MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING DEPARTMENT

EE464 STATIC POWER CONVERSION
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HARDWARE PROJECT REPORT

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1. Introduction

In this hardware project, we are expected to design a forward converter with an input between 24V and 48V and a regulated output of 10V. Furthermore, output power is expected to reach 40 W under full load. On the other hand, only 2 percent of line regulation, load regulation and output voltage peak to peak ripple are allowed.

As Karkas Co, we started our studies from the day one and achieved to demonstrate our fully completed project on the demo day successfully. Firstly, we investigated all project types and prefer to implement forward converter rather than flyback converter due to following reasons:

- gapless core can be used, higher Lm, less loss, less ripple
- LC output filter, continuous output current
- direct and higher power transfer through transformer (better utilization)

Karkas Co was also aware of following drawbacks and took action accordingly.

- increased cost due to extra diode and filter inductor
- negative effect of big filter inductor to the compactness of the system
- higher voltage requirement for the mosfet

Secondly, controller is selected and operation frequency is determined accordingly. After that, magnetic design is completed for both transformer and output inductor. Turn numbers and cores are determined after the calculations. Winding the transformer and output inductor is performed by company members. At the same time, diode and mosfet selections are made and ordered. Detailed information for design and component/controller selection is mentioned at the following parts of the report.

After succeeding the power stage of the project on a stripboard, Karkas Co continued to work for the higher efficiency, compact design and robustness. To achieve higher efficiency, we preferred a mosfet with a lower Rds and two parallel windings are used in the transformer. For compact design, PCB is designed and produced. Implementing our converter on a PCB also improved robustness.

This report includes the project specifications, solution approach and design considerations. Simulation results supporting the theoretical calculations and test results are also provided in the report. Moreover, encountered problems during the project and the learning outcomes are mentioned.

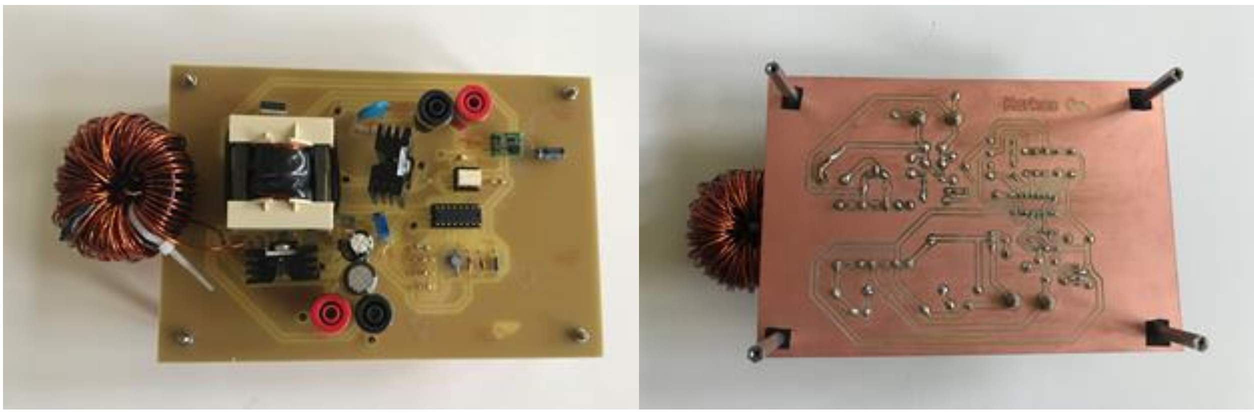

Figure 1: Top and bottom views of the final product respectively

2. Project Specifications

Type: FOR#4
Input Voltage: 24V-48V
Output Voltage: 10V
Output Power: 40W
Output Voltage Peak to Peak Ripple: 2%
Line Regulation: 2%
Load Regulation: 2%

3. Design Considerations

3. A - Controller Selection

We have used TL494 Pulse-Width Modulation Control Circuit in order to achieve closed loop control of the converter. TL494 has two error amplifiers, an oscillator, a dead-time controller, a 5 V regulator and two output transistors as can be seen in Figure 2.

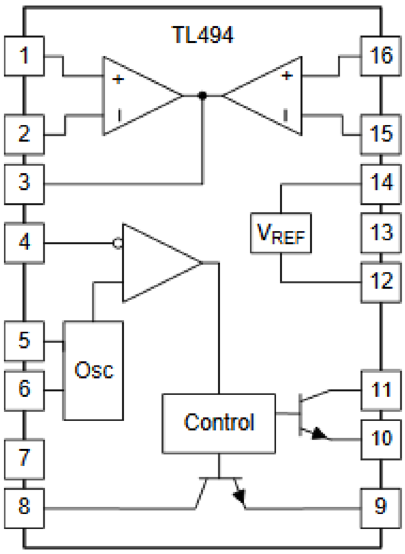

Figure 2: Block diagram of TL494 Analog Controller

The first thing we did was determining the oscillator frequency. As we all know increasing switching frequency decreases the size of magnetic components. However, it increases the switching loss of the MOSFET and also increases the core loss of the transformer. So, optimum switching frequency for this converter was decided as 30 kHz. The frequency of the controller can be controlled via a resistor and a capacitor which is connected to its 5th and 6th pins. The required value of resistor and capacitor is calculated from following equation.

$$f = \frac{1}{R \times C} \qquad (1)$$

The capacitor value is chosen as 1 nF, since it has the smallest frequency variation at this capacitor value as can be seen in Fig.3. Again from the figure we have understood that the required value of resistor is 45 kOhm.

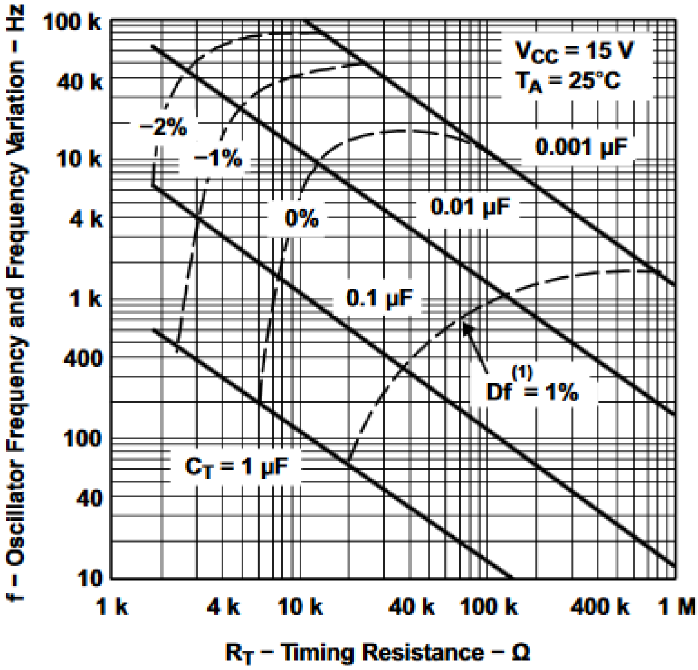

Figure 3: Oscillator frequency vs resistance graph of analog controller

The next thing to do was limiting the duty cycle of the controller to %50. Since we design a forward converter whose N1:N3 ratio is equal to 1, the maximum allowed duty cycle to leave enough time for demagnetizing is %50. This is configurable with dead-time control section of the controller. The equation which governs the maximum duty cycle is given the following equation where R1 and R2 values can be seen in Fig.4.

$$D_{max} = (0.05 + 0.35 * R_2) \quad (2)$$

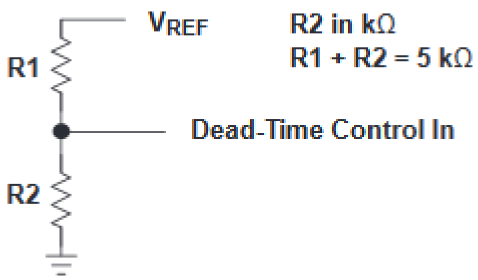

Figure 4: Dead-time control circuit

The R2 value can be found as 1.28 kOhm from the above equation. We have used the closest value we could find which was 1.2 kOhm. Since, R1+R2 is recommended to be 5 kOhm we have used 3.9 kOhm resistor as R1. With this configuration we have achieved maximum duty cycle of 0.47 which is enough for our design.

