

**EE464**

**STATIC POWER CONVERSION-II**

**Term Project Simulation Report**

**Group Isolated**

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Table of Contents

[Introduction 3](#_Toc76193524)

[Project Description 4](#_Toc76193525)

[Topology Selection 4](#_Toc76193526)

[Forward Converter 4](#_Toc76193527)

[Flyback Converter 5](#_Toc76193528)

[Analytical Calculations 6](#_Toc76193529)

[Transformer Calculations 6](#_Toc76193530)

[Skin Effect 6](#_Toc76193531)

[Ferrite Core Calculations 6](#_Toc76193532)

[Iron Powder Core Calculations 9](#_Toc76193533)

[Core Selection 9](#_Toc76193534)

[Selecting Turns and Wire Size 10](#_Toc76193535)

[Component Power Calculations 12](#_Toc76193536)

[Component Selection 14](#_Toc76193537)

[Simulations 16](#_Toc76193538)

[Power Losses 19](#_Toc76193539)

[Ferrite Core Transformer Power Losses 19](#_Toc76193540)

[Iron Powder Core Transformer Power Losses 20](#_Toc76193541)

[Core Losses 20](#_Toc76193542)

[Copper Losses 21](#_Toc76193543)

[Mosfet power Loss 21](#_Toc76193544)

[Diode Loss 21](#_Toc76193545)

[Snubber Loss 21](#_Toc76193546)

[PCB Design 23](#_Toc76193547)

[Conclusion 25](#_Toc76193548)

# 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

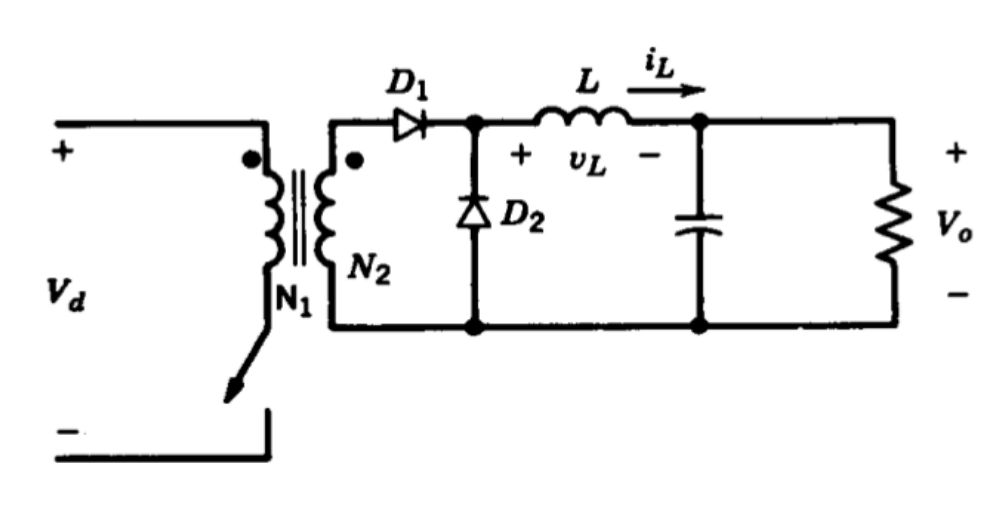


Figure 1: Forward Converter Topology

**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

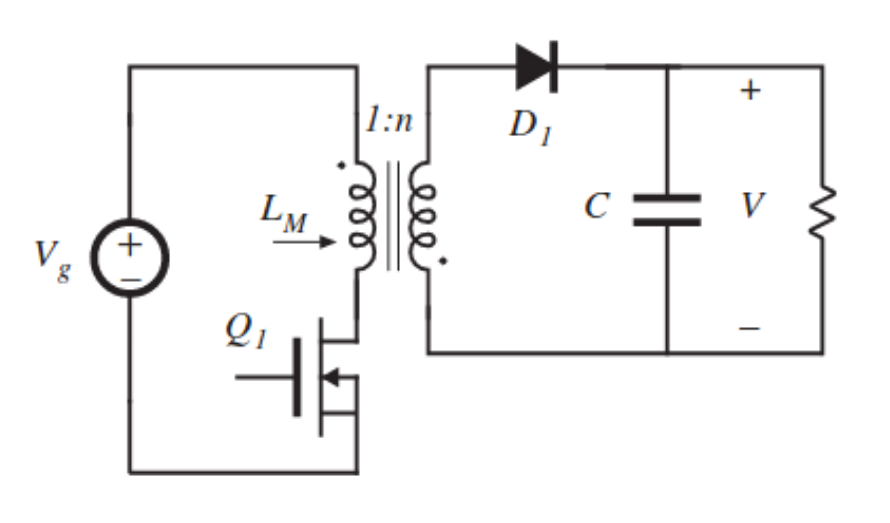


Figure 2: Flyback Converter Topology

**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 () 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.

|  |  |  |
| --- | --- | --- |
|  |  | [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.

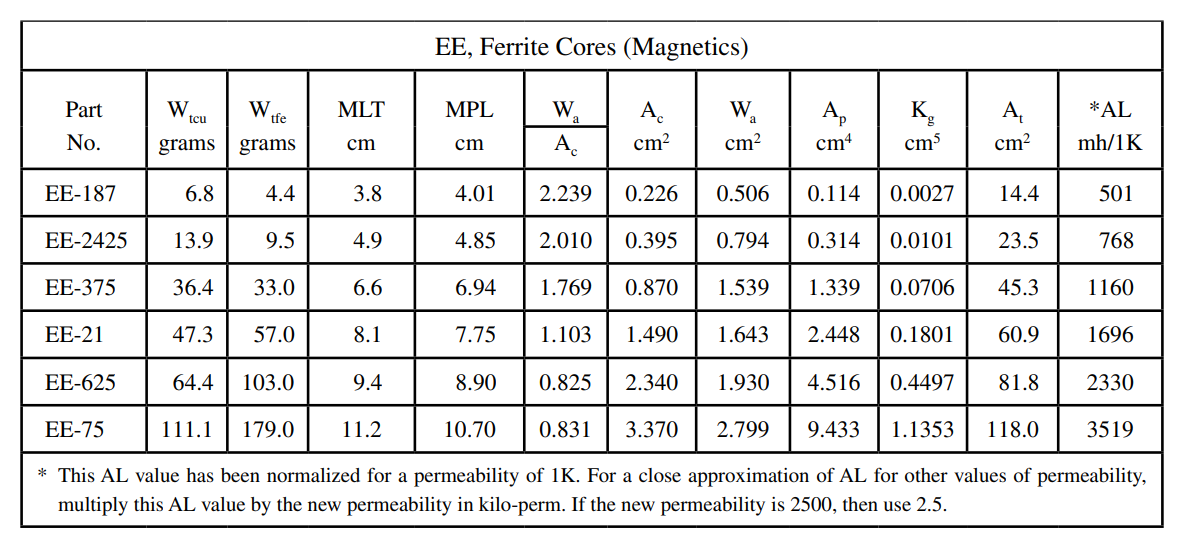
|  |  |  |
| --- | --- | --- |
|  |  | [2] |

