Teaching Aids in SMPC

Construction Project in the
Curriculum of
Switched Mode Power Conversion

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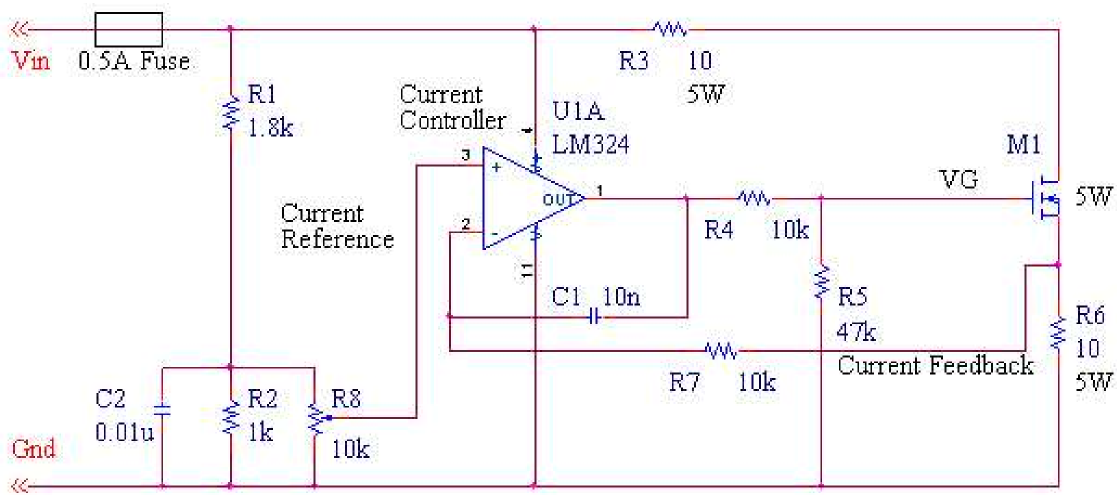


Figure 1.1: Constant Current Load

1.2 Circuit Discription

The circuit shown in Fig 1.1 is a constant current load on the 15V input. A MOSFET is used in the linear mode with closed loop control to achieve constant current performance. The resistor R_8 is a variable resistor. The current drawn from the source is proportional to the voltage across R_8 (0 to 0.5A for R_8 varying from 0 to $10k\ \Omega$).The mathematical relationships in the converter are as follows.

$$V_s = iR_6 \tag{1.1}$$

$$V_{ref} = V_G \left[\frac{R_2||R_8}{R_1 + (R_2||R_8)}\right] \tag{1.2}$$

$$Z_f = \frac{1}{sC_1} \tag{1.3}$$

$$Z_1 = R_7 \tag{1.4}$$

$$V_A = V_{REF}[1 + \frac{Z_F}{Z_I}] - V_S\frac{Z_F}{Z_I} \tag{1.5}$$

$$V_G = V_A \left[\frac{R_5}{R_4 + R_5}\right] \tag{1.6}$$

$$V_{ref} = V_g - V_s \tag{1.7}$$

$$i = I[1 - \frac{V_T}{V_{GS}}]^2 \tag{1.8}$$

The last equation is the V_{GS} vs I_D characteristics of a MOSFET in the active region. From the device characteristics, I and V_T can be evaluated. For example for the device IRF540 (IRF540), consider the pair of operating points (V_{gs} = 5V, I_d = 15A, V_{ds} = 5V; and V_{gs} = 7V, I_d = 70A, V_{ds} = 5V). From this data, one can find I and V_t. For IRF540, these parameters are 396A and 4.023V.

Under ideal and stable operating conditions, with an integrator in the control loop, the output current is very nearly

$$i = \frac{V_{ref}}{R_6} \tag{1.9}$$

Dynamic model of the converter may be carried out as an exercise. This circuit may serve as the load for the house-keeping power supply built in Construction Project No. 01.

Evaluate the steady state voltage of every node in the circuit and the current in every branch in the circuit. Verify the same in the assembled circuit. For the device used in the circuit, evaluate the parameters I and V_T from the data sheet. Evaluate the small signal model of the circuit at the operating point with the potentiometer R_8 set at 0.5 setting and input voltage at 15V.

1.3 Mounted and Bare PCB Boards

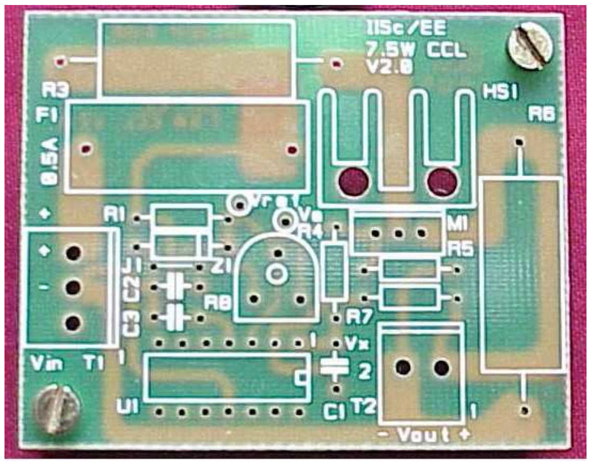


Figure 1.2: BareBoard

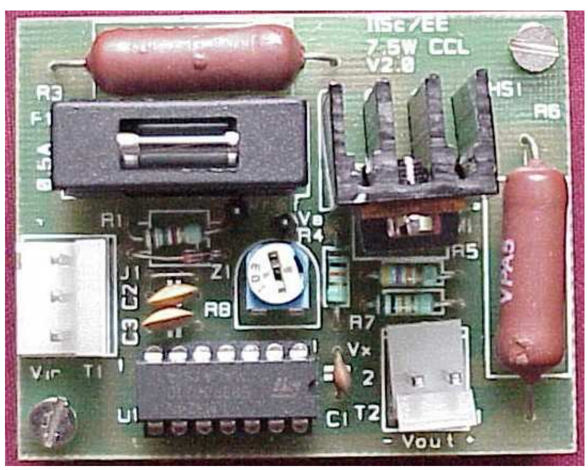


Figure 1.3: MountedBoard

1.4 Bill of Materials

Table 1.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1	$1.8k\ \Omega$	1	0.35	0.35
2	Resistor	R2	$1k\ \Omega$	1	0.35	0.35
3	Resistor	R3	$10\ \Omega$	1	0.35	0.35
4	Resistor	R4	$10k\ \Omega$	1	0.35	0.35
5	Resistor	R5	$47k\ \Omega$	1	0.35	0.35
6	Resistor	R6	$10\ \Omega$	1	0.35	0.35
7	Resistor	R7	$10k\ \Omega$	1	0.35	0.35
8	Potentiometer	R8	$10k\ \Omega$	1	0.35	0.35
9	Capacitor	C1	10nF,50V	1	2.50	2.50
10	Capacitor	C2	0.1 μF,50V	1	2.50	2.50
11	Mosfet	M1	4A,40V,5W	1	16.00	16.00
12	Linear IC	U1	LM324	1	10.00	10.00
13	Fuse	F1	0.5A,230V	1	5.00	5.00
14	Terminal Connector	T1,T2		2	1.00	2.00
15	PCB			1	25.00	25.00
					TOTAL	65.08

Chapter 2

7.5W 15V Voltage Regulator with Current Limits

2.1 Circuit Diagram

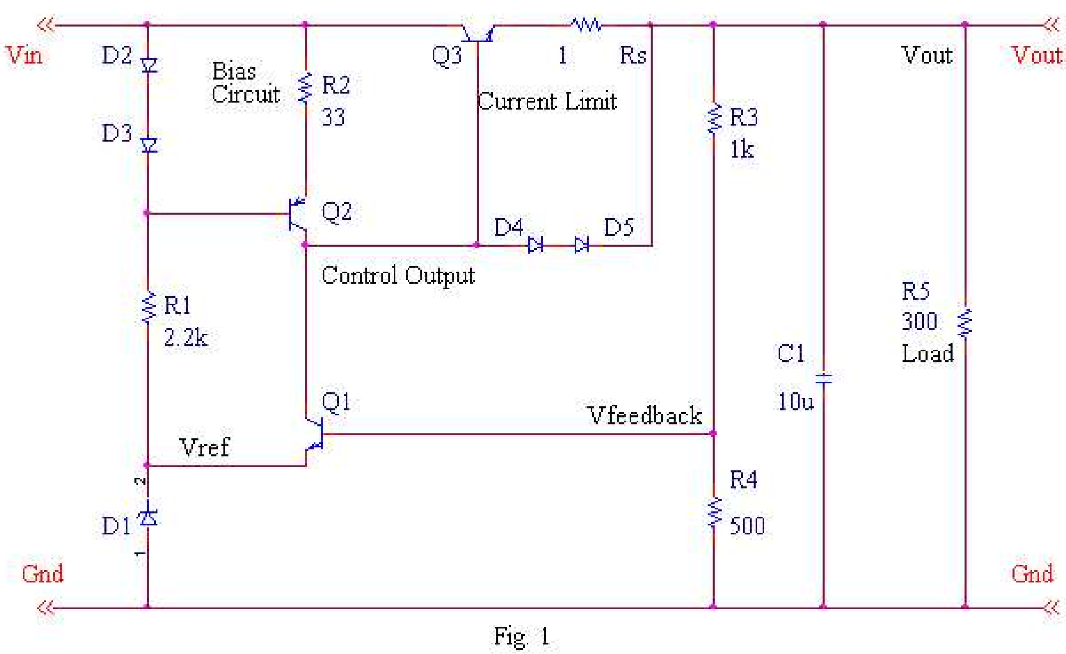


Figure 2.1: Voltage Regulator with Current Limits

2.2 Circuit Discription

The circuit shown in Fig. 1 is a BJT based series pass regulator.. A BJT (Q_3) is used in the linear mode with closed loop control to achieve constant output voltage. The resistor chain R_4 and R_5 determine the feedback ratio of the output. The feedback is compared with the reference voltage provided by D_1 (a 5 V zener). Q_1 acts as the feedback amplifier. The base bias for the output pass transistor is provided by the constant current drive Q_4. Current limit is provided by spill over diodes D_4 and D_5.
The mathematical relationships in the converter are as follows.

$$V_{REF} = V_{D1} \tag{2.1}$$

$$V_{FB} = V_{OUT}\left[\frac{R_4}{R_1 + R_4}\right] \tag{2.2}$$

$$I_{B1} = \frac{V_{FB} - V_{REF}}{R_3||R_4} \tag{2.3}$$

$$I_{C1} = \beta_1 I_{B1} \tag{2.4}$$

$$I_{BIAS} \simeq \frac{V_{BE}}{R_2} \tag{2.5}$$

$$I_{B3} = I_{BIAS} - I_{C1} \tag{2.6}$$

$$I_{OUT} \simeq \beta_3 I_{B3} \tag{2.7}$$

$$V_{OUT} = I_{OUT} R_5 \tag{2.8}$$

The bias current gets diverted when the drop in R_S is more than one diode drop.

$$I_{LIMIT} = \frac{V_{BE}}{R_S} \simeq 0.8A \tag{2.9}$$

Steady state analysis of the converter may be carried out as an exercise. The transistors may be replaced by the Eber-Moll model for the purpose of analysis. The diodes may be modeled as voltage drops.
Evaluate the steady state voltages of every node in the circuit and the current in every branch of the circuit for an input voltage of 25V and a load resistance of 50 Ω. Verify the same in the assembled circuit. Evaluate the power dissipation in Q_1, Q_2, and Q_3.

2.3 Mounted and Bare PCB Boards

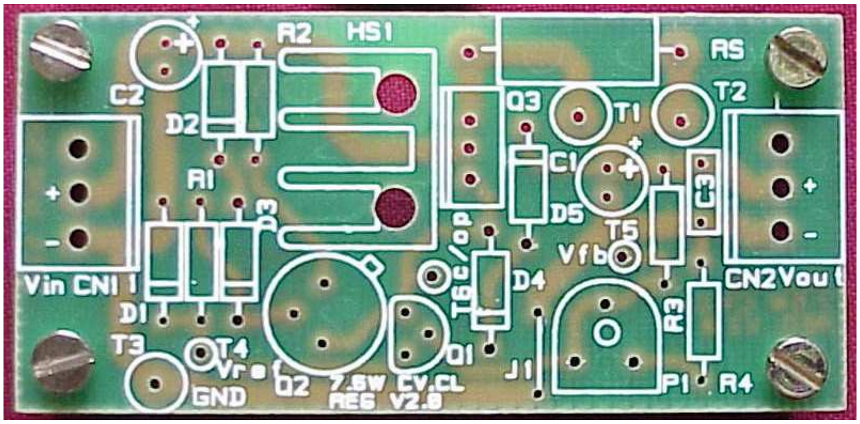


Figure 2.2: BareBoard

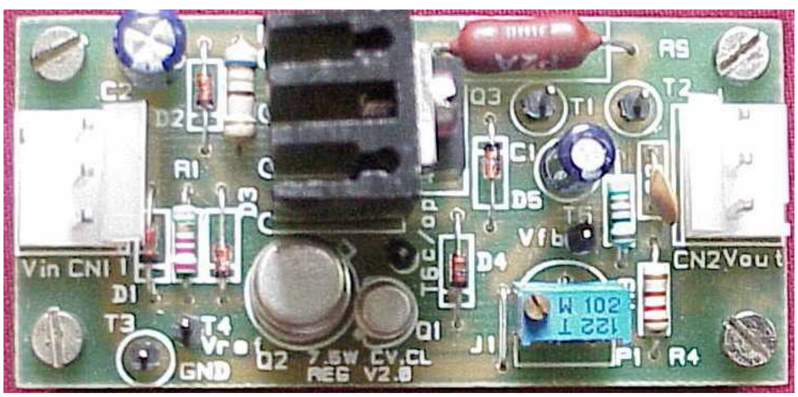


Figure 2.3: MountedBoard

2.4 Bill of Materials

Table 2.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1	$2.2k\ \Omega$	1	0.35	0.35
2	Resistor	R2	$4.7k\ \Omega$	1	0.35	0.35
3	Resistor	R3	$1k\ \Omega$	1	0.35	0.35
4	Resistor	R4	5000 Ω	1	0.35	0.35
5	Resistor	R5	300 Ω,1W	1	0.35	0.35
6	Resistor	Rs	1 Ω	1	0.35	0.35
7	Diode	D1	5V,400mW,Zener	1	1.00	1.00
8	Diode	D2,D3,D4,D5	IN4148	4	1.00	4.00
9	Capacitor	C1	10nF,50V	1	2.50	2.50
10	Transistor	Q1	2N222	1	5.00	5.00
11	Transistor	Q2	2N2904, 1W	1	5.00	5.00
12	Transistor	Q3	2A, 100V, 25W	1	10.00	10.00
13	Terminal Connector	T1,T2		2	1.00	1.00
14	PCB			1	25.00	25.00
					TOTAL	55.60

Chapter 3

7.5W Constant Current Constant Voltage Regulator

3.1 Circuit Diagram

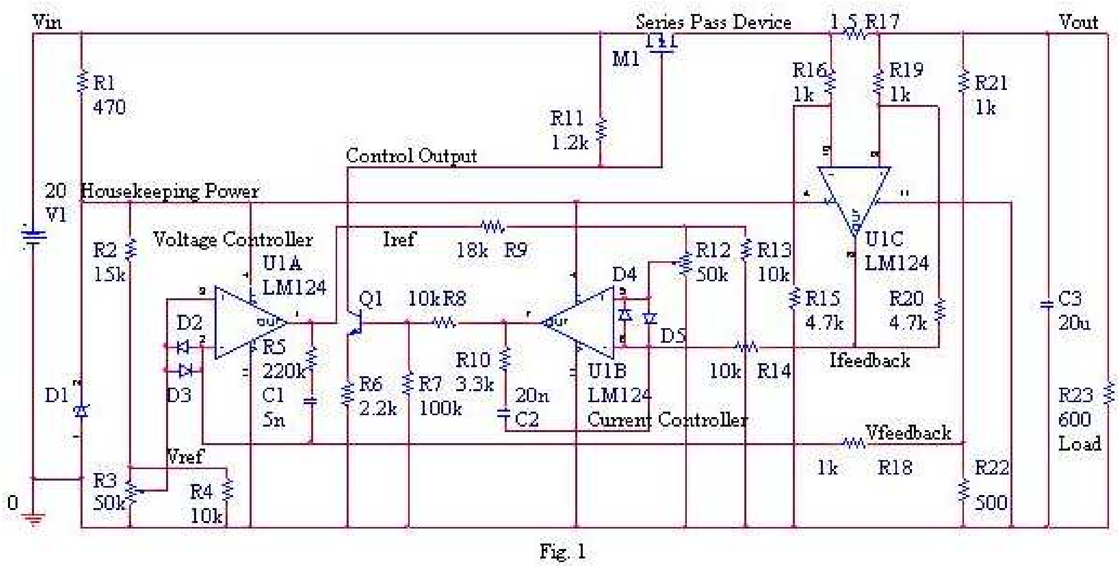


Figure 3.1: Linear Constant Current Constant Voltage Load

3.2 Circuit Discription

The circuit shown in Fig. 1 is a CCCV regulator. It works from source voltage of 20V to 35V. It provides constant current (settable below 500 mA) and constant voltage output (settable below 15V). The CC value is settable by the POT R12. The CV value is settable by the POT R3. The main power device M1 is a P channel MOSFET. The current feedback is through R17. The voltage feedback is through R21 and R22. The housekeeping power is from zener D1 biased with the resistor R1. Current signal is amplified with U1C (gain of 10). U1B is the current controller working as a PI amplifier. U1A is the voltage controller working as a PI amplifier. R3 sets the voltage reference (Full POT setting 15V). The voltage controller output is attenuated through R9 and R13 and serves as the current reference. R12 sets the current limit (Full POT setting 0.5A).

Current Feedback:

$$I_{feedback} = 1.5i\frac{R_{20}}{R_{19}} = 7i \tag{3.1}$$

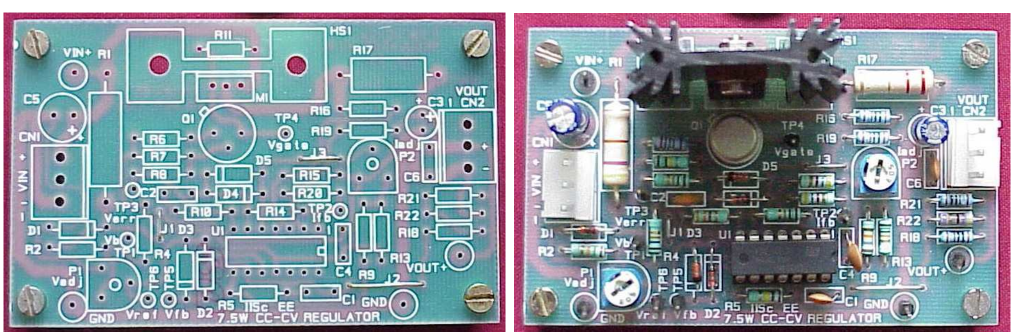
Current reference is variable from 0 to 4.75V (Saturation level of U1A through R9, R13 and R12. The corresponding current limit is variable between 0 and 650 mA).

Voltage Feedback:

$$V_{feedback} = V_{out}\frac{R_{22}}{R_{21}+R_{22}} = \frac{V_{out}}{3} \tag{3.2}$$

Voltage reference is variable from 0 to 5 V (Zener D1 voltage through R2, R3 and R4. The corresponding set voltage is variable between 0 and 15 V).