After determining dead time control, we have focused on soft-start. Soft-start is fairly simple to implement with TL494 Analog Controller. Connecting a capacitor parallel with R1 resistor at Fig.4. is enough to have a soft-start on forward converter. The amount of time which soft-start takes is calculated from following equation where R2 is 1.2 kOhm and soft-start time is decided as 12 ms which is equal to 360 cycle with 30 kHz frequency. So, capacitor value can be found as 10 uF.

$$T_{soft} = R_2 * C_S \quad (3)$$

Afterwards, we have determined the reference value voltages of the error amplifiers. As mentioned before, there are two error amplifiers in TL494. However, we have used only one error amplifier in the converter. The second error amplifier is generally used for current limiting which limits the output current to a certain value. The circuit schematic of the first error amplifier can be seen in Fig.5.

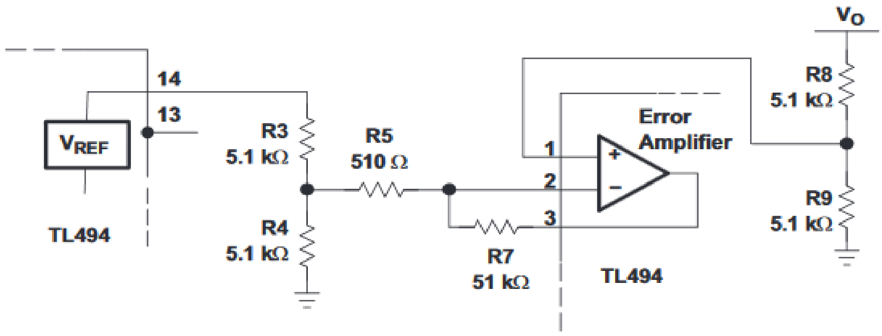

Figure 5: Error amplifier circuit

We have used 1 kOhm resistors for R3,R4 and R5 in Fig.5. This setup creates a 2.5 V reference voltage at inverting terminal of the amplifier. R7/R5 ratio determines the gain of the amplifier. We have used 5 kOhm resistor as R7 so that the gain of the amplifier is equal to 5. Increasing the gain results in a faster response. However, it may cause instability in the system which is not desirable.

Finally, the circuit schematic of the analog controller can be seen in Fig.6. Since, the second amplifier is not used its inverting terminal is connected to 5 V and the non-inverting terminal is connected to ground so that it always gives positive output. Output transistors are connected in common-emitter configuration. Output of the controller is the collector terminals of the output transistors.

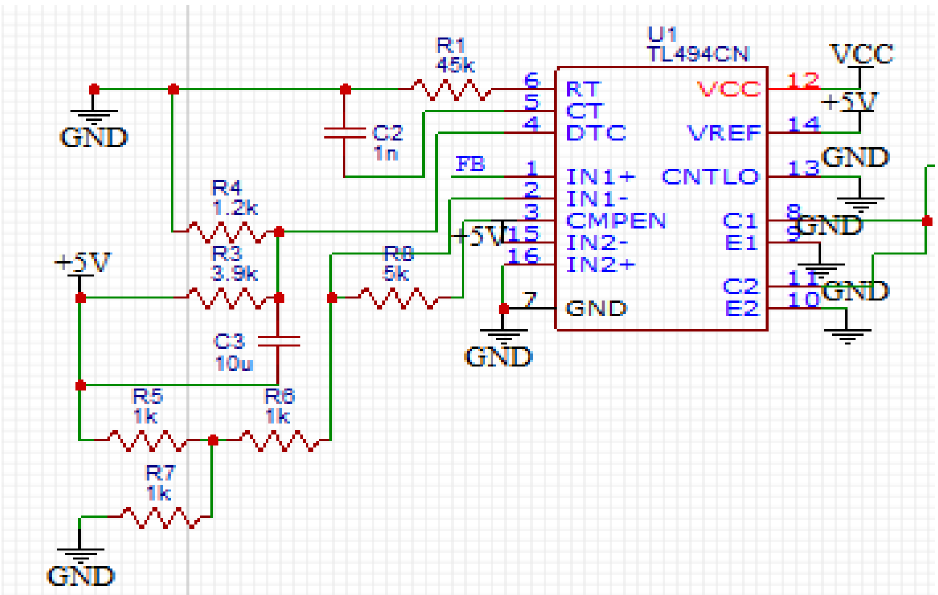

Figure 6: Circuit schematic of the analog controller

3. B- Transformer Design

For the transformer design we altered the magnetic design we had for the second simulation project slightly. However, for the sake of the continuity of the report, a summary of the design is presented here. Note that, we added more turns to the second winding since it turned out that our output voltage was slightly less than 10V in our first trials of the project.

Step 1: Area Product: Core choice is done according to the area product which is found by (4) as 1.05 cm^4, the parameters of the equation are listed below.

$$W_a * A_c = \frac{P_{out} * J}{K * B_{max} * f} \qquad (4)$$

- P, output power 40 W
- J, current density 500 circ.mil/A
- B, flux density 1300 Gauss
- K for forward converter 0.0005
- F, switching frequency 30 kHz

Step 2: Selecting a core from the ones offered by the department: Among the cores offered by the laboratory, with its 1.21 cm^4 area product *0P43434EC* was the most suitable one for us. It is an E core with cylindrical middle leg made from P type material. Properties of this core can be seen in Figure 7.

Part Number	Perm	Material	Shape	AL Inductance nH/T²	OD / Length mm	ID / Leg Length mm	HT / Height mm	Ve Volume mm³	Le Path Length mm	Ae Cross Section mm²	WaAc
☐ 0P43434EC	2500	P	ETD	2933	35	17.3	11.1	7640	78.6	97.1	1.21

Figure 7: Parameters of the selected core

Step 3: Calculating number of turns: Calculating the primary and secondary turn numbers are done using Eqn. (5) and (6), respectively.

$$N_{pri} = \frac{V_{pmax} * 10^8}{4 * B * f * A_e} \qquad (5)$$

V_{pmax} is maximum voltage of primary side while A_e is the cross-section area of the core. Required number of turns for primary side is found as **26**.

$$N_{sec} = \frac{(V_{out} + V_{margin}) * N_{pri}}{V_{pmin} * D_{max}} \qquad (6)$$

It is a common practice to choose N_1 and N_3 equal to each other in forward converter design. However, these limits the duty cycle to 0.5 as the core needs time to demagnetize. As our input range is 24-48V, secondary winding turns must be large enough to achieve 10V at the secondary winding terminals. Therefore, V_{pmin} is used to calculate the secondary winding number. Using Eqn. (6), the resultant secondary side number of turns is **24**.

As it was mentioned at the beginning of this part due to the effect of our controller, we needed to increase the second winding's turn number to **31**.

Step 4: Cable sizes: 4 A/mm^2 is commonly accepted in power electronics designs, according to this our cable selections for windings are as follows, and then we checked their feasibility using winding factor formula in Eqn. (7).

- Primary winding AWG 17
- Secondary winding AWG 15
- Tertiary winding AWG 25

$$K_{win} = \frac{A_{copper}}{A_{window}} = 0.6 \quad (7)$$

Step 5: DC Loss Calculation: To find the DC loss we needed the total length of the windings; therefore, we have calculated mean length per turn using Eqn. (8). The total DC resistance of the cables is found as 46 mΩ. From $I^2 * R$ formula, the copper loss of the transformer is found as 0.73 Watts. Note that this was before we increased the turn number of the secondary winding.

$$MLT = \left(\frac{E}{2} - \frac{F}{2}\right) * 0.5 * 2\pi \quad (8)$$

Step 6: Core Loss: To calculate the core loss of the transformer, we used Steinmetz core loss equation which is given by Eqn. (9) and obtain 0.71 Watts core loss as the result.

$$P_{core} = V_{core} * 3.2 * f^{1.46} * B^{2.75} * (2.45 - 0.031T + 0.000165T^2) \quad (9)$$

To fully utilized the transformer core, we had to make recalculations to get a close core and copper loss results. Therefore; we prepared a MATLAB script which is given in Appendix I.

