EE464

STATIC POWER CONVERSION-II

Term Project Simulation Report

Group Isolated

Contributors

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Introduction

The aim of this project is to provide the transformation that will convert the high voltage power supply output suitable for the low voltage range devices. Therefore, the study is about to reduce the input voltage ranging from 220V to 400V for the Tesla Model S's equipment that needs 12V input voltage. Since one of the most important requirements of the project was to provide an isolated system design, the topology types used in the given operating ranges, which will allow isolated converter design, were examined. Afterwards, the controller was selected according to the selected topology and the frequency range, duty cycle and turns ratio values to be operated were determined. With the completion of the transformer design and component selections in accordance with the simulation results taken from the selected controller, the theoretical calculations and the power loss calculations of the system have been completed.

Project Description

In this project, we are asked to design an isolated DC/DC converter in order to convert 220-400VDC input voltage to 12VDC with 100W output power. The specifications and requirement for the projects are following:

- Minimum Input Voltage: 220 V
- Maximum Input Voltage: 400 V
- Output Voltage: 12 V
- Output Power: 100 W
- Output Voltage Peak-to-Peak Ripple: 4%
- Line Regulation: 3%
- Load Regulation: 3%

Topology Selection

Forward Converter

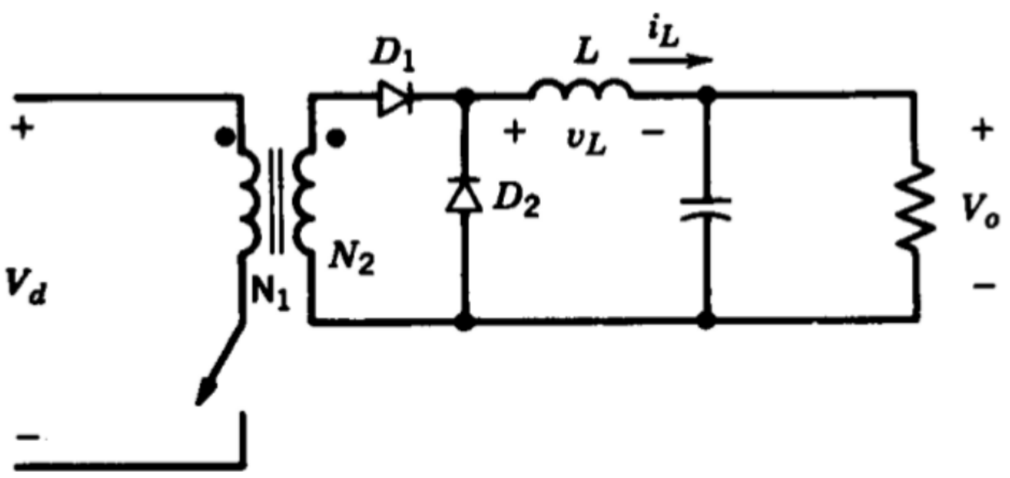

Figure 1: Forward Converter Topology

Advantages:

- Allows smaller transformer design than a flyback converter
- Better at isolated high-power applications
- Switching device has less voltage stress across it
- Low power losses and noise
- Does not require any snubber circuit

Disadvantages:

- The transformer core must be freed from unintentionally stored energy with each cycle
- Requires additional inductor at the output side
- More expensive
- Harder to control

Flyback Converter

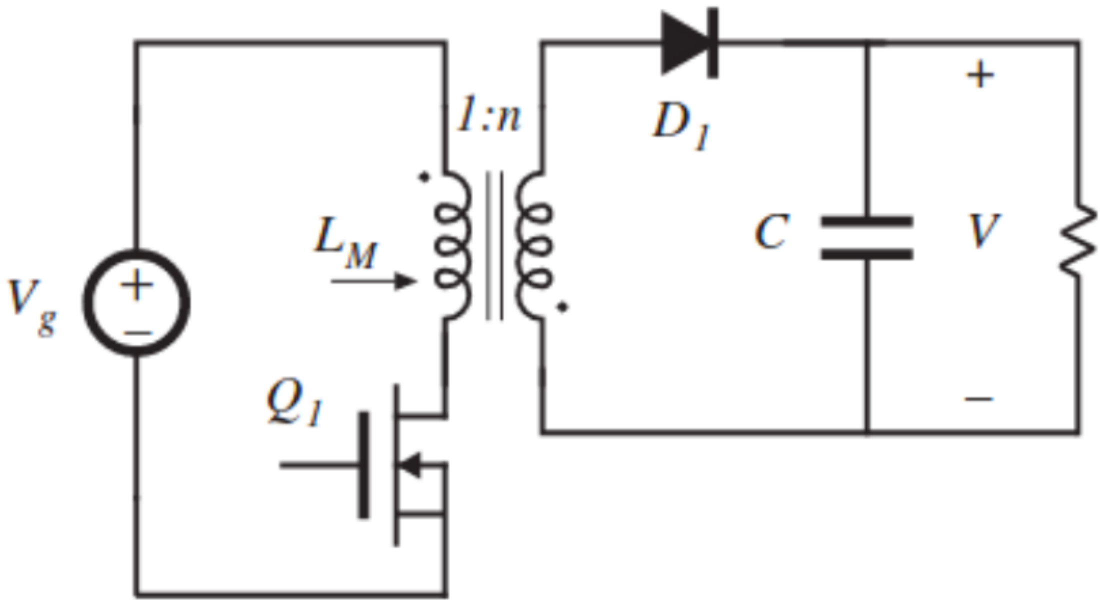

Figure 2: Flyback Converter Topology

Advantages:

- Better utilization of transformer
- Output inductor and diode ensure continuous output current
- More efficient to filter out high-frequency components
- Easier to control
- DCM operation allows soft switching
  - Allows to use smaller transformer core
  - Reduce switching losses

Disadvantages:

- Higher voltage stress across the MOSFET
- Gain changes a lot in DCM operation

Forward and Flyback converter topologies have been considered and examined in detailed while deciding on the topology which will be used in the project. According to the advantages and disadvantages of the both topologies, it has been decided to work on the Flyback converter design. While making the topology selection, some of the important factors have been evaluated as providing easier control of the converter and finding isolated controller options that meets the project requirements. In addition to these, the difficulty of controlling the forward converter and the possibility of causing problems in cases where the energy on the transformer could not be discharged regularly, made it certain to prefer the flyback converter topology.

