DC/DC Voltage Regulator

Complete Design Report

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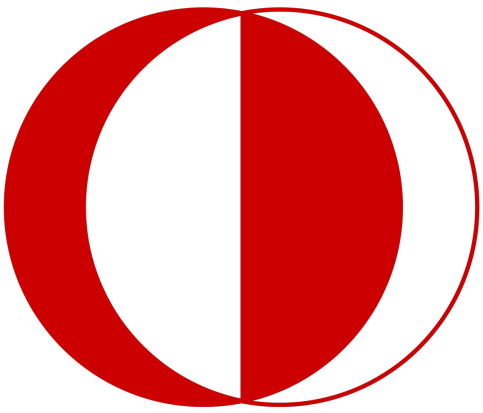
A report presented for the sake of
Humanity and Science



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1 Introduction

Switch mode power supplies are commonly used to DC/DC converter applications. Beside of voltage control, it provides galvanic isolations. In this project we used Forward Converter topology which is good choice when output need high current and power range is below 200W. In addition, UC3844 IC is examined and simulated in order to obtain constant output voltage with current control. This document aims to discuss component selections,cost and power estimation according to teoric and computational simulation results.

2 Forward Converter topology

Forward converter topology is derived from buck converter, at each cycle input transfer power to load side. To avoid saturation at core we choose to use reset windigs.Details are shown Figure 1.

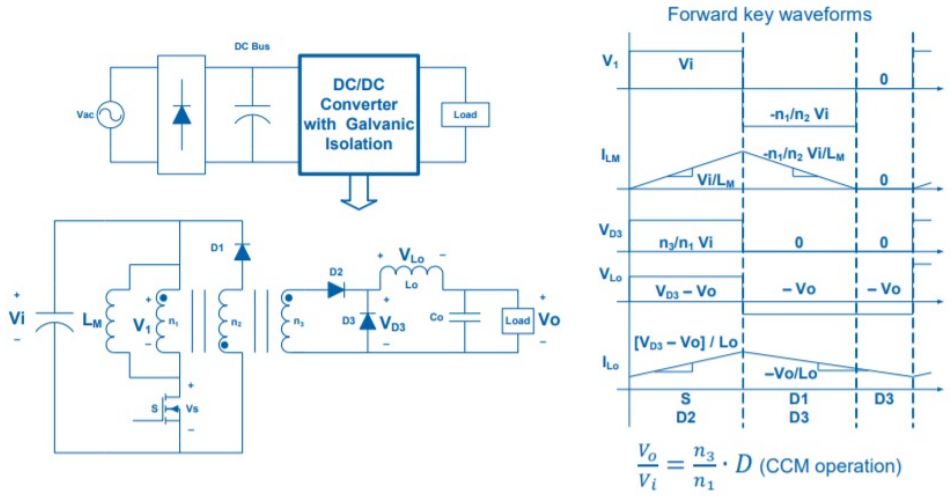

Figure 1: Diagram,schematic and basic waveforms for Forward converter with reset winding cited [5]

In this project, we had different design options as can be seen from Figure 2.

	Project No	FLY #1	FLY #2	FLY #3
FLYBACK	Minimum Input Voltage (V)	24	24	200 Vac
	Maximum Input Voltage (V)	48	48	240 Vac
	Output Voltage (V)	15	10	5
	Output Power (W)	60	60	60
	Output Volt. Peak-to-Peak Ripple (%)	4	4	5
	Line Regulation (%)	2	2	3
	Load Regulation (%)	2	2	3

FORWARD	Minimum Input Voltage (V)	24	24	200 Vac
	Maximum Input Voltage (V)	48	48	240 Vac
	Output Voltage (V)	15	10	5
	Output Power (W)	48	48	48
	Output Volt. Peak-to-Peak Ripple (%)	2	2	3
	Line Regulation (%)	2	2	3
	Load Regulation (%)	2	2	3

Figure 2: Different Design alternatives of the project

From these alternatives, Forward #1 option is selected. Although, Forward Converter has more components and it is more complex than Flyback Converter, it has some important advantages over Flyback converter such as:

- It has better transformer utilization. It transfers its energy instantly across the transformer and it does not need energy storage element in transformer. For that reason, transformer can be more ideal with higher magnetizing inductance and no air gap

- Output inductor and freewheeling diode ensure continuous output current and it causes less ripple at the output. Furthermore, since main energy storage element is inductor, output capacitor can be smaller than flyback.
- It has less voltage and current stresses on switching components because of larger magnetizing inductance.

Disadvantages of Forward Converter compared to Flyback:

- It is more expensive than flyback because of extra freewheeling diode and output inductor.
- It has minimum load requirements because gain changes a lot in DCM operations

3 Design Equations

The following specifications are design eqution for Forward Converter Design.

Minimum Input Voltage (V)	24
Maximum Input Voltage (V)	48
Output Voltage (V)	15
Output Power (W)	48
Output Volt. Peak-to-Peak Ripple (%)	2
Switching Frequency (fs)	100 kHz

Table 1: Design specifications

3.1 Transformer Considerations

First of all we should calculate turn ratio of transformer. For the sake of simplicity reset winding and primary winding ratio is same.

$$n_1 = n_3 \tag{1}$$

This equation limit max duty ratio to 50%, since core cant demagnetize faster than magnetizing time. Primary and secondary winding ratio can found when critical points are considered. When Input decreased minimum, Duty cycle reached max. ratio.At this point this converter should supply desired V_o.

$$V_o < v_i \frac{n_3}{n_1} D \quad \Longrightarrow \quad \frac{n_3}{n_1} > \frac{V_o}{V_i \cdot D} = 1.33 \implies 2 \tag{2}$$

When $V_o = 15V$ as specifications, extra voltage drop on D_2 around 1V.
$V_{o,max} = 16V$.
Minimum voltage is 24 V.
Maximum D is 50%.
At this point we choose R type material ferrite core (Code:0R45959EC). We selected since,R type core loss is less than P type core. According to this core turning factor can found from Lenz Rule,

$$V = n_1 \frac{d\phi}{dt} \implies V_{i,max} = \frac{n_1 \cdot B_{sat} \cdot A_e}{Dmax \cdot T_s} \tag{3}$$

$$\therefore n_1 > 2.18$$

$V_{i,max}$=48 V
D_{max}=0.5
B_{sat}=0.3
$A_e = 368mm^2$ taken from datasheet [3].

This is minimum turning ratio to avoid core saturation. To calculate max turn number we should calculate wire type to know wire size. At the worst scenario we have $V_{in,min} = 24V$. For primary winding,

$$I_{primary} = \frac{P_o}{V_{in,min}} = 2A \tag{4}$$

For secondary winding,

$$I_{secondary} = \frac{I_{primary}}{n} = 1A \tag{5}$$

Since this currents ratings are for ideal case, it is safer to choose higher rating wires.From AWG chart,for primary and reset windings can use AWG #16, Secondary AWG #18. Selection criteria is max current. Their properties are shown at table 2.