As the name suggest 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.

|  |  |  |
| --- | --- | --- |
|  |  | [3] |

Considering both the value, saturation conditions of the ferrite cores, window area, permeability and inductance value per , 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



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.

|  |  |  |
| --- | --- | --- |
|  |  | [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].

|  |  |  |
| --- | --- | --- |
|  |  | [5] |

: Maximum flux density, [T]

: Area Product, []

: Window utilization, 0.29

|  |  |  |
| --- | --- | --- |
|  |  | [6] |

: Primary wire area

|  |  |  |
| --- | --- | --- |
|  |  | [7] |

: Required number of primary strands

|  |  |  |
| --- | --- | --- |
|  |  | [8] |

: Window area of the core

: 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].

|  |  |  |
| --- | --- | --- |
|  |  | [9] |

: Iron area

: Magnetic path length

: 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.

|  |  |  |
| --- | --- | --- |
|  |  | [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.

|  |  |  |
| --- | --- | --- |
|  |  | [11] |

: New number of turns for the primary

|  |  |  |
| --- | --- | --- |
|  |  | [12] |

: 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.

|  |  |  |
| --- | --- | --- |
|  |  | [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.

|  |  |  |
| --- | --- | --- |
|  |  | [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 | (mutual inductance) | (primary strands) | (secondary strands) | (window utilization) |
| 6 | 80µH | 9 | 67 | 0.1 |

## Iron Powder Core Calculations

### Core Selection

The iron powder core selection for flyback converter design is based on the energy storage. Therefore, it is important to calculated the amount of energy where the core should reach in the time. This can be calculated using the peak current and inductance of the primary.

= Output Power (Watts) = 100 W

= Minimum input voltage (Volts) = 220 V

= Maximum duty cycle = = 0.35

= Switching frequency (kHz) = 100 kHz

The primary inductance can be calculated using the primary peak voltage as Equation …:

By using calculation, a core selection can be made according to the energy desired to be stored.

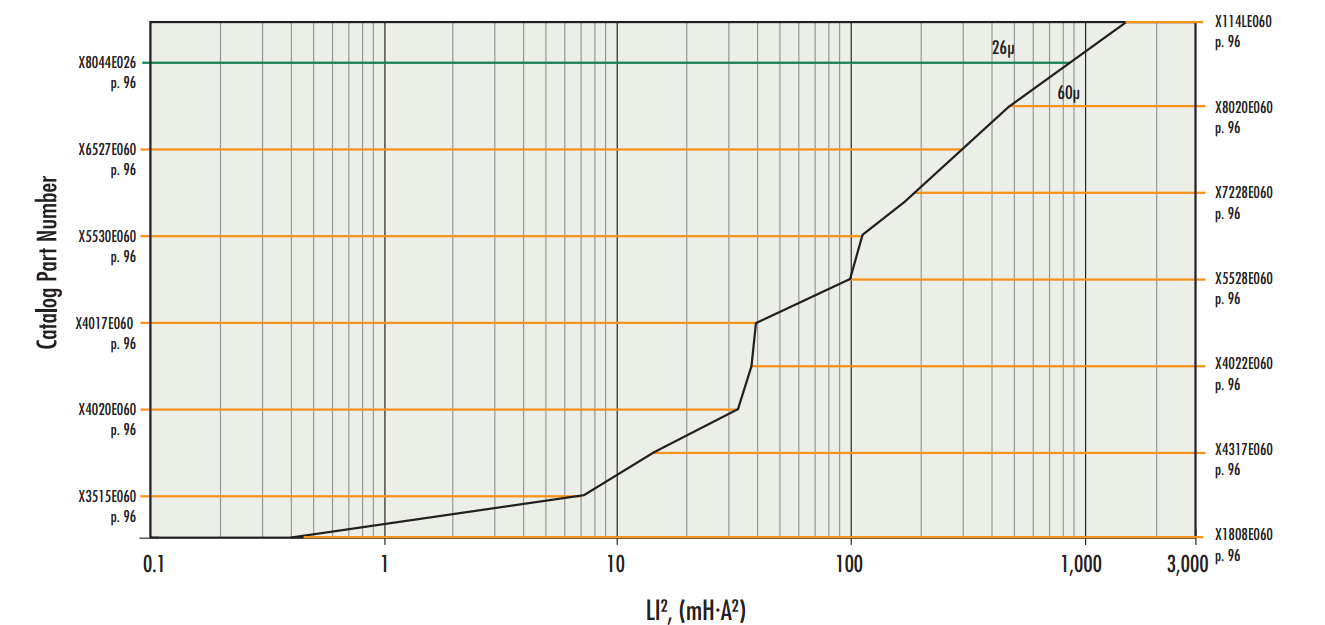


Figure 1: XFlux E Core enery storage table

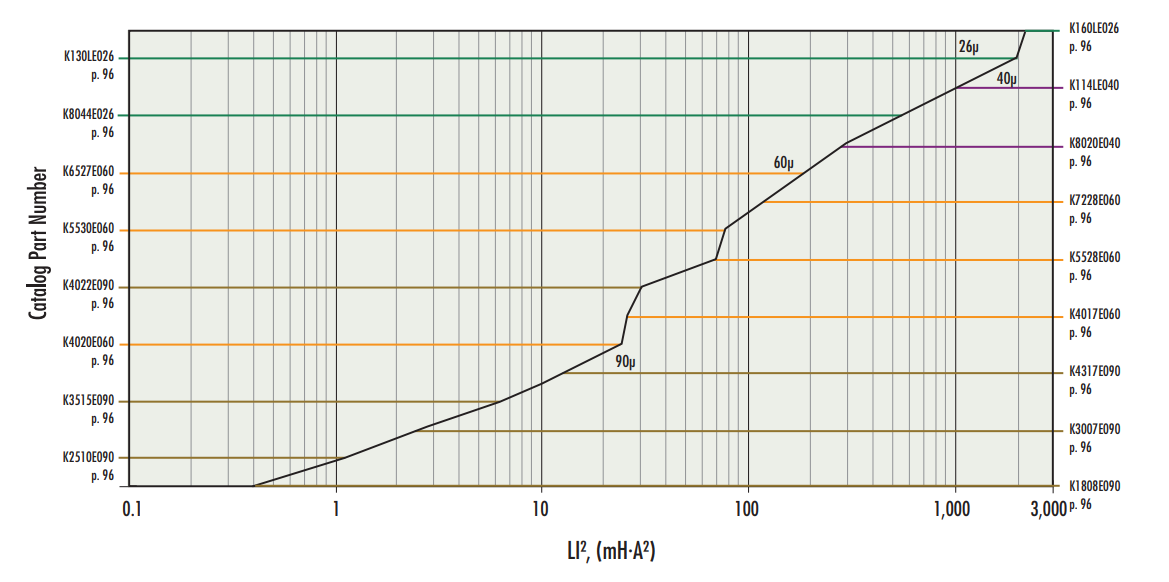


Figure 2: Kool Mµ E Core enery storage table

According to the energy storage tables of XFlux and Kool Mµ E cores (Figure … and …), it is deemed appropriate to use K3007E90 core for smaller transformer design where it allows around 2.5 mH\*A2 energy.