Analytical Calculations

Transformer Calculations

In an isolated flyback converter design, the core selection completely depends on the operating frequencies. As the operating frequency increases, maximum flux density created will decrease; therefore, increasing operating frequency is an advantage to prevent saturation in the core and also helps to use smaller core structure with increased efficiency. Smaller transformer core also helps to decrease the cost and size of the converter with a considerable amount. Therefore, the calculations of the transformer have been conducted considering 100kHz operating frequency, even though it will be adjusted by the flyback controller itself.

Moreover, operating region is also an important factor while deciding the size of the transformer core, where DCM operation allows to design smaller transformers by limiting flux density in the core and prevents from the saturation problems. Therefore, DCM operation has been assumed to be used in the design while calculating transformer values and dwell time duty ratio (D_w) is assumed to be 0.1.

In the first transformer design of the process, ferrite cores with an additional gap will be considered using Kg method, which allows to calculate required air gap, fringing losses and the cable losses in the transformer design. Moreover, this method allows to count the required strands number for the Litz wire design according to the selected core properties.

Skin Effect

Operating frequency of the transformer is a primary property while deciding the cable size, which will be used during the design. Increasing operating frequency will cause current to flow from more outer part of the cable. Therefore, the middle part of the cable will be useless in the conduction period and this will cause increase in the resistance values. Considering this relationship between the frequency and cable size, it is preferred to design the transformer cables as Litz wire with multiple strands by calculating the number of layers which should be used for primary and secondary sides. Considering this perspective, calculating the skin depth for 100kHz gave an important clue while deciding the size of the cable which will be layered.

$$\varepsilon = \frac{6.62}{\sqrt{f}} = \frac{6.62}{\sqrt{100 \times 10^3}} = 0.0209 \rightarrow Wire\ Diameter = 2\varepsilon = 0.0418 \qquad [1]$$

According to the calculation done in the [1], it had been decided to use #26 AWG wire as base wire while designing the Litz wire size and number of layer requirements.

Ferrite Core Calculations

The first specification which should be considered while designing the transformer for flyback converter is that the energy storage capability of the core. Therefore, the inductance needed for the storage of a specific amount of energy storage is also important.

$$R_{in(eqiv)} = \frac{\left(V_{in(min)}\right)^2}{P_{in(max)}} \rightarrow L = \frac{R_{in(equiv)} T D_{max}^2}{2} \rightarrow Energy = \frac{L I_{p(pk)}^2}{2} \qquad [2]$$

As the name suggest K_g value, which is a core geometry values includes both energy requirements of the transformer application. Therefore, this value has been calculated first to decide the limiting value for the power handling capacities of the core selection.

$$K_e = 0.145 P_o B_m^2 \times 10^{-4} \quad \rightarrow \quad K_g = \frac{(Energy)^2}{K_e \propto} \; [cm^5] \qquad [3]$$

Considering both the K_g value, saturation conditions of the ferrite cores, window area, permeability and inductance value per N^2, EE-21 core have been chosen to be the core of the transformer design to continue with the calculations.

Table 1. Design data for EE ferrite cores

EE, Ferrite Cores (Magnetics)											
Part No.	W_{tcu} grams	W_{tfe} grams	MLT cm	MPL cm	$\frac{W_a}{A_c}$	A_c cm^2	W_a cm^2	A_p cm^4	K_g cm^5	A_t cm^2	*AL mh/1K
EE-187	6.8	4.4	3.8	4.01	2.239	0.226	0.506	0.114	0.0027	14.4	501
EE-2425	13.9	9.5	4.9	4.85	2.010	0.395	0.794	0.314	0.0101	23.5	768
EE-375	36.4	33.0	6.6	6.94	1.769	0.870	1.539	1.339	0.0706	45.3	1160
EE-21	47.3	57.0	8.1	7.75	1.103	1.490	1.643	2.448	0.1801	60.9	1696
EE-625	64.4	103.0	9.4	8.90	0.825	2.340	1.930	4.516	0.4497	81.8	2330
EE-75	111.1	179.0	11.2	10.70	0.831	3.370	2.799	9.433	1.1353	118.0	3519
* This AL value has been normalized for a permeability of 1K. For a close approximation of AL for other values of permeability, multiply this AL value by the new permeability in kilo-perm. If the new permeability is 2500, then use 2.5.											

Before getting into the core calculations, the peak and rms values of the primary current have been calculated for the future calculations considering both current density in the core and strands numbers required for the transformer design.

$$I_{p(pk)} = \frac{2P_{o(max)}T}{\eta V_{in(min)} t_{on(max)}} \; [amps\ peak], \quad I_{p(rms)} = I_{p(pk)} \sqrt{\frac{t_{on}}{3T}} \; [amps] \qquad [4]$$

Moreover, the values of the selected core structure have been used to calculate the current density, wire area in the core, required number of strands and number of turns with the Equations [5], [6], [7], [8].

$$J = \frac{2(Energy) \times 10^4}{B_m A_p K_u} \quad [A/cm^2] \qquad [5]$$

B_m: Maximum flux density, [T]