AWG	Area mmˆ2	Max. Current Amperes
AWG#16	1.31	3.7
AWG#18	0.823	2.3

Table 2: Wire properties

Core window area is calculated from datasheet.Also geometry parameters are taken from datasheet [3].

$$A_w = (E - F) \cdot D = 510mm^2 \tag{6}$$

Since area of wires are known max turn can be calculate by,

$$N_{max} = \frac{k_{fill} \cdot A_w}{A_{pri} + n \cdot A_{sec} + A_{reset}} = 71.73 \tag{7}$$

Note that fill factor is 0.3 for litz wire.Increasıng turn is good because flux density decreasing and core loss decreasing according to Steinmetz equation, but increased turn also increase resistance of wire and copper loss increased. Core loss equation,

$$P_{fe} = K_{fe}(B_{peak})^{\beta} A_c l_m \tag{8}$$

P_{fe} at 100kHz,100mT given $85mW/cm^3$
P_{fe} at 100kHz,200mT given $550mW/cm^3$
By using these values steinmetz parameters calculated as,

$$\therefore \beta = 2.7 \quad , K_{fe} = 42$$

Core loss is simply $I^2 R_{ac}$ but wires new resistance should be calcualted by skin effect.Since skin depth decrease wire area new resistance calculated by,

$$R_{ac} = \frac{n \cdot MLT \cdot \rho}{Area} \tag{9}$$

To find optimum turn number loss calculated at matlab script which provided at github repo.

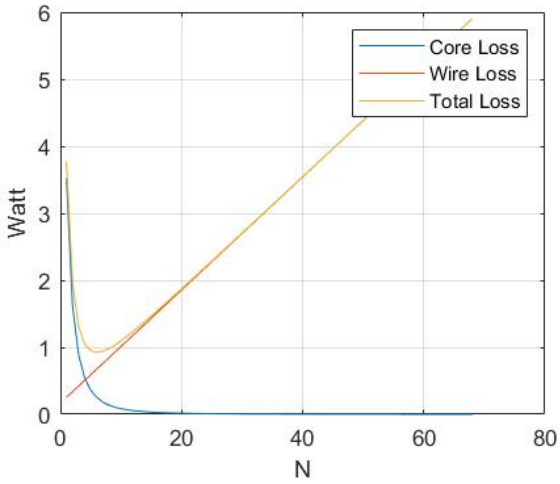

Figure 3: According to number of turn Total loss calculated

It is better to select turn ratio 8 which Total loss is 1 Watt. At this number $R_{pri} = R_{reset} = 0.05k\Omega$, $R_{sec} = 0.06k\Omega$.
By using AL number windings inductance found and,

$$X_m = k \cdot \sqrt{X_1 \cdot (X_2 + X_3)} = 1060\mu H \tag{10}$$

Since reset and secondary windings direction same they summed. Also from Steinmetz eqn. R_m can found.Where applied voltage is 48 V.

$$P_{fe} = 0.1375Watt \implies R_m = \frac{V^2}{P_{fe}} = 16.7k\Omega \tag{11}$$

3.2 MOSFET Considerations

Since when switch is off, reset windig decharge core, beside of input voltage additional voltage seen on mosfet.

$$V_s = V_i + \frac{n_1}{n_2} \cdot V_i = 96V \tag{12}$$

For the worst case, selected $V_i = 48V$. To be stay at the safe side lets make it 150V.

$$I_i = \frac{P_i}{V_i} = 2.22A \tag{13}$$

To be safe side minimum current of mosfet should be 5 A. We selected to use IRFB4127PbF [2], its voltage is 200V and $R_{on} = 20m\Omega$.
According to datasheet turn on and turn off time is totally 120ns.This much smaller than switching t_off and t_off.

$$P_{cond} = I_{rms}^2 \cdot R_{on} = 0.27W \tag{14}$$

$$P_{switching} = \frac{1}{2} \cdot V_{off} I_{rms} (t_r + t_f) f_s = 1.55W \tag{15}$$

Lets use heatsink,Model No. :529802B02500G. Its Rca=3.7C/W. MOSFET Rth is 0.52.Assume enviroment temperature is 30C. Thus,

$$T_j = C_{normal} + P_{total} \cdot (R_{JC} + R_{CS} + R_{JA}) = 38.37Celcius. \tag{16}$$

3.3 Output Inductor Considerations

Since %2 voltage ripple, current change is $I_{ripple} = 0.02 \cdot \frac{P_o}{V_o} = 0.064A$Assume we apply 48 V input, and capacitor is big enough to constat output,

$$V_L = L\frac{di}{dt} \implies nV_i - V_o = L\frac{I_{ripple}}{DT_s} = 130\mu H \tag{17}$$

$$\therefore L > 130\mu H$$

We considered ripple voltage limit in our simulations and we chose 470 µH inductor according to our simulations. In addition, previous 10 A current rating selection must be valid for inductor. Therefore, we picked an inductor with 10 A maximum DC current and 470 µH inductance which is "AGP4233-474ME" inductor from Coilcraft. It has also 11.5 m maximum DC resistance and we used that value in our simulations. Since inductors has nonideal series resistance values, there are power losses of these resistance values also. AGP4233-474ME inductor has 11.5 m resistance and it has 3.2 A current. Therefore, power losses on inductor can be calculated as follows:

$$P_{inductor} = I^2 \cdot R = 3.2^2 \cdot 11.5 \cdot 10^{-3} = 0.1W \tag{18}$$

3.4 Capacitor Considerations

When $V_in = 48V$, D=0.156,

$$\Delta V = V_{ripple} = \frac{V_o}{50} = 0.3V \tag{19}$$

$$\Delta Q = C\Delta V \tag{20}$$

$$I_o DT_s = CV_{ripple} \tag{21}$$

$$\therefore C > 16\mu F$$

Because of ripple voltage limit, we chose 150 µF capacitor. In addition, we select voltage rating of capacitor as 50 V because of safety limit and possibility of voltage oscillation in case of soft start does not working. Therefore, we picked "860080675012" capacitor from Würth Elektronik [4].From datasheet impedance at 100kHz is 0.068Ω.

$$impedance = ESR + \frac{1}{jwC} \implies ESR = 0.05\Omega \tag{22}$$

3.5 Diode Considerations

As can be seen from Figures 4, there are 100 Volts when diodes are OFF and there are 3.2 A current when they are ON. Therefore, because of safety margin and high current possibility at the starting we chose 200 V and 10 A ratings for diodes. Hence, we picked "DPG10I200PM" [1] fast recovery diodes. For diodes another important parameter is reverse recovery time and this diode has 35 ns which is enough for 100 kHz frequency applications.