3.3 Mounted and Bare PCB Boards



(a) BareBoard (b) MountedBoard

Figure 3.2: PCB Board

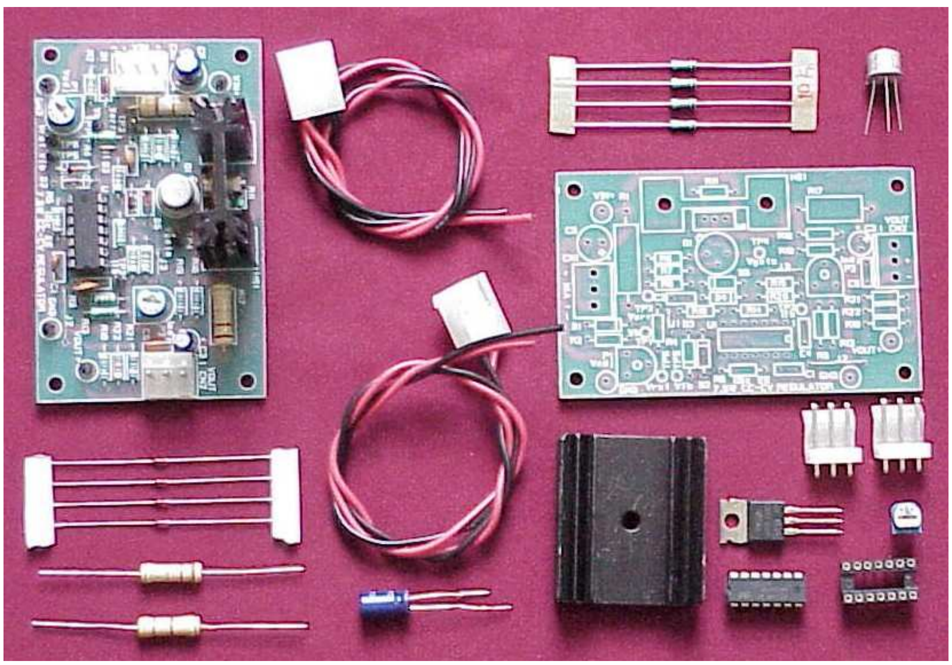


Figure 3.3: Components Used

3.4 Bill of Materials

Table 3.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1	470 Ω,2W	1	1	1
2	Resistor	R16,R18,R19,R21,	$1k$ Ω	4	0.35	0.35
3	Potentiometer	R3,R12	$50k$ Ω	2	0.50	1.00
4	Resistor	R4,R8,R13,R14	$10k$ Ω	4	0.35	0.35
5	Resistor	R5	$220k$ Ω	1	0.35	0.35
6	Resistor	R6	$2.2k$ Ω	1	0.35	0.35
7	Resistor	R7	$100k$ Ω	1	0.35	0.35
8	Potentiometer	R9	$18k$ Ω	1	0.50	0.50
9	Resistor	R10	$3.3k$ Ω	1	0.35	0.35
10	Resistor	R11	$1.2k$ Ω	1	0.35	0.35
11	Resistor	R2	$15k$ Ω	1	0.35	0.35
12	Resistor	R15,R20	$4.7k$ Ω	2	0.35	0.70
13	Resistor	R17	1.5 Ω,1W	1	0.50	0.50
14	Resistor	R22	500 Ω	1	0.35	0.35
15	Resistor	R23	600 Ω	1	0.35	0.35
16	Capacitor	C1	10nF,50V	1	2.50	2.50
17	Capacitor	C2	0.150 μF,50V	1	2.50	2.50
18	Capacitor	C3	2 μF,50V,Electrolytic	1	2.50	2.50
19	Capacitor	C4	0.1 μF,50V	1	2.50	2.50
20	Mosfet	M1	2A,40V,P Channel	1	16.00	16.00
21	Linear IC	U1	LM324	1	10.00	10.00
22	Diode	D1	15V,400mW,Zener	1	2.50	2.50
23	Diode	D2,D3,D4,D5	IN4148	4	2.50	10.00
24	Terminal Connector	T1,T2		2	1.00	2.00
25	PCB			1	25.00	25.00
					TOTAL	87.20

Chapter 4

7.5W Non-Isolated Boost Converter

4.1 Circuit Specification

This section covers a simple closed loop controlled boost converter with the following specifications.

- Input: 8V to 12V
- Output: 15V, 0.05A to 0.5A
- Topology: Non-isolated Boost followed by 3 pin Linear regulator
- Controller: UC494C(UC494C)
- Switching Frequency: 100 kHz
- Protection: None
  Figure below shows the full circuit diagram of the non-isolated boost converter operating from 12V battery (8V to 12V) providing regulated output power at 15V (0.5 A). The controller used is UC494 of Unitrode make.

4.2 Circuit Discription

1. Starting Power Supply:
   The starting power supply is obtained from $D_1(1N4148)$ and $C_1(10\ \mu F)$.

2. Oscillator Section:
   R_8 ($4.7k\ \Omega$) and C_2 (2.2 nF) determine the switching frequency. The switching frequency is given by

$$F_s = \frac{1.11}{R_t C_t} = 100KHz \tag{4.1}$$

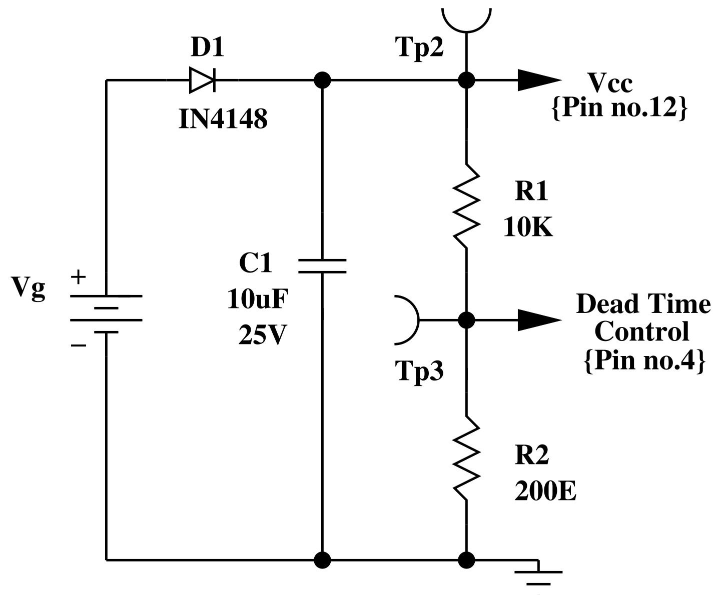


Figure 4.1: Startup and Dead Time Control Circuit

The selected switching frequency is approximately 100 kHz.

3. Minimum Pulse-Width:
   The minimum ON time is decided by the dead time control circuit $R_1(10k\ \Omega)$ and $R_2(220\ \Omega)$. On a ramp voltage of 3V, and an internal additional bias voltage of 0.1 V, this is selected to be 15%.

4. Reference Voltage:
   The internal reference is 5 V. The circuit uses a reference voltage of 2.5 V through the potential divider R_{10} ($10k\ \Omega$) and R_{11} ($10k\ \Omega$).

5. Biasing-out the unused amplifier:
   The controller has two internal amplifiers a and b. The amplifier outputs are wired such that the higher of the two outputs will prevail (wired OR). The amplifier b is not used and hence it is biased (non-inverting input to ground and inverting input to 2.5 V) such that its output is low.

6. Maximum Pulse-width limit:
   The amplifier output (Compensation pin) is compared with the internal ramp to generate the duty ratio. The amplifier output requires to be clamped below the peak of the ramp in order that the maximum duty ratio is well below 3 V, which is the peak of the ramp. For this purpose, the amplifier output is provided with a clamp circuit consisting of Q_1 (2N2222), R_6 ($10k\ \Omega$), R_7 ($10k\ \Omega$), and Q_2 (2N2907). The clamp level is obtained from a biased diode network consisting of D_2, D_3, D_4 (1N4148)

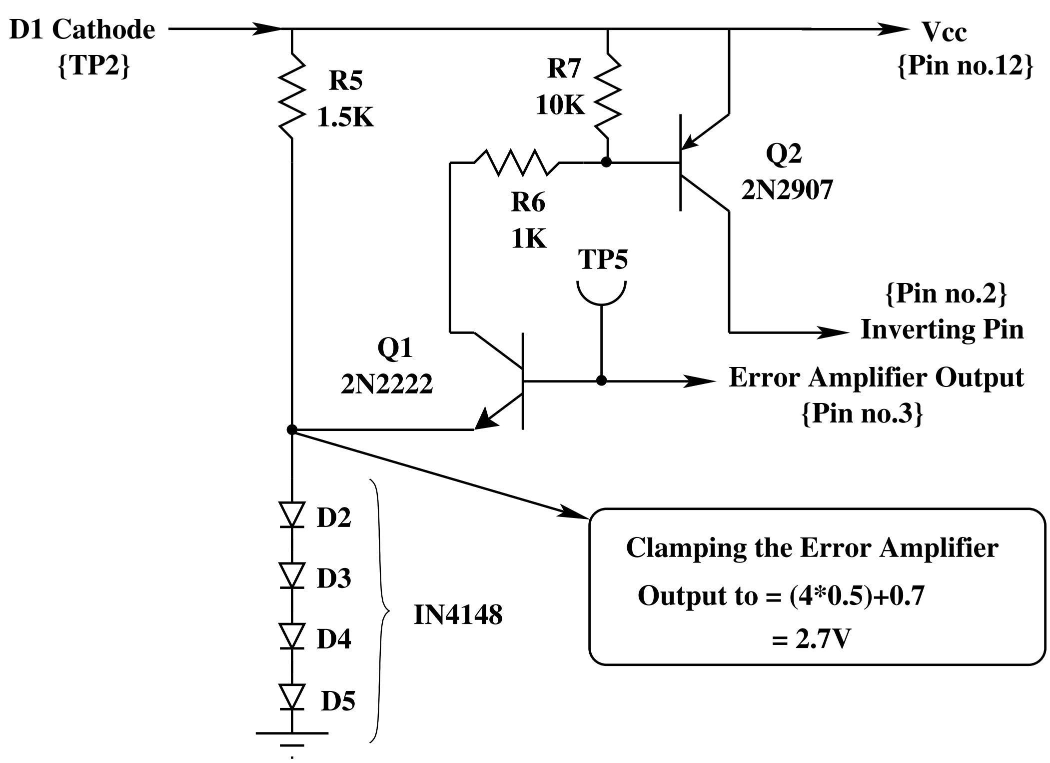


Figure 4.2: Maximum Pulse Width Circuit

and R_5 ($1.5k\ \Omega$). The clamp level is 4 diode drops including the base-emitter drop of Q_1.

7. Duty ratio:
The input voltage is in the range of 8 to 12 V. The output of the boost converter is designed for 17V. The range of duty ratio is from 0.29 to 0.53.

8. Main Inductor:
The rated current is 0.3 A. The ripple current is chosen as 0.1 A. With maximum on time of 5.3 μs, at input voltage of 8V, this gives an inductor value of approximately 400 μH.

9. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44)

10. The diode carries about 0.5 A average current and blocks about 20 V and suitable for 100 kHz switching. The reverse recovery time has to be better than 50ns. MUR110 is selected.(MUR110)

11. The output capacitor required has to limit the voltage ripple to about 1%(0.17V). This capacitor is selected to be 220 μF (an order of magnitude

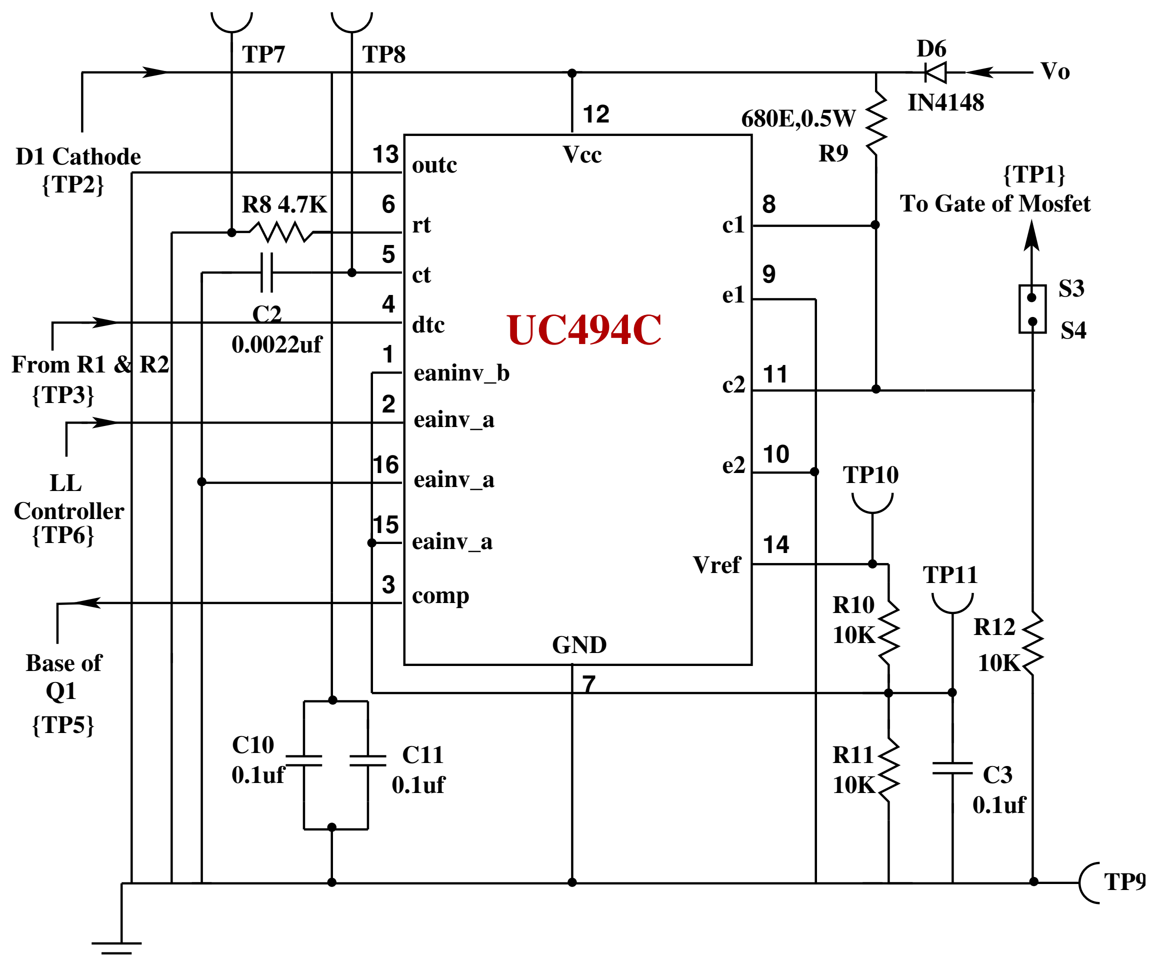


Figure 4.3: Controller Circuit

higher than the desired value).

12. The natural frequency of the converter is

$$Natural\ Frequency = \frac{1-d}{\sqrt{\{LC\}}} \tag{4.2}$$

which is ranging from 1584 rad/sec to 2393 rad/sec. The higher frequency is at higher voltage.

13. The dc gain from duty ratio to output voltage consists of modulator gain and converter gain. The modulator gain is the reciprocal of the ramp peak in the modulator. In UC494, it is 1/3.5. The converter dc gain is

$$DCGain = \frac{V_G}{[1-d]^2} \tag{4.3}$$

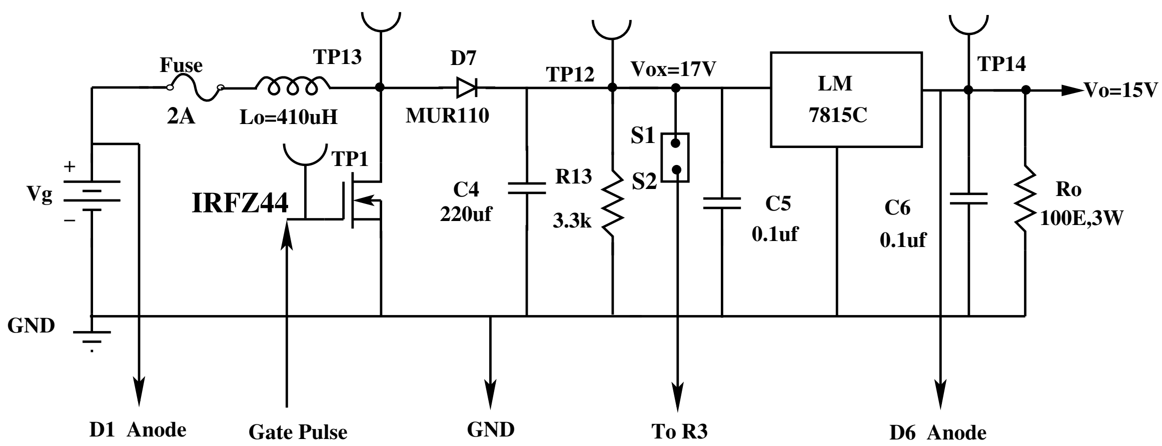


Figure 4.4: Power Circuit of Boost Converter

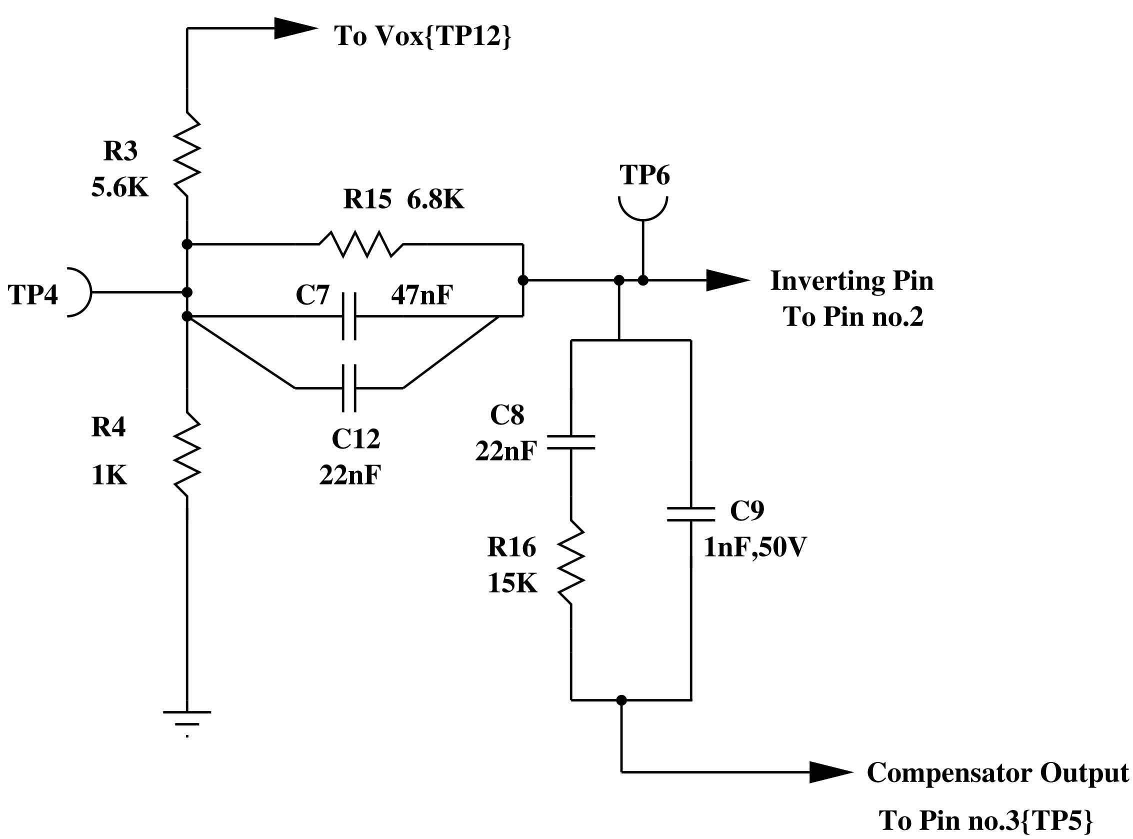


Figure 4.5: Feedback Circuit

This gain varies from 36 to 24. The overall gain is therefore 10.28 to 6.827 for the converter. The lower gain is at higher voltage.

14. The closed loop control used is a PI controller with lead/lag compensator. The PI corner frequency $[1/(R_{16}C_8)]$ is chosen at 1000 rad/sec The lead/lag compensator frequencies are chosen as $[1/(R_{15}C_7)]$ 1269 rad/sec and $[1/(C_7(R_3||R_4||R_{15})]$44000 rad/sec .