A_p: Area Product, $[cm^4]$

K_u: Window utilization, 0.29

$$A_{pw} = \frac{I_{p(rms)}}{J} \quad [6]$$

A_{pw}: Primary wire area

$$S_{np} = \frac{A_{wp}}{\#26(bare\ area)} \quad [7]$$

S_{np}: Required number of primary strands

$$N_p = \frac{K_u\, W_a/2}{3(\#26(bare\ area))} \quad [turns] \quad [8]$$

W_a: Window area of the core

N_p: Number of primary turns

Because of the high permeability values of the ferrite cores, storing the required energy in the core requires some additional gap. Calculation of the additional gap for storing previously specified energy value can be observed from Equation [9].

$$l_g = \frac{0.4\pi N^2 A_c \times 10^{-8}}{L} - \frac{MPL}{\mu} \quad [cm] \quad [9]$$

A_c: Iron area

MPL: Magnetic path length

μ: Permeability of the core material

It should be also considered that even though adding a gap to increase the energy storage capability of the ferrite core is a preferred method at some cases, it has some disadvantages as fringing flux. Therefore, this effect should be also calculated to consider its effect on the power loss of the transformer design.

$$F = 1 + \frac{l_g}{\sqrt{A_c}} \ln\left(\frac{2G}{l_g}\right) \quad [10]$$

Moreover, the fringing flux also has an effect on the number of required turns in the primary side of the transformer and the peak flux density as follows.

$$N_{np} = \sqrt{\frac{l_g L}{0.4\pi A_c F 10^{-8}}} \quad [11]$$

N_{np}: New number of turns for the primary

$$B_{pk} = \frac{0.4\pi N_{np} F I_{p(pk)} 10^{-4}}{l_g + \frac{MPL}{\mu}} \quad [T] \quad [12]$$

MPL: Magnetic path length

As the number of turn and strands values of the primary have been completed, ESR resistance of this side can be also determined by considering both the designed Litz wire strands, #26 AWG copper wire resistance property, number of turns in the primary and the magnetic path length of the selected core.

$$R_p = MLT(N_{np})\left(\frac{\mu\Omega/cm}{S_{np}}\right) \times 10^{-6}\ [\Omega] \qquad [13]$$

Moreover, secondary side of the transformer can be calculated with the values, which have been calculated so far. Decided duty cycle and dwell time duty ratio plays an important role while calculating the secondary side of the transformer. Moreover, the voltage drop on the output part of the flyback converter is assumed to be 1V during the calculations.

$$N_s = \frac{N_{np}(V_o + V_d)(1 - D_{max} - D_w)}{V_p D_{max}} \qquad [14]$$

Other than the turn number of the secondary of the transformer, same calculations have been applied to calculate secondary peak current, rms current, wire area, secondary strands number, and winding resistance.

Turns ratio	L_m(mutual inductance)	S_p(primary strands)	S_s(secondary strands)	K_u(window utilization)
6	80μH	9	67	0.1

Component Power Calculations

Specifications of project are

$V_{in(min)}$ =220 V,

$V_{in(max)}$ =400V,

P_{out} =100W,

V_{out}=12V

We have to decide some values for calculation and to get smaller transformer and ripples we decide switch frequency as 100khz. Our system will operate in Discontinuous conduction mode and we decide dwell time as one over ten period time. Also, maximum duty ratio as taken 0.2. Our secondary side diode will operate at high current so we can't just assume its on voltage as zero volt, before deciding diode we take diode on voltage as 1V. Transformer won't operate at 100% efficiency and before designing that we assume efficiency as 90%. So decided values are as given.

f_S = 100kHz

D_{dwell} = 0.1

D_{max}= 0.2 at 220V and D_{min} = 0.11 at 400V

V_{diode} = 1 V

$\eta_{transformer}$ = 0.9

Primary and Secondary powers

By using output power and output voltage, average output current calculated. Then diodes power dissipation added and secondary sides total power calculated. Transformer is not ideal and we choose efficiency as 90% percent and primary sides power calculated with including core loss.

$I_{out(avg)} = P_{out} / V_{out} = 8.33$ A

$P_{diode} = V_{diode} \times I_{out(avg)} = 8.33$ W

$P_{secondary} = P_{diode} + P_{out} = 108.33$ W

$P_{primary} = P_{secondary} / \eta_{transformer} = 120.37$ W

Primary and secondary sides peak current:

Primary and secondary sides inductor current is triangular shape and its peak value calculated with the following equations.

For 220 volt source voltage:

$I_{in(avg)} = P_{primary} / V_{in(min)} = 0.55$ A

$I_{in(peak)} = 2 \times (I_{in(avg)} / D_{max}) = 5.47$ A

For 400 volt source voltage:

$I_{in(avg)} = P_{primary} / V_{in(max)} = 0.55$ A $= 0.30$ A

$I_{in(peak)} = 2 \times (I_{in(avg)} / D_{min}) = 5.47$ A

$I_{secondary(peak)} = 2 \times (I_{out(avg)} / (1 - D_{max} - D_{dwell})) = 23.\ 80$ A

Ratings of Components

Transformer, Mosfet, Diode and Output Capacitor are important components for flyback converter, Transformer's calculation showed in previous part and turn ratio taken as 6. Mosfet, Diode and Output Capacitors required ratings analytically calculated in following equations.