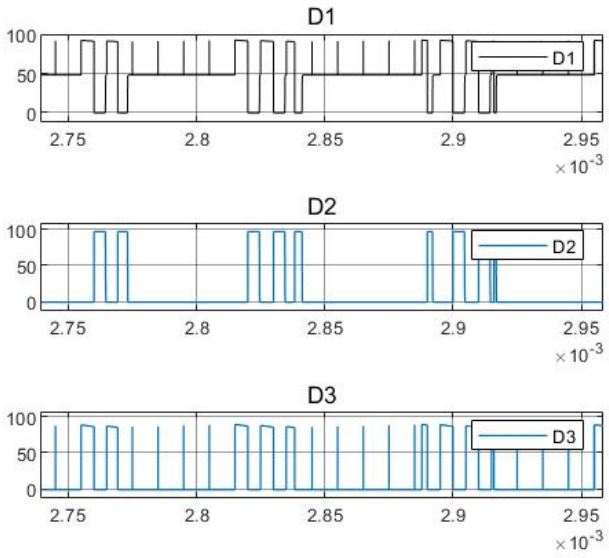

Figure 4: Diodes

Output diodes has 0.98 V voltage drop and at steady state their current will be 3,2 A. When one diode is ON the other diode is OFF at the output. Therefore, we can calculate conduction losses by simply multiply voltage drop and forward current.

$$P_{conduction} = V_f I_f = 0.98V \cdot 32A = 3.13W \tag{23}$$

For calculating switching losses of diodes, reverse recovery charge, blocking voltage and switching frequency is needed. From Figure 5, we can estimate our reverse recovery charge as 0.1 µC. Blocking voltage is 100 V from simulations and switching frequency is 100 kHz.

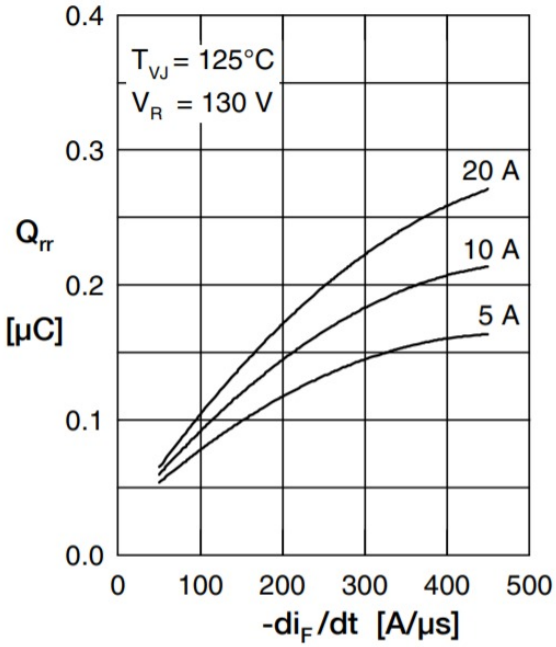

Figure 5: Reverse recovery charge values of DPG10I200PM

From these values, switching losses of two diodes can be calculated as follows:

$$P_{switching} = Q_R V_R f_s = 2 \cdot 0.1 \cdot 10^{-}6 \cdot 100V \cdot 100kHz = 2W \tag{24}$$

We used same heatsink that we use at mosfet

$$T_j = C_{normal} + P_{total} \cdot (R_{JC} + R_{CS} + R_{JA}) = 73Celcius. \tag{25}$$

4 Input to Output TF

To derive TF, first I will find small signal circuit equivalent. Forward converter can be treated as a buck converter with $V_{in} = n \cdot V_{in}$ where n is transformer ratio.

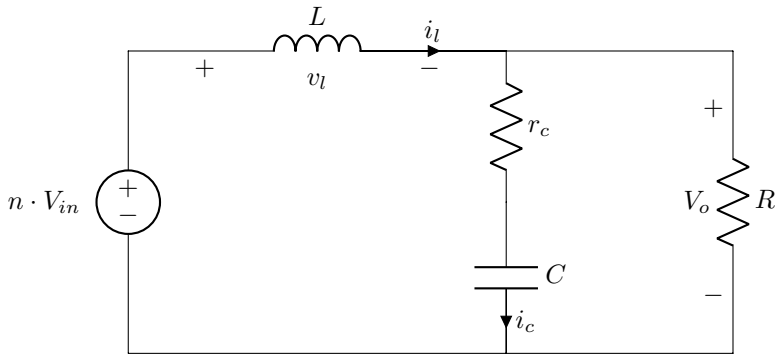

Figure 6: Simplified Forward Converter when switch is on

KVL at the outer path,

$$-nV_{in} + L\frac{di}{dt} + i_o R = 0 \tag{26}$$

Since,

$$i_o = i_l - i_c \tag{27}$$

$$L\frac{di}{dt} = nV_{in} - Ri_l + Ri_c \tag{28}$$

Find i_c by KVL on inductor and capacitor

$$-nV_{in} + L\frac{di}{dt} + i_c r_c + V_c = 0 \tag{29}$$

$$i_c = \frac{nV_{in} - L\frac{di}{dt} - V_c}{r_c} \tag{30}$$

Insert i_c into equation 3,

$$\hat{i}_l = \frac{di}{dt} = \frac{nV_{in}}{L} - \frac{r_c R}{(r_c + R)L}\frac{R}{(r_c + R)L}V_c \tag{31}$$

We know that $R >> r_c$ so we can simplify equation as,

$$\hat{i}_l = \frac{nV_{in}}{L} - \frac{r_c}{L}i_l - \frac{1}{L}v_c \tag{32}$$

Start derive V_c by KCL at output node,

$$i_c = i_l - \frac{V_o}{R} \tag{33}$$

Since,

$$v_o = v_c + r_c i_c \tag{34}$$

$$i_c = \frac{R}{R + r_c} i_l - \frac{1}{R + r_c} v_l \tag{35}$$

Since,

$$\hat{v}_c = \frac{i_c}{C} \tag{36}$$

$$\hat{v}_c = \frac{R}{C(R + r_c)} i_l - \frac{1}{C(R + r_c)} v_l \tag{37}$$

We know that $R >> r_c$ so we can simplify equation as,

$$\hat{V}_c = \frac{1}{C} i_l - \frac{1}{RC} v_l \tag{38}$$

According to state space equations,

$$\begin{bmatrix} \hat{i}_l \\ \hat{v}_c \end{bmatrix} = \begin{bmatrix} -\frac{r_c}{L} & -\frac{1}{v_c} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_l \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{n}{L} \\ 0 \end{bmatrix} V_{in} \tag{39}$$