3. C- Filter Inductor Design

The inductance value of the output filter is 500 uH according to our calculations. We have started the inductor design procedure by listing all available inductor cores according to a few important parameters such as inductance factor, volume, core loss density at 10 kHz and 0.1 T etc. Since, the efficiency of the inductor is a crucial factor for our design we have started inductor design with the cores with highest inductance factors. We have written a Matlab script to ease the calculations since inductor design requires a few iterations.

Toroid Core	u	Al	Core Loss	Volume	L*I^2	Window area (mm^2)	Cross Section Area (mm^2)	Path Length (mm)
55928A2	MPP-160	201	900	4150		156	65.4	63.5
77442A7	Kool-90	202	900	21300		427	199	107
77111A7	Kool-26	33	900	20700		948	144	143
77310A7	Kool-125	90	1000	1800		139	31.7	56.7
77439A7	Kool-60	135	900	20300	35	427	199	107
79192A7	Max-60	138	700	28600	65	514	229	125
79083A7	Max-60	81	700	10600	25	427	107	98.4
79440A7	Max-26	59	700	21300		427	199	107
88071A7	Amo-60	61	1000	5340		297	65.6	81.4
88894A7	Amo-60	75	1000	4150		156	65.4	63.5
77050A7	Kool-125	56	1000	340	0.15	38.3	10.9	31.2
79894A7	Max-60	75	700	4150	5	156	65.4	63.5

Figure 8: Spreadsheet of available cores' parameters

We have selected the 77442-toroid core with 202 nH/Turn^2. The first thing to calculate is the number of turns required to have 500 uH inductance. We have used the following formula for this purpose. Number of turns is found as 57 from this equation.

$$N = \sqrt{\frac{L}{A_L}} \qquad (9)$$

Next, we have decided on the cable size. There will be 4 A DC current on the inductor. With AWG 15 cable, which has 1.65 mm^2 cable cross section area, we have acquired 2.4 A/mm^2 current density which is an acceptable value. After that, we have found the length of the cable by multiplying mean length per turn value with the number of turns.

$$L_{cable} = MLT * N = 3.94\, m \quad (10)$$

Then, we have found the total resistance of the cable by multiplying the length of the cable with resistance/length value of the AWG 17 cable.

$$R_{cable} = L_{cable} * R_{AWG\ 15} = 66\, mOhm \qquad (11)$$

After finding DC resistance, power loss of the cable can be calculated as follows.

$$P_{copper} = I^2 * R_{cable} = 0.66\, W \qquad (12)$$

Since, there will be a very small ripple value on the inductor current, we have expected very insignificant core loss at the core and AC loss at the cable. We have followed this procedure for several different cores and decided on using the 77442 core.

3. D- Capacitor Selection

Since we work with high switching frequency, we had a wide option for capacitance selection for the output filter which can be seen in Figure 9. As our filter inductor is 500uH we decided to go with a 10u capacitor. According to the equation below, our cutoff frequency is 2250Hz which is comparably lower than 30 kHz.

$$f = \frac{1}{2\pi(L\ x\ C)} \qquad (13)$$

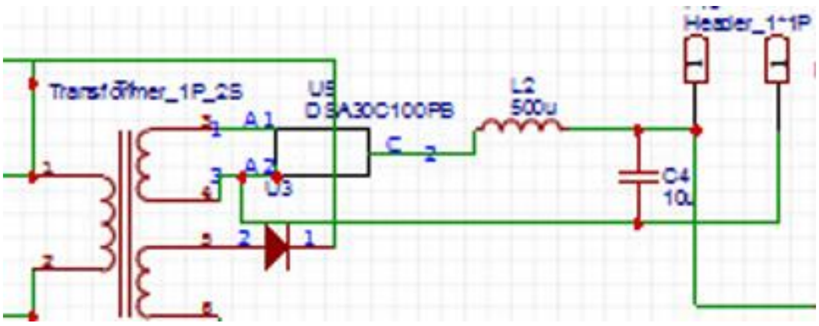

Figure 9: Output inductor and Capacitor

3. E - Buck Converter

We needed 15V dc supplies to feed optocouplers and the analog controller. Not to use extra power supplies we used Pololu D36V6F15 (in Fig. 10) which is a compact switching Buck voltage regulator that regulates input voltage up to 50V to 15V regulated DC voltage. It can work up to 600mA however, since we used it for V_{cc} inputs of the Optocouplers and the analog controller we did not need much.

In Figure 11, connections pin connections of the integrated circuit are shown. It is highly recommended to connect a capacitor between the input and ground terminal if the input is greater than 38V.

Figure 10: Pololu IC Buck Converter

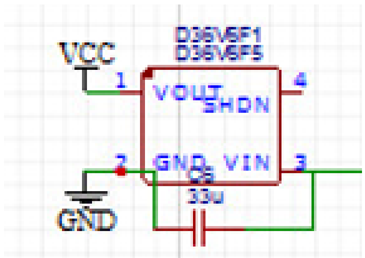

Figure 11: Pin connections of the Buck Converter

3. F - Digital Optocoupler

We used a digital optocoupler TLP250F to direct analog converter outputs to the gate of the mosfet. The reason we chose this model over TLP350 is that we are working with a higher switching frequency than TLP350 can handle. In Figure 12, pin connections of the optocoupler can be observed. 8th pin is connected to the Buck converter output, 15V whereas the 6th and 5th pins are connected to the gate. Grounds should be isolated. Finally, we connected two headers to 2nd and the gate connection to observe analog controller and optocoupler outputs, respectively.

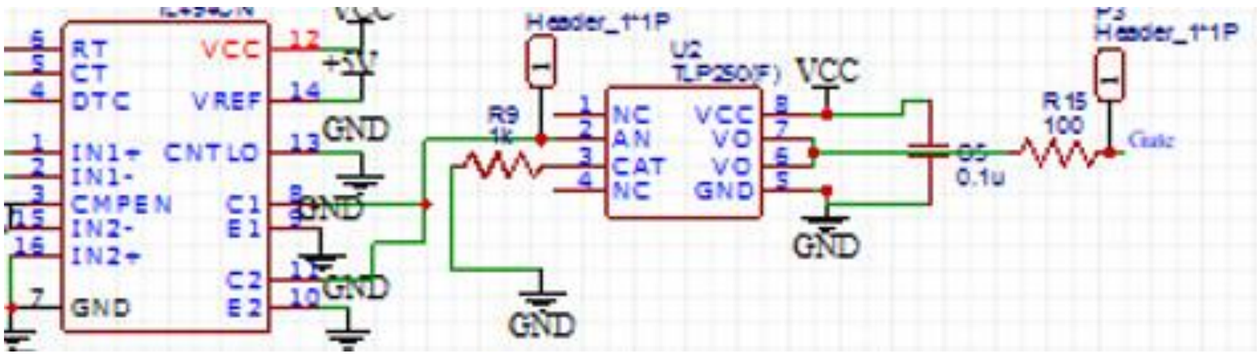

Figure 12: Pin connections of the optocoupler

3. G- Analog Optocoupler

To isolate the controller with output, we used TLP521GB as the analog optocoupler whose pin connections can be seen in Figure 13. Again, ground connections must be different for complete isolation. 1st pin is connected to the output of the Forward converter while the 4th pin is connected to the output of the Buck converter. Resistors at the right-hand side of the analog converter are selected as 1, 20, and 10 kΩ so that when the voltage on load is 10V, as it is intended, the voltage on header, which is connected to the analog controller, is 2.5 V. As we recall reference voltage of the analog controller was 2.5V as well.

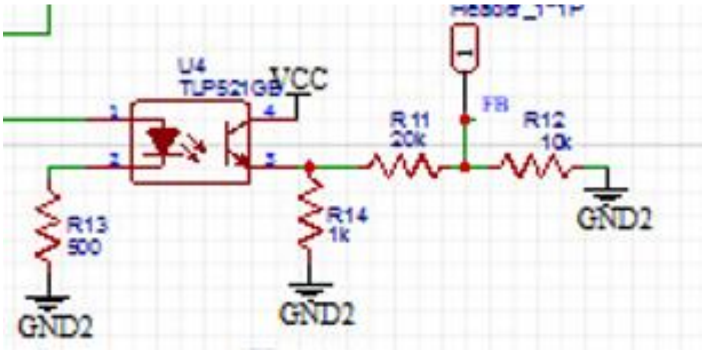

Figure 13: Pin connections of the analog optocoupler

3. H - Mosfet Selection

Our initial choice of mosfet was PJP8NA50. While selecting a mosfet our initial concerns and PJP8Na50's parameters are listed below:

- Maximum drain-source Voltage, V_{DS} 500V
- Maximum drain current, I_{DS} 8A
- Turn on time, rise+delay 44ns
- Turn-off time, fall+delay 65ns

However, we should have taken $R_{ds,on}$ under consideration as well. Because it was 0.9Ω, which decreased our efficiency. Also, even though we used snubbers (1kΩ and 1uF), our mosfet tended to burn out due to heat after some time. At this point, we see that maybe we have performed any thermal calculations we would not have lost all that time changing burned mosfets.