### Selecting Turns and Wire Size

Calculation of the primary inductance and choosing the material type allow to design the turns of the wires with respect to the core data. Kool Mµ cores have different permeability chooses, where 90µ has been considered to prevent too much copper losses by decreasing the turn number with an increased permeability. The selected core for the selected permeability have inductance of . Therefore, number of primary turns can be calculated as Equation …, which is proposed by the Magnetics.

= Output voltage (V)

= Diode voltage drop (V-> taken to be 1V)

Moreover, average voltage of the primary side of the transformer should be known to determine the cable thickness needed.

Due to the high frequency where the transformer is expected to operate, cable selection should be made according to the skin effect.

=Skin depth

=Resistivity of the Material

= (Relative Permeability) \*(Permeability Constant)

If the selected cable is greater than the skin depth, current will flow only around the cable, not in the middle. Therefore, the cable selection has been done considering skin depth value to decrease amount of the AC losses. For this reason, AWG 26 cable has been selected due to its diameter. On the other hand, AWG 26 cable is capable of transmitting 0.361 A current. Therefore, paralleling 2 cables in the primary and 12 cables in the secondary has been deemed appropriate.

Another value to be checked after the cable selection is the core utilization value, where it shows if the cables fit inside the core window and how much space do they take up.

, = Number of parallel cables in the primary and secondary

= Winding area of the bobbin which will used in the E core (PCB3007T1)

## Component Power Calculations

Specifications of project are

Vin(min) =220 V,

Vin(max) =400V,

Pout =100W,

Vout=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.

fS = 100kHz

Ddwell = 0.1

Dmax= 0.35 at 220V and Dmin = 0.1925 at 400V

Vdiode = 1 V

ɳtransformer = 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.

Iout(avg)= Pout / Vout = 8.33 A

Pdiode = Vdiode x Iout(avg) = 8.33 W

Psecondary = Pdiode + Pout = 108.33 W

Pprimary = Psecondary / ɳtransformer = 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:

Iin(avg) = Pprimary / Vin(min) = 0.547 A

Iin(peak) = 2 x ( Iin(avg) / Dmax) = 3.12 A

For 400 volt source voltage:

Iin(avg) = Pprimary / Vin(max)  = 0.30 A

Iin(peak) = 2 x ( Iin(avg) / Dmin) = 3.12 A

Isecondary(peak) = 2 x (Iout(avg) / (1 - Dmax - Ddwell)) = 30.30 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.

Nturn = 6

For Mosfet:

VDS(max) = Vin(max) + (Vout x Nturn) = 497.71 V

IDS(peak) = Iin(peak) = 3.12 A

For Diode:

VD(max) = Vout(max) + (Vin(max) / Nturn) = 78.67 V

ID(max) = Isecondary(peak) = 30.30 A

Output Capacitor:

At the output 2 capacitor parallely connected. Single ones values 330 uF - 13 mΩ so net values 660 uF – 6.5 mΩ.

∆Vout(max) = Vout x (3/100) = 0.36 V

IC(pp) =(Iout(avg) x (1+ ((Dmax + Ddwell) / (1 - Dmax - Ddwell))) = 15.15 A

∆VESR = ESR x IC(pp) = 0.0985 V

∆QC = Iout(avg) x (Dmax + Ddwell) / fS = 3.75x10-5 C

∆VC  = ∆QC / Cout = 56.8 mV

∆Vout = ∆VESR + ∆VC  = 0.1553 V

# 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** |
| VDS , Breakdown voltage | 700V |
| ID, Continuous current | 10A at TC =20 oC |
| ID,pulse Pulsed Drain current | 25.9 A |
| RDS,ON | 450mΩ |
| Qg | 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** |
| VR , Blocking voltage | 250V |
| IRMS, Continuous current | 40A |
| IFRM, Peak Repetitive Forward Current | 80A |
| VF | 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 337ULR016MFF. 2 capacitors placed at parallel to decrease ESR and increase the capacitance.

Table 4. Output Capacitor Ratings

|  |  |
| --- | --- |
| **Parameter** | **Value - Description** |
| C, Capacitance | 330uF |
| VC,MAX Rating | 16V |
| IC,ripple | 4.3A |
| ESR | 13mΩ |
| Price | $0.2925 x 2 |

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 400V input voltage. Controller change its frequency at different conditions when 220 V applied switching frequency is 107 kHz and at 400 V its frequency become 130 kHz.

