output Capacitor	$0,12606
Transformer Core	$1,00000
RFB1	$0,00084
RFB2	$0,02160
RTC	$0,14000
Rsense	$0,12420
R_I_reg	$0,00083
R_load	$0,00105
R_ser(C7)	$0,00240
R_ser(C9)	$0,00084
C7	$0,00264

R_ser(C3)	$0,00240
C3	$0,00170
C1	$0,00511
C5	$0,00220
C8	$0,14887
C9	$0,01250
D2	$0,02055
R-Pot	$0,93000
D5	$0,65000
D4	$0,01460
Voltage Protection circuit	
Mosfet	$5,93000
PNP Transistor	$0,16198
Zener	$0,03246
C1	$0,00125
Total Cost	**$12,92408**

Conclusion

To conclude, PL Electronics have designed a quasi resonant flyback circuit, which is utilized to charge 12 V battery from a 400 V high voltage battery. These types of circuits and converters are used everywhere that needs a constant DC voltage such as electric cars. Therefore, the purpose of the project is to follow up the latest technologies on the power electronics.

In the first part of this report, the topology of the converter is discussed with the comparison of different topologies. The reason for the topology selection is given in this part. In the second part, the circuit design and simulation results are provided with the selected components. In the third part, the PCB design and cost analysis of the project is provided.

This project helps us improve our engineering skills in circuit design, simulations, and our project management skills. Additionally, this project gave us an opportunity to implement the theoretical knowledge of us on EE464 lecture.

Appendix

Our MATLAB Code for magnetic design and some components::

```
%%Flyback Converter

%Circuit Parameters
Vin_min=220;
Vin_max=400;
Vout=12;
Pout=100;
R_Load=Vout^2/Pout;
I_out_avg=Pout/Vout;

V_sw_on=0.2;%Mosfet on voltage
V_diode_on=0.8;%Diode forward voltage drop

%Limitations
Vout_ripple=4/100;% output ripple
D_max=0.40;
B_sat=0.3;
Kcu=0.4;%Winding factor
Fs=100e3;%37-50kHz
Skin_depth=75/sqrt(Fs);%Skin depth in mm
KRF=0.6;%Input current ripple factor
Current_Density=4;%Current Density A/mm^2
K_margin=1.25;
u_r=1500;
u_0=4*pi*1e-7;

%Equations
n=ceil((Vin_min-V_sw_on)/(Vout+V_diode_on)*D_max/(1-D_max)); %N1/N2
D_min=1/((Vin_max-V_sw_on)/((Vout+V_diode_on)*n)+1);

D_IL=2*I_out_avg/((1-D_max)*n);

Lm=Vin_min*D_max/(Fs*D_IL);
%Lm=(Vin_min*D_max)^2/(2*Pout*Fs*KRF);

I_sw_max=Pout/(Vin_min*D_max)+D_IL/2;
Vds_max=Vin_max/(1-D_min);
```

```
C_out=I_out_avg*D_max/(Vout_ripple*Vout*Fs);

I_Diode=I_out_avg;

%Transformer Design E-core with gap
N1_min=@(Ae)Lm*I_sw_max*1e6/(B_sat*Ae); %Function to calculate Primary turn input is
area of core Ae in mm^2
d_air_gap=@(Ae)u_0*N1_selected^2*Ae*1e-4/Lm; %required air gap in mm;

Ae=84.3;%pi*7.68^2;%mm^2

N1_selected=ceil(N1_min(Ae));
N2_calc=round(N1_selected/n);
d_air_gap_calc=d_air_gap(Ae);

N1_wire_len=N1_selected*2*pi*sqrt(Ae/pi);
N2_wire_len=N1_selected/n*2*pi*sqrt(Ae/pi);
N3_wire_len=N2_wire_len;

wire_area_N1=N1_selected*I_sw_max/Current_Density; %mm^2
wire_area_N2=N2_calc*I_out_avg/Current_Density;%mm^2
wire_area_N3=N2_calc*100e-3/Current_Density;%mm^2

Total_wire_area=wire_area_N1+wire_area_N2+wire_area_N3;
winding_window_area=Total_wire_area/Kcu; %mm^2
winding_window_height=sqrt(Total_wire_area);

Transformer_Volume=winding_window_height*winding_window_area*6; %mm^3;

%AWG Area in mm^2 List 1-40
AWG_Area=[42.4 33.6 26.7 21.2 16.8 13.3 10.5 8.37 6.63 5.26 4.17 3.31 2.62 2.08 1.165
1.31 1.04 0.823 0.653 0.518 0.41 0.326 0.258 0.205 0.162 0.129 0.102 0.081 0.0642 0.0509
0.0404 0.032 0.0254 0.0201 0.016 0.0127 0.01 0.00797 0.00632 0.00501];
[minValue,N1_AWG] =min(abs(AWG_Area-I_sw_max/Current_Density));
[minValue2,N2_AWG] =min(abs(AWG_Area-I_out_avg/Current_Density));
N3_AWG=length(AWG_Area);
% Result Section

fprintf("Mosfet V_DS(on)=%0.2fV
I_DS(on)=%0.2f\n",Vds_max*K_margin,I_sw_max*K_margin);
fprintf("Diode V_D(reverse)=%0.2fV
I_D(on)=%0.2fA\n",2*Vds_max*K_margin/n,I_out_avg*K_margin);
fprintf("Output Capacitance=%0.2fuF\n",C_out*1e6*K_margin);

fprintf("Transformer N1 Turns=%d Cable=AWG%d
Length=%0.2fm\n",N1_selected,N1_AWG,N1_wire_len*K_margin*1e-3);
fprintf("Transformer N2 Turns=%d Cable=AWG%d
Length=%0.2fm\n",N2_calc,N2_AWG,N2_wire_len*K_margin*1e-3);
```

```
fprintf("Transformer N3 Turns=%d Cable=AWG%d
Length=%0.2fm\n",N2_calc,N3_AWG,N3_wire_len*K_margin*1e-3);
fprintf("Transformer Winding window area=%0.2fmm^2 Air gap=%0.2fmm, Ae=%0.2fmm^2
Estimated
Volume=%0.2fmm^3\n",winding_window_area,d_air_gap_calc,Ae,Transformer_Volume);
fprintf("Transformer Lm=%0.2fmH Fs=%dkHz\n",Lm*1e3,Fs);

>> Selection_Script_v2
Mosfet V_DS(on)=692.10V I_DS(on)=2.87
Diode V_D(reverse)=115.35V I_D(on)=10.42A
Output Capacitance=86.81uF
Transformer N1 Turns=35 Cable=AWG20 Length=1.42m
Transformer N2 Turns=3 Cable=AWG14 Length=0.12m
Transformer N3 Turns=3 Cable=AWG40 Length=0.12m
Transformer Winding window area=65.99mm^2 Air gap=0.07mm, Ae=84.30mm^2 Estimated
Volume=2034.16mm^3
Transformer Lm=0.38mH Fs=100000kHz
```

References

http://electronicsbeliever.com/how-quasi-resonant-flyback-works-detailed-operation/

https://www.analog.com/media/en/technical-documentation/data-sheets/lt8316.pdf