For switch off position A matrix hasn't changed.But B matrix multiplied with duty ratio so,

$$\begin{bmatrix} \hat{i}_l \\ \hat{v}_c \end{bmatrix} = \begin{bmatrix} -\frac{r_c}{L} & -\frac{1}{v_c} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_l \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{dn}{L} \\ 0 \end{bmatrix} V_{in} \tag{40}$$

Find v_o as state space variables,

$$v_o = v_c + r_c i_c \tag{41}$$

Since,

$$i_c = i_l - \frac{v - o}{R} \tag{42}$$

$$v_o = v_c + r_c i_l - \frac{v_o r_c}{R} \tag{43}$$

$$v_o = \frac{r_c R}{r_c + R} i_l + \frac{R}{(r_c + R)} v_c \tag{44}$$

Since $r_c << 1$,

$$v_o = r_c i_l + v_c \tag{45}$$

$$C = \begin{bmatrix} r_c \\ 1 \end{bmatrix} \tag{46}$$

$$\frac{v_o(s)}{d(s)} = C^T [SI - A]^{-1} B V_{in} \tag{47}$$

After a lengthy evaluation control to output TF is,

$$G_{vd} = \frac{\widetilde{v_o}}{\widetilde{d}}\bigg|_{\widetilde{v_i}=0} = \frac{nV_{in}}{LC} \left[\frac{sr_c C + 1}{s^2 + s(\frac{r_c}{L} + \frac{1}{RC}) + \frac{1}{LC}} \right] \tag{48}$$

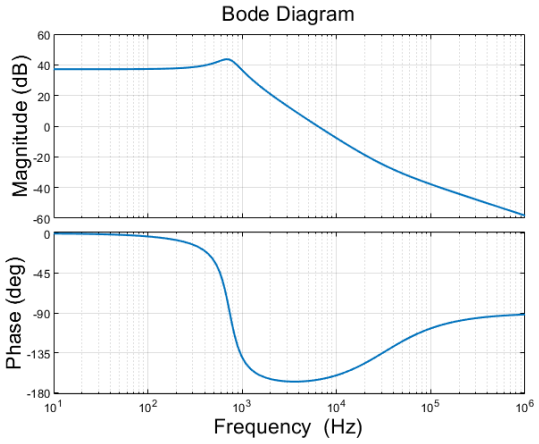

Figure 7: Bode plot of control to output TF

According to [**erickson**] Crossover Frequency is defined as the frequency where the magnitude of loop gain is unity.Limit for f_c is pole frequency since we want to operate unity gain at f_c.For power application switching frequency selected as one in ten or five.For this application I select as,

$$f_c = \frac{f_{sw}}{5} = 20kHz \tag{49}$$

Since $f_{ESR} = 32kHz$ and $f_{LC} = f734Hz$,

$$f_{LC} < f_c < f_{ESR} < f_{sw}/2 \tag{50}$$

Compensator Type	Relative location of the crossover and power-stage frequencies	Typical Output Capacitor
Type II (PI)	$F_{LC} < F_{ESR} < F_0 < F_S/2$	Electrolytic, POS-Cap, SP-Cap
Type III-A (PID)	$F_{LC} < F_0 < F_{ESR} < F_S/2$	POS-Cap, SP-Cap
Type III-B (PID)	$F_{LC} < F_0 < F_S/2 < F_{ESR}$	Ceramic

Figure 8: Compensator Selection table

According to table 8 I select Type 3-A compensator for this application.Type 3 compensator supplies phase boost for this converter to operate stable region.

5 Compensator Parameters

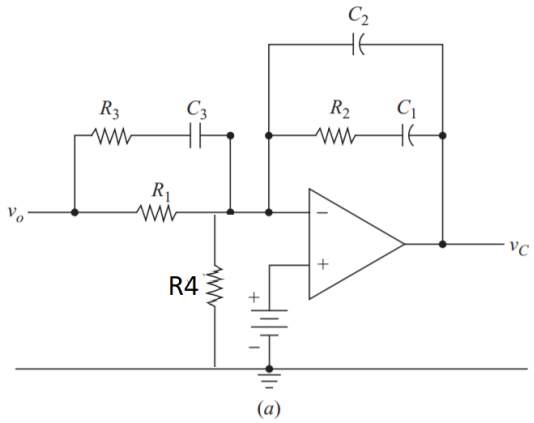

Figure 9: Type 3 Compensator

This compensator is referred from [**erickson**] book except one extension.R_4 added to adjust input voltage range. When $f_c = 20kHz$, from bode plot phase angle is -146 and gain is -20 db. $V_{ref} = 3V$, which corresponds -9.5db.

$$|G(jw_o)| = 29.5dB = 29.5Gain \tag{51}$$

$$\theta_{comp} = \theta_{phase-margin} - \theta_{converter} = 45 - (-146) = 191 \tag{52}$$

$$K = tan\Big(\frac{191+90}{2}\Big)^2 = 7.75 \tag{53}$$

$$R_2 = \frac{|G(j\omega_{co})|R_1}{\sqrt{K}}$$
$$C_1 = \frac{\sqrt{K}}{\omega_{co}R_2} = \frac{\sqrt{K}}{2\pi f_{co}R_2}$$
$$C_2 = \frac{1}{\omega_{co}R_2\sqrt{K}} = \frac{1}{2\pi f_{co}R_2\sqrt{K}}$$
$$C_3 = \frac{\sqrt{K}}{\omega_{co}R_1} = \frac{\sqrt{K}}{2\pi f_{co}R_1}$$
$$R_3 = \frac{1}{\omega_{co}\sqrt{K}C_3} = \frac{1}{2\pi f_{co}\sqrt{K}C_3}$$

Figure 10: Type 3 Compensator equations

To start lets choose $R_1 = 1k\Omega$, Afterwards by using formulas at figure 5, other parameters found as,

$$R_2 = 10.77k\Omega \quad , \quad C_1 = 2nF \quad , \quad C_2 = 0.26nF \quad , \quad C_3 = 22nF \quad , \quad R_3 = 130\Omega \tag{54}$$

It is suitable to measure output voltage with $\frac{v_o}{3}$,

$$v_{ref} = \frac{v_o}{3}\frac{R_4}{R_4+R_1} \implies R_4 = \frac{v_{ref}R_1}{\frac{v_o}{3} - v_{ref}} = 1.5k\Omega \tag{55}$$