$N_{turn} = 6$

For Mosfet:

$V_{DS(max)} = V_{in(max)} + (V_{out} \times N_{turn}) = 472$ V

$I_{DS(peak)} = I_{in(peak)} = 5.47$ A

For Diode:

$V_{D(max)} = V_{out(max)} + (V_{in(max)} / N_{turn}) = 78.67$ V

$I_{D(max)} = I_{secondary(peak)} = 23.80$ A

Output Capacitor:

$\Delta V_{out(max)} = V_{out} \times (3/100) = 0.36$ V

$I_{C(pp)} = (I_{out(avg)} \times (1 + ((D_{max} + D_{dwell}) / (1 - D_{max} - D_{dwell})))) = 11.90$ A

$\Delta V_{ESR} = ESR \times I_{C(pp)} = ESR \times 11.90$

$\Delta Q_C = I_{out(avg)} \times (D_{max} + D_{dwell}) / (C_{out} \times f_S) = 2.5\times10^{-5}$ C

$\Delta V_C = \Delta Q_C / C_{out} = 2.5\times10^{-5} / C_{out}$

$\Delta V_{out} = \Delta V_{ESR} + \Delta V_C = ESR \times 11.90 + 2.5\times10^{-5} / C_{out}$

When C_{out} is infinity ESR must be smaller than 30.25 mΩ

When ESR is zero C_{out} must be bigger than 69.44 uF

Component Selection

In the previous part, we have decided the required component values with the LTSpice simulation tool and calculations. To provide a reliable design, we considered the inrush currents and surge voltages. Therefore, we have chosen our components by considering the maximum power rating and its tolerance. Also, in order to decrease the final size of the design, we tried to choose the component in small packages.

At first, we have decided on the controller. We have needed a flyback controller which provides 100W power and around 100kHz frequency range to decrease the size of the transformer. Also, to make the simulation part easier, we looked for the Analog Design Manufacturer. In the end we have decided on the LT8316 controller.

Then, we looked for the semiconductor components which are MOSFET as a switch, diodes for the secondary side of the converter and for biasing of the controller. As a mosfet, we have decided on IPAN70R450P7S. Its ratings are given in Table 2.

Table 2. Mosfet Ratings

Parameter	**Value - Description**
V_{DS} , Breakdown voltage	700V
I_D, Continuous current	10A at T_C =20 °C
$I_{D,pulse}$ Pulsed Drain current	25.9 A
$R_{DS,ON}$	450mΩ
Q_g	13.1nC
Price	$1.05

Then, the diode of the secondary side is chosen as MBR40250G which provides 40A continuous current and 80A repetitive current.

Table 3. Diode Ratings

Parameter	**Value - Description**
V_R , Blocking voltage	250V
I_{RMS}, Continuous current	40A
I_{FRM}, Peak Repetitive Forward Current	80A
V_F	0.86V
Price	$1.82000

The biasing diode is chosen as to provide 5A continuous and 8A surge current. Also, it needs a small forward voltage. For this purpose, we have decided on BAS3010A03WE6327HTSA1 diode.

Then, we have worked on the capacitors and resistors in the circuit. The most important capacitor is output capacitor and the most important resistor is sense resistor. The output capacitor is chosen as it represents low ESR value and appropriate capacitance and voltage rating. Therefore, it is chosen as RNL1C681MDS1.

Table 4. Output Capacitor Ratings

Parameter	Value - Description
C, Capacitance	680uF
$V_{C,MAX}$ Rating	25V
$I_{C,ripple}$	7A
ESR	8mΩ
Price	1.50$ - (QTY:1)

The sense resistor should be in small resistance value and should handle the power that will flow through it. Therefore, it is chosen as WK73S2ATTDR10J which is 100mΩ and 1W power rating resistor.

The other capacitors and resistors are chosen according to their voltage value on the simulation. The important thing is here, they are chosen the smallest package in the required ranges.

Simulations

After components selected their model implemented in LTspice and simulations test applied under given condition.

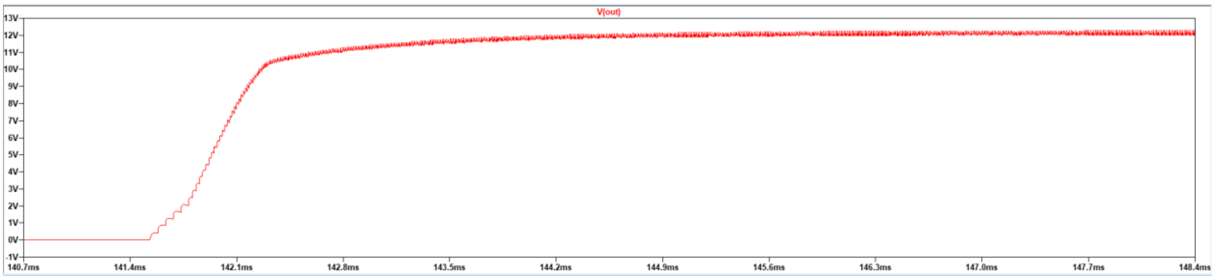

Figure 3: Output voltage waveform

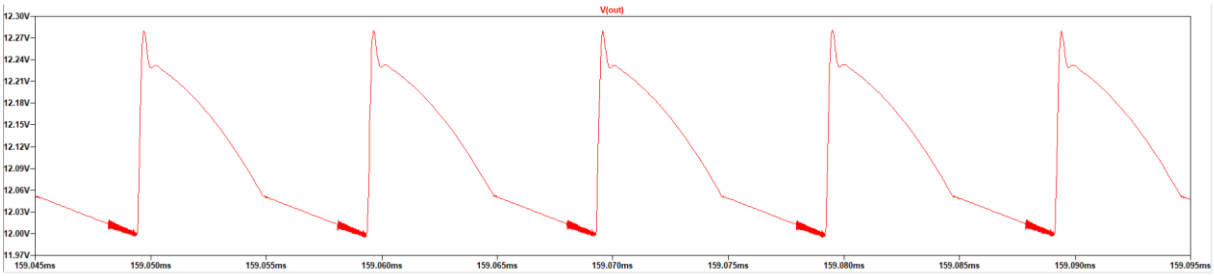

Figure 4: Output voltage close view waveform

As seen in the figure 3 after system turn on output voltage increase to the 12 V and give stable output voltage. Figure 4 shows ripple of output voltage and it is 0.28 V so output voltage ripple ratio is 2.33% and it is appropriate for project requirements.