15. The loop gain band-width on unity feedback will be 5310 to 6710 rad/sec. The dc feedback gain is

$$DC\ Feedback\ Gain = \frac{15}{7.65} \tag{4.4}$$

16. The loop-gain cross-over frequency is 7160 rad/sec to 10500 rad/sec.

17. R_{13} serves as a bleeder load.

18. The output consists of a 3 pin regulator 7815 (U1). C_5 and C_6 are the input and output capacitors of the 3 pin regulator.

19. The MOSFET drive is through the pull up resistor R_9 (680 Ω) and the gate shunt resistor R_12 ($10k\ \Omega$)

20. R_{14} is the on-board load 30%. Additional 70% load may be connected off-board.

21. D_5 is the power supply diode fed from 15 V, following start-up.

4.3 Practical Bode Plot using Network Analyser

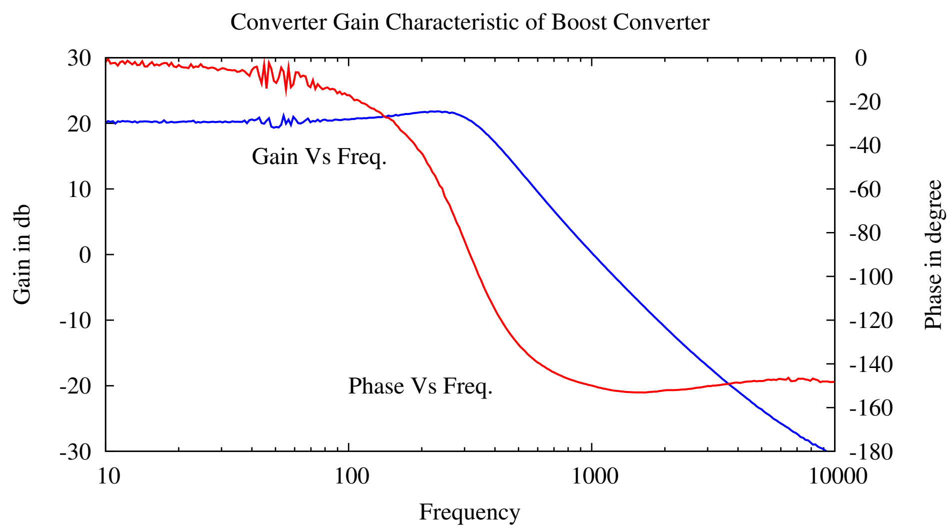


Figure 4.6: Converter Gain Bode Plot of Boost Converter

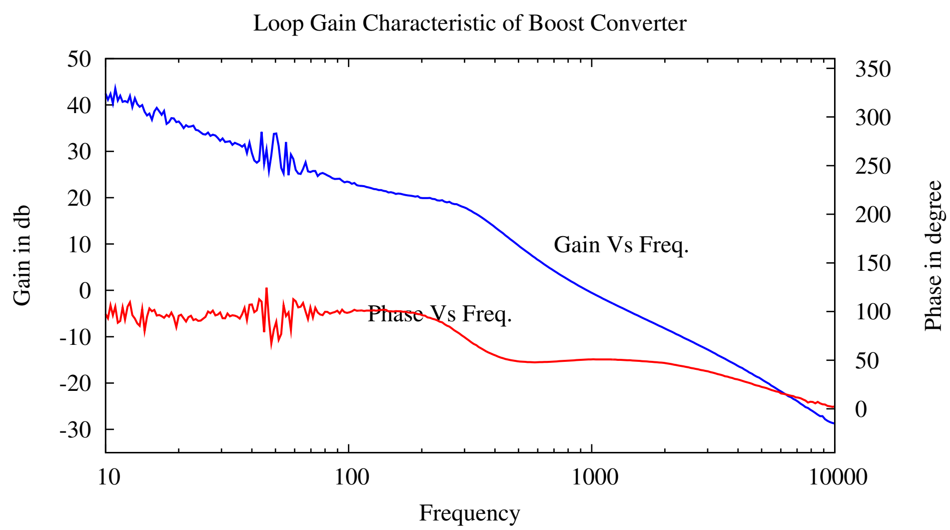


Figure 4.7: Closed Loop Gain Bode Plot of Boost Converter

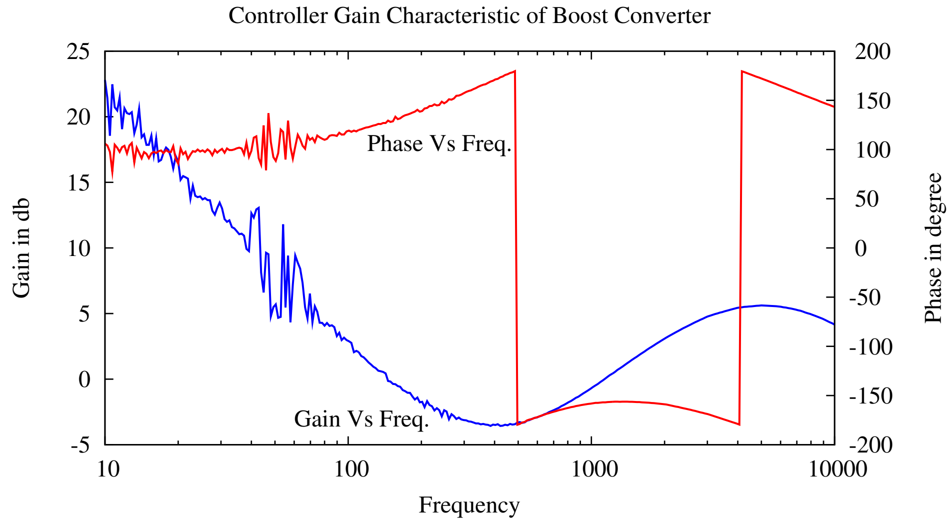


Figure 4.8: Controller Gain Bode Plot of Boost Converter

4.4 Mounted and Bare PCB Boards

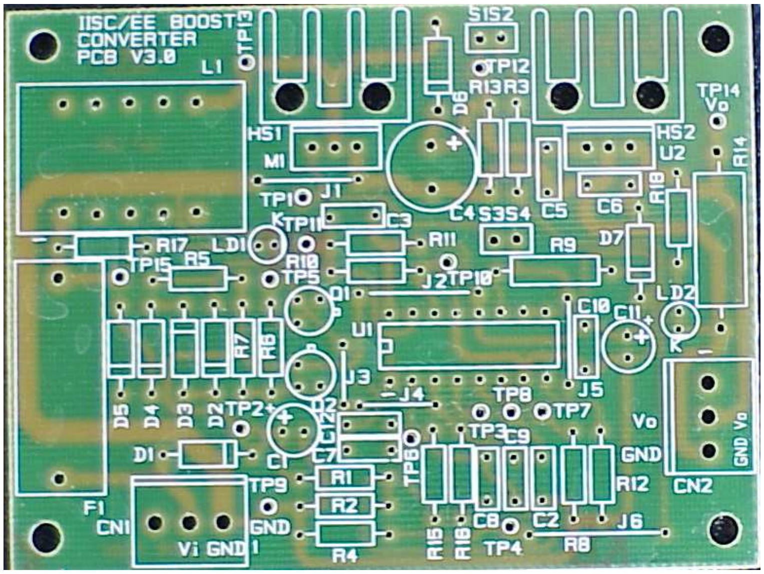


Figure 4.9: Bare PCB Board of Boost Converter

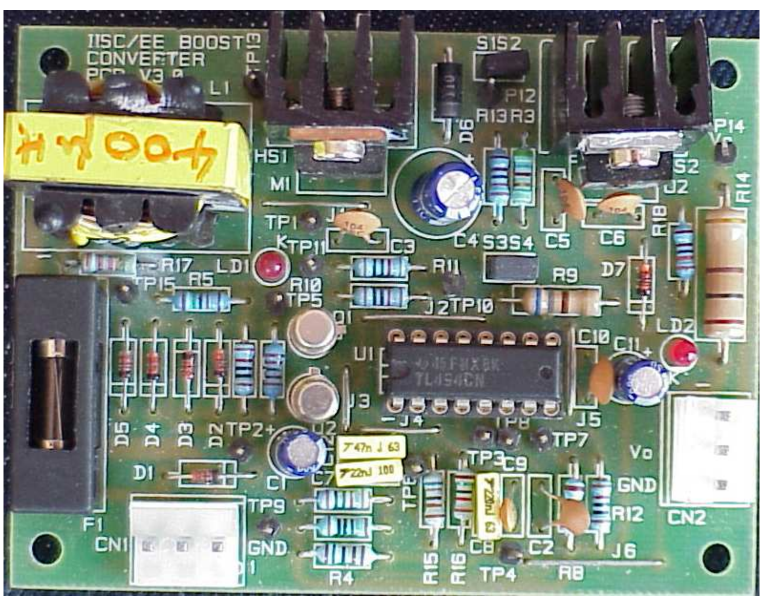


Figure 4.10: Mounted PCB Board of Boost Converter

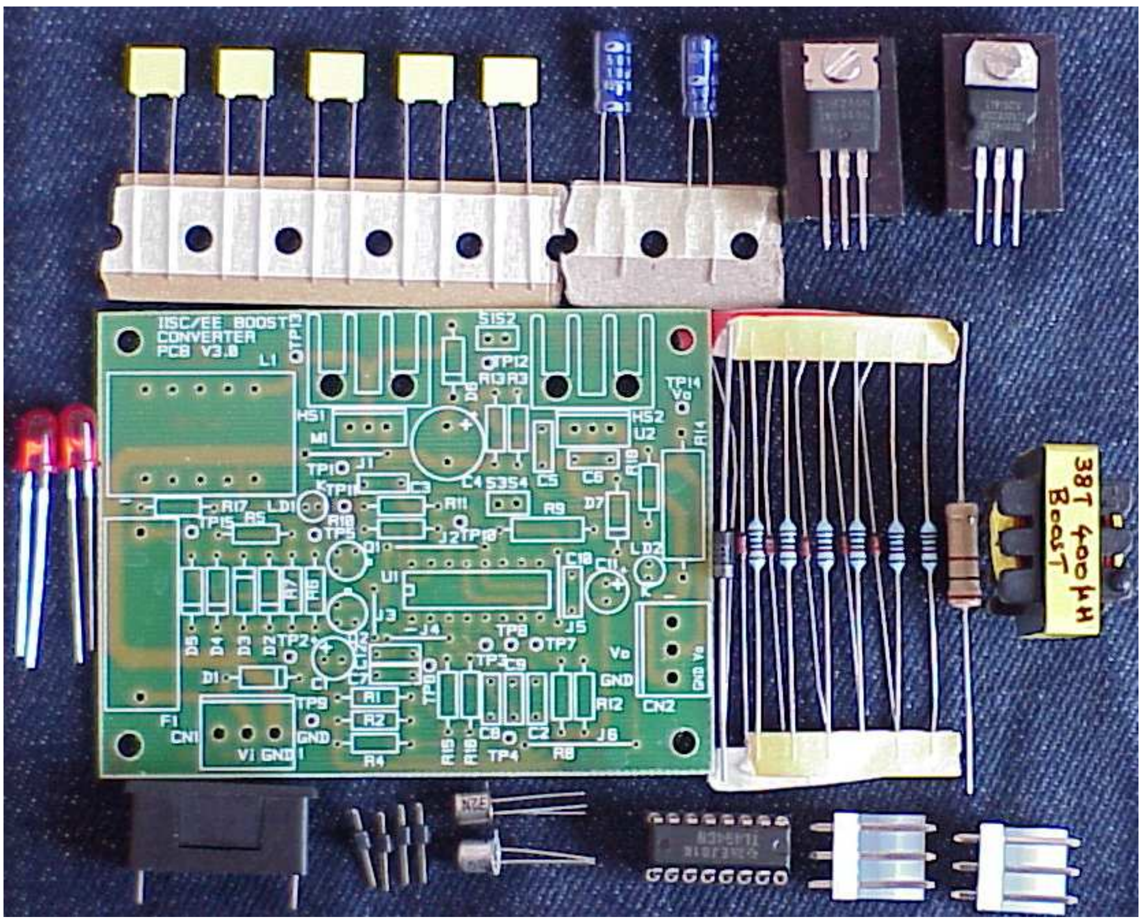
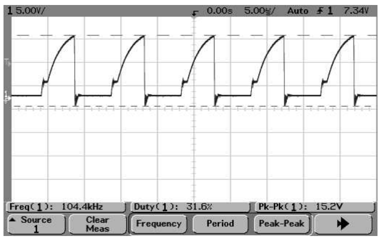
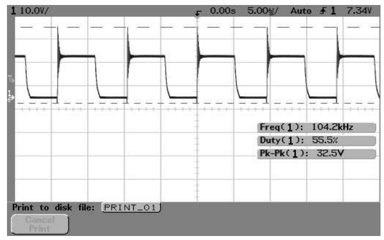


Figure 4.11: Components used in Boost Converter

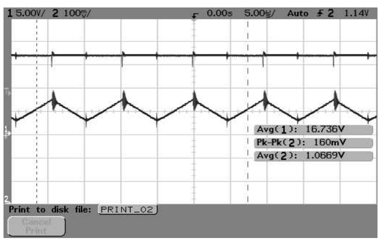
4.5 Pratical Waveform of the Boost Converter



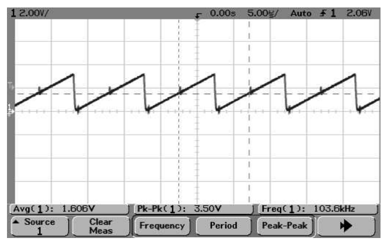
(a) Gate Voltage



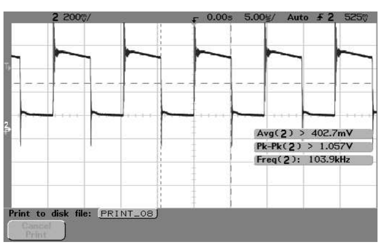
(b) Switch Voltage



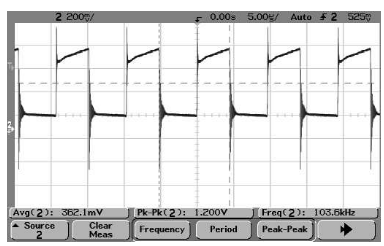
(c) Output voltage and Input Current of Boost Converter



(d) Ramp Voltage



(e) Diode Current



(f) Switch Current

4.6 PCB Films for Solder and Components Side

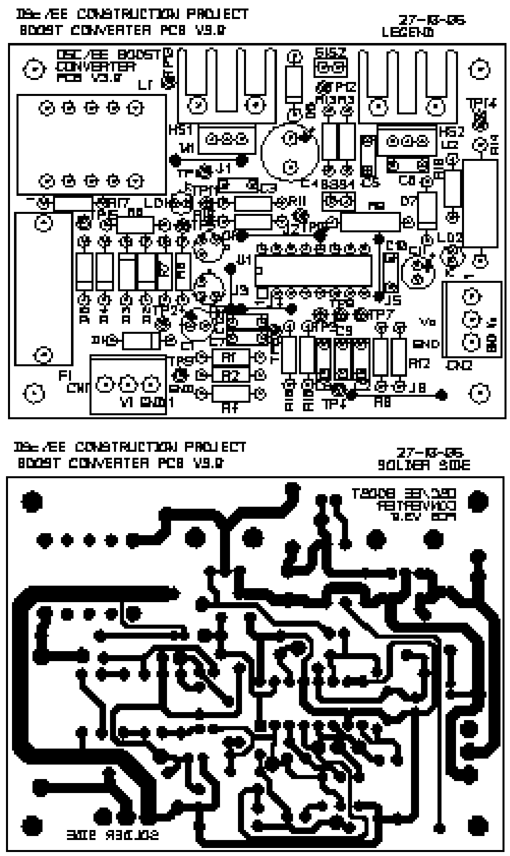


Figure 4.12: Solder and Component Side of Boost Converter

4.7 Bill of Materials

Table 4.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Amount
1	Resistor	R1,R7,R10 R11,R12	$10k\ \Omega$	5	0.35	1.75
2	Resistor	R2	200 Ω	1	0.35	0.35
3	Resistor	R3	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	R4,R6	$1k\ \Omega$	2	0.35	0.70
5	Resistor	R5	$1.5k\ \Omega$	1	0.35	0.35
6	Resistor	R8	$4.7k\ \Omega$	1	0.35	0.35
7	Resistor	R9	680 Ω	1	0.50	0.50
8	Resistor	R13	$3.3k\ \Omega$	1	0.35	0.35
9	Resistor	R14	100 Ω,3W	1	3.50	3.50
10	Resistor	R15	$6.8K\ \Omega$	1	0.35	0.35
11	Resistor	R16	$15K\ \Omega$	1	0.35	0.35
12	Capacitor	C1	10 μF,25V	1	0.50	0.50
13	Capacitor	C2	0.0022 μF,63V	1	2.50	2.50
14	Capacitor	C3,C5, C6,C10	0.1 μF,50V	4	1.00	4.00
15	Capacitor	C4	220 μF,25V	1	2.00	2.00
16	Capacitor	C7,C8	0.022 μF,50V	2	2.50	5.00
17	Capacitor	C12	0.047 μF,50V	1	2.50	2.50
18	Capacitor	C9	0.001 μF,50V	1	2.50	2.50
19	Capacitor	C11	0.01 μF,	1	0.50	0.50
20	Fuse	F1	1A,230V	1	1.00	1.00
21	Mosfet	M1	IRFZ44N	1	16.00	16.00
22	Inductor	L1	400 μH	1	25.00	25.00
23	Transisor	Q1	2N2222	1	4.50	4.50
24	Transisor	Q2	2N2907	1	4.50	4.50
25	Diode	D1,D2,D3, D4,D5	IN4148	5	0.40	2.00
26	Diode	D6	MUR110	1	8.00	8.00
27	Linear IC	U1	UC494	1	7.00	7.00
28	Linear IC	U2	LM7815C	1	7.00	7.00
29	Test Points	T1	Berg Stick	18	0.10	1.80
28	Jumpers	NMJ,GJ		2	0.10	0.20
30	16 Pin IC Base	U1b		1	5.00	5.00
31	Terminal Connector	T1,T2		2	3.00	6.00
32	Heat Sink	HS1,HS2	P149	2	5.00	10.00
33	PCB	7.5W HKPS V3.0	Size-8.35*6.44cm	1	25.00	25.00
					TOTAL	151.40

Chapter 5

7.5W Non-Isolated Flyback Converter

5.1 Circuit Specification

This section covers a simple closed loop controlled flyback converter with the following specifications.

- Input: 15V to 25V
- Output: 15V, 0.5A, 7.5W
- Topology: Non-isolated Boost followed by 3 pin Linear regulator
- Controller: UC494C(UC494C)
- Switching Frequency: 100 kHz
- Protection: None
  Figures below shows the full circuit diagram of the non-isolated flyback converter operating from 25V battery (15V to 25V) providing regulated output power at 15V (0.5 A). The controller used is UC494 of Unitrode make.

5.2 Circuit Discription

1. Starting Power Supply:
   The starting power supply is obtained from $D_1(1N4148)$ and $C_1(10\ \mu F)$.

2. Oscillator Section:
   R_8 ($4.7k\ \Omega$) and C_2 (2.2 nF) determine the switching frequency. The switching frequency is given by

$$F_s = \frac{1.11}{R_t C_t} = 100KHz \tag{5.1}$$

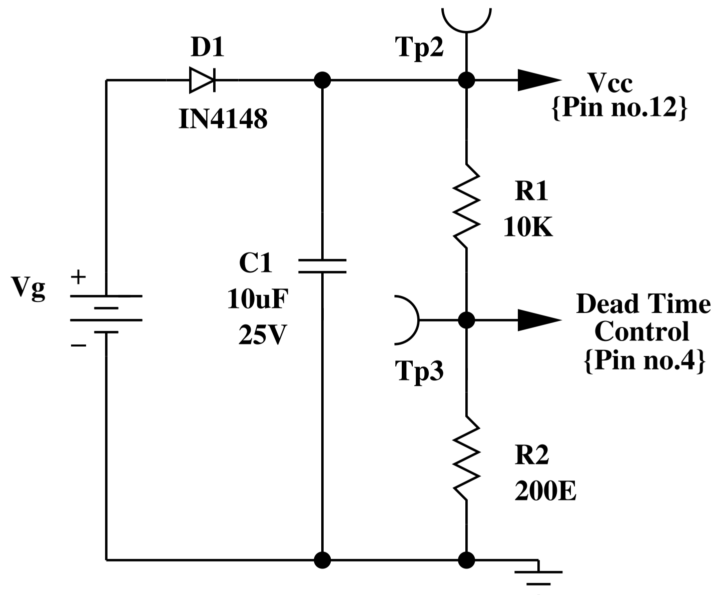


Figure 5.1: Startup Circuit

The selected switching frequency is approximately 100 kHz.