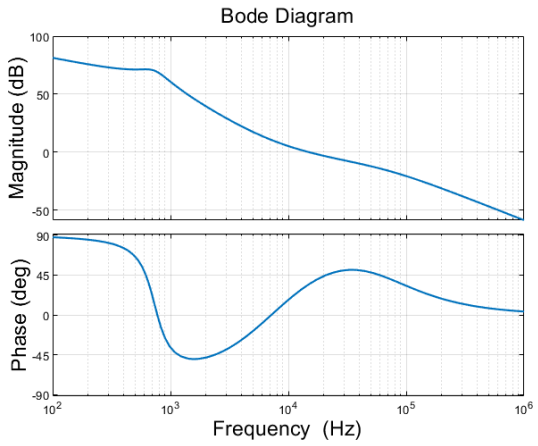

Figure 11: Bode plot of converter with compensator

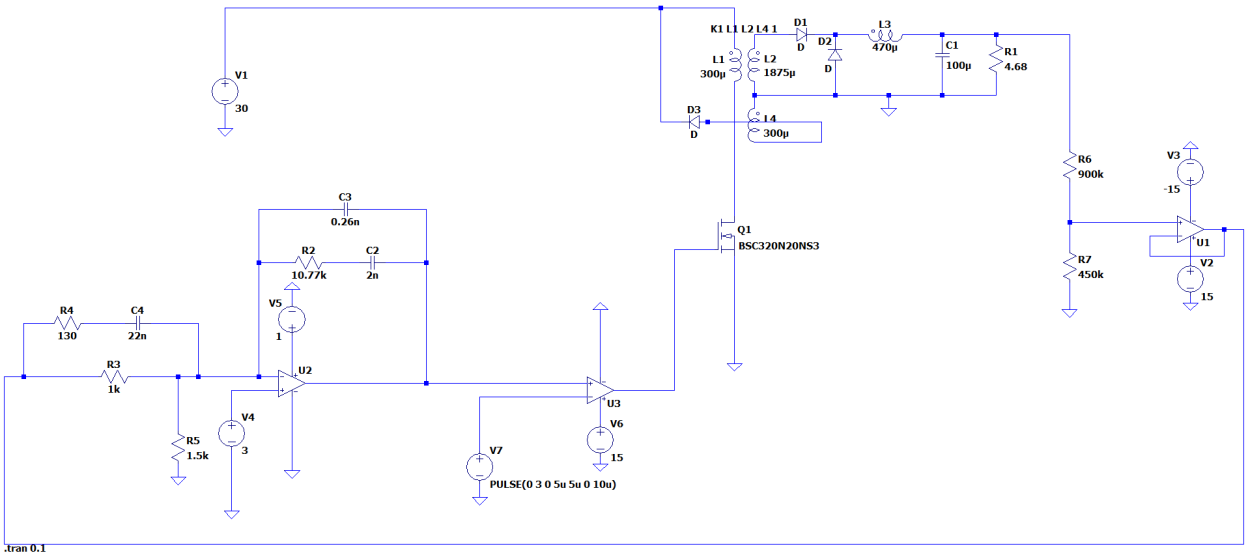

Figure 12: LTspice circuit with compensator design

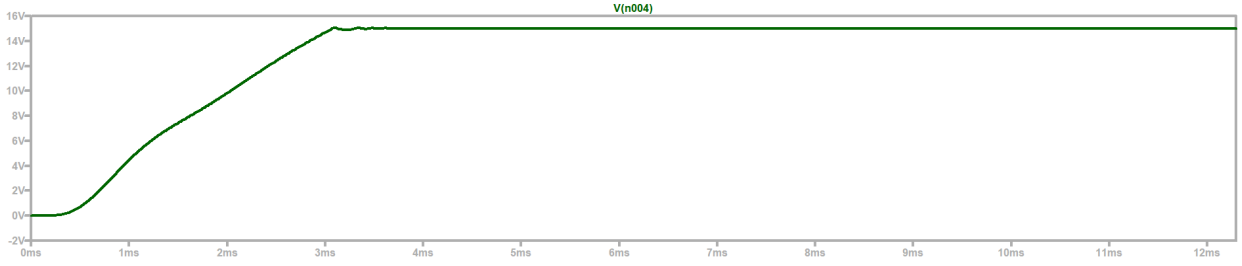

Figure 13: Output voltage of Forward converter with compensator

6 Current Mode Controller

We select LT3758 current mode controller for this application.According to datasheet output voltage formula determined by feedback loop,

$$V_o = 1.6 \cdot \left(1 + \frac{R2}{R1}\right) \tag{56}$$

To have 15V resistor selected as,

$$R1 = 10k\Omega \quad , \quad R2 = 83.75k\Omega \tag{57}$$

Sense pin is directly fed from to source of mosfet.R_{sense} used at the source of mosfet.According to datasheet

$$R_{sense} = \frac{80mV}{I_{l-peak}} = 0.01\Omega \tag{58}$$

Since operating frequency is 100kHz, according to datasheet $140k\Omega$ fasten to RT pin. Also error amplifier used in this controller. At the datasheet they suggest to use typical application parametes at the datasheet.