Therefore; we switched to UF640L-TA3-T with given parameters:

- Maximum drain-source Voltage, V_{DS} 200V
- Maximum drain current, I_{DS} 18A
- Turn on time, rise+delay 63ns
- Turn-off time, fall+delay 91ns
- R_{don} 0.18Ω

Also, it is worth mentioning here that with the usage of snubbers the switching peaks reduced from 200V to 90V.

3. I - Diode Selections

We decided to use a 3 leg Schottky diode for D1 and D2 and another 2 leg Schottky diode for D3, in Fig. 14.

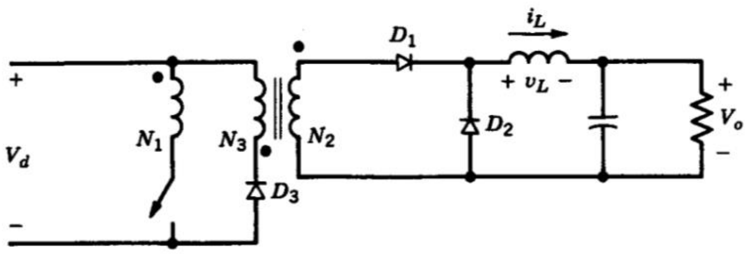

Figure 14: Forward Converter with tertiary winding

<u>Diode selection for D1 and D2:</u> Our first and final choice was DSA30C100PB, which is a common cathode, low loss and soft recovery high performance Schottky diode whose parameters are given below:

• Forward voltage drop, V_f	0.91V
• Maximum repetitive reverse blocking voltage, V_{RRM}	100V
• Maximum non-repetitive reverse blocking voltage, V_{RRM}	100V
• RMS current, I_{RMS}	35A
• Reverse current, I_R	250uA

<u>Diode selection for D3:</u> We chose MBR10100G Schottky for D3 with parameters below:

• Forward voltage drop, V_f	0.7-0.95 V
• Maximum repetitive reverse blocking voltage, V_{RRM}	100V
• Average Rectified Forward Current	10A
• Peak Repetitive Forward Current	20A
• Reverse current, I_R	600uA

4. Simulation Results

4. A - Voltage and Current on Mosfet

You can see our simulation results from Project 2 of the drain-source voltage and drain current in Figure 15. There is a great amount of peak voltage between drain and the source of the mosfet. Therefore; used a snubber circuit for mosfet. Our initial choice was a 10 nF capacitor and 1 mOhm resistor for snubber, since we did not want to a lot of power to dissipate at snubber circuit. The results can be seen in Figure 16. However, this snubber was not adequate for the project so we switched to 1kΩ and 1uF resistor and capacitor. This reduced to our peak voltage from 200V to 90V. Unfortunately, we forgo to take photos of the waveforms.

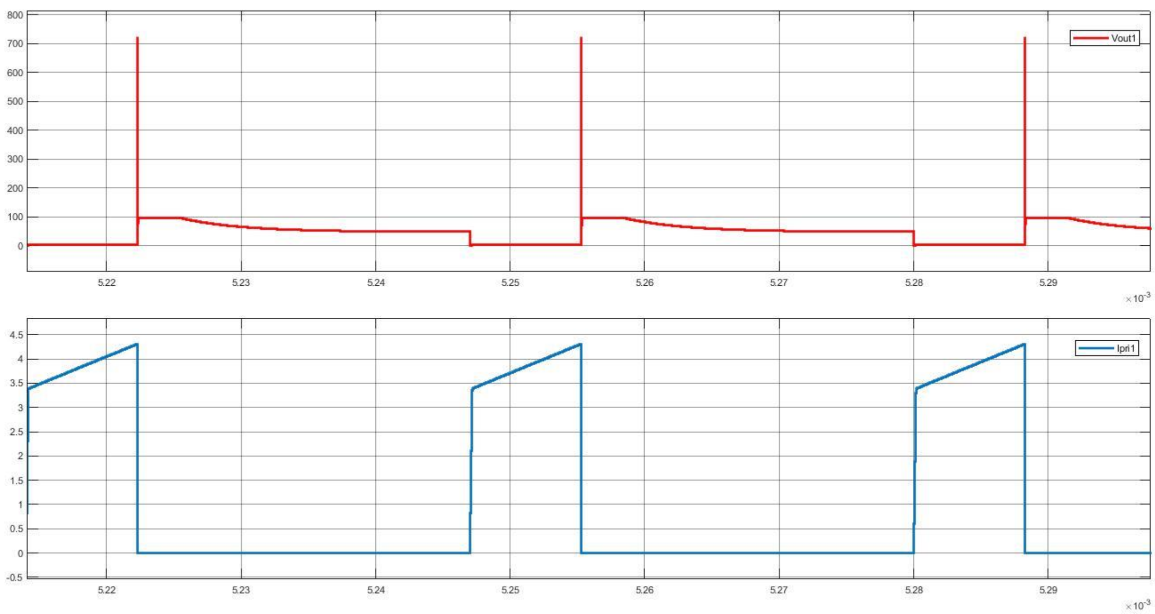

Figure 15: MOSFET voltage and current waveforms

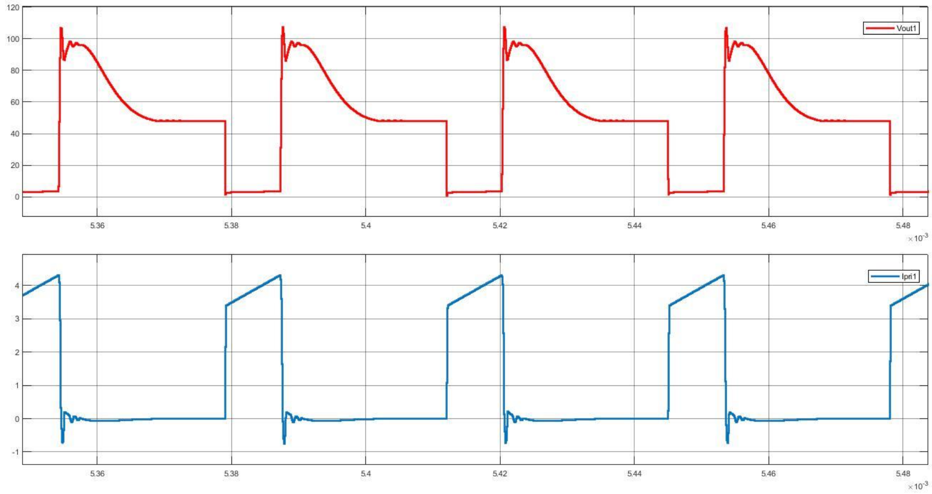

Figure 16: MOSFET voltage and current waveforms with snubber

4. B - Converter Operation

In the simulations of 24 input voltage and %50 duty cycle, 10 V and 4 A output with 1.4% output voltage ripple is achieved which can be seen in Figure 17; while with 48V input voltage and 0.25 duty, the ripple increased to 1.8% as it can be seen in Figure 18.