3. Minimum Pulse-Width:
The minimum ON time is decided by the dead time control circuit $R_1(10k\ \Omega)$ and R_2 (220 Ω). On a ramp voltage of 3V, and an internal additional bias voltage of 0.1 V, this is selected to be 15%.

4. Reference Voltage:
The internal reference is 5 V. The circuit uses a reference voltage of 2.5 V through the potential divider R_{10} ($10k\ \Omega$) and $R_1 1$ ($10k\ \Omega$).

5. Biasing-out the unused amplifier:
The controller has two internal amplifiers a and b. The amplifier outputs are wired such that the higher of the two outputs will prevail (wired OR). The amplifier b is not used and hence it is biased (non-inverting input to ground and inverting input to 2.5 V) such that its output is low.

6. Maximum Pulse-width limit:
The amplifier output (Compensation pin) is compared with the internal ramp to generate the duty ratio. The amplifier output requires to be clamped below the peak of the ramp in order that the maximum duty ratio is well below 3 V, which is the peak of the ramp. For this purpose, the amplifier output is provided with a clamp circuit consisting of Q_1 (2N2222), R_6 ($10k\ \Omega$), R_7 ($10k\ \Omega$), and Q_2 (2N2907). The clamp level is obtained from a biased diode network consisting of D_2, D_3, D_4 (1N4148)

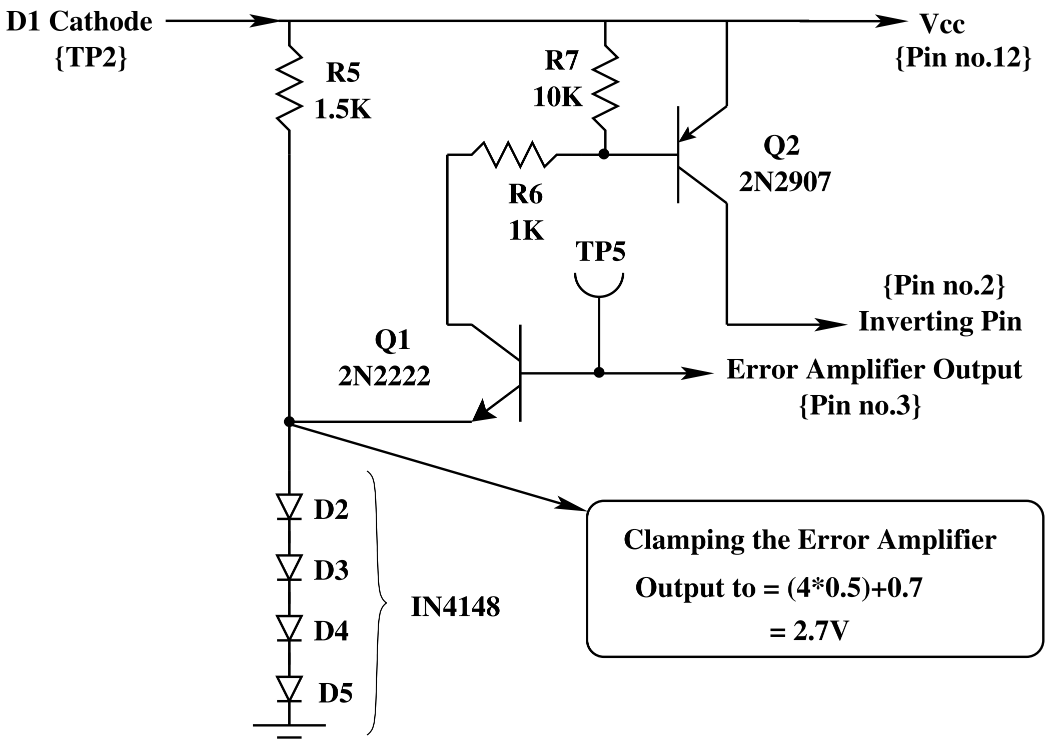


Figure 5.2: Maximum Pulse Width Circuit

and R_5 ($1.5k\ \Omega$). The clamp level is 4 diode drops including the base-emitter drop of Q_1.

7. Duty ratio:
The input voltage is in the range of 15 to 25. The output of the boost converter is designed for 17V. The range of duty ratio is from 0.49 to 0.62.

8. Main Inductor:
The rated current is 1.11 A. The ripple current is chosen as 0.22 A. With maximum on time of 6 μs, at input voltage of 15V, this gives an inductor value of approximately 400 μH with turns ratio oof 0.691, the primary is 48 turns and secondary is 33 turns.

9. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44)

10. The diode carries about 0.5 A average current and blocks about 20V and suitable for 100 kHz switching. The reverse recovery time has to be better than 50ns. MUR110 is selected.(MUR110)

11. The output capacitor required has to limit the voltage ripple to about

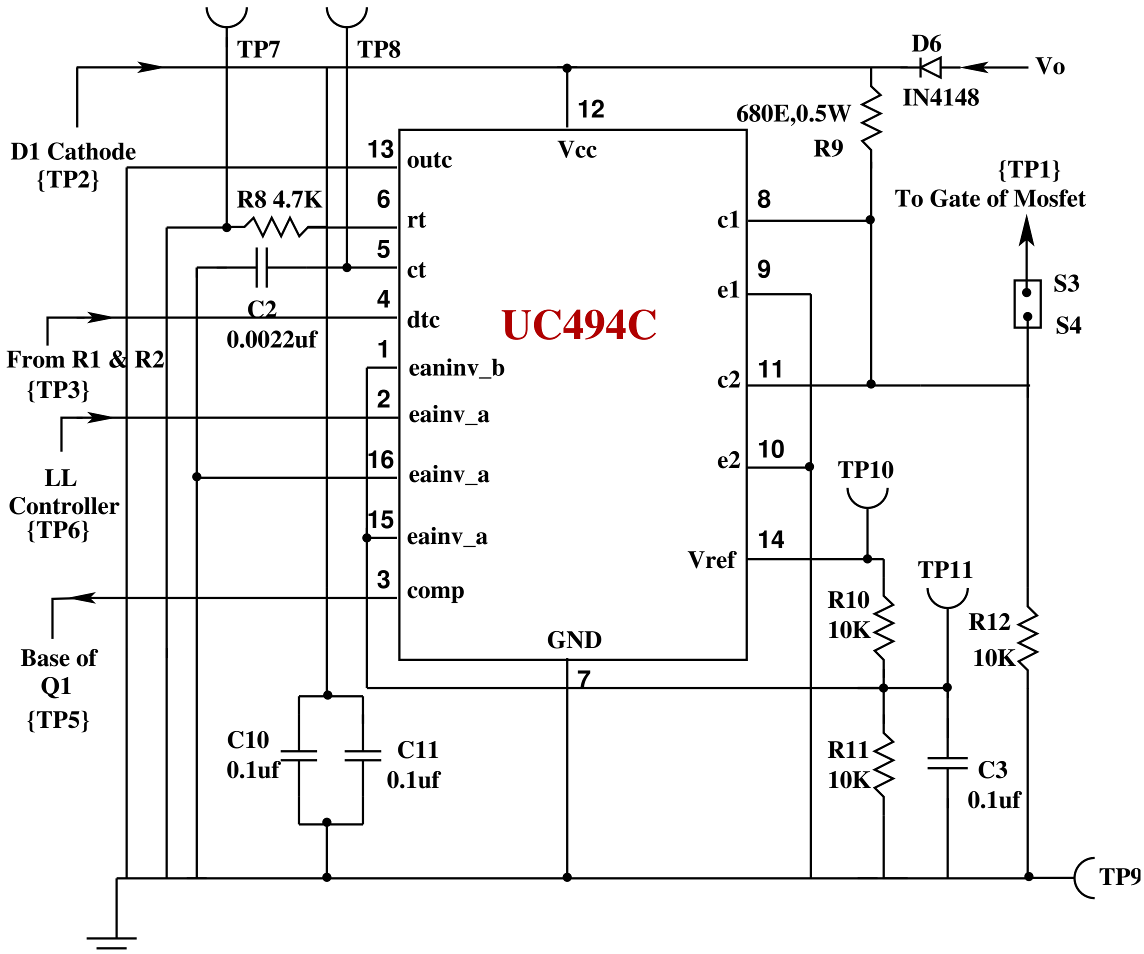


Figure 5.3: Controller Circuit

1%(0.17V). This capacitor is selected to be 220 μF (an order of magnitude higher than the desired value).

12. The natural frequency of the converter is

$$Natural\ Frequency = \frac{1-d}{\sqrt{\{LC\}}} \tag{5.2}$$

which is ranging from 1265 rad/sec to 1698 rad/sec. The higher frequency is at higher voltage.

13. The dc gain from duty ratio to output voltage consists of modulator gain and converter gain. The modulator gain is the reciprocal of the ramp peak in the modulator. In UC494, it is 1/3.5. The converter dc gain is

$$DC\ Gain = \frac{nV_G}{[1-d]^2} \tag{5.3}$$

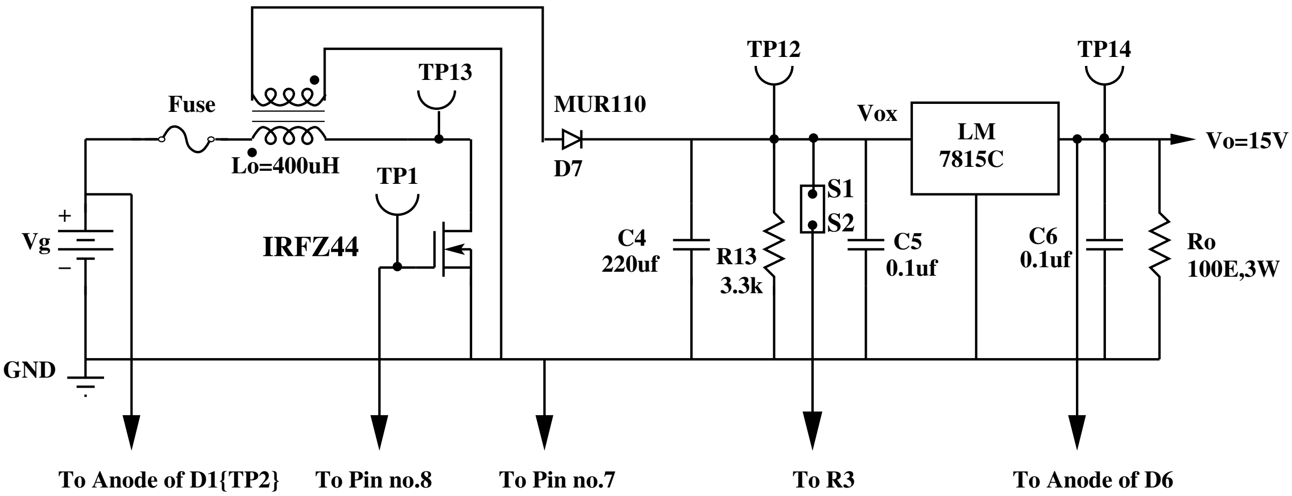


Figure 5.4: Power Circuit of Flyback Converter

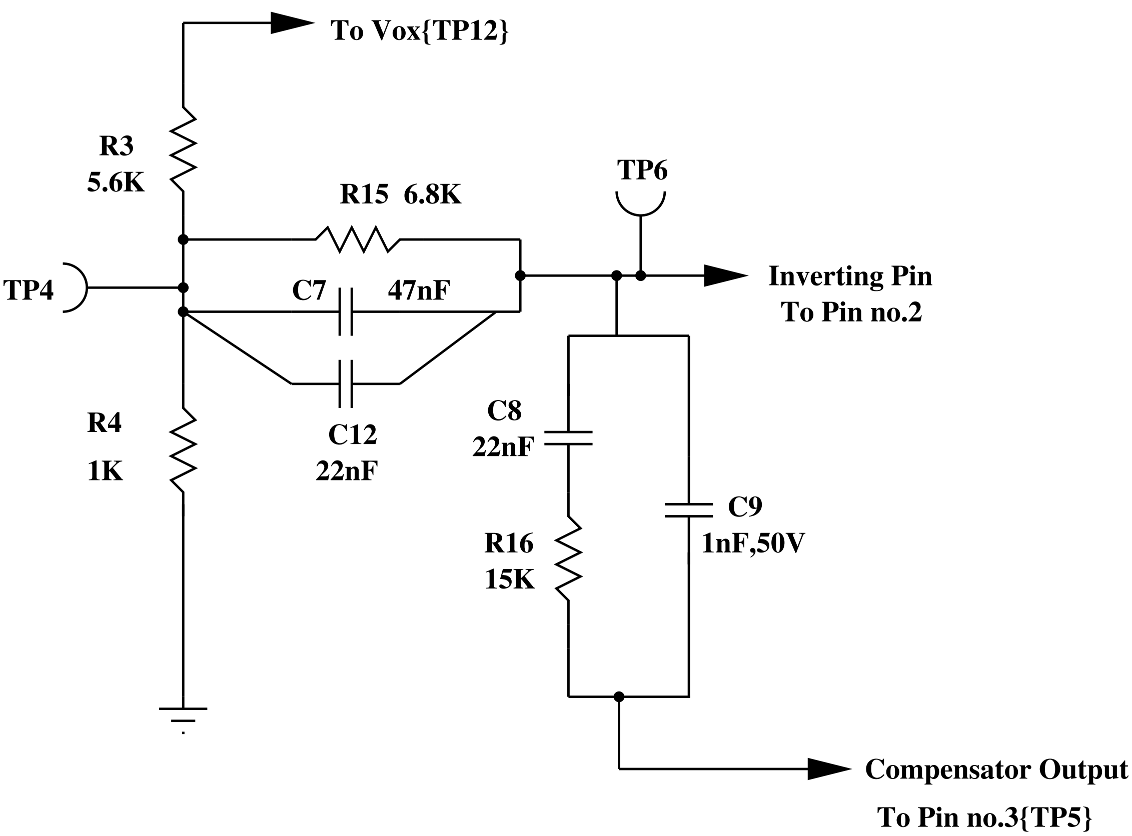


Figure 5.5: Feedback Circuit

This gain varies from 72 to 66. The overall gain is therefore 20.47 to 18.87 for the converter. The lower gain is at higher voltage.The closed loop control used is a PI controller with lead/lag compensator. The PI corner frequency $[1/(R_{16}C_8)]$ is chosen at 3030 rad/sec. The lead/lag compensator frequencies $[1/(R_{15}C_7)]$ are chosen as 2220 rad/sec and $[1/(C_7R_3||R_4||R_{15})]$22000 rad/sec .

14. The loop gain band-width on unity feedback will be 5900 to 7610 rad/sec. The dc feedback gain is

$$DC\ Feedback\ Gain = \frac{15}{7.548} \tag{5.4}$$

15. The loop-gain cross-over frequency is 5700 rad/sec to 8150 rad/sec.
16. R_{13} serves as a bleeder load.
17. The output consists of a 3 pin regulator 7815 (U1). C_5 and C_6 are the input and output capacitors of the 3 pin regulator.
18. The MOSFET drive is through the pull up resistor R_9 (680 Ω) and the gate shunt resistor R_12 (10k Ω)
19. R_{14} is the on-board load 30%. Additional 70% load may be connected off-board.
20. D_5 is the power supply diode fed from 15 V, following start-up.

5.3 Practical Bode Plot using Network Analyser

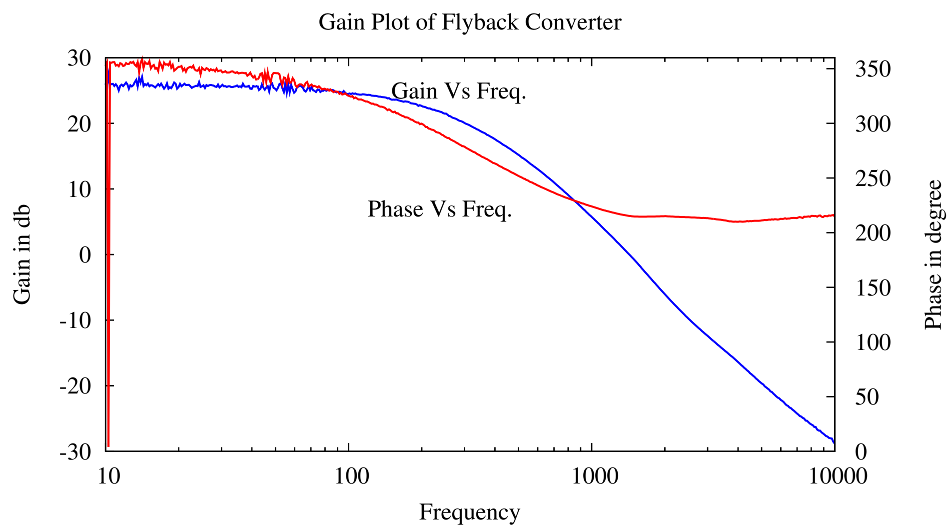


Figure 5.6: Converter Gain Bode Plot of Flyback Converter

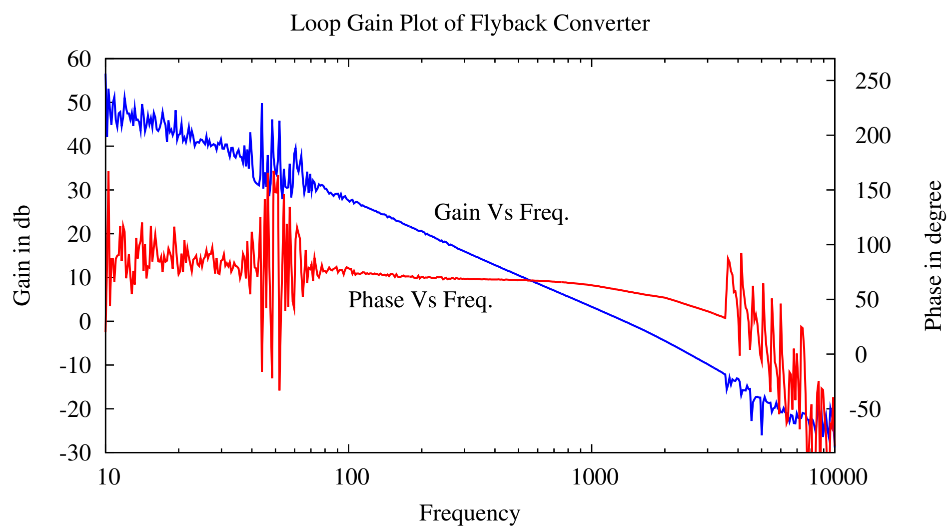


Figure 5.7: Closed Loop Gain Bode Plot of Flyback Converter

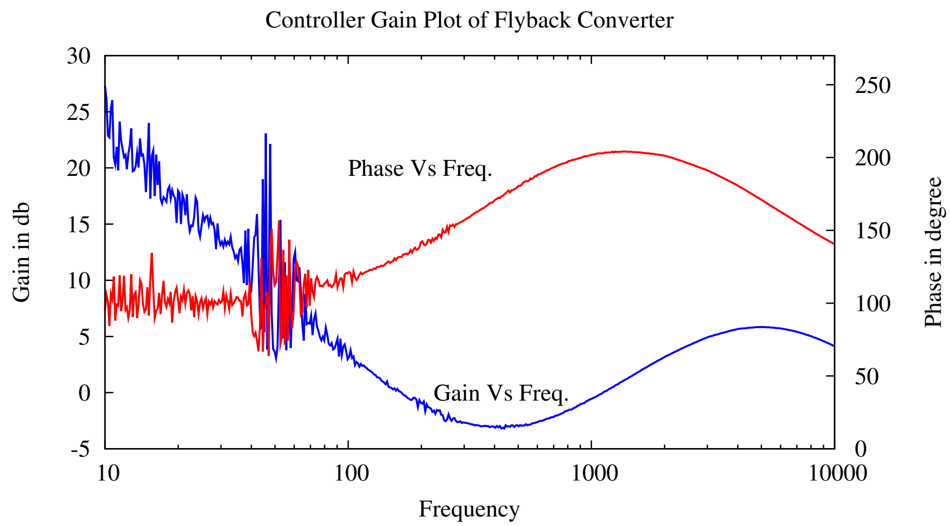
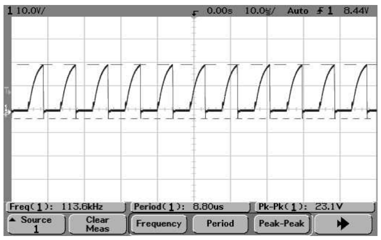
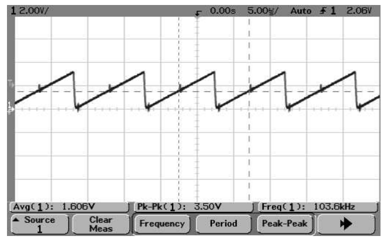