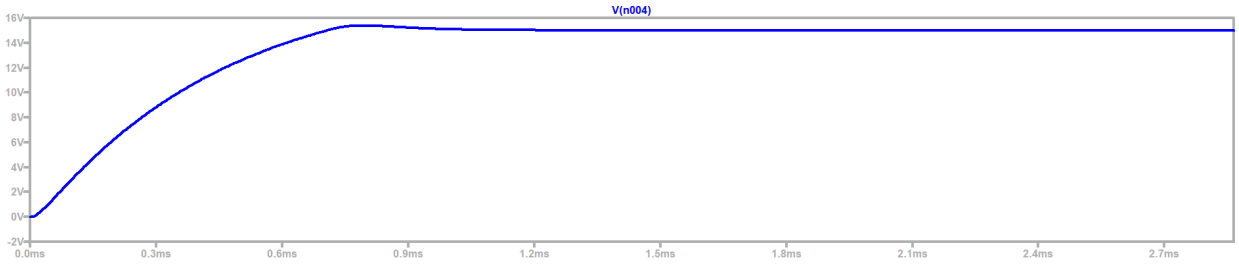

Figure 14: Output Voltage with current mode controller

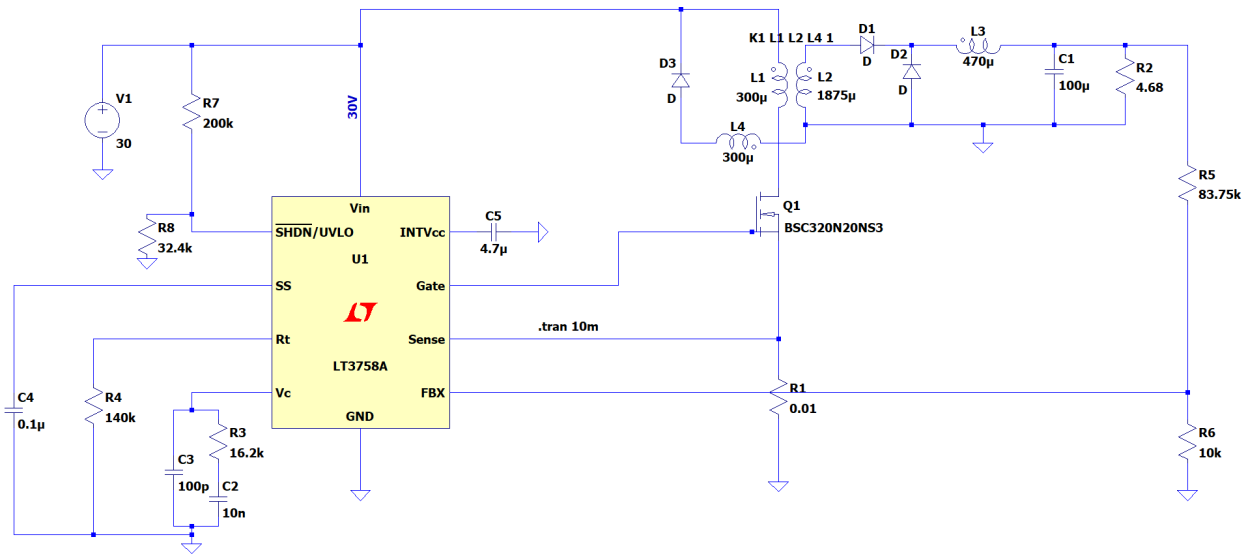

Figure 15: Circuit with current mode controller

Current mode controller is advantageous when compare with voltage control compensator. It is important that settling time of current mode controller is 5 times better than voltage control.Also steady state ripple decreases.

7 Efficiency and Thermal Analysis

7.1 Thermal Circuit Simulation

Thermal analysis checked by calculations before. In this section we will prove that simulation tools also gives close result with calculations.

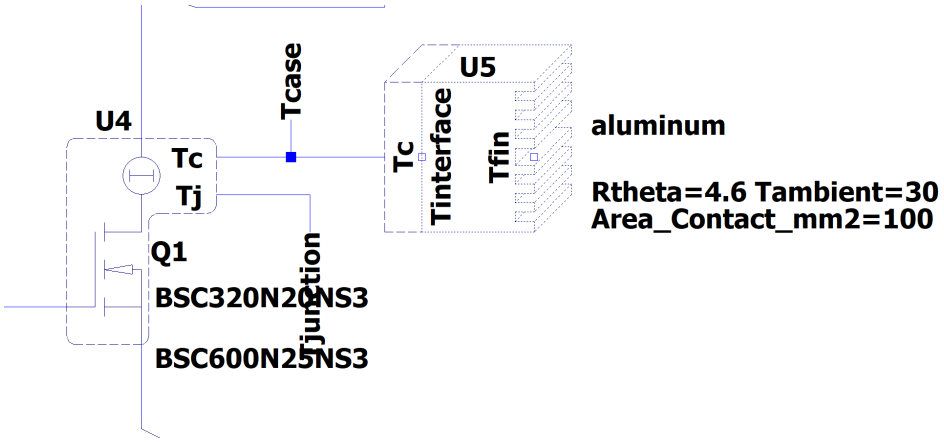

Figure 16: Thermal analysis simulation design

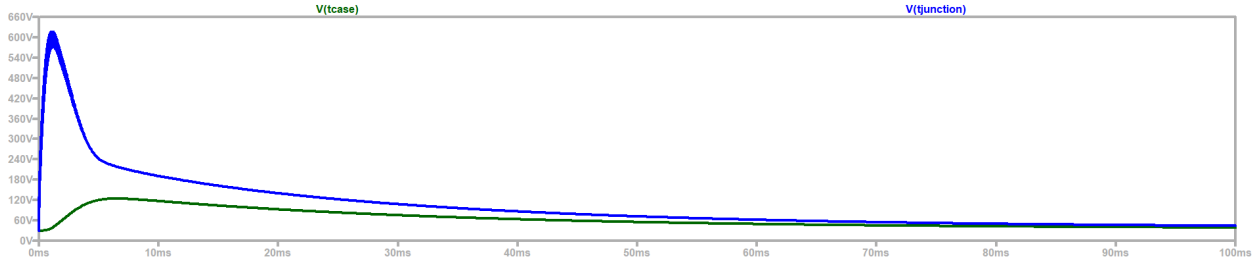

Figure 17: Junction and case temperatures when voltage compensator used

Figure 12 shows that FET temperature is saturated at 40 Celcius if ambient is 30 celcius.It is expected since we calculated analytically 38 Celcius.

7.2 Efficiency Simulation

As calculated analytically at design equations,

$$P_{total,loss} = P_{transformer} + P_{mosfet} + 2 \cdot P_{diode} + P_{inductor} = 13.1W \tag{59}$$

$$eff = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{48W}{48W + 13.1W} = \%78 \tag{60}$$

We construct a forward converter at simulink environment with current mode controller.Efficiency of circuit with all nonidealities calculated at that simulink program. You can find it in github repository under simulation results.According to that simulation efficiency calculated as %73. This is close to our analytical result.