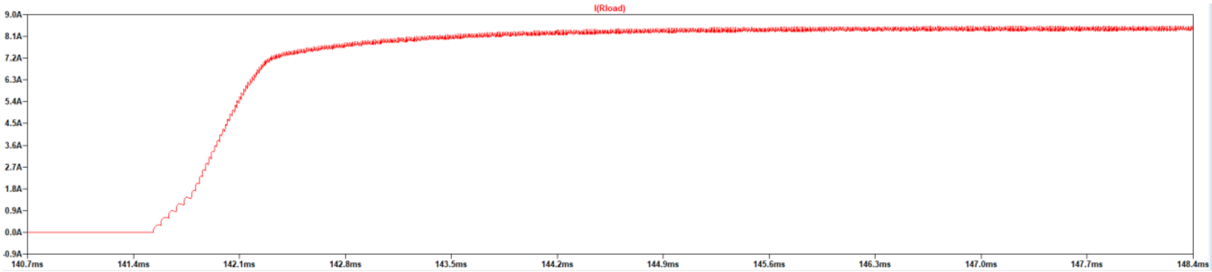

Figure 5: Output current waveform

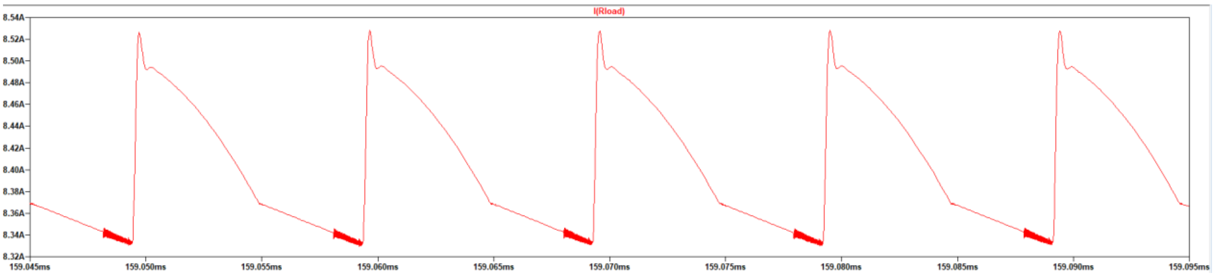

Figure 6: Output current close view waveform

In simulation tested load taken as fully resistive component and it is 1.44Ω so output current waveforms same as voltage and output power 101.15 W and it is little exceeding our rated power.

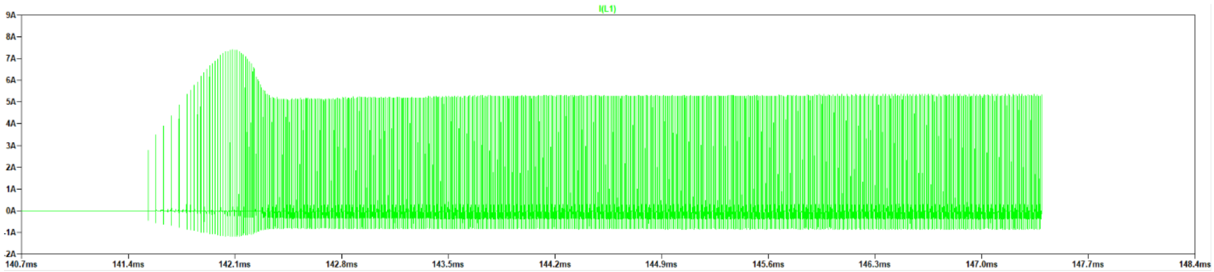

Figure 7: Primary inductor current waveform

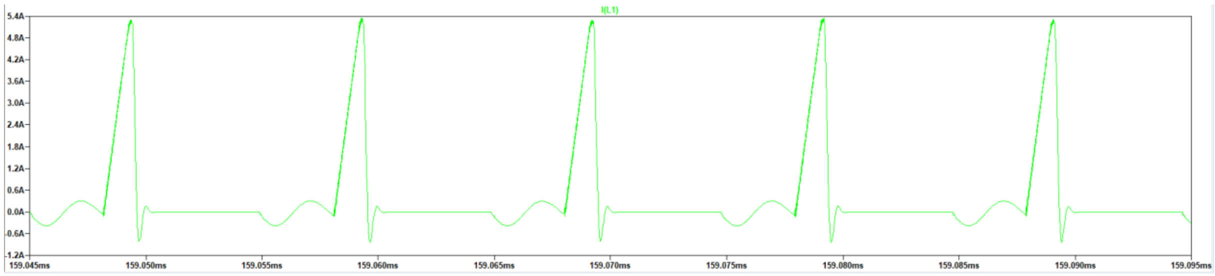

Figure 8: Primary inductor current close view waveform

When we look at the figure 7 its seen that initially current increase up to 7.5A then it is settled at 5.2A because initially output voltage is zero and system have to charge output capacitance and feedback system of the controller increase duty cycle and this result higher primary current. At figure 8 triangular shape of inductor current seen at mosfet on.