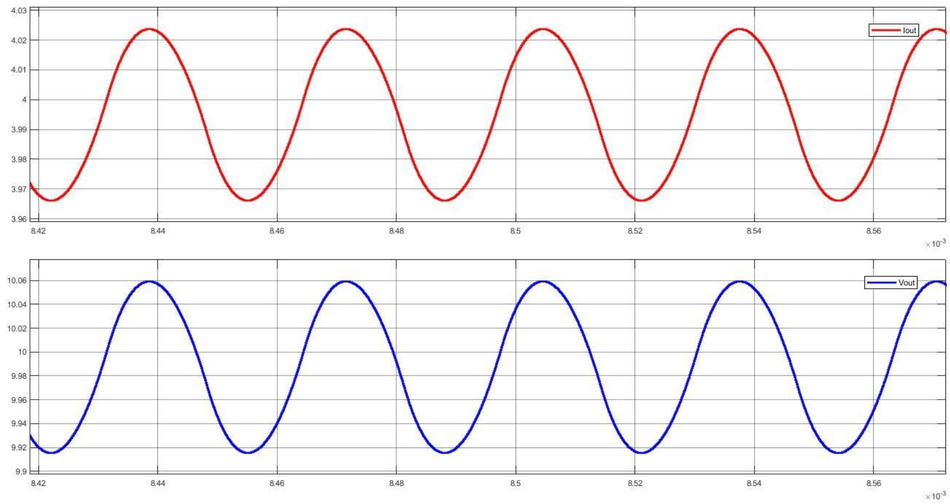

Figure 17: Output voltage when input is 24V

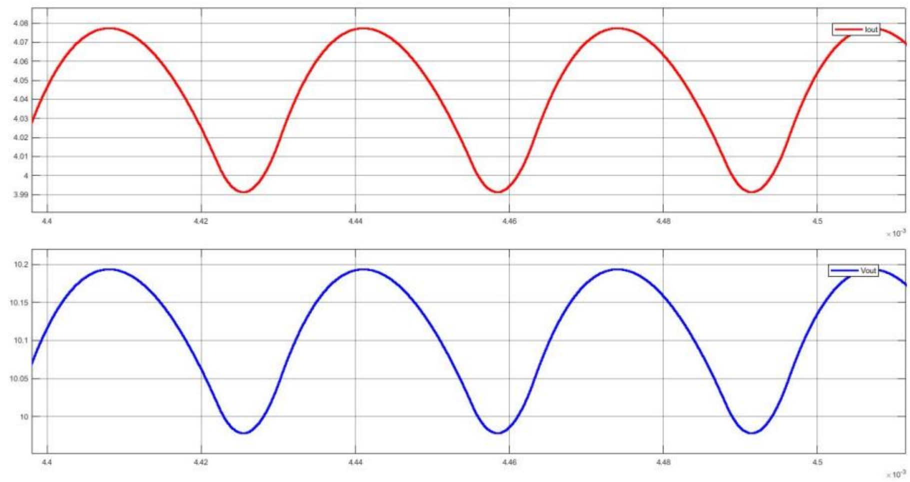

Figure 18: Output voltage when input is 48V

4. C- Efficiency

Efficiency at full load (2.5Ω), 75%, 50%, and 25% (10Ω) are found by Eqn. (14) to (18).

$$\eta_{full} = \frac{40}{49.57} x100 = 80.7\% \quad (14)$$

$$\eta_{75} = \frac{30.51}{39} x100 = 78.2\% \quad (15)$$

$$\eta_{50} = \frac{20.68}{28.26} x100 = 73.2\% \quad (16)$$

$$\eta_{25} = \frac{10.52}{17.33} x100 = 60.7\% \quad (17)$$

5. Test Results

5. A - Transformer Test

5. A.1 - Open Circuit Turns Ratio Test

The purpose of this test is to make sure numbers of turns are correct. As mentioned in transformer design part, expected results are such that $N_1 = 26$ $N_2 = 24$ and $N_1 / N_2 = 26/24 = 1.0833$.

We measured L1 after the connecting the LCR meter to the primary side of the coil. Then measured L2 after connecting LCR meter to the secondary side of the coil (See Figure 19). The LCR meter displayed the turn ratio N. (See Figure 20)

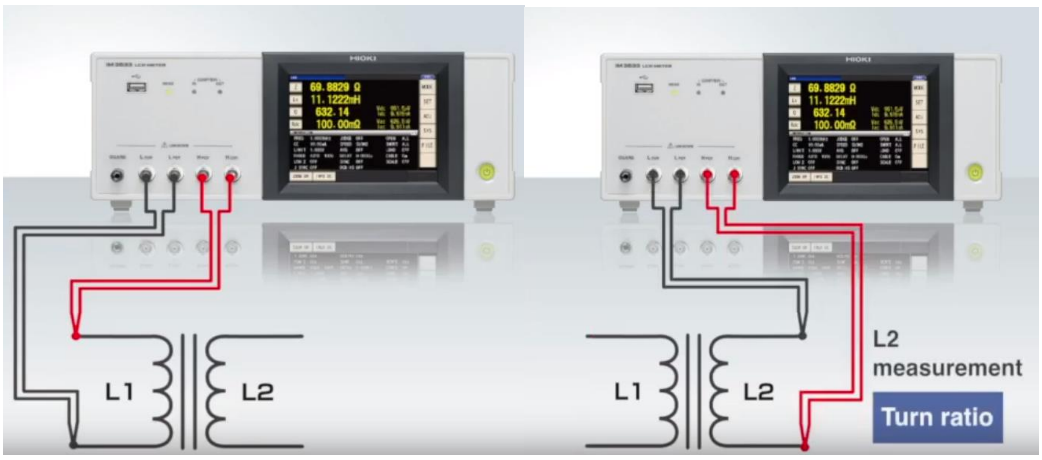

Figure 19 - Open Circuit Test Configuration

Figure 20 - Turns Ratio Test Result

As can be seen from the Figure 20, result is completely consistent with the calculations.

5. A.2 - Short Circuit Leakage Inductance Test

We applied short circuit test to find out leakage inductance and resistance of the transformer. Test configuration is shown in the Figure 21. Results were satisfactory since the leakage inductance is almost 1% of the inductance we found at open circuit test. 116.93 mOhm resistance value is fulfilling for high efficiency purposes.

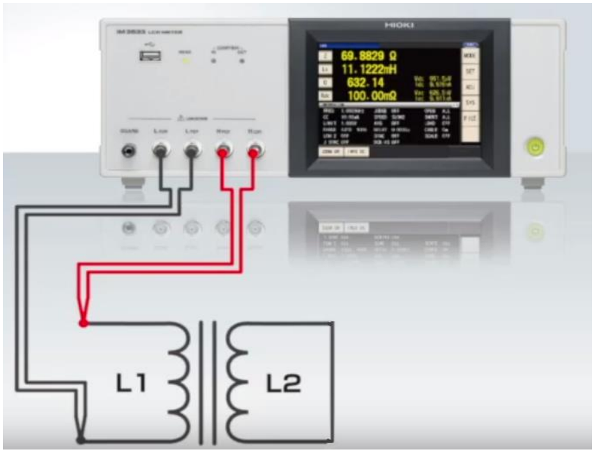

Figure 21 - Short Circuit Test Configuration

Figure 22 - Leakage Flux Results

5. B - Inductor Test

In Equation 11, we calculated the R_{cable} as 0.66 mOhm for the inductor. As can be seen from the Figure 23 (considering the extra cable lengths for the holders) resistance value of the output inductor is completely consistent with the calculations. Furthermore, we considered the DC Bias curve of the toroid at 4A and we achieved 0.7 mH x 0.72 = 500 uH as needed.

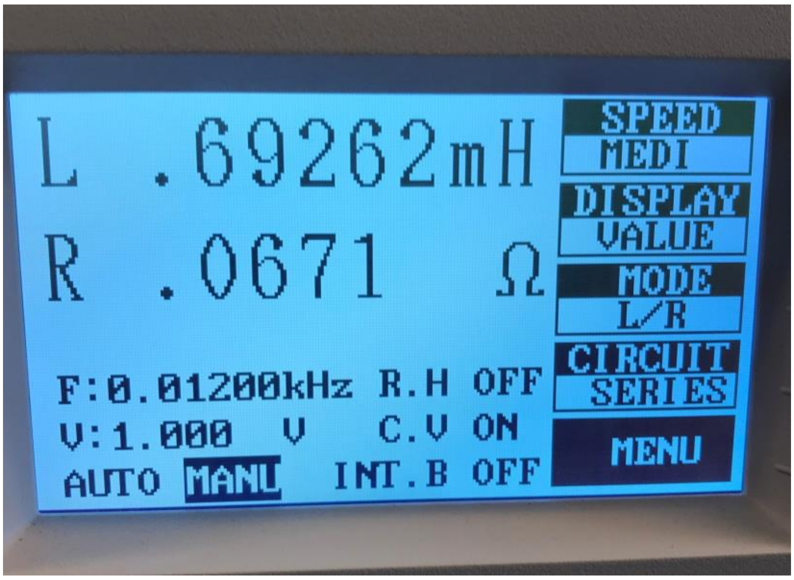

Figure 23 - L and R values of the output inductor at the RCL meter

5. C - Efficiency Test

Before making final arrangements to keep output voltage at 10V we conducted a efficiency test at full load, open loop. As can be seen from the Figure 24 power delivered to the load is 52.9 Watt. Also, power delivered by the DC Source is shown in Figure 25 and it is 71.8 Watt.