Figure 5.8: Controller Gain Bode Plot of Flyback Converter

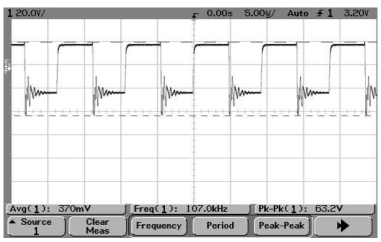
5.4 Pratical Waveform of the Flyback Converter



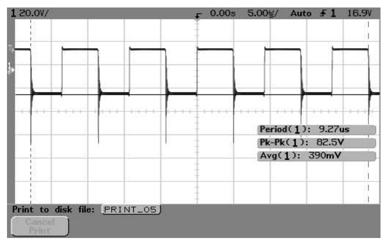
(a) Gate Voltage



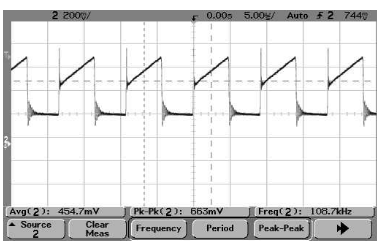
(b) Ramp Voltage



(c) Primary Inductor Voltage



(d) Seconday Inductor Voltage



(e) Primay Current

(f) Output voltage and Output Current of Flyback Converter

5.5 Mounted and Bare PCB Boards

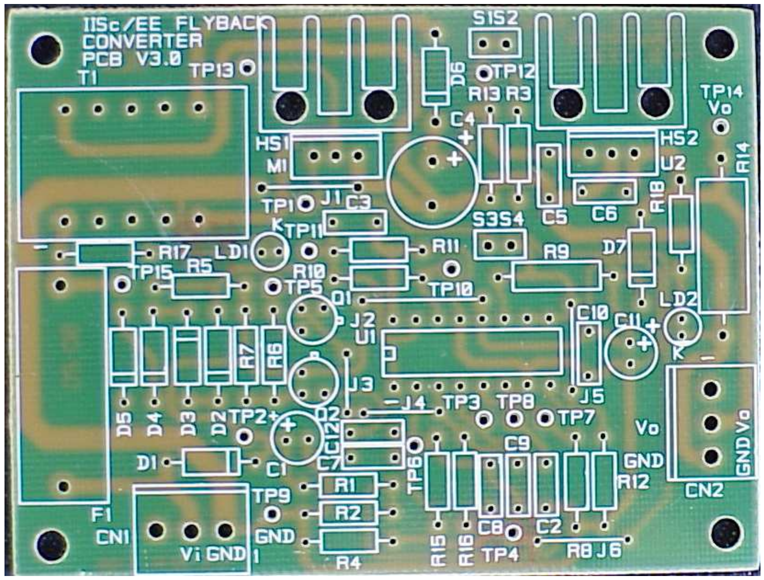


Figure 5.9: Bare PCB Board of Flyback Converter

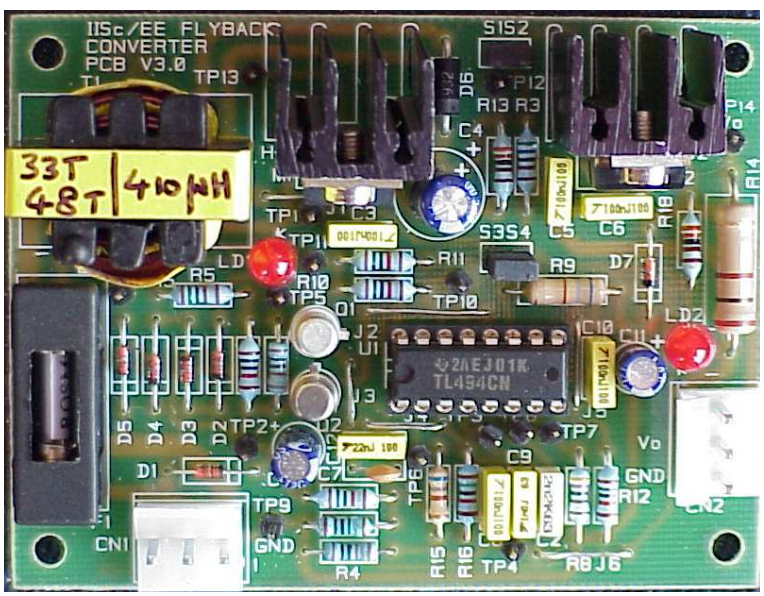


Figure 5.10: Mounted PCB Board of Flyback Converter

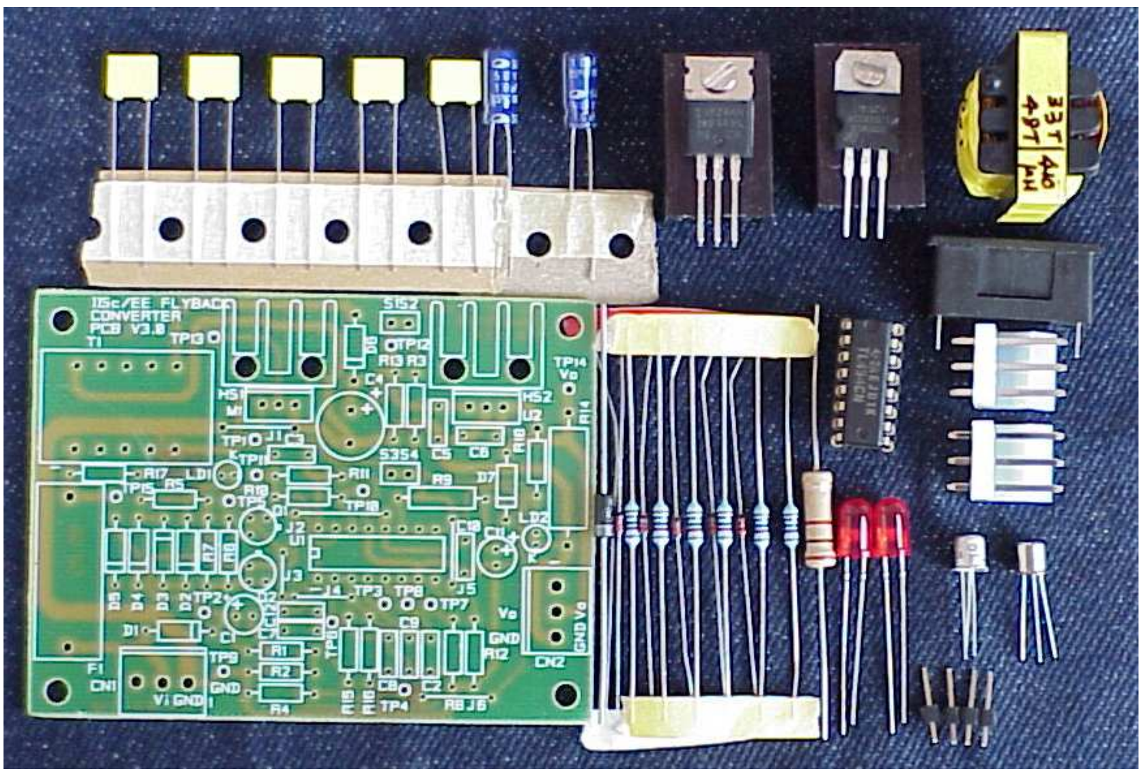


Figure 5.11: Components used in a Flyback Converter

5.6 PCB Films for Solder and Components Side

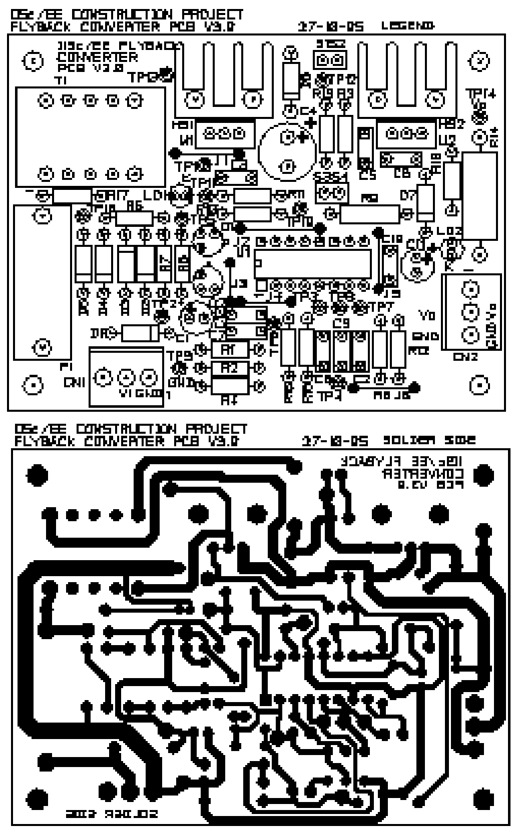


Figure 5.12: Solder and Component Side of Flyback Converter

5.7 Bill of Materials

Table 5.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Amount
1	Resistor	R1,R7,R10, R11,R12	$10k\ \Omega$	5	0.35	1.75
2	Resistor	R2	$200\ \Omega$	1	0.35	0.35
3	Resistor	R3	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	R4,R6	$1k\ \Omega$	2	0.35	0.70
5	Resistor	R5	$1.5k\ \Omega$	1	0.35	0.35
6	Resistor	R8	$4.7k\ \Omega$	1	0.35	0.35
7	Resistor	R9	$680\ \Omega$	1	0.50	0.50
8	Resistor	R13	$3.3k\ \Omega$	1	0.35	0.35
9	Resistor	R14	$100\ \Omega$,3W	1	3.50	3.50
10	Resistor	R15	$6.8k\ \Omega$	1	0.35	0.35
11	Resistor	R16	$15k\ \Omega$	1	0.35	0.35
11	Capacitor	C1	$10\ \mu F$,25V	1	0.50	0.50
13	Capacitor	C2	$0.0022\ \mu F$,63V	1	2.50	2.50
14	Capacitor	C3,C5, C6,C10	$0.1\ \mu F$,50V	4	1.00	4.00
15	Capacitor	C4	$220\ \mu F$,25V	1	2.00	2.00
16	Capacitor	C12,C8	$0.022\ \mu F$,50V	2	2.50	5.00
17	Capacitor	C7	$0.047\ \mu F$,50V	1	2.50	2.50
18	Capacitor	C9	$0.001\ \mu F$,50V	1	2.50	2.50
19	Capacitor	C11	$0.01\ \mu F$,	1	0.50	0.50
20	Fuse	F1	1A,230V	1	1.00	1.00
21	Mosfet	M1	IRFZ44N	1	16.00	16.00
22	Inductor	L1	$410\ \mu H$ 1A,48/33 Turns	1	25.00	25.00
23	Transisor	Q1	2N2222	1	4.50	4.50
24	Transisor	Q2	2N2907	1	4.50	4.50
25	Diode	D1,D2,D3, D4,D5	IN4148	5	0.40	2.00
26	Diode	D6	MUR110	1	8.00	8.00
27	Linear IC	U1	UC494	1	7.00	7.00
28	Linear IC	U2	LM7815C	1	7.00	7.00
29	Test Points	T1	Berg Stick	20	0.10	2.00
30	16 Pin IC Base	U1b		1	5.00	5.00
31	Terminal Connector	T1,T2		2	3.00	6.00
32	Heat Sink	HS1,HS2	P149	2	5.00	10.00
33	PCB	7.5W Flyback V3.0	Size-8.35*6.44cm	1	25.00	25.00
34	Jumper	J1,J2	Jumpers	2	0.50	1.00
					TOTAL	155.90

Chapter 6

7.5W Non-Isolated Forward Converter

6.1 Circuit Specification

This section covers a simple closed loop controlled forward converter with the following specifications.

- Input: 10V to 15V
- Output: 17V, 0.5A, 7.5W
- Topology: Non-isolated Forward Converter
- Controller: UC494C(UC494C)
- Switching Frequency: 100 kHz
- Protection: None
  Figures below shows the full circuit diagram of the non-isolated forward converter operating from 15V battery (10V to 15V) providing regulated output power at 17V (0.45 A). The controller used is UC494 of Unitrode make.

6.2 Circuit Discription

1. Starting Power Supply:
   The starting power supply is obtained from $D_1(1N4148)$ and $C_1(10\ \mu F)$.

2. Oscillator Section:
   R_8 ($4.7k\ \Omega$) and C_2(2.2 nF) determine the switching frequency. The switching frequency is given by

$$F_s = \frac{1.11}{R_t C_t} = 100KHz \tag{6.1}$$

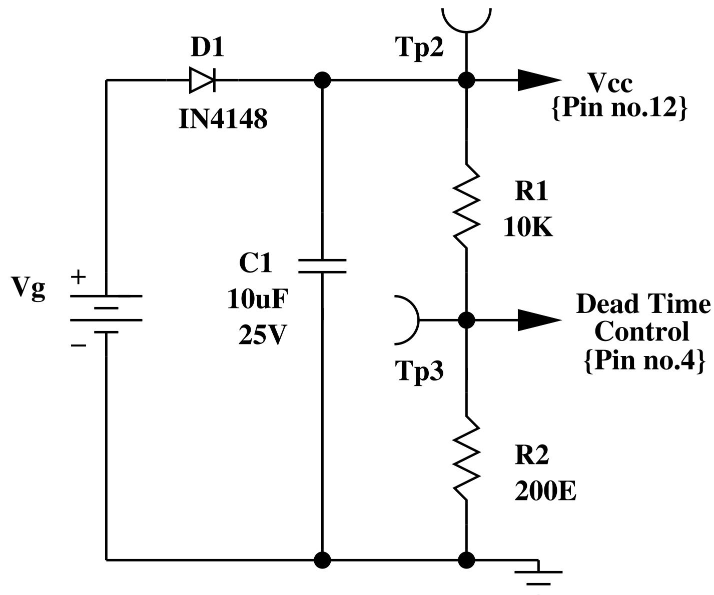


Figure 6.1: Startup Circuit

The selected switching frequency is approximately 100 kHz.

3. Minimum Pulse-Width:
The minimum ON time is decided by the dead time control circuit $R_1(10k\,\Omega)$ and R_2 (220 Ω). On a ramp voltage of 3V, and an internal additional bias voltage of 0.1 V, this is selected to be 15%.

4. Reference Voltage:
The internal reference is 5 V. The circuit uses a reference voltage of 2.5 V through the potential divider R_{10} ($10k\ \Omega$) and R_11 ($10k\ \Omega$).

5. Biasing-out the unused amplifier:
The controller has two internal amplifiers a and b. The amplifier outputs are wired such that the higher of the two outputs will prevail (wired OR). The amplifier b is not used and hence it is biased (non-inverting input to ground and inverting input to 2.5 V) such that its output is low.

6. Maximum Pulse-width limit:
The amplifier output (Compensation pin) is compared with the internal ramp to generate the duty ratio. The amplifier output requires to be clamped below the peak of the ramp in order that the maximum duty ratio is well below 3 V, which is the peak of the ramp. For this purpose, the amplifier output is provided with a clamp circuit consisting of Q_1 (2N2222), R_6 ($10k\ \Omega$), R_7 ($10k\ \Omega$), and Q_2 (2N2907). The clamp level is obtained from a biased diode network consisting of D_2, D_3, D_4 (1N4148)

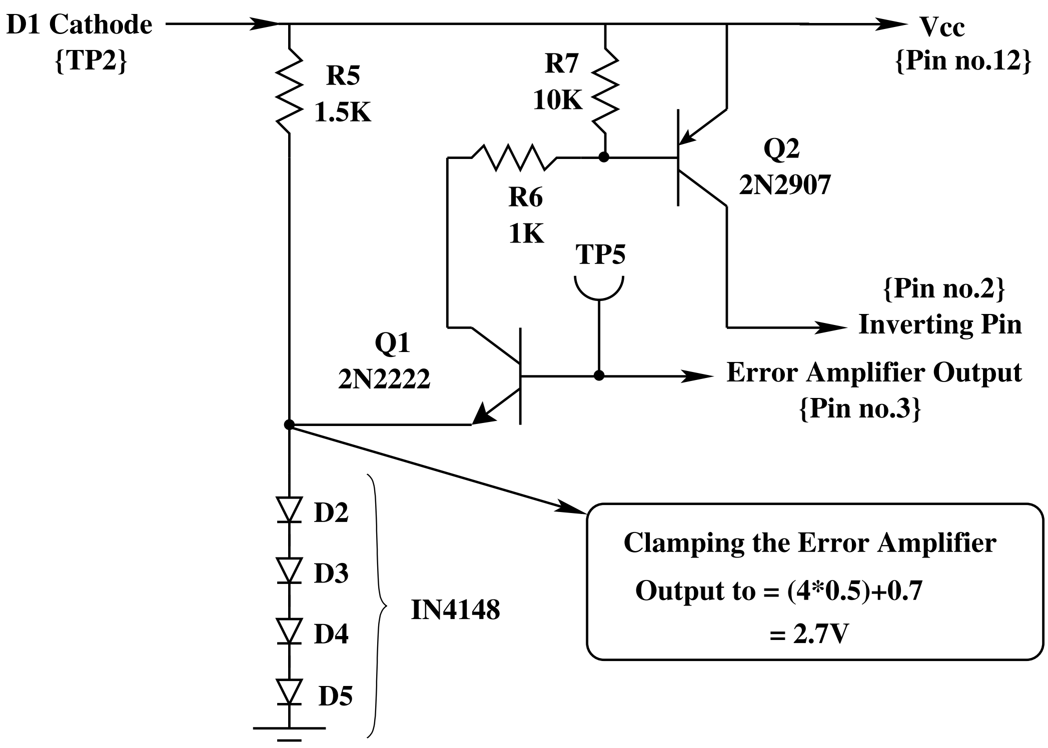


Figure 6.2: Maximum Pulse Width Circuit

and R_5 ($1.5k\ \Omega$). The clamp level is 4 diode drops including the base-emitter drop of Q_1.

7. Duty ratio:
   The input voltage is in the range of 10 to 15. The output of the boost converter is designed for 17V. The range of duty ratio is from 0.56 to 0.37.

8. Main Inductor:
   The rated current is 0.5A. The ripple current is chosen as 0.05A. With maximum on time of 3.33 μs, at input voltage of 15V, this gives an inductor value of approximately 2000 μH with turns ratio of 3, the primary is 15 turns and secondary is 45 turns.

9. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44)

10. The diode carries about 0.5 A average current and blocks about 20V and suitable for 100 kHz switching. The reverse recovery time has to be better than 50ns. MUR110 is selected.(MUR110)

11. The output capacitor required has to limit the voltage ripple to about

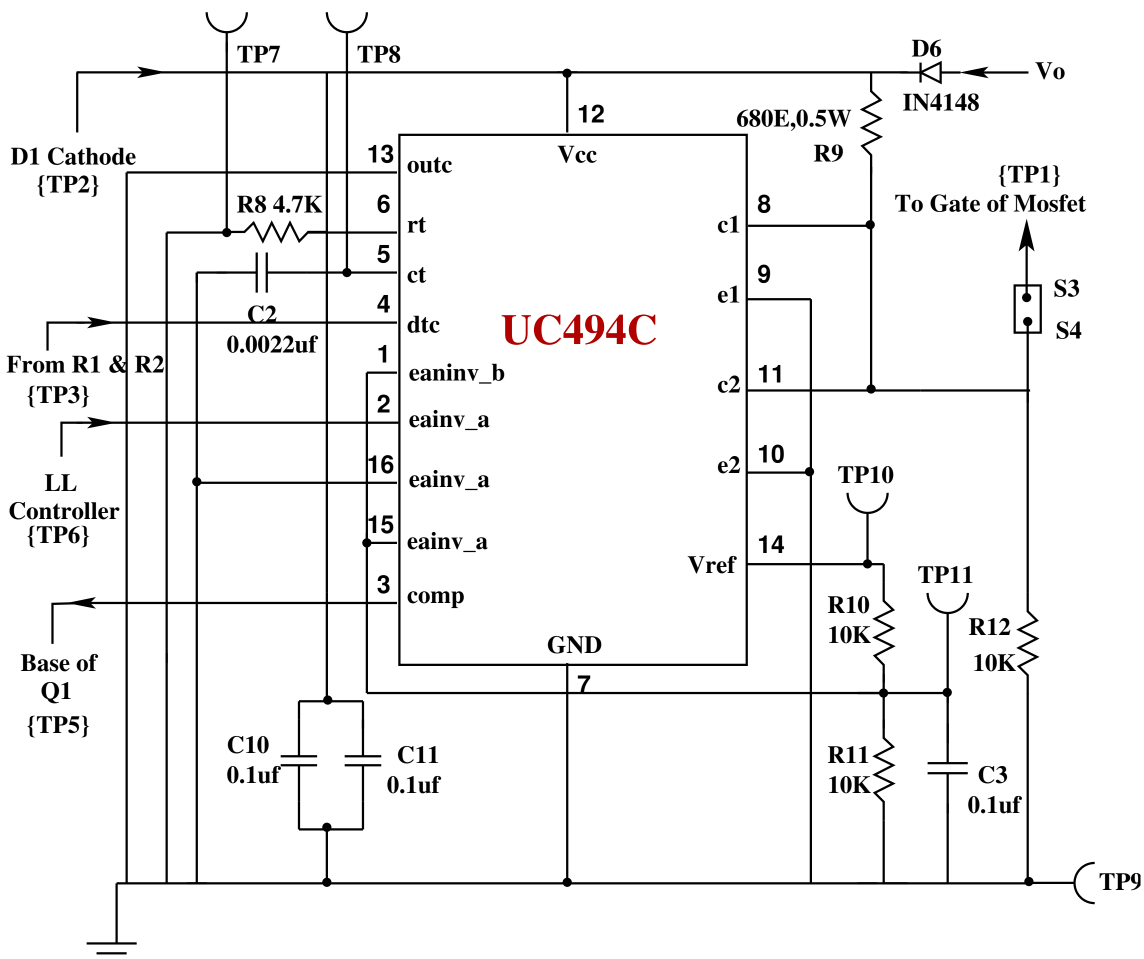


Figure 6.3: Controller Circuit

1%(0.17V). This capacitor is selected to be 220 μF (an order of magnitude higher than the desired value).

12. The natural frequency of the converter is

$$Natural\ Frequency = \frac{1}{\sqrt{\{LC\}}} \tag{6.2}$$

which is 1507.5 rad/sec. The higher frequency is at higher voltage.

13. The dc gain from duty ratio to output voltage consists of modulator gain and converter gain. The modulator gain is the reciprocal of the ramp peak in the modulator. In UC494, it is 1/3.5. The converter dc gain is

$$DC\ Gain = nV_G \tag{6.3}$$

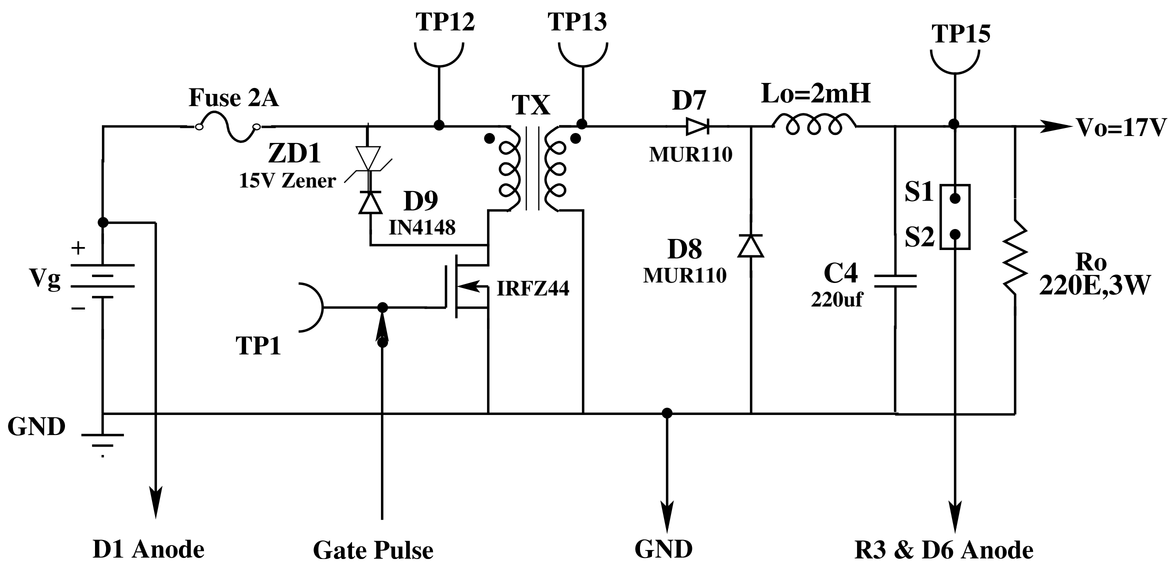


Figure 6.4: Power Circuit of Forward Converter

This gain varies from 30 to 45. The overall gain is therefore 8.75 to 12.85 for the converter. The lower gain is at higher voltage.

14. The closed loop control used is a PI controller with lead/lag compensator. The PI corner frequency $[1/(R_{16}C_8)]$ is chosen at 1820 rad/sec. The lead/lag compensator frequencies $[1/(R_{15}C_7)]$ are chosen as 1587 rad/sec and $[1/(C_7 R_3||R_4||R_{15})]$15000 rad/sec .

15. The loop gain band-width on unity feedback will be 5900 to 7610 rad/sec. The dc feedback gain is

$$DC\ FeedbackGain = \frac{25}{10.848} \tag{6.4}$$

16. The loop-gain cross-over frequency is 6380 rad/sec to 7260 rad/sec.

17. R_{13} serves as a bleeder load.

18. The MOSFET drive is through the pull up resistor R_9 (680 Ω) and the gate shunt resistor $R_1 2$ ($10k\ \Omega$)

19. R_{14} is the on-board load 30%. Additional 70% load may be connected off-board.

20. D_5 is the power supply diode fed from 15 V, following start-up.

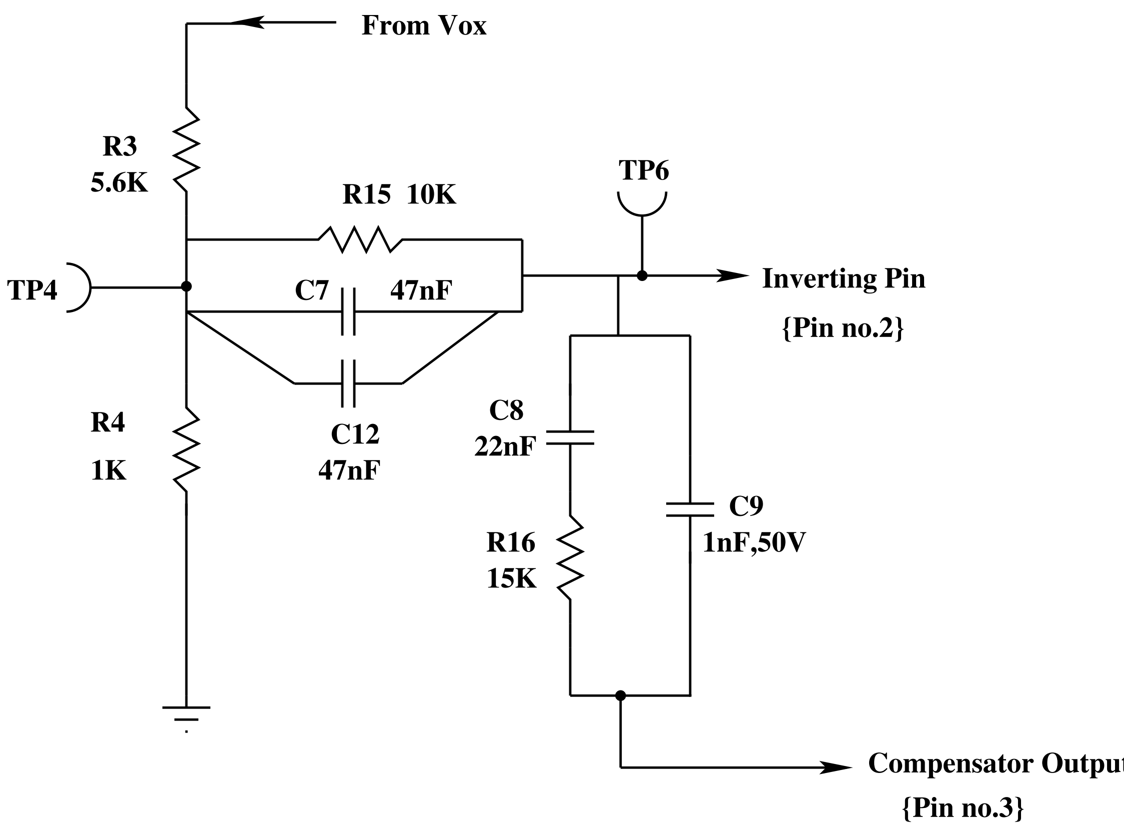


Figure 6.5: Feedback Circuit

6.3 Practical Bode Plot using Network Analyser

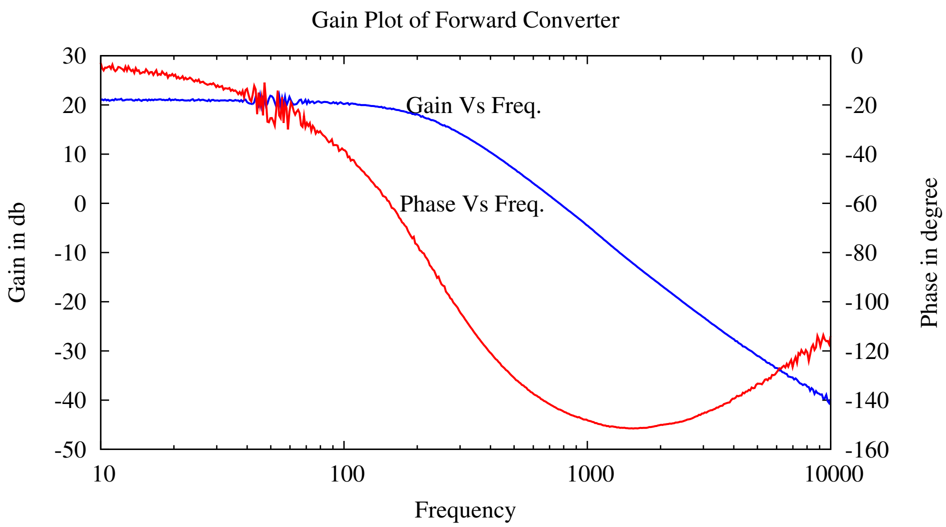


Figure 6.6: Converter Gain Bode Plot of Forward Converter

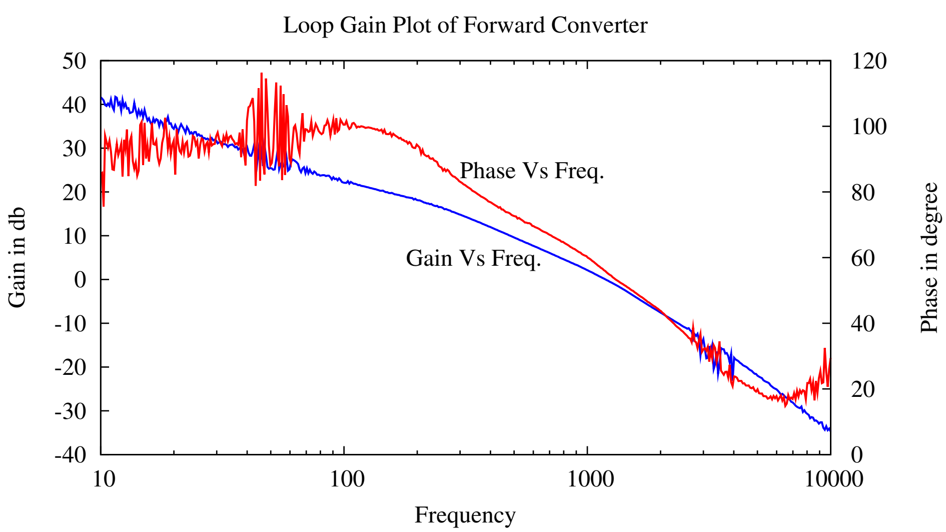


Figure 6.7: Closed Loop Gain Bode Plot of Forward Converter

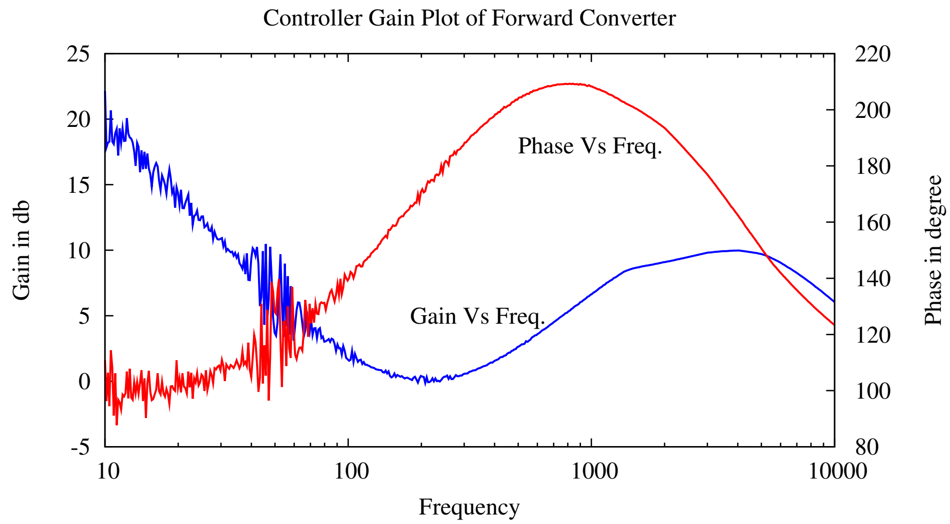


Figure 6.8: Controller Gain Bode Plot of Forward Converter

6.4 Mounted and Bare PCB Boards

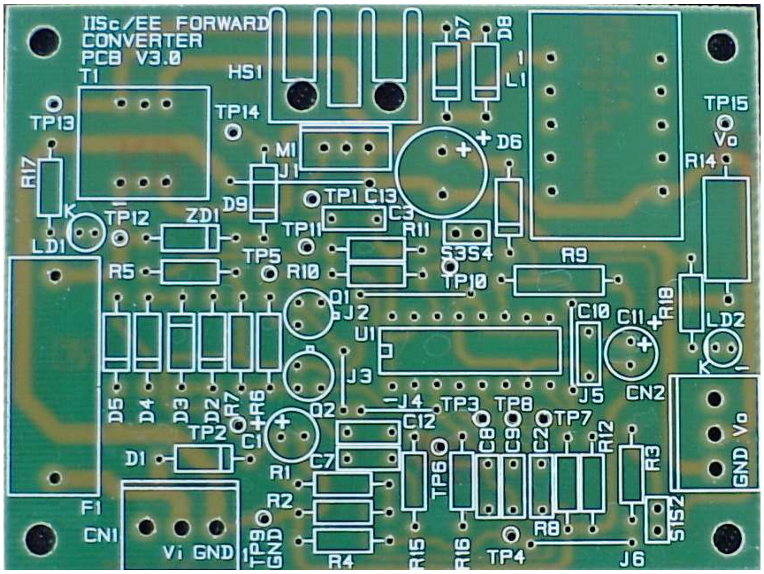


Figure 6.9: Bare PCB Board of the Forward Converter

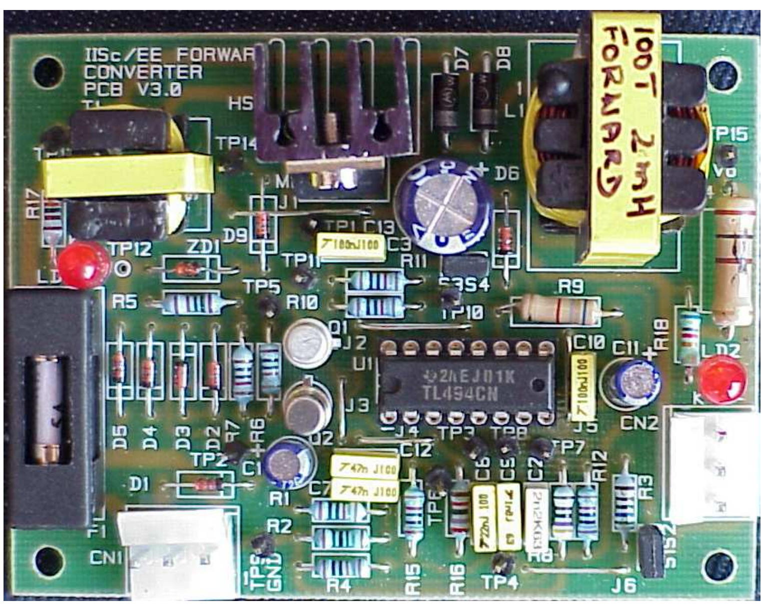


Figure 6.10: Mounted PCB Board of the Forward Converter

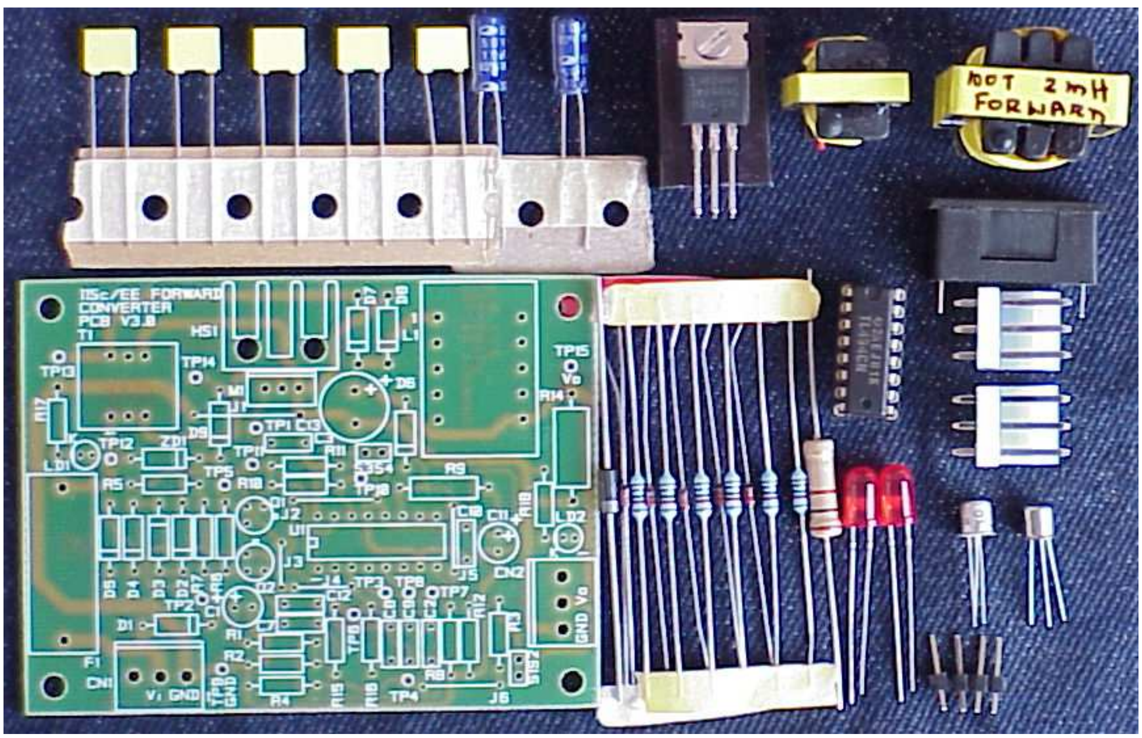
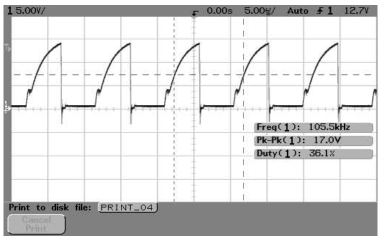
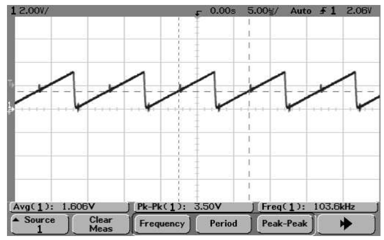