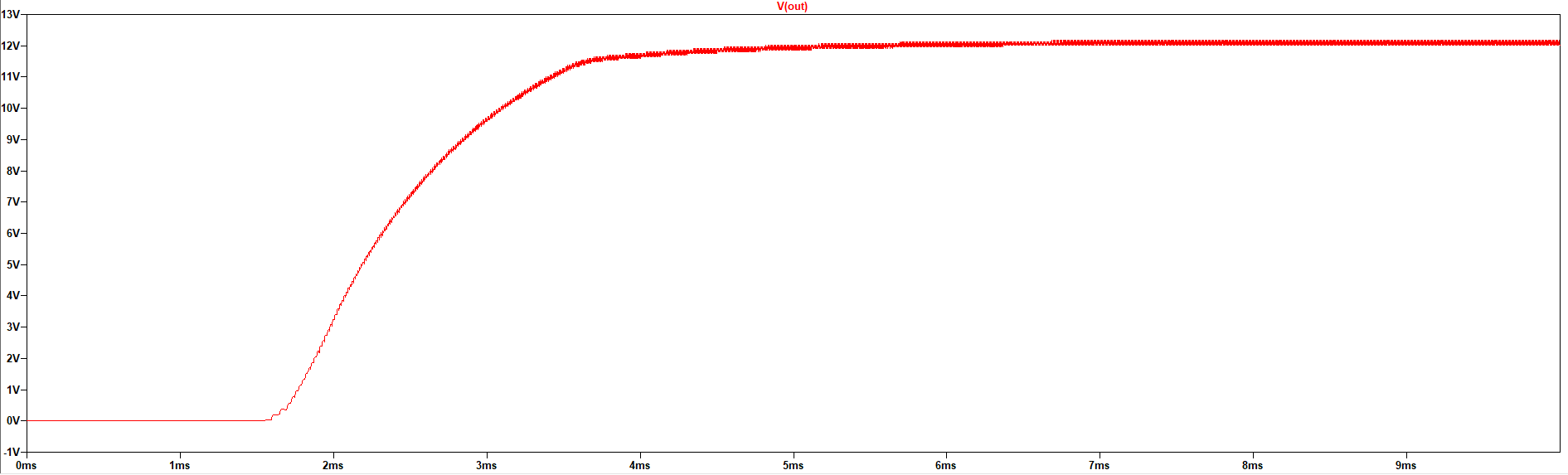


Figure 3: Output voltage waveform

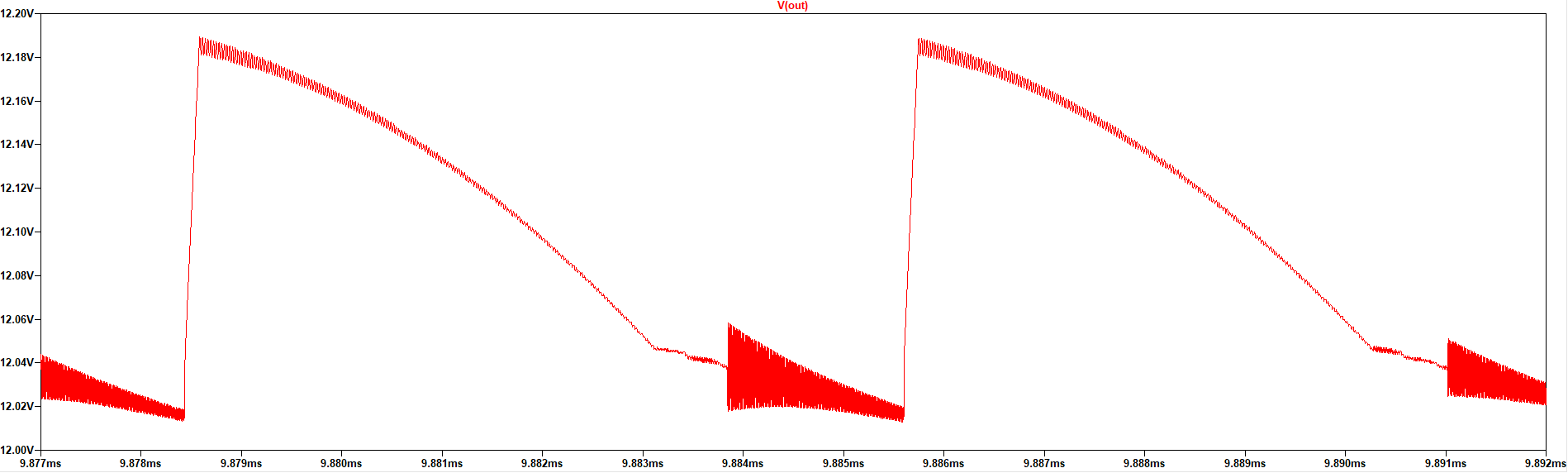


Figure 4: Output voltage close view waveform

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 0.17 V so output voltage ripple ratio is 1.417% and it is appropriate for project requirements.