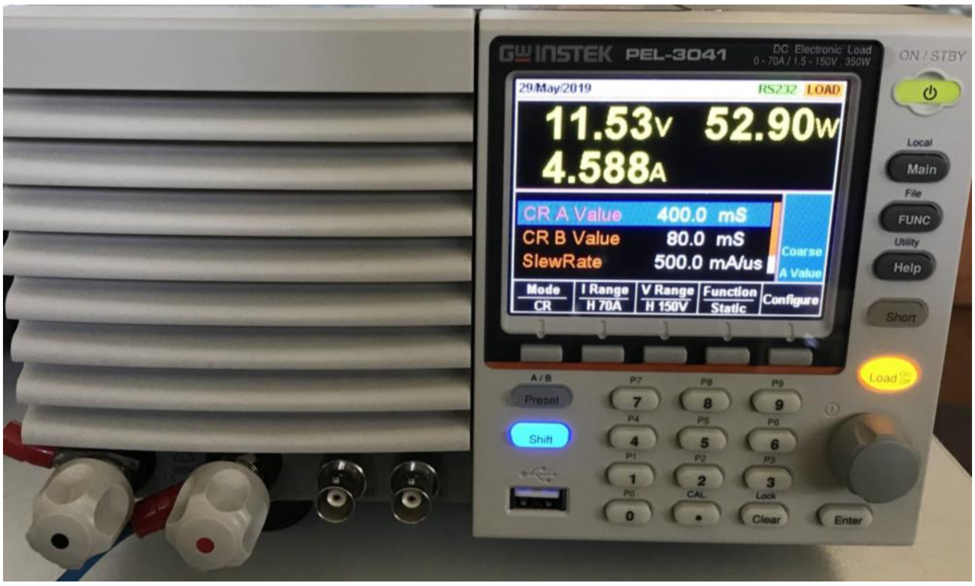

Figure 24: Power Delivered to Full Load

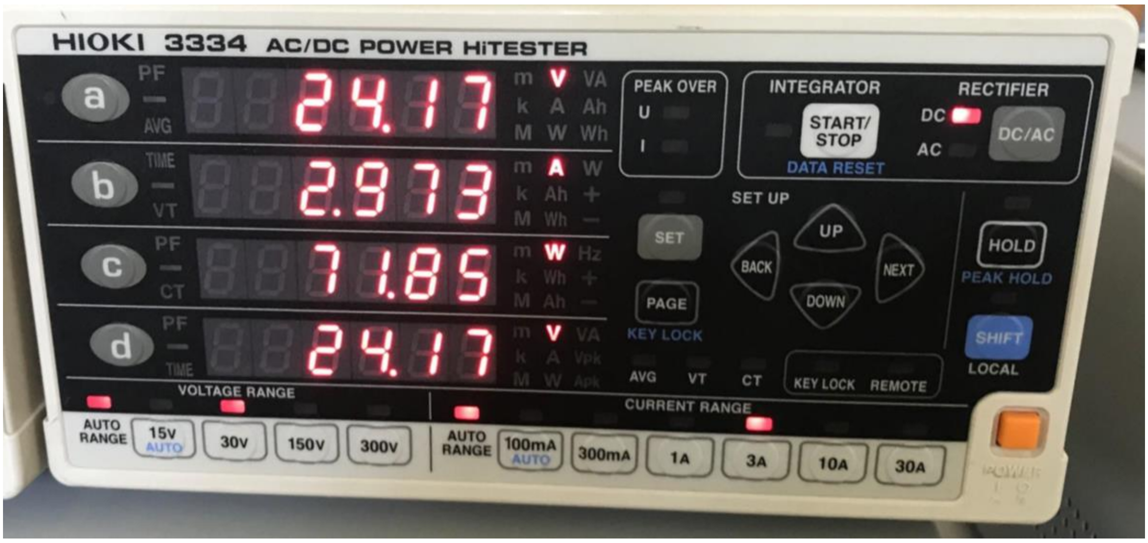

Figure 25: Power Delivered by DC Source

So, the resultant efficiency is:

$$\text{n} = \frac{Output\ Power}{Input\ Power} x100 \ = \frac{52.9\ W}{71.8\ W}\ x\ 100 = 74\%$$

5. D – Soft Start Test

We observed the output voltage and current at the oscilloscope screen while starting the operation of converter. As can be seen from the Figure 26, we achieved to desired output voltage at a certain time. As mentioned in the analog controller part, we selected soft start time as 360 cycles by using the Equation 3. 360 cycles at 30 kHz means 12-14 milliseconds. It's clear that test results are completely consistent with the calculations (soft start occurs approximately at 14 milliseconds at both full load and half load).

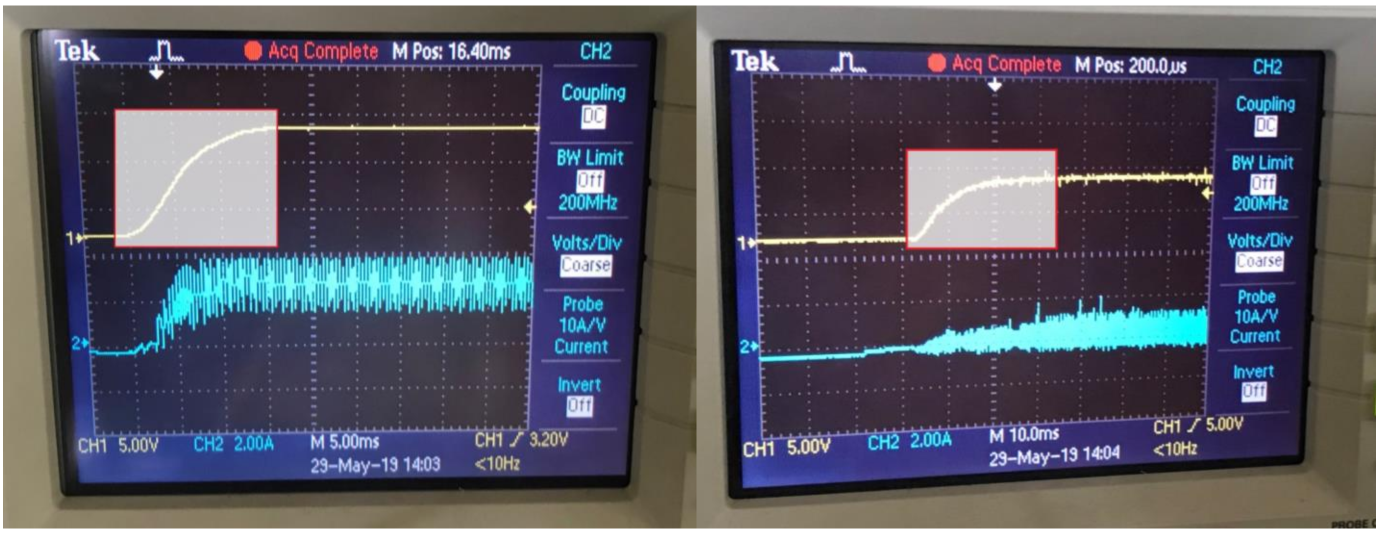

Figure 26: Voltage and Current soft starts at full Load and half load respectively

5. E - Output Voltage Ripple and Output Current Ripple Test

Output voltage and output current graphs are observed on the oscilloscope screen. As it is clearly shown in Figure 27, there are almost no ripples at the output voltage and output current is in CCM.