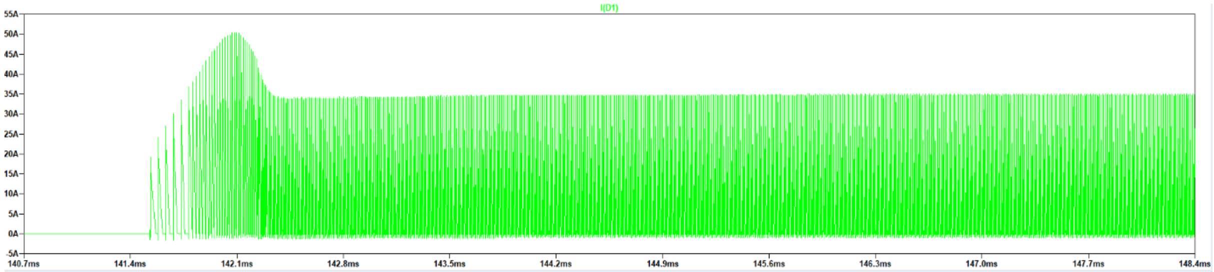

Figure 9: Secondary inductor current waveform

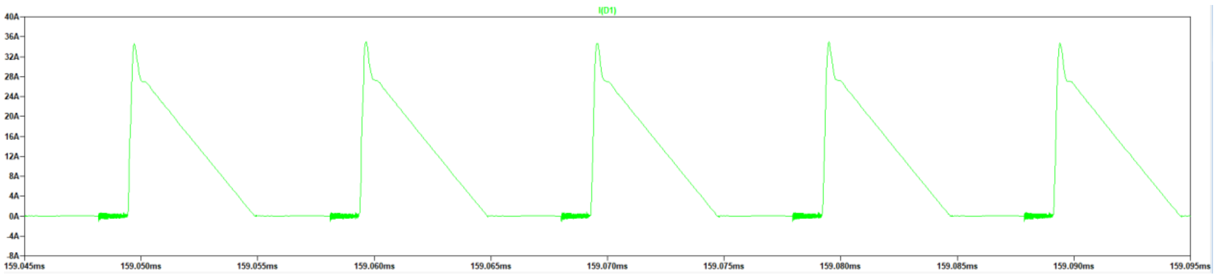

Figure 10: Secondary inductor current close view waveform

Secondary part of transformer has higher current density and its pulsative current reach 50 A at initial time then it is fixed at 35A.

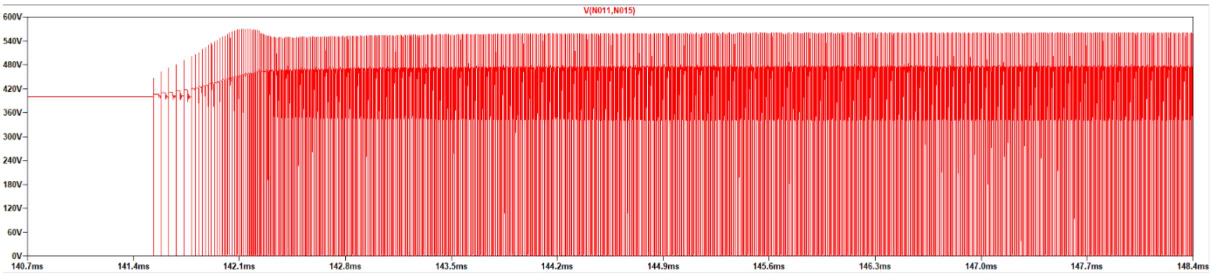

Figure 11: Mosfet voltage waveform

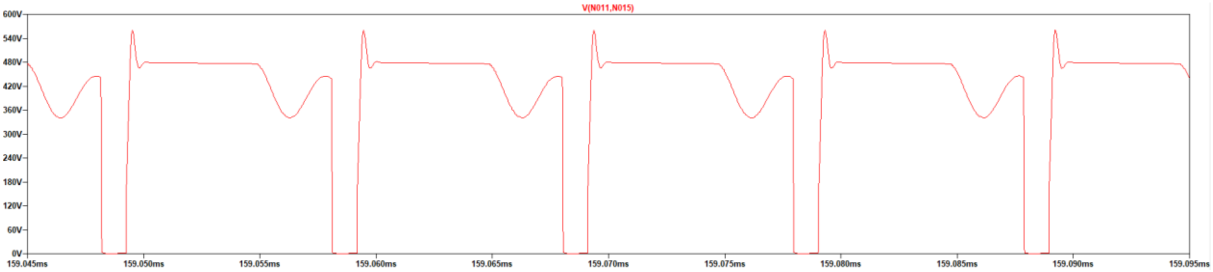

Figure 12: Mosfet voltage close view waveform

Selected mosfets breakdown voltage is 700 V and as seen in the figure 12 its voltage jumps to the 560V when it is turn of because of the leakage inductance then it decrease to the 478V. At D_{dwell} time its voltage oscillates. When looked at the figure 9 and 11 they're in the our mosfets operation region.

Figure 13: Diode voltage waveform

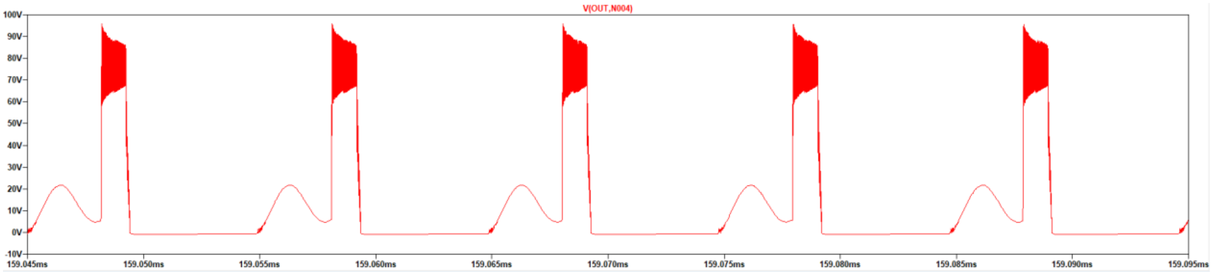

Figure 14: Diode voltage close view waveform

Selected diode breakdown voltage is 250 V and it can operate this voltage ratios. Diodes continuous current 40 A and as figure 9 shows secondary sides current reach 50 A initially but it is pulsative current and diode can operate pulsative current up to 80 A.