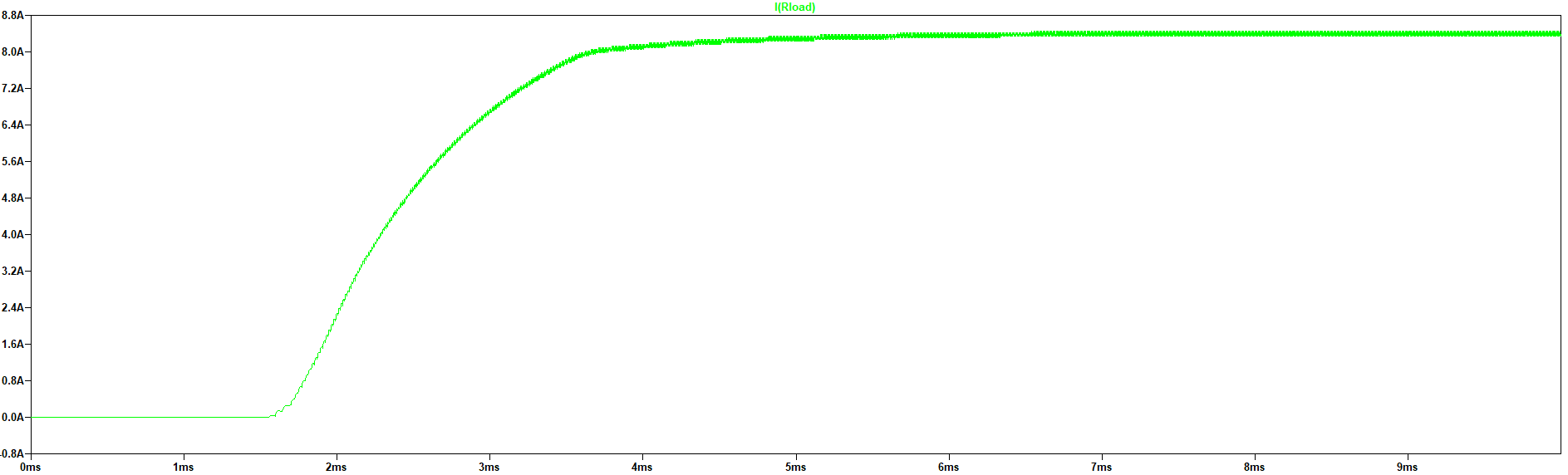


Figure 5: Output current waveform

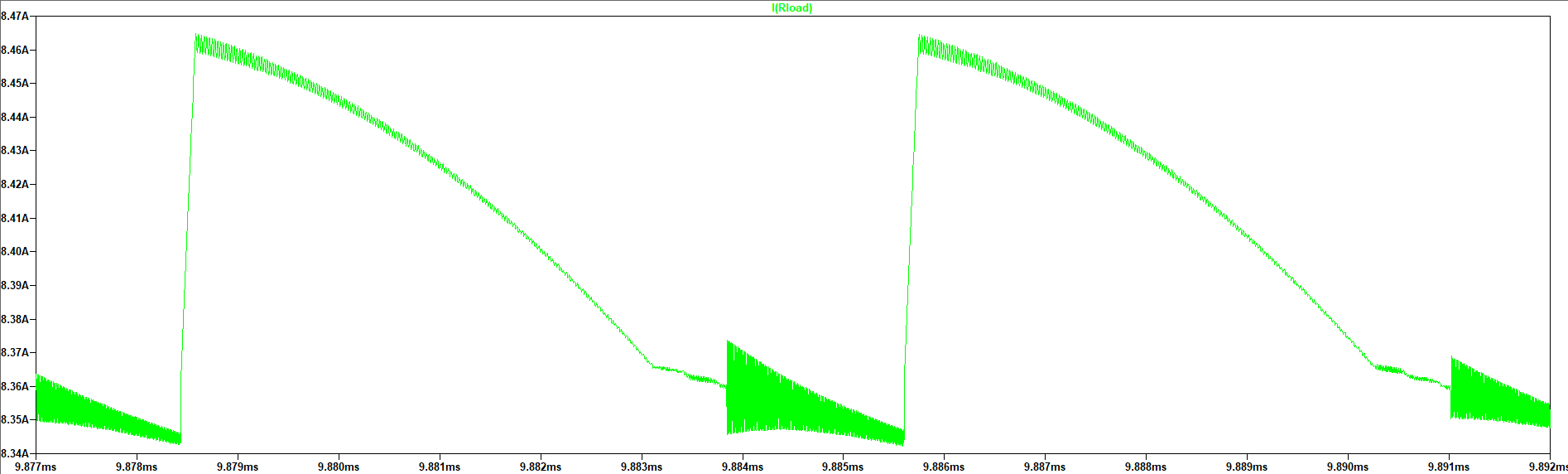


Figure 6: Output current close view waveform

In simulation tested load taken as fully resistive component and it is 1.44Ω so output current waveforms same as voltage and output power 101.7 W and it is little exceeding our rated power because voltage is little higher than 12V.

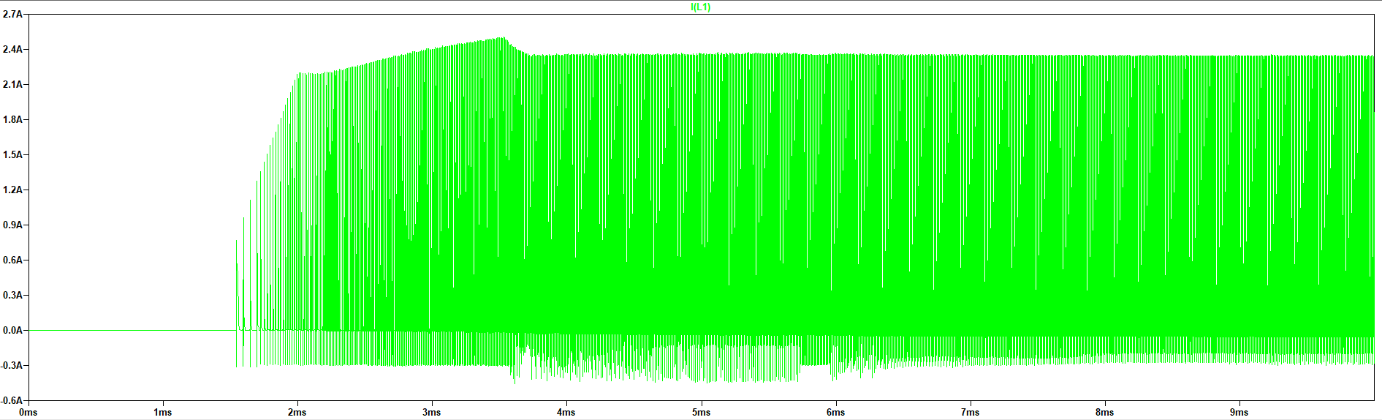


Figure 7: Primary inductor current waveform

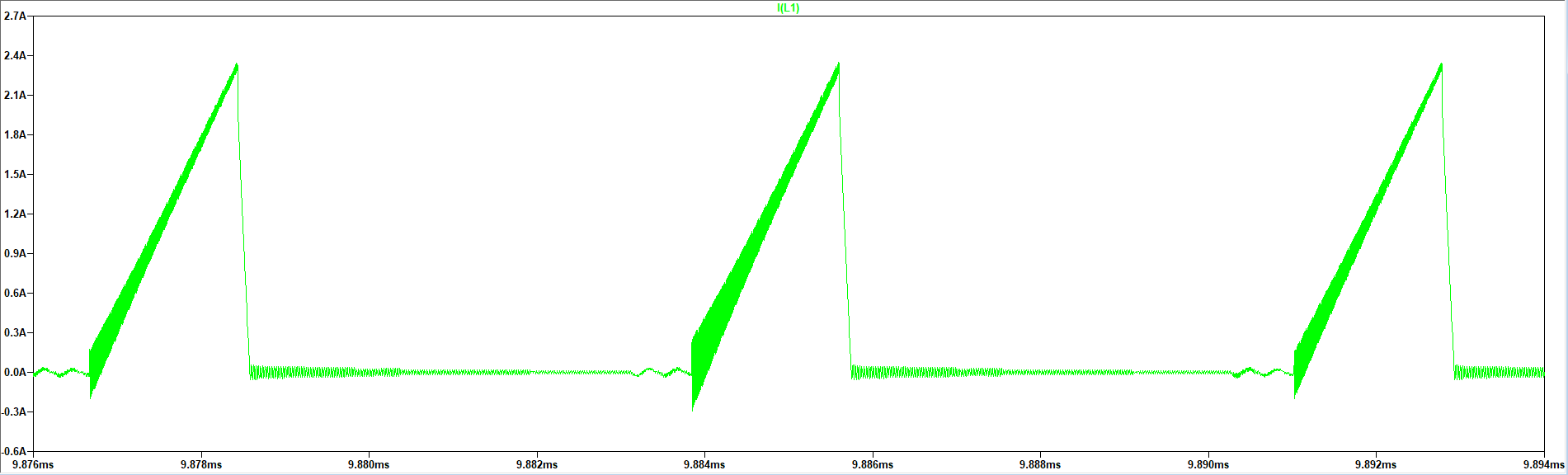


Figure 8: Primary inductor current close view waveform

When we look at the figure 7 its seen that initially current increase up to 2.5A then it is settled at 2.3A 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.