8 Complete simulation in Simulink

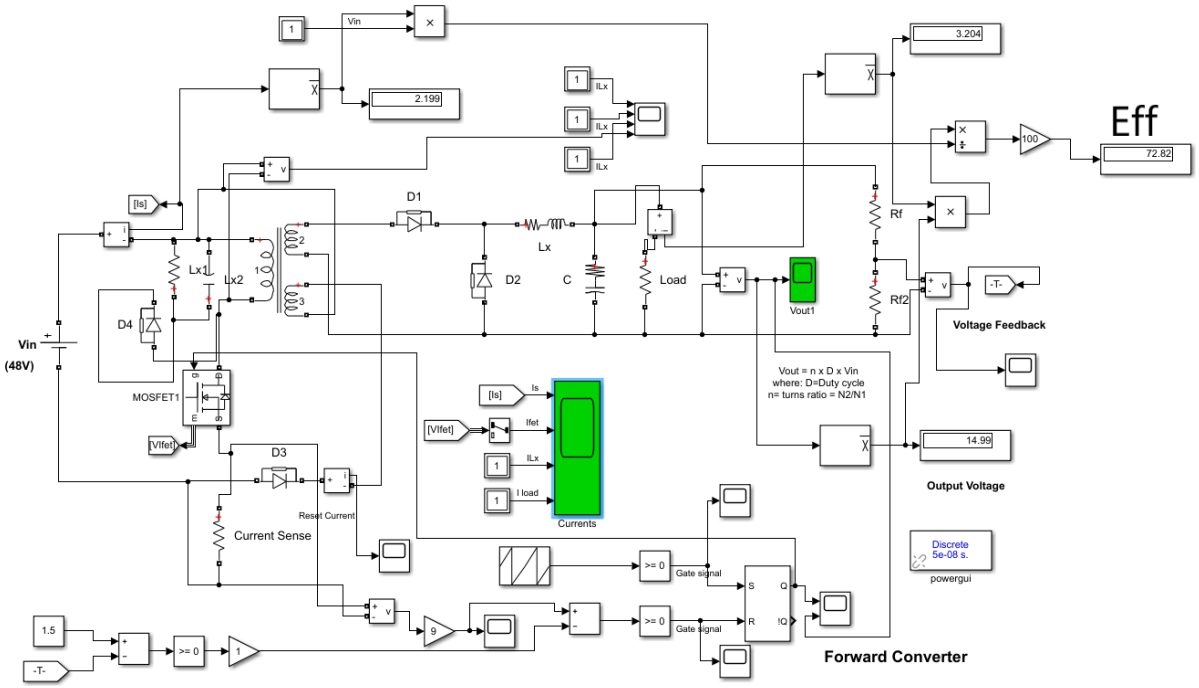

Figure 18: Simulink simulation with calculated efficiency

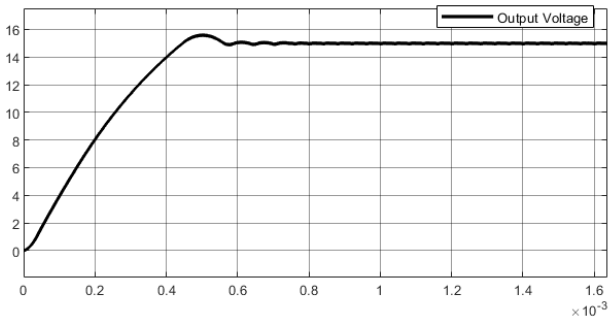

Figure 19: Output of Forward converter with current mode controller

9 PCB Design

PCB design is one of the most important part of this project. Because it is more professional design tool than stripboard implementation and its easy to implement for designed circuit. Firstly, circuit schematic of whole design has been drawn in KiCad. Whole circuit schematic can be seen from Figure 1.

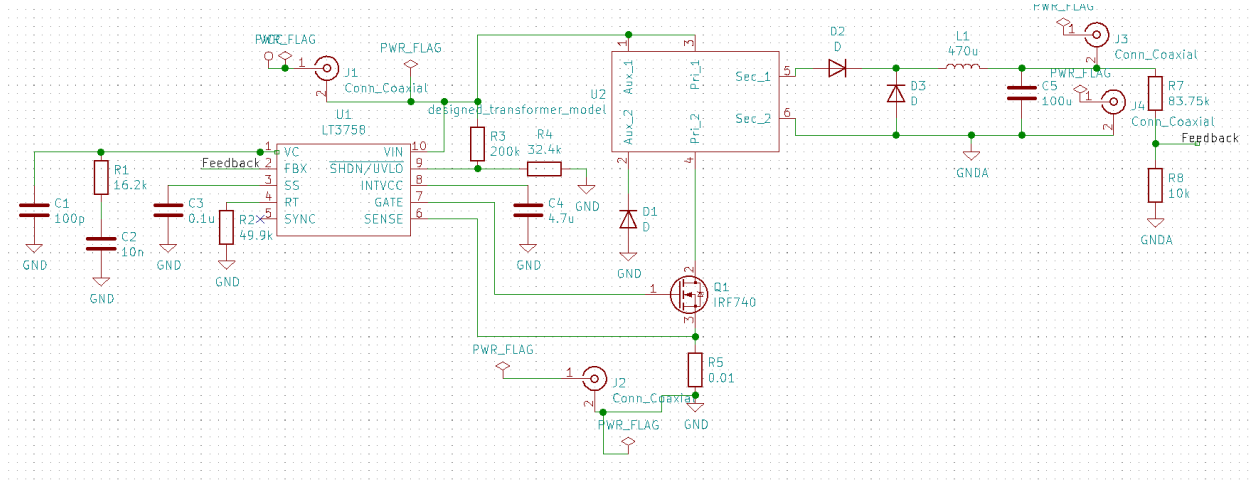

Figure 20: Circuit Schematic of Designed Circuit

In this schematic, controller, passive components, diodes, transistors and designed transformer is shown. Symbol of designed transformer is created by us because there is no proper symbol for a transformer with two main and one auxiliary winding. Transformer symbol has four input and two output. After completing circuit schematic, next task is arranging proper footprints to all components. Most of the components has their own footprints on KiCad, but some of them has no footprints of their own. Therefore, proper footprints have been drawn in KiCad, according to their packages. For example, footprints of transformer and output inductor has been drawn by us and matched their own schematic symbols. Then, next task is creating PCB layout. Connections between components were completed according to their footprints. Created PCB layout can be seen from Figure 2.

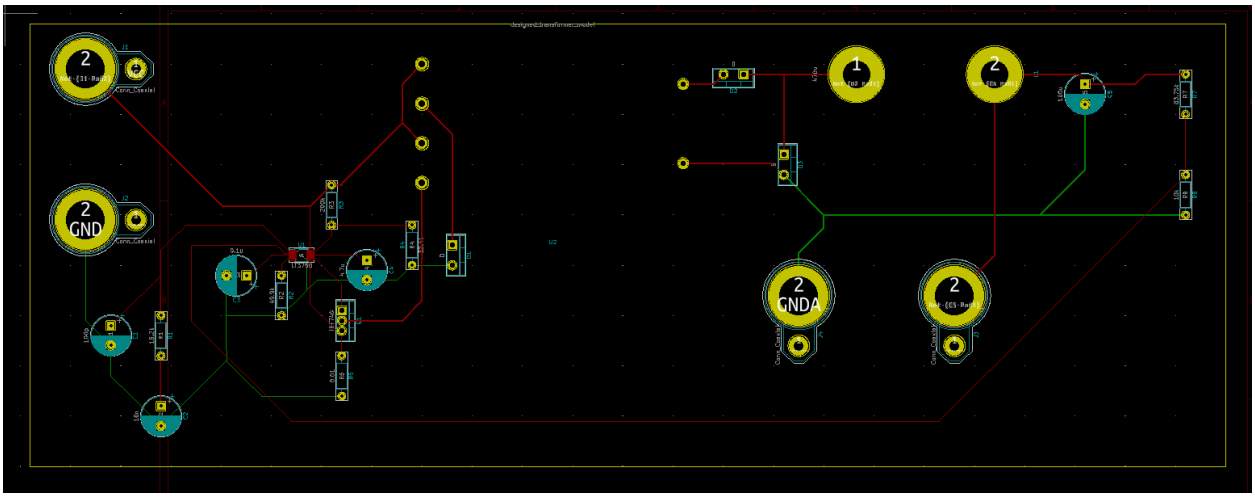

Figure 21: PCB Layout of the Circuit Schematic (without ground pads)

Widths of connections has been arranged according to current and power ratings of the components. There are use conventions for copper thicknesses and widths. We used below conventions to arrange widths of traces.