Power Losses

Transformer Power Losses

Required length of wire have been calculated for both primary and secondary in the transformer calculations part. Moreover, required number of strands also considered in both sides. A third winding is also necessary similar with the secondary side of the transformer for carrying reference voltage to the feedback pin of the transformer. As the primary and secondary windings' resistances and rms currents have been calculated before, their copper losses can also be calculated.

$$P_{cu} = I_p^2 R_p + I_s^2 R_s = 0.036 \qquad [15]$$

In addition to the copper losses, there is also core losses exist due to fringing flux caused by the added gap in the ferrite core.

$$B_{ac} = \frac{0.4\pi N_{np} F \left(\frac{I_{p(pk)}}{2}\right) 10^{-4}}{l_g + \frac{MPL}{\mu}} \quad [T] \qquad [16]$$

B_{ac}: AC flux density

$$WK = 4.855 \times 10^{-5} (f)^{1.63} (B_{ac})^{2.62} \quad [W/kg] \qquad [17]$$

WK: Watts per kilogram

$$P_{fe} = \left(\frac{mW}{g}\right) W_{rfe} \times 10^{-3} = 5.3823 \ [W] \qquad [18]$$

P_{fe}: Core loss

$$P_{\Sigma} = P_{cu} + P_{fe} = 5.4183 \, [W] \qquad [19]$$

P_{Σ}: Total power loss

Conduction Losses

According to the Equation [20] MOSFET conduction loss is 0.25W.

$$P_{on,M} = \left[I_{out}^2 + \frac{\Delta I_L^2}{12} \right] R_{on,M} \, D \qquad [20]$$

According to the Equation [21] diode conduction loss is 7.61W.

$$P_{on,D} = V_f I_{out} (1 - D) \qquad [21]$$

Switching Losses

According to the Equation [22] MOSFET conduction loss is 0.291.

$$P_{sw,M} = \frac{1}{2} V_{in} I_{out} \left(t_{rise} + t_{fall}\right) f_{sw} \qquad [22]$$

According to the Equation [23] MOSFET conduction loss is

$$P_{sw,D} = \frac{1}{2} V_{in}\, I_{rr}\, t_{rr}\, f_{sw} \qquad [23]$$

PCB Design

At this part of the project, we have drawn the schematic library and footprints of the selected component. The circuit schematic from the simulation tool is given below.

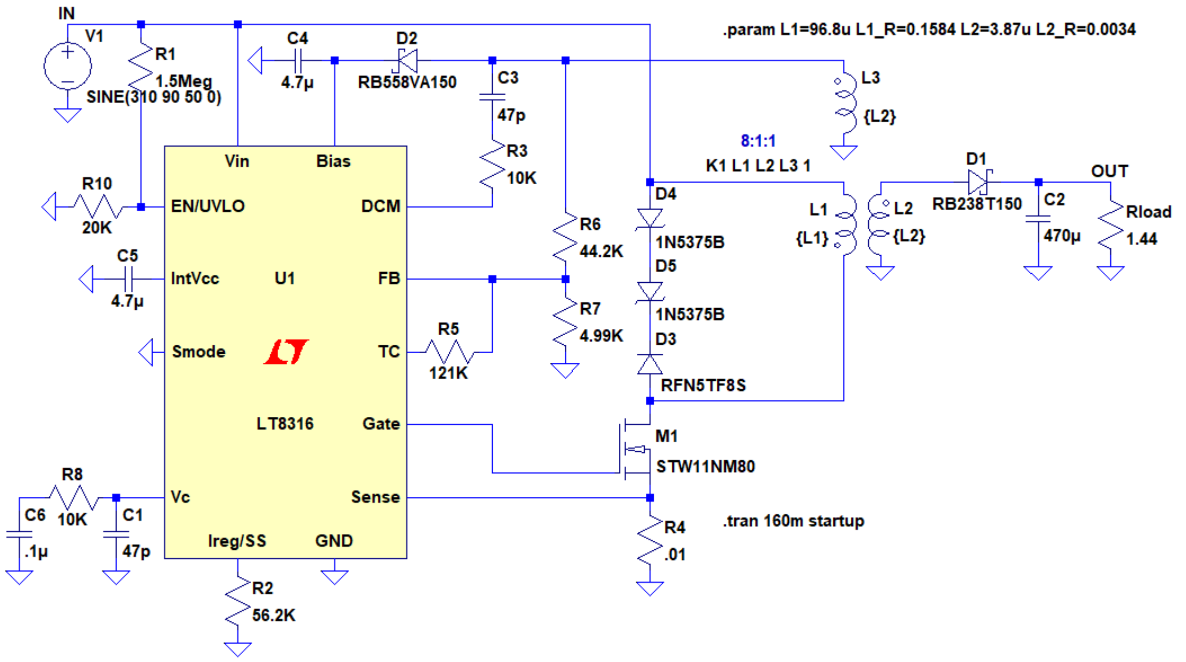

Figure 1. Circuit schematic

According to this schematic, the PCB design will be composed of 9 resistors, 6 capacitors, 2 diodes, 1switch, 1 controller 1 transformer and 1 snubber unit. In order to decrease the size of the final circuitry, we chose the resistors and capacitors as small packaged as possible. The schematic of the PCB can be seen in Figure 2.