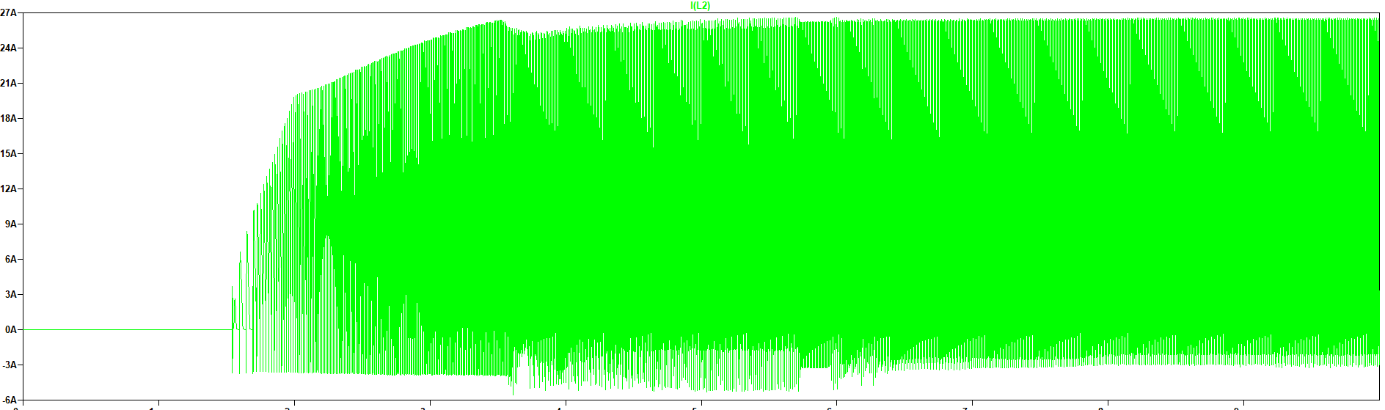


Figure 9: Secondary inductor current waveform

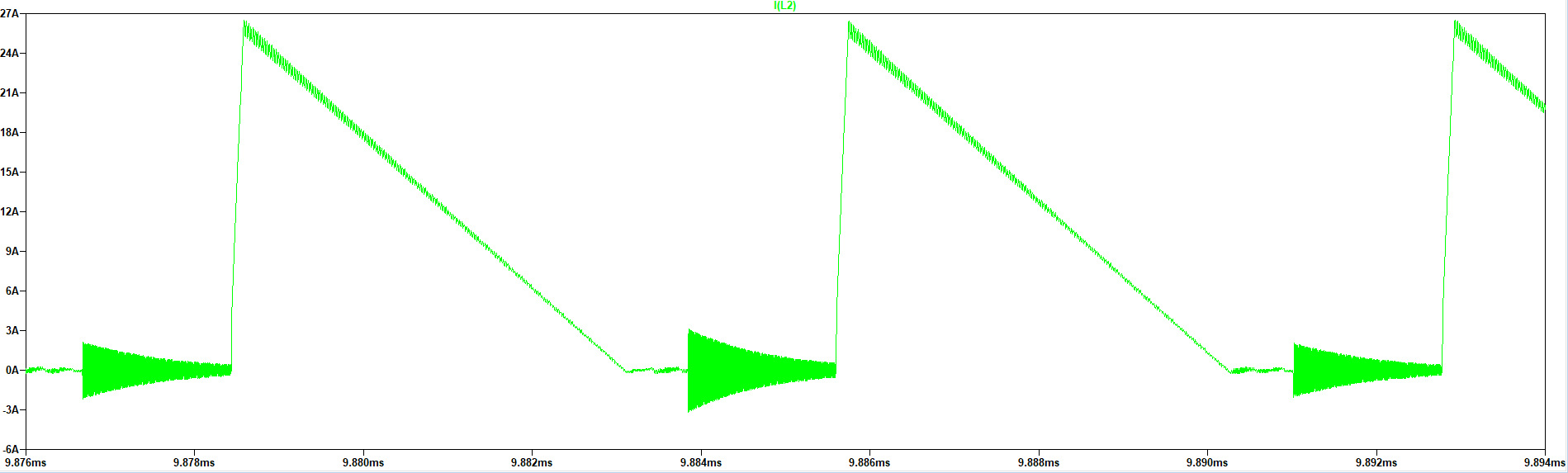


Figure 10: Secondary inductor current close view waveform

Secondary part of transformer has higher current density and its current reach 27 A since controller has soft start so its current does not increase much initially.