- **Determine the maximum current flow for the trace, I (A).**

  Current can be determined from either of the following equations:

  $I = V2/R$ or $I = P/V$ or $I = \sqrt{(P/R)}$

- **Determine the expected temperature rise, T (°C).**

  This should be known or estimable from circuit operation design.

- **Determine the trace cross-sectional area, A (mils2).**

  Use curve fitting constants, k, b and c, to approximate the IPC-2152 curve that relates area to current carrying capacity.

- For internal layers: k = 0.024, b = 0.44, c = 0.725
- For external layers: k = 0.048, b = 0.44, c = 0.725

  $A = (I/(k \times Tb))1/c$

- **Determine the trace width, w (mils).**

  This should be set.

- **Determine the PCB copper thickness, Δ (mils).**

  $\Delta = A/w$

Figure 22: Conventions that we follow

After completing PCB layout; 3D image, gerber files to manufacturing and bill of materials (BOM) of designed PCB is obtained by using KiCad tools. 3D images can be seen from Figures 21

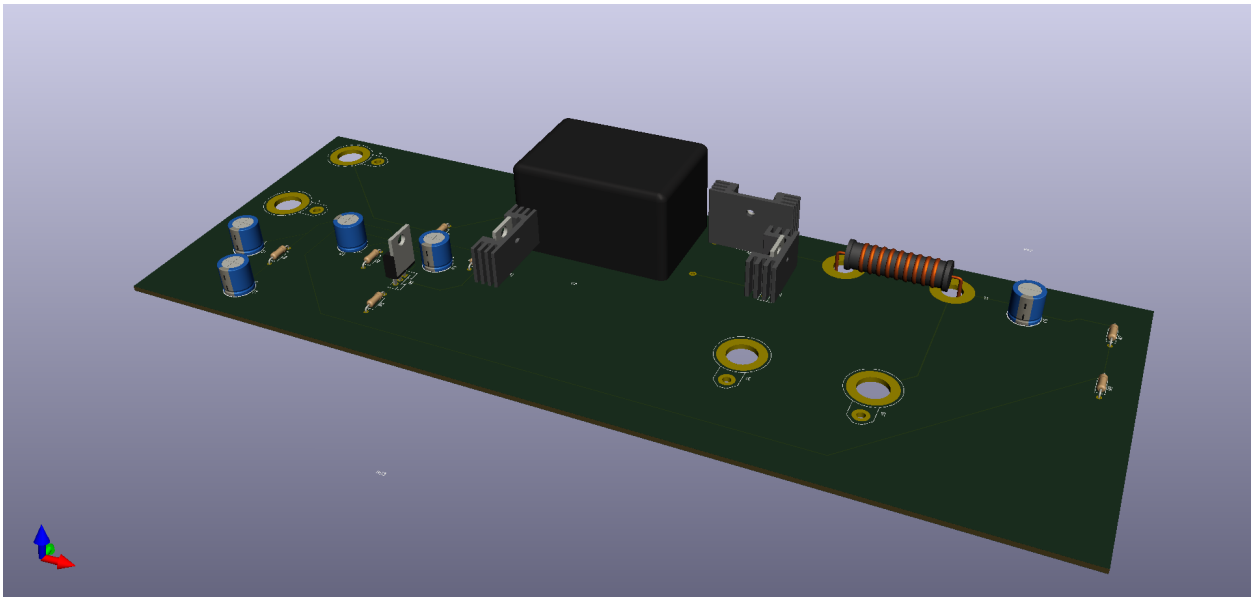

Figure 23: 3d view of PCB

You can find BOM file at the github repository. We also order 1000 piceses of pcbs from pcbway.

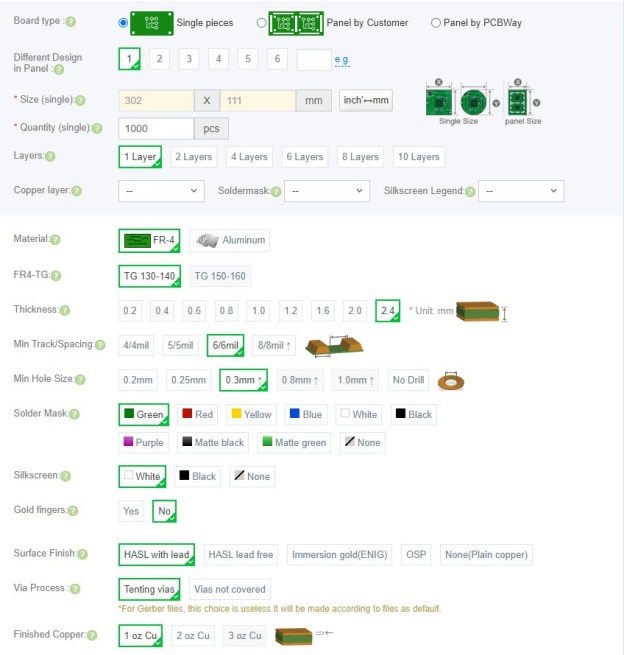

Figure 24: Ordered pcb properties

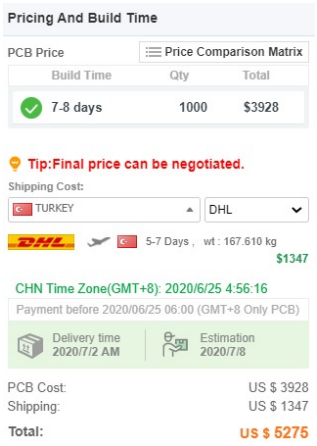

Figure 25: PcbWay bill

10 Conclusion

Forward converter designed with simulations, calcualtions and pcb designs. Observed how non-ideal characteristic affect converter. Investigate different control strategies on converter. Current mode control is advantageous on voltage control. We also analyzed that circuit temperature according to heatsink.

References

[1] *DPG diode.* `https://ixapps.ixys.com/Datasheet/DPG10I200PM.pdf`.

[2] *irfb4127pbf POWER MOSFET*. https://pdf.direnc.net/upload/irf740a-datasheet.pdf.

[3] *0R45959EC R Material Core*. https://www.mag-inc.com/Media/Magnetics/Datasheets/0R45959EC.pdf.

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