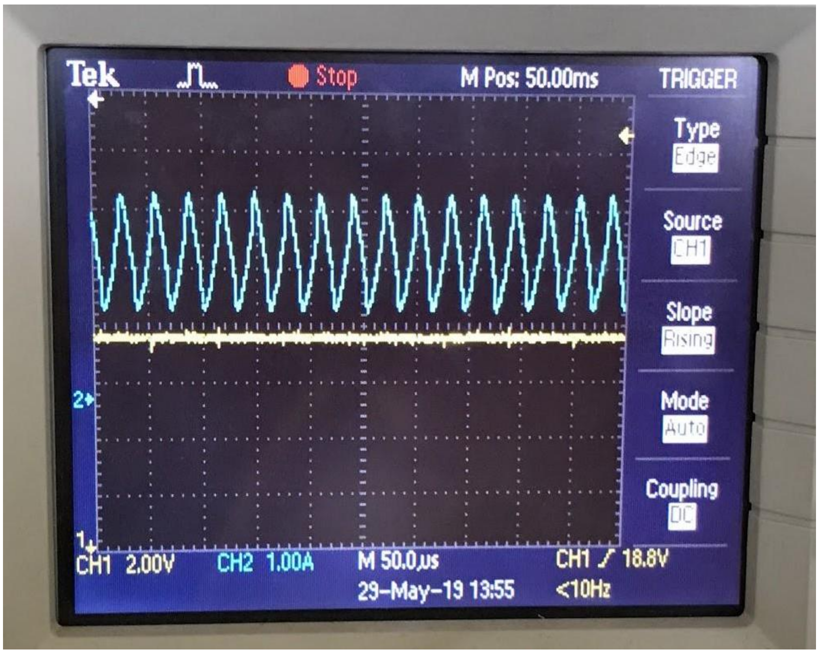

Figure 27: Output Voltage and Output Current vs time at the oscilloscope screen

5. F – Load Regulation Test

While the converter is operating at the light load we brought it to the full load as a step change. As can be seen From the Figure 28, controller reacts very fast to this change and we see no oscillations in the output voltage. It comes to same value before the change is applied in a considerably short time.

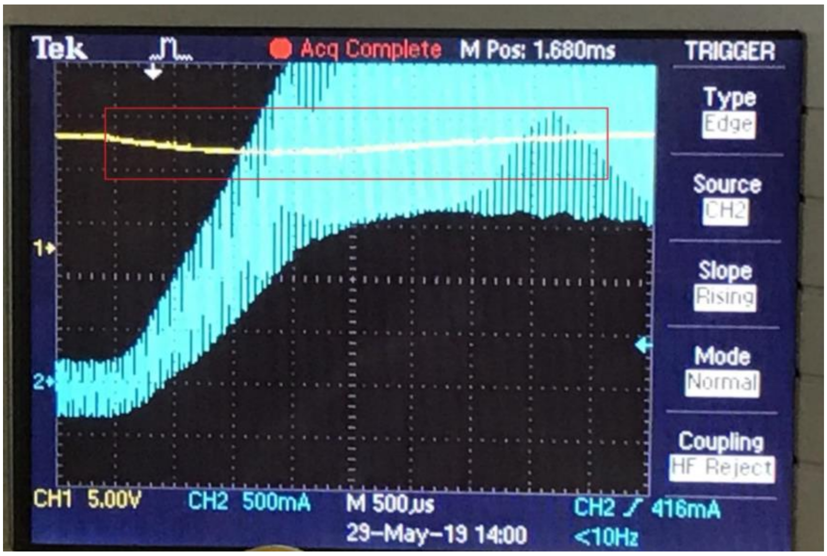

Figure 28: Output Voltage and Output Current vs time when load is changed from light load to full load

5. G – Thermal Test

Forward converter is operated at full load for 3 minutes and temperatures of the MOSFET, diode and transformer are observed with thermal camera at each minute. As can be seen from the Figure 29, MOSFET, diode and transformer are the components which get heated the most. Temperatures of these components increase with time and come to a saturation at 65 degree levels which is satisfactory (see Figure 30).

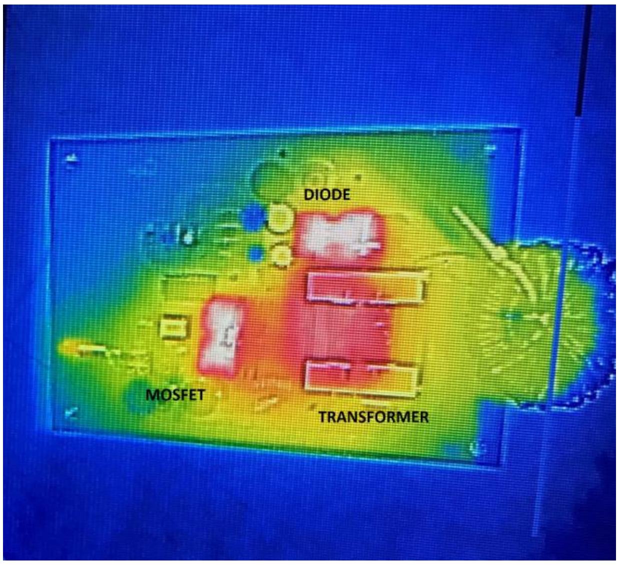

Figure 29: Determination of most heated components

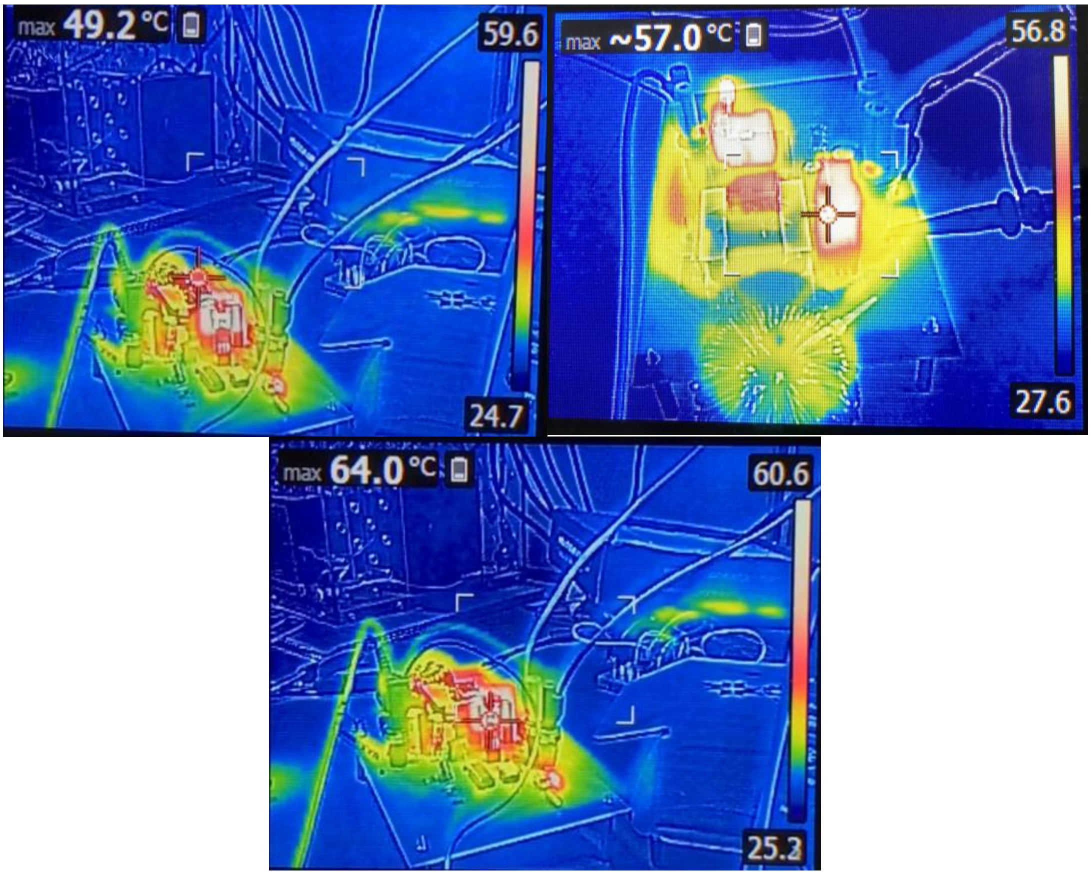

Figure 30 - Thermal camera screenshots the after 1-2-3 minutes operation respectively