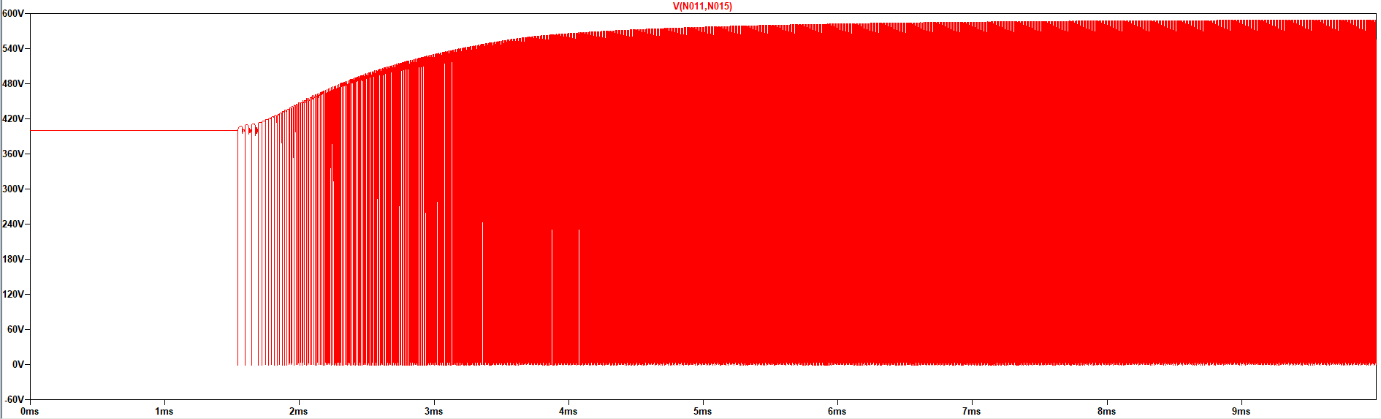


Figure 11: Mosfet voltage waveform

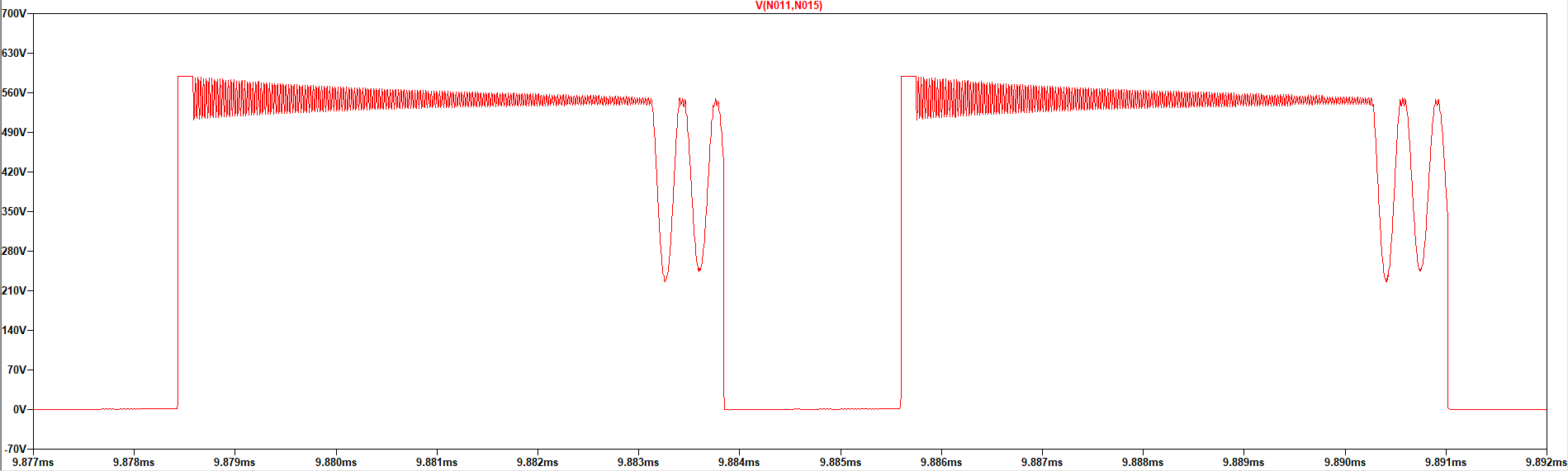


Figure 12: Mosfet voltage close view waveform

Selected mosfets breakdown voltage is 700 V and as seen in the figure 12 its voltage jumps to the 600V when it is turn of because of the leakage inductance. At Ddwell time its voltage oscillates. When looked at the figure 7 and 11 they’re in the our mosfets operation region.

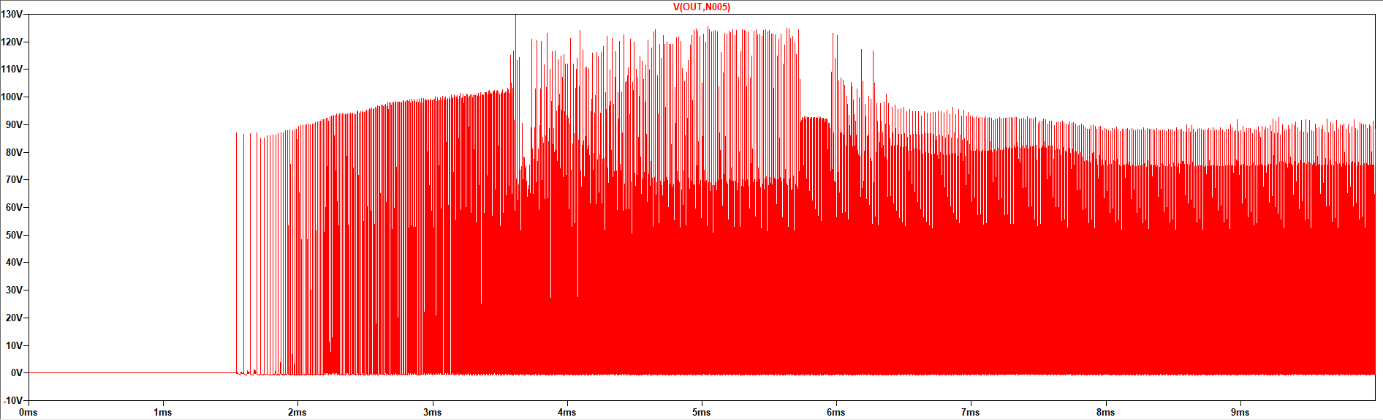


Figure 13: Diode voltage waveform

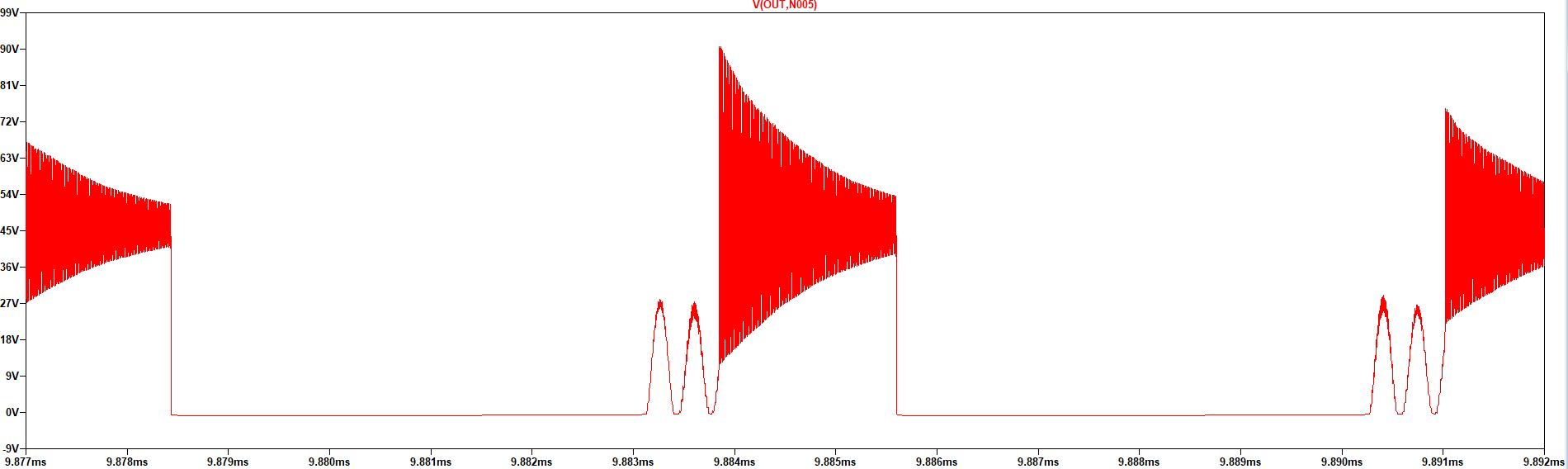


Figure 14: Diode voltage close view waveform

Selected diode breakdown voltage is 250 V and it can operate this voltage as seem in the figure 13 ratios. Diodes continuous current 40 A and as figure 9 shows secondary sides current reach 27 A and it is lower than continuous current .