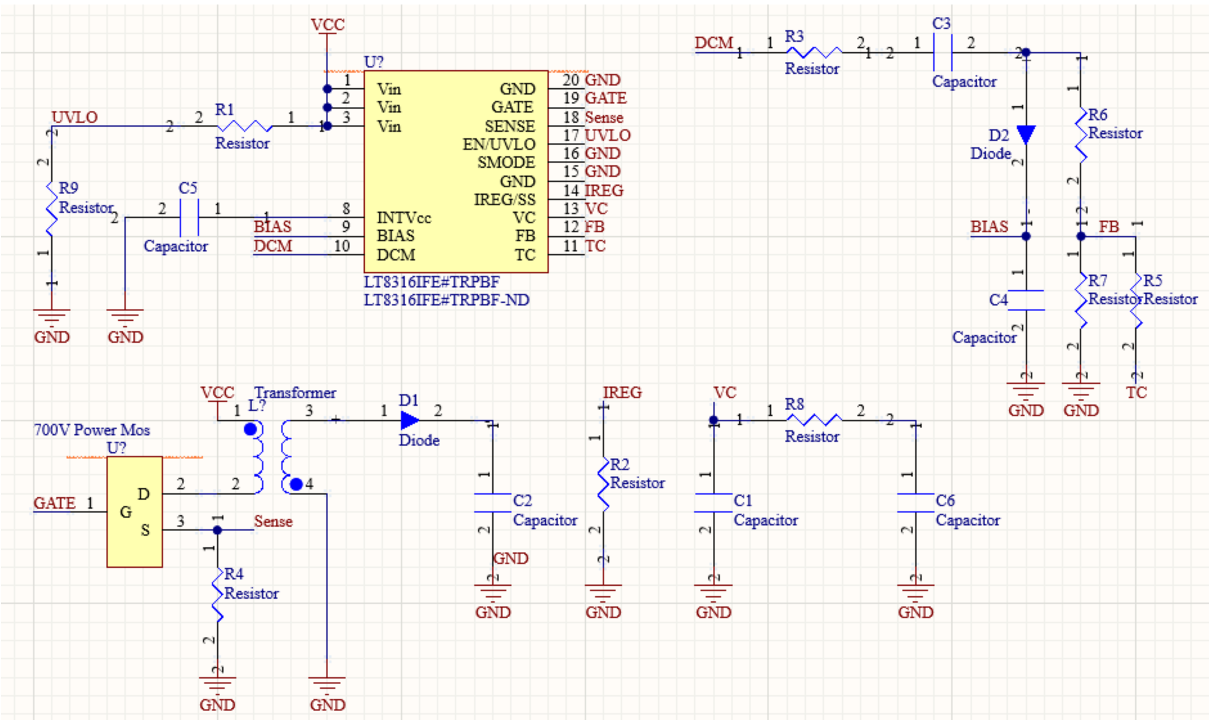

Figure 2. Schematic of the PCB

In this step, we placed all the component' footprints and 3D models except the transformer, which will be final design made after the feedback session. However, we did not have chance to design the layout of the PCB since some of the calculations are still in progress about magnetic design. We have worked on an application not in order to design a fine PCB which does not create or effect any of the EMI signals and does not violate the isolation of the converter.

The first think that we will consider is the ground gridding. The ground layer has an important role in the PCB design since all the currents and signals that come to the circuit must leave the circuit and should not cause any interference. In order to decrease the noise on the circuit, we will design the ground as a polygon at the underneath of the controller and other components to supply a short current loop. Also, the bypass capacitors will be placed according to the Figure 3.

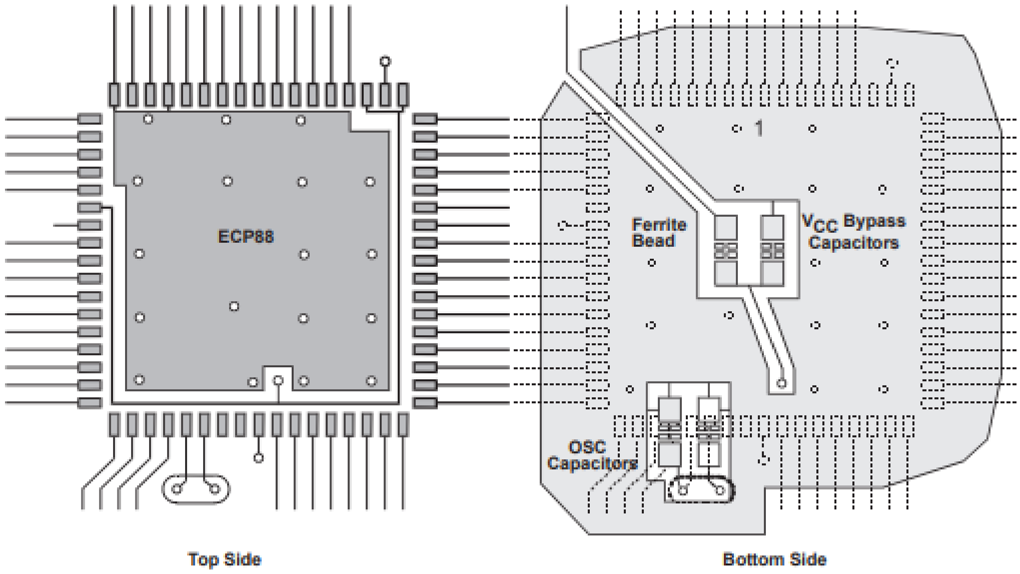

Figure 3. Controller Groung Example [1]

The other important thing is input and output power points. Since our design supplies around 8.5A current, the output power traces should be placed as they do not damaged due to rising temperature. For the trace size calculation Saturn PCB Toolkit will be used.

The other important thing is about getting feedback from the circuitry. To do this, we are using 100mΩ sense resistor. The replacement of this resistor is important since it is very low resistor, the point of the connection may cause change in the read voltage level. The traces should be placed as symmetrical.

In the PCB layout, the controller should be placed close to the power input. With this arrangement, the high-speed logic has less chance to pollute other signal traces. The transformer should be placed away from the controller in order to decrease the possible noises. Also, it should be considered the crosstalk problem while placing the traces, the space between the traces is important in order to decrease the capacitive and inductive crosstalk.

Conclusion

Within the scope of this project, it is aimed to create a circuit that will perform the voltage conversion operation between the high voltage battery and low voltage battery in Tesla Model S vehicles. Thanks to this transformation, the devices in the low voltage range (12V) will be operated by using 220V – 400V input voltage. Since the system has high input voltage and low output voltage value, an isolated structure has been specifically studied. For this reason, isolated converter topologies were examined one by one and their advantages and disadvantages were evaluated. Later, studies were carried out on the transformer design to be used in isolated power transmission. After determining the required duty cycle and turns ratio values, the system was simulated and the rated values of the required components were determined. Lastly, theoretical calculations have been completed with component selection and power loss calculations.