Figure 6.11: Material used for Forward Converter

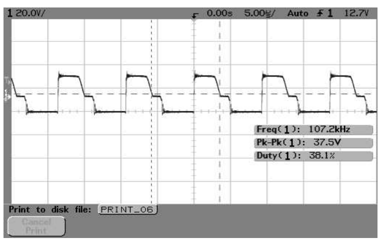
6.5 Pratical Waveform of the Forward Converter



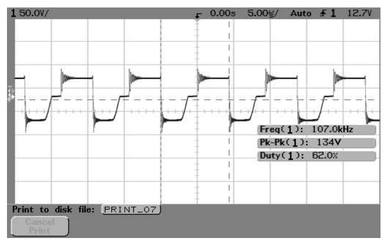
(a) Gate Voltage



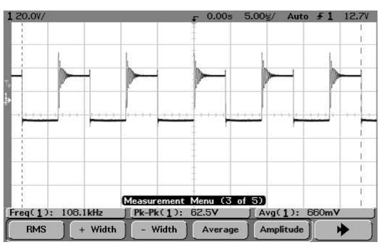
(b) Ramp Voltage



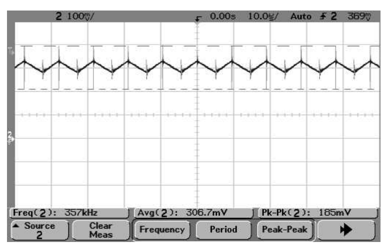
(c) Primary Transformer Voltage



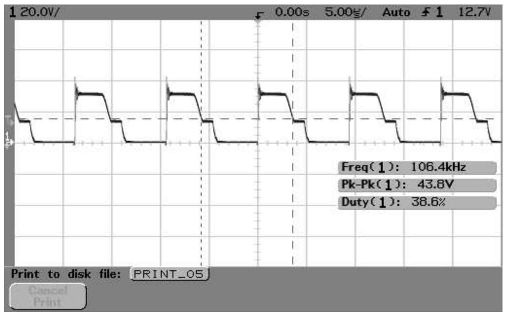
(d) Seconday Transformer Voltage



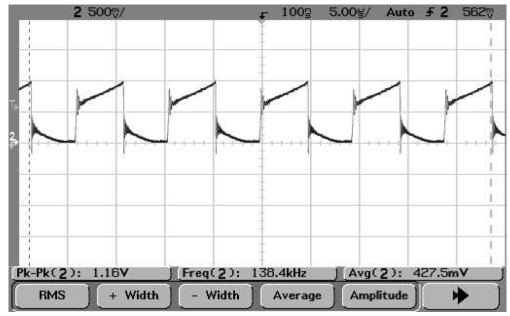
(e) Inductor Voltage



(f) Inductor Current



(g) Switch Voltage



(h) Primary Current

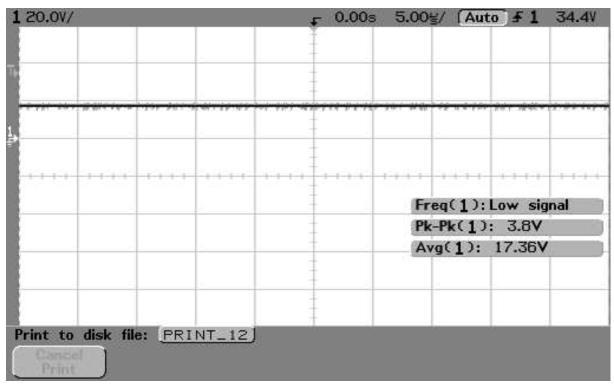


Figure 6.12: Output Voltagefor Forward Converter

6.6 PCB Films for Solder and Components Side

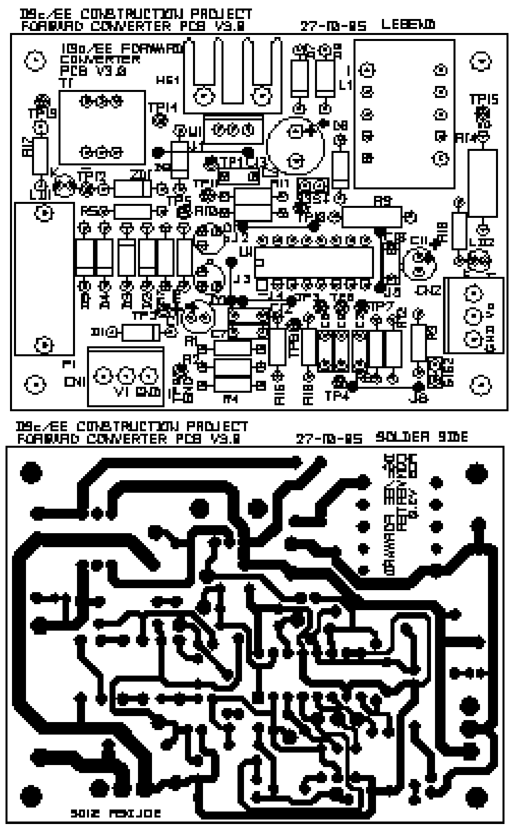


Figure 6.13: Solder and Component Side of CMC-Boost Converter

6.7 Bill of Materials

Table 6.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Amount
1	Resistor	R1,R7,R10, R11,R12,R16	$10k\ \Omega$	6	0.35	2.10
2	Resistor	R2	200 Ω	1	0.35	0.35
3	Resistor	R3	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	R4,R6	$1k\ \Omega$	2	0.35	0.70
5	Resistor	R5	$1.5k\ \Omega$	1	0.35	0.35
6	Resistor	R8	$4.7k\ \Omega$	1	0.35	0.35
7	Resistor	R9	680 Ω	1	0.50	0.50
8	Resistor	R13	$3.3k\ \Omega$	1	0.35	0.35
9	Resistor	R14	100 Ω,3W	1	3.50	3.50
10	Resistor	R15	$47K\ \Omega$	1	0.35	0.35
11	Capacitor	C1	10 μF,25V	1	0.50	0.50
12	Capacitor	C2	0.0022 μF,63V	1	2.50	2.50
13	Capacitor	C3,C10	0.1 μF,50V	2	1.00	2.00
14	Capacitor	C4	220 μF,25V	1	2.00	2.00
15	Capacitor	C7,C8	10 μF,50V	2	2.50	5.00
16	Capacitor	C13	0.047 μF,50V	1	2.50	2.50
17	Capacitor	C9	0.001 μF,50V	1	2.50	2.50
18	Capacitor	C11	0.01 μF,	1	0.50	0.50
19	Fuse	F1	1A,230V	1	1.00	1.00
20	Mosfet	M1	IRFZ44N	1	16.00	16.00
21	Transformer	T1	1A,15/45 Turns	1	25.00	25.00
22	Transisor	Q1	2N2222	1	4.50	4.50
23	Transisor	Q2	2N2907	1	4.50	4.50
23	Diode	D1,D2,D3,D4, D5,D6,D9	IN4148	7	0.40	2.80
24	Diode	D8,D21	MUR110	2	8.00	16.00
25	Linear IC	U1	UC494	1	7.00	7.00
26	Inductor	L1	2mH	1	25.00	25.00
27	Test Points	T1	Berg Stick	20	0.10	2.00
28	16 Pin IC Base	U1b		1	5.00	5.00
29	Terminal Connector	T1,T2		2	3.00	6.00
30	Heat Sink	HS1	P149	1	5.00	5.00
31	PCB	7.5W Forward V3.0		1	25.00	25.00
32	Jumper	J1,J2	Jumpers	2	0.50	1.00
33	Diode	ZD10	15V, Zener	1	2.00	2.00
					TOTAL	174.20

Chapter 7

7.5W Current Mode Control of Boost Converter

7.1 Circuit Specification

This section covers a simple closed loop current mode controlled boost converter with the following specifications.

- Input: 12V to 20V
- Output: 30V, 0.25A, 7.5W
- Topology: Non-isolated Boost Converter
- Controller: UC3843(UC3843)
- Switching Frequency: 50 kHz
- Protection: None
  Figure 7.1 and 7.2 shows the full circuit diagram of the non-isolated boost converter operating from 20V battery (12V to 20V) providing regulated output powerreport at 30V (0.25 A). The controller used is UC3843 of Unitrode make.

7.2 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

7.2.1 Control Circuit:

1. Controller: The controller used here is UC3843. It is 8 pin IC with maximum supply voltage is 40V.
2. C_2,C_{sh} are all used for filtering.

3. Reference voltage: IC has a internal reference Voltage of 5V.
4. Oscillator Section: Switching Frequency is determined by R_t and C_t
$$F_s = \frac{1.72}{R_t C_t} = 50KHz \tag{7.1}$$
5. Slope Compensation: Transitor Q_4 and R_v forms the Slope Compensation Circuit.The Slope Compensation circuit is required when the circuit is operating with a duty ratio more then 0.5.
6. Controller: Resistor R_f and Capacitor C_f forms the PI controller circuit.
7. Current Sense: UC3843 IC Pin 3 is the Current Sense Pin, it sense the rectified switch current from the Current Transfomer. This rectified Current gets added with the slope compensation voltage and this the Current Sensed by the IC.
8. R_b is the Bleeder resistance used, based on the value of R_b we decide the current sensed to be less then 1V threshold at pin no.3.

7.2.2 Power Circuit:

1. It Consists of the Boost Converter with include a Inductor, Switch, Diode , Capacitor and Load.
2. Duty Ratio: The input voltage is in the range of 12 to 20 V. The output of the boost converter is designed for 30V. The range of duty ratio is from 0.6 to 0.33.
3. Main Inductor: The rated current is 0.25 A. The ripple current is chosen as 0.5 A. With maximum on time of 12 μs, at input voltage of 12V, this gives an inductor value of approximately 200 μH.Inductor is 200H with 29 Turns of 22 SWG.
4. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.
5. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)
6. The capacitor C1 has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 220F.
7. Current Transformer: The CT is used to sense the switch current. The Core used is E 16/8/5 of SWG 28 with 1:200 Turns.
8. The Load Resistor used is 120E.[7.5W]

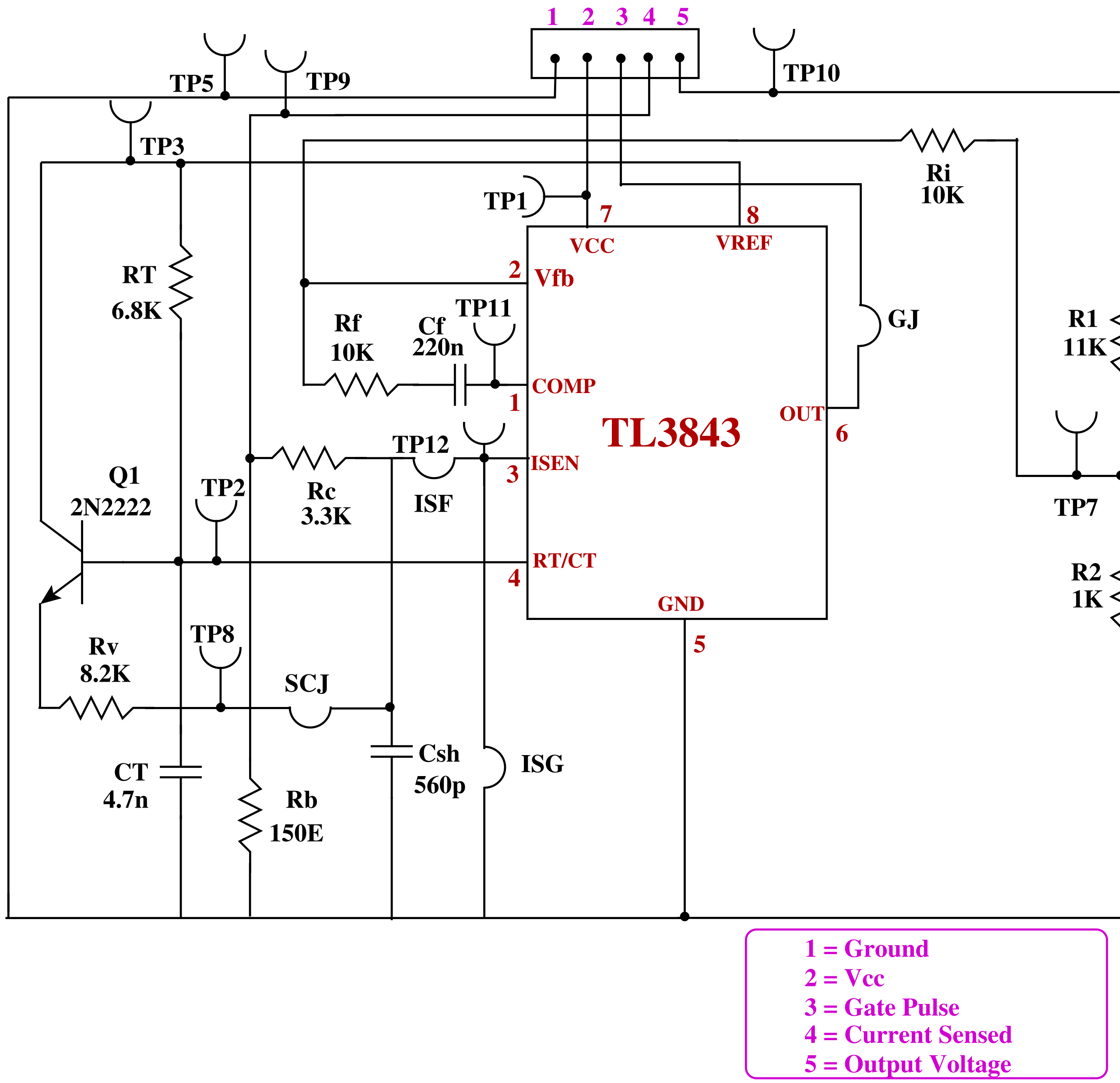


Figure 7.1: Control Circuit for Current Mode Control of Boost Converter

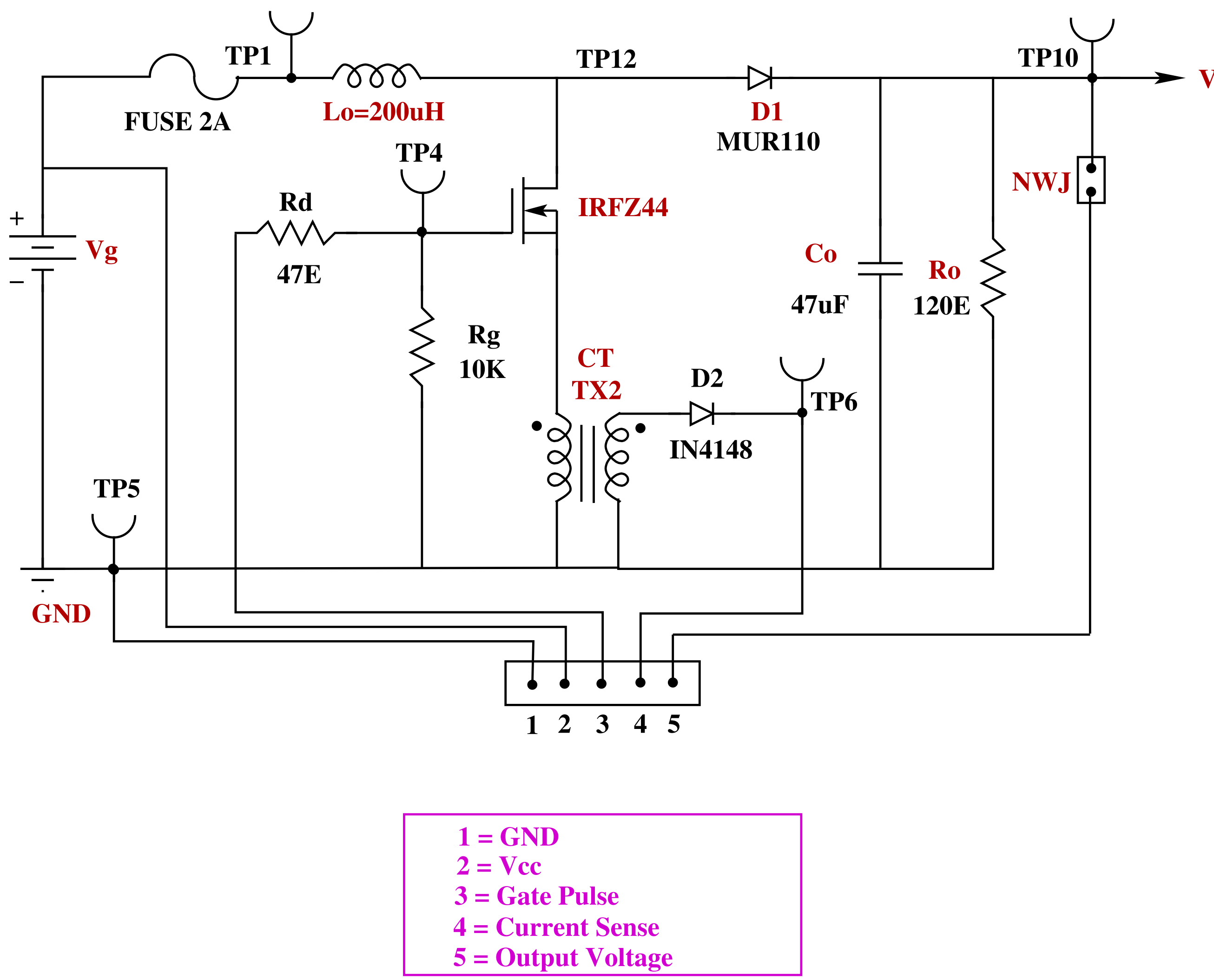


Figure 7.2: Power Circuit for Current Mode Control of Boost Converter

7.3 Practical Bode Plot using Network Analyser

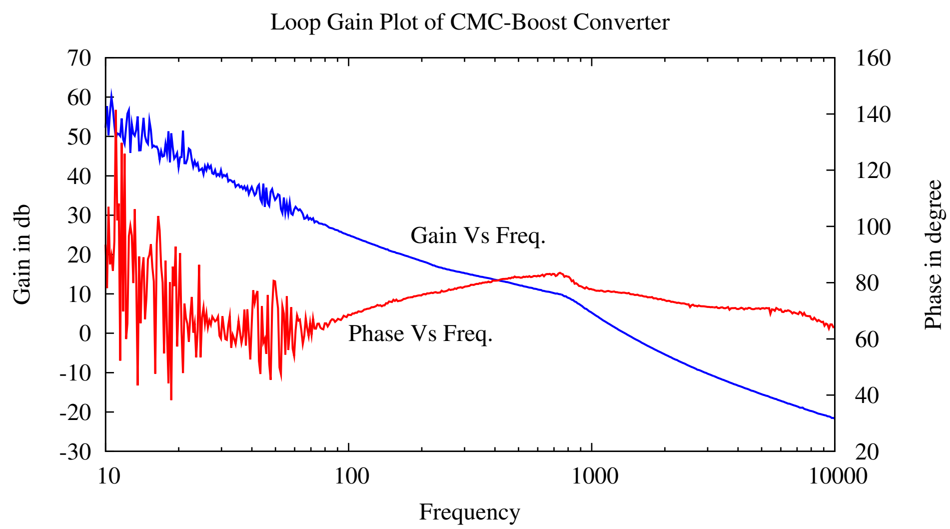
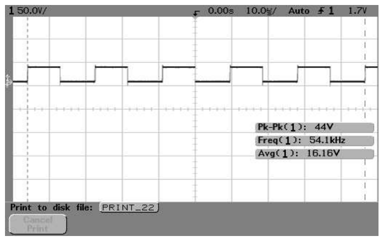
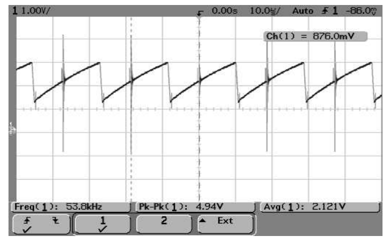