APPENDIX I:

MATLAB code written for the transformer calculations is given:

```
P=40;                %Watts
J=500;               %circ.mils/amp or 400 A/cm^2
K=0.0005;            %constant 0.0005 for forward converter
B=1600;              %max flux density
f=30000;             %frequency Hz
Vpmax=48;            %maximum primary voltage V
Vpmin=24;            %minimum primary voltage V
Vout=10;             %output voltage
Iout=4;              %outout current
Ae=0.971;            %cross section area for 0P43434EC cm^2
Vcore=7.64;          %volume of the core in cm^3
Window_3434=1.21/Ae;    %window area of 0P43434EC in cm^2
T=50;                %ambient temperature
Nt=26;               %reset winding number of turns
A_25=0.00162;        %AWG 25 copper area in cm^2
R_25=106.2;          %mohm/m for AWG25
A_17=0.0104;         %AWG 17 copper area in cm^2
R_17=16.61;          %mohm/m for AWG17
A_16=0.0131;         %AWG 16 copper area in cm^2
R_16=13.17;          %mohm/m for AWG16
A_15=0.0165;         %AWG 15 copper area in cm^2
R_15=10.45;          %mohm/m for AWG15


WA=P*J/(K*B*f);                                    %Area product
Np=round(Vpmax*1e08/(4*B*f*Ae));                   %primary number of turns
Ns=round(((Vout+1)*Np)/(Vpmin*0.5));               %secondary number of turns
Pcore=Vcore*3.2*(f^1.46)*((B/10000)^2.75)*(2.45-0.031*T+0.000165*T^2)*1e-06;    %core loss in W, f in Hz, B in G
mlt=(((0.0256/2-0.0111/2)/2)+0.0111/2)*2*pi;       %calculation of mean length per turn of the cable in m
Lcop=mlt*(Np+Ns+Nt);                               %total cable length in m
Kwind=(A_17*Np+A_15*Ns+A_25*Nt)/Window_3434;       %winding factor of 0P43434EC
Rcop=R_15*Lcop;                                    %total dc resistance of copper in mOhm
Pcop=Rcop*(Iout^2)/1000;                           %copper loss in Watts
```

APPENDIX II:

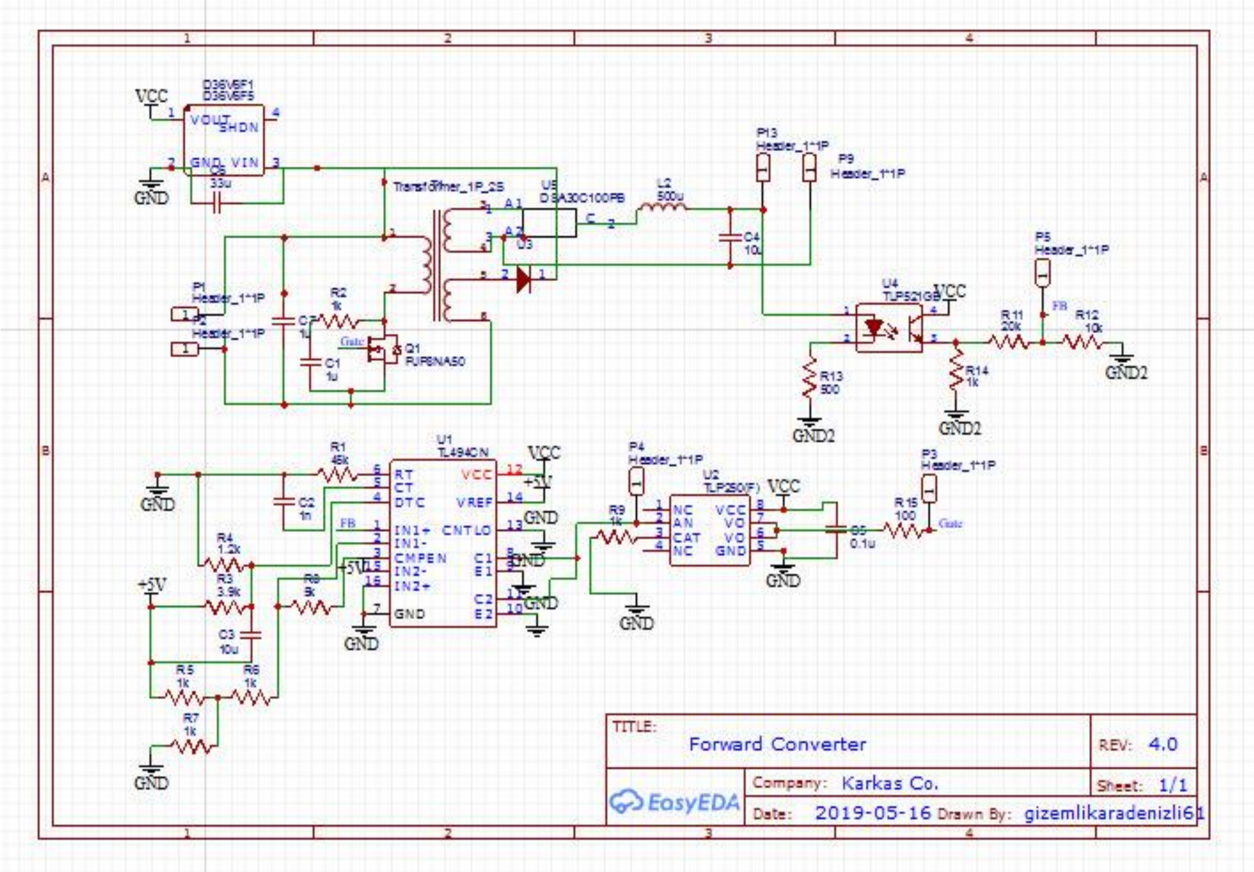

Figure 31: Overall System Schematic

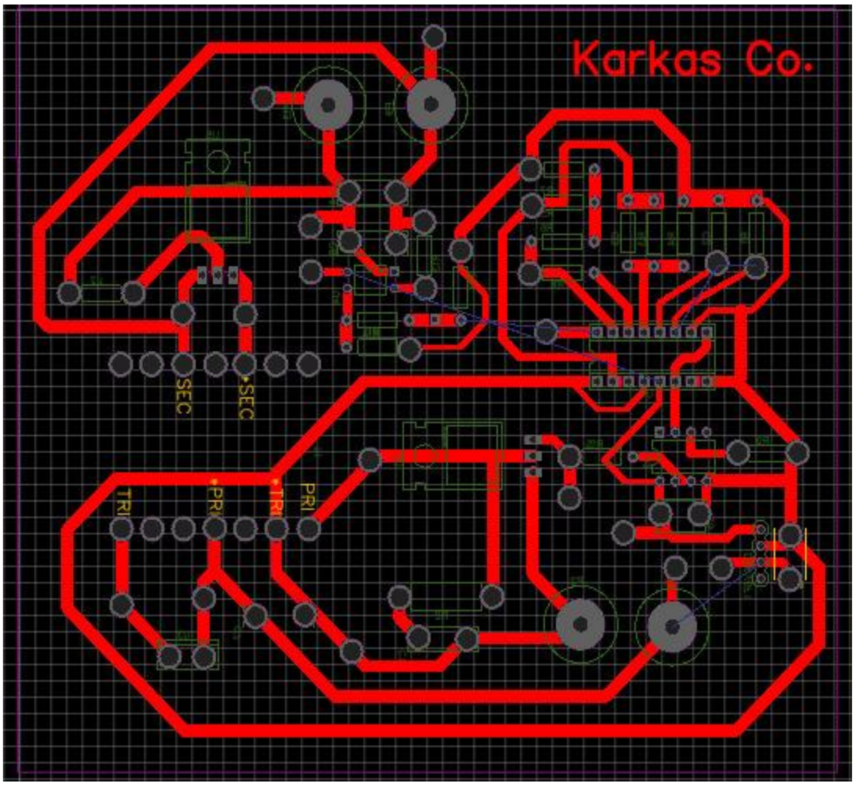

Figure 32: PCB Design