# Power Losses

## Ferrite Core Transformer Power Losses

Ferrite Core 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.

|  |  |  |
| --- | --- | --- |
|  |  | [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.

|  |  |  |
| --- | --- | --- |
|  |  | [16] |

: AC flux density

|  |  |  |
| --- | --- | --- |
|  |  | [17] |

: Watts per kilogram

|  |  |  |
| --- | --- | --- |
|  |  | [18] |

: Core loss

|  |  |  |
| --- | --- | --- |
|  |  | [19] |

: Total power loss

## Iron Powder Core Transformer Power Losses

### Core Losses

It is deemed appropriate to calculate core losses of the iron powder core using the peak current of the primary side by the Equation …:

This core loss calculation gives a value for the material time, but it should be recalculated using the core dimensions as Equation … shows:

= the magnetic path length

= Cross sectional area of the core

### Copper Losses

Copper losses of the transformer design can be divided into two parts while on of them is DC losses, other one represents AC losses. Since the cable selection has been done considering the skin depth, the AC and DC resistances can be assumed to be almost the same.

= Resistance of the cable per meter

Therefore, the total loss of the transformer including core and copper losses considering the skin effect can be calculated as follows:

## Mosfet power Loss

According to the Equation [20] mosfet conduction loss is 0.0157W.

|  |  |  |
| --- | --- | --- |
|  |  | [20] |
|  |  |  |

According to the Equation [21] mosfet switching loss is 0.8285W.

|  |  |  |
| --- | --- | --- |
|  |  | [21] |
|  |  |  |

## Diode Loss

According to the Equation [22] diode conduction loss is 8.083W.

|  |  |  |
| --- | --- | --- |
|  |  | [22] |

According to the Equation [23] diode switching loss is 0.0032W

|  |  |  |
| --- | --- | --- |
|  |  | [23] |

## Snubber Loss

According to the Equation [24] snubber loss is 4 W.

|  |  |
| --- | --- |
|  | [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.

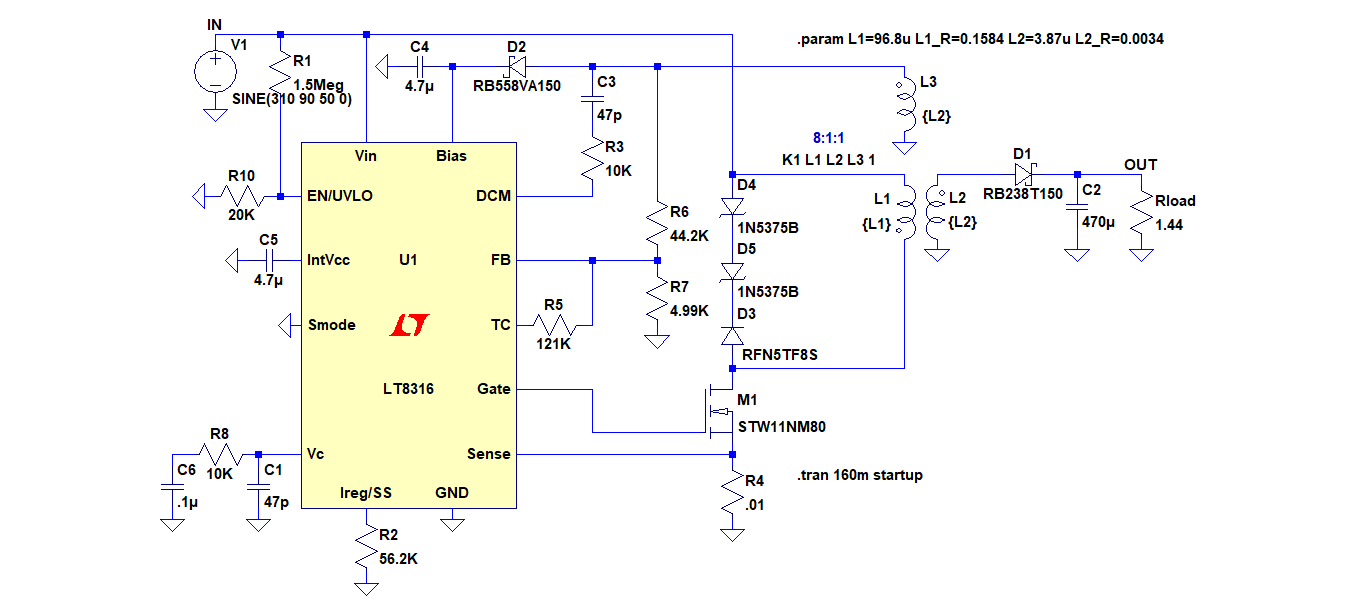


Figure 1. Circuit schematic

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.

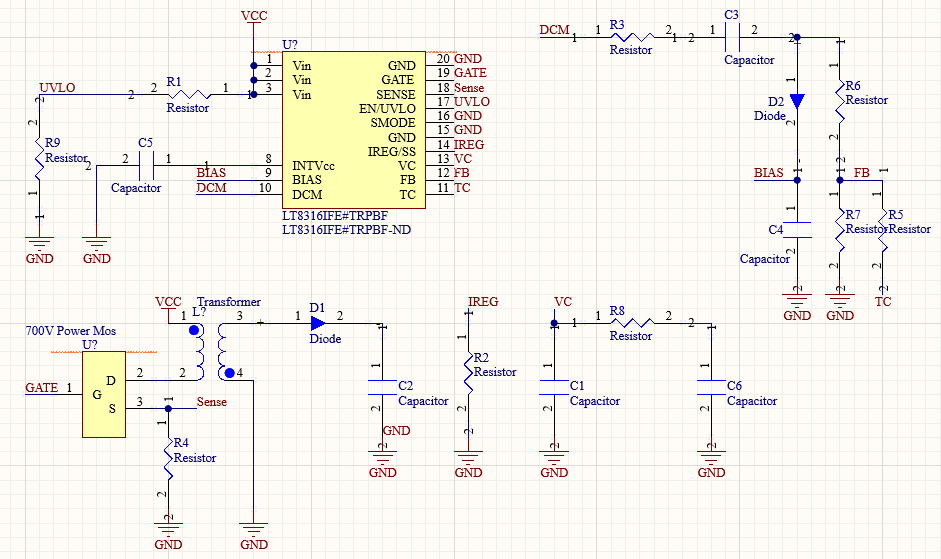


Figure 2. Schematic of the PCB

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.

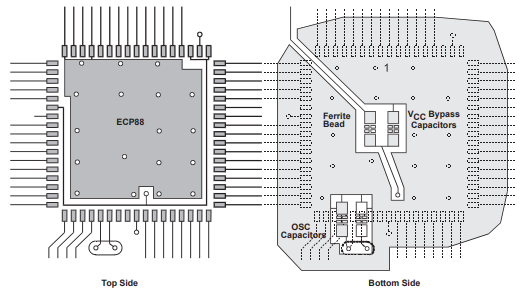


Figure 3. Controller Groung Example [1]

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.