Figure 7.3: Loop Gain Bode Plot of CMC-Boost Converter

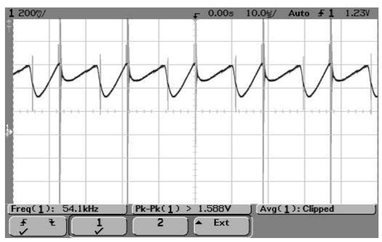
7.4 Pratical Waveform of the CMC-Boost Converter



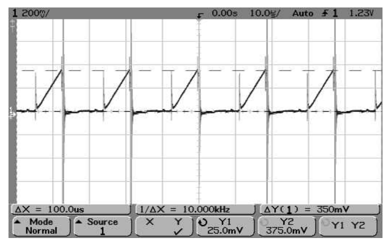
(a) GateVoltage



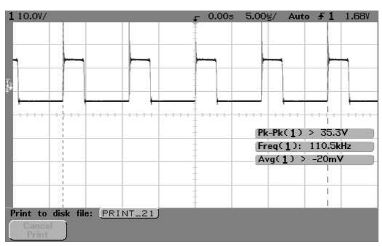
(b) Ramp Voltage



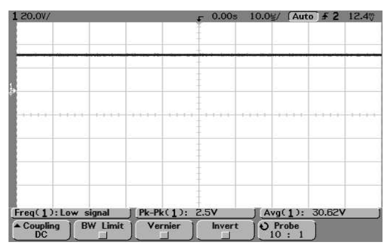
(c) Compensated curent and Voltage



(d) Current Sensed



(e) Inductor Voltage



(f) Output voltage

7.5 Mounted and Bare PCB Boards

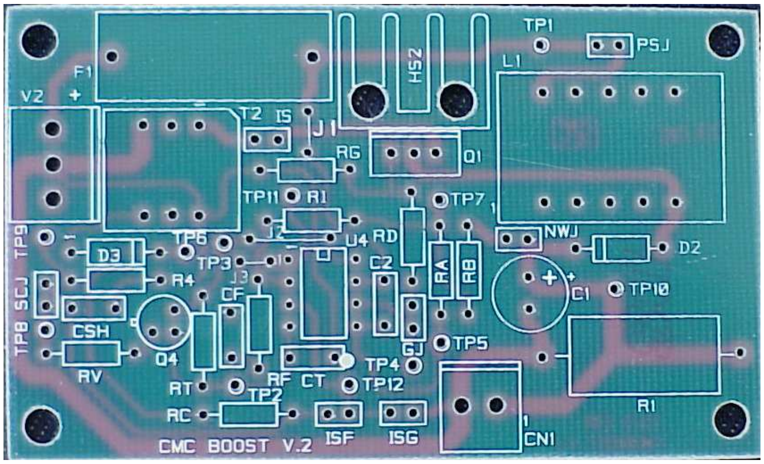


Figure 7.4: Bare PCB Board of the CMC-Boost Converter

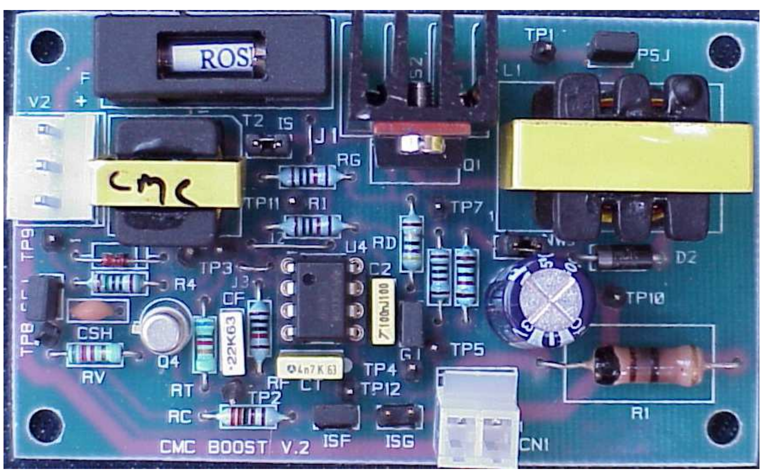


Figure 7.5: Mounted PCB Board of the CMC-Boost Converter

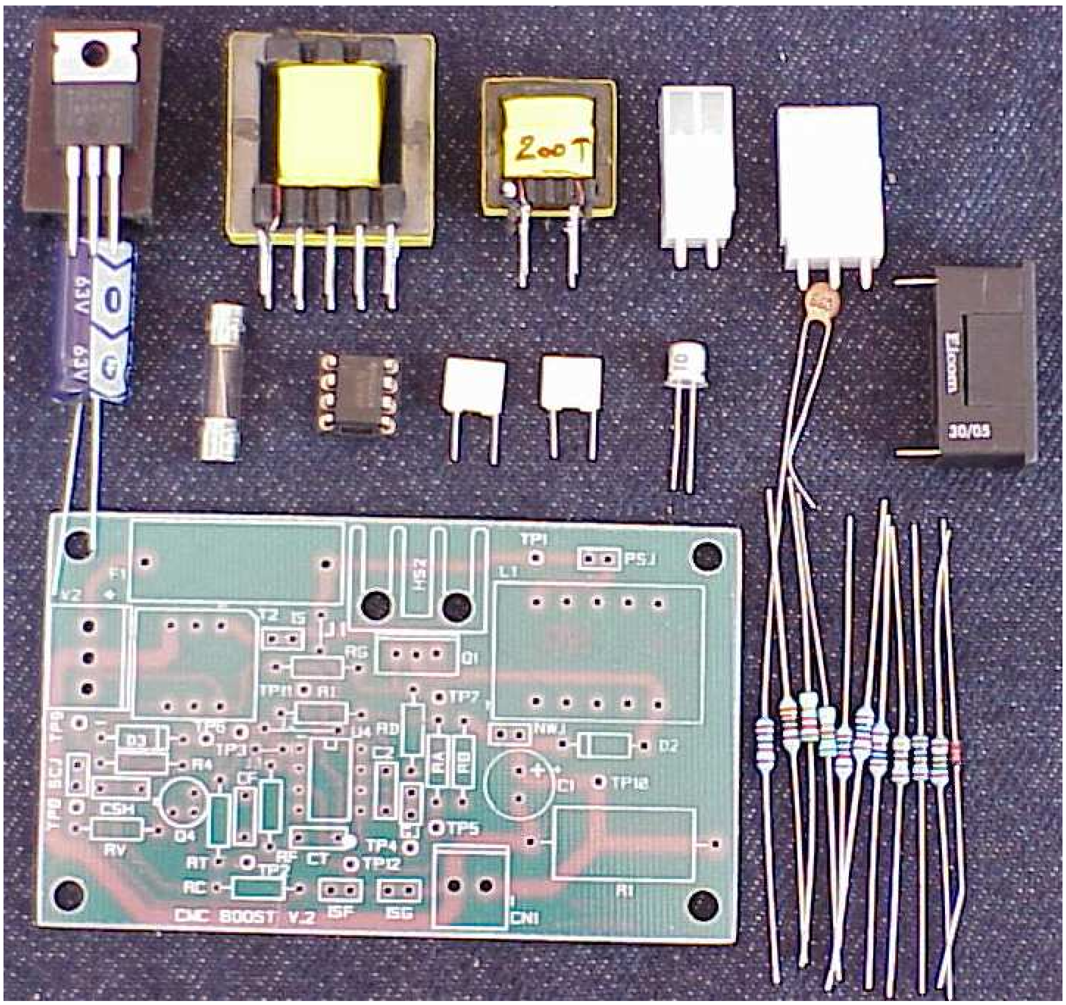


Figure 7.6: Components used in CMC-boost Converter

7.6 PCB Films for Solder and Components Side

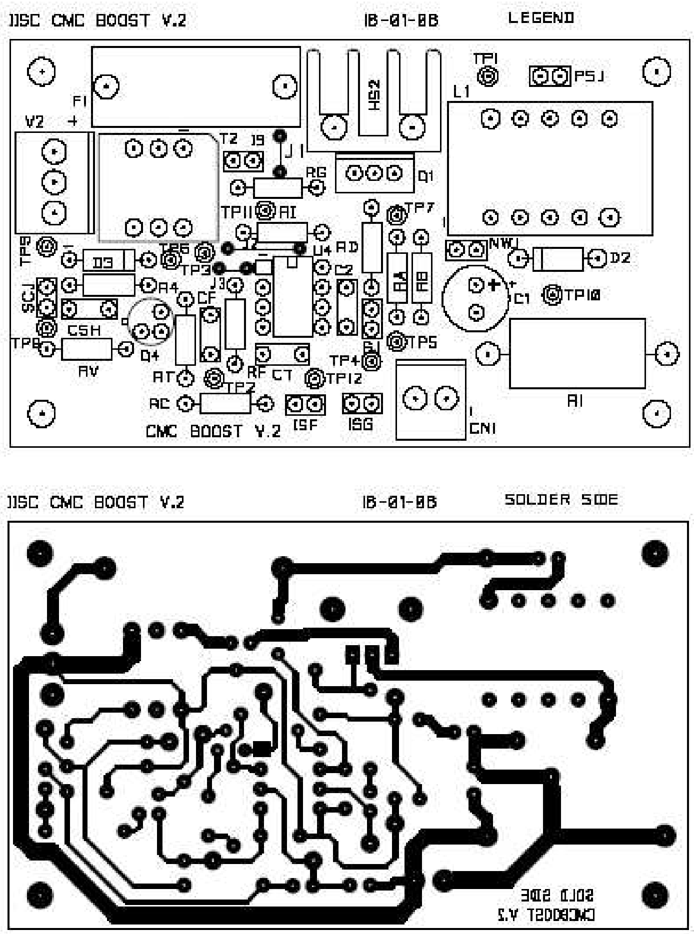


Figure 7.7: Solder and Component Side of CMC-Boost Converter

7.7 Bill of Materials

Table 7.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg,Rf,Ri,Rb	$10k\ \Omega$	4	0.35	1.40
2	Resistor	Rt	$6.8k\ \Omega$	1	0.35	0.35
3	Resistor	Rv	$8.2k\ \Omega$	1	0.35	0.35
4	Resistor	R4	$150\ \Omega$	1	0.35	0.35
5	Resistor	Rd	$47\ \Omega$	1	0.35	0.35
6	Resistor	Risen	$3.3k\ \Omega$	1	0.35	0.35
7	Resistor	Ra	$1k\ \Omega$	1	0.35	0.35
8	Resistor	R1	$120\ \Omega$	1	3.00	3.00
9	Capacitor	Csh	$560pF$	1	2.00	2.00
10	Capacitor	C2,C3	0.22 μF,63V	1	2.50	5.00
11	Capacitor	C1	220 μF,25V	1	2.00	2.00
12	Capacitor	Cf	0.022 μF,50V	2	2.50	5.00
13	Capacitor	Ct	0.0047 μF,50V	1	2.50	2.50
15	Current Transformer	T2	1:200	1	15.00	15.00
16	Mosfet	M1	IRFZ44N	1	16.00	16.00
17	Inductor	L1	200 μH	1	25.00	25.00
18	Transisor	Q1	2N2222	1	4.50	4.50
19	Diode	D3	IN4148	1	0.40	0.40
20	Diode	D2	MUR110	1	8.00	8.00
21	Linear IC	U1	UC3843	1	7.00	7.00
22	Test Points	T1-T10	Berg Stick	20	0.10	2.00
23	Jumpers	NMJ,GJ,IS, SCJ,PSJ,ISG		6	0.10	0.60
24	8 Pin IC Base	U1b		1	5.00	5.00
25	Terminal Connector	T1,T2		2	3.00	6.00
26	Heat Sink	HS1	P149	2	5.00	5.00
27	PCB	7.5W CMC BOOST		1	25.00	25.00
					TOTAL	142.50

Chapter 8

7.5W Current Mode Control of Forward Converter

8.1 Circuit Specification

This section covers a simple closed loop current mode controlled forward converter with the following specifications.

- Input: 10V to 15V
- Output: 5V, 1.5A, 7.5W
- Topology: Non-isolated Forward Converter
- Controller: UC3843(UC3843)
- Switching Frequency: 100 kHz
- Protection: None
  Figure 1 shows the full circuit diagram of the non-isolated forward converter operating from 15V battery (10V to 15V) providing regulated output power at 5V (1.5 A). The controller used is UC3843 of Unitrode make.

8.2 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

8.2.1 Control Circuit:

1. Controller: The controller used here is UC3843. It is 8 pin IC with maximum supply voltage is 40V.
2. C_2,C_{sh} are all used for filtering.

3. Reference voltage: IC has a internal reference Voltage of 5V.

4. Oscillator Section: Switching Frequency is determined by R_t and C_t

$$F_s = \frac{1.72}{R_t C_t} = 100KHz \tag{8.1}$$

5. Slope Compensation: The Slope Compensation circuit is not required since we are operating more then 50% duty cycle.

6. Controller: Resistor R_f and Capacitor C_f forms the PI controller circuit.

7. Current Sense: UC3843 IC Pin 3 is the Current Sense Pin, it sense the rectified switch current from the Current Transfomer. This rectified Current gets added with the slope compensation voltage and this the Current Sensed by the IC.

8. R_b is the Bleeder resistance used, based on the value of R_b we decide the current sensed to be less then 1V threshold at pin no.3.

8.2.2 Power Circuit:

1. It Consists of the Forward Converter with include a Inductor, Switch, Diode ,Capacitor and Load.

2. Duty Ratio: The input voltage is in the range of 10 to 15 V. The output of the boost converter is designed for 30V. The range of duty ratio is from 0.5 to 0.33.

3. Main Inductor: The rated current is 1.5 A. The ripple current is chosen as 0.3 A. With maximum on time of 5 μs, at input voltage of 10V, this gives an inductor value of approximately 110 μH.Inductor is 110H with 29 Turns of 22 SWG.

4. Current Transformer: The CT is used to sense the switch current. The Core used is E 16/8/5 of SWG 28 with 1:200 Turns.

5. Transformer: The Transformer has a turns ratio of 1.5. With SWG 22 used for the primary winding and SWG 23 used for the secondary winding. Core used is EE 16/8/5.The primary turns is 12 and secondary turns is 12.

6. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44. Mosfet drive is through the R_g and R_d.(IRFZ44)

7. The Diode Carries about 1.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)

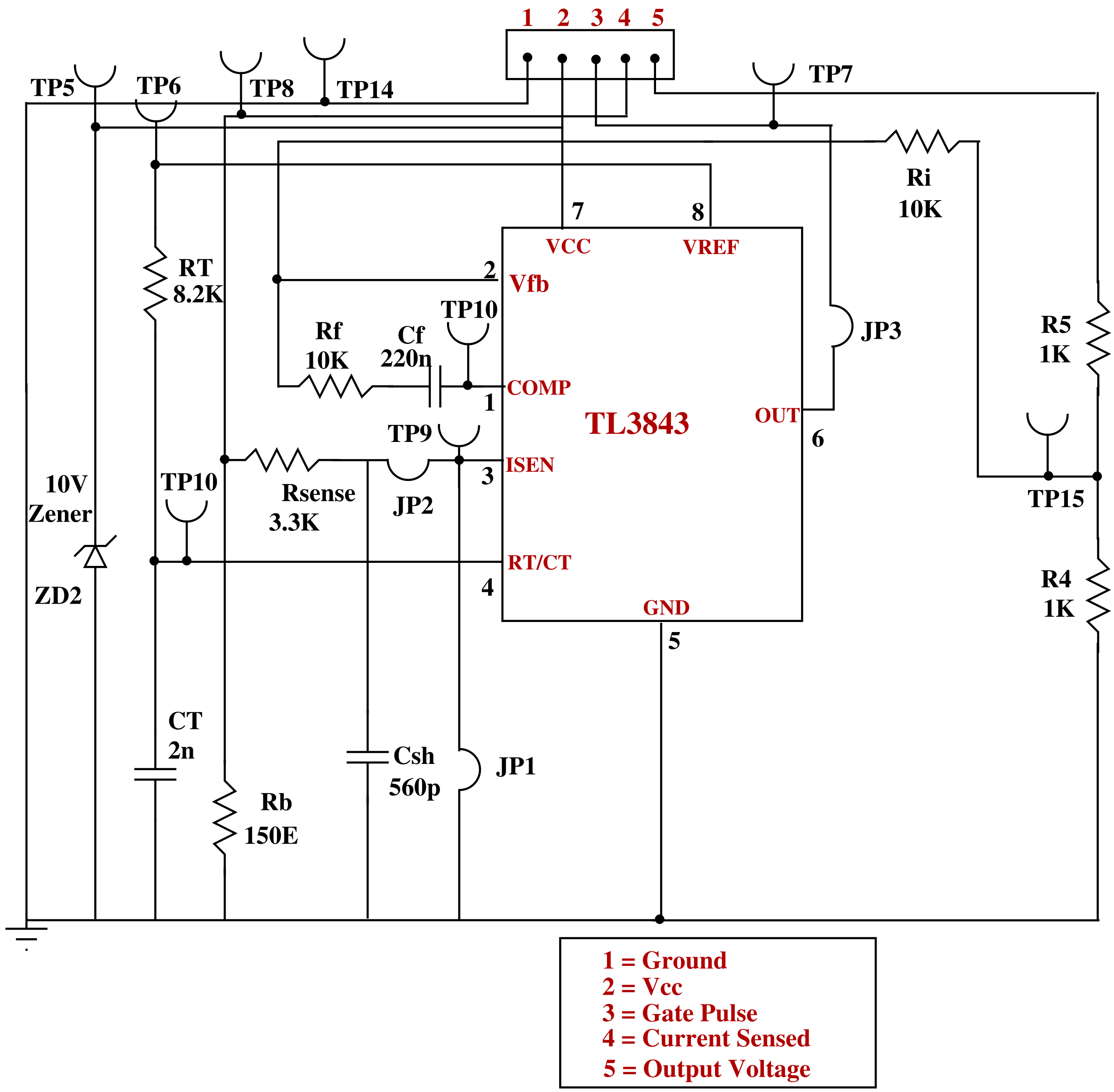


Figure 8.1: Control Circuit for Current Mode Control of Forward Converter

8. The capacitor C_1 has to limit the voltage ripple to about 1%. This Capacitor is selected to be 47F.

9. The Load Resistor used is 3.33E.[7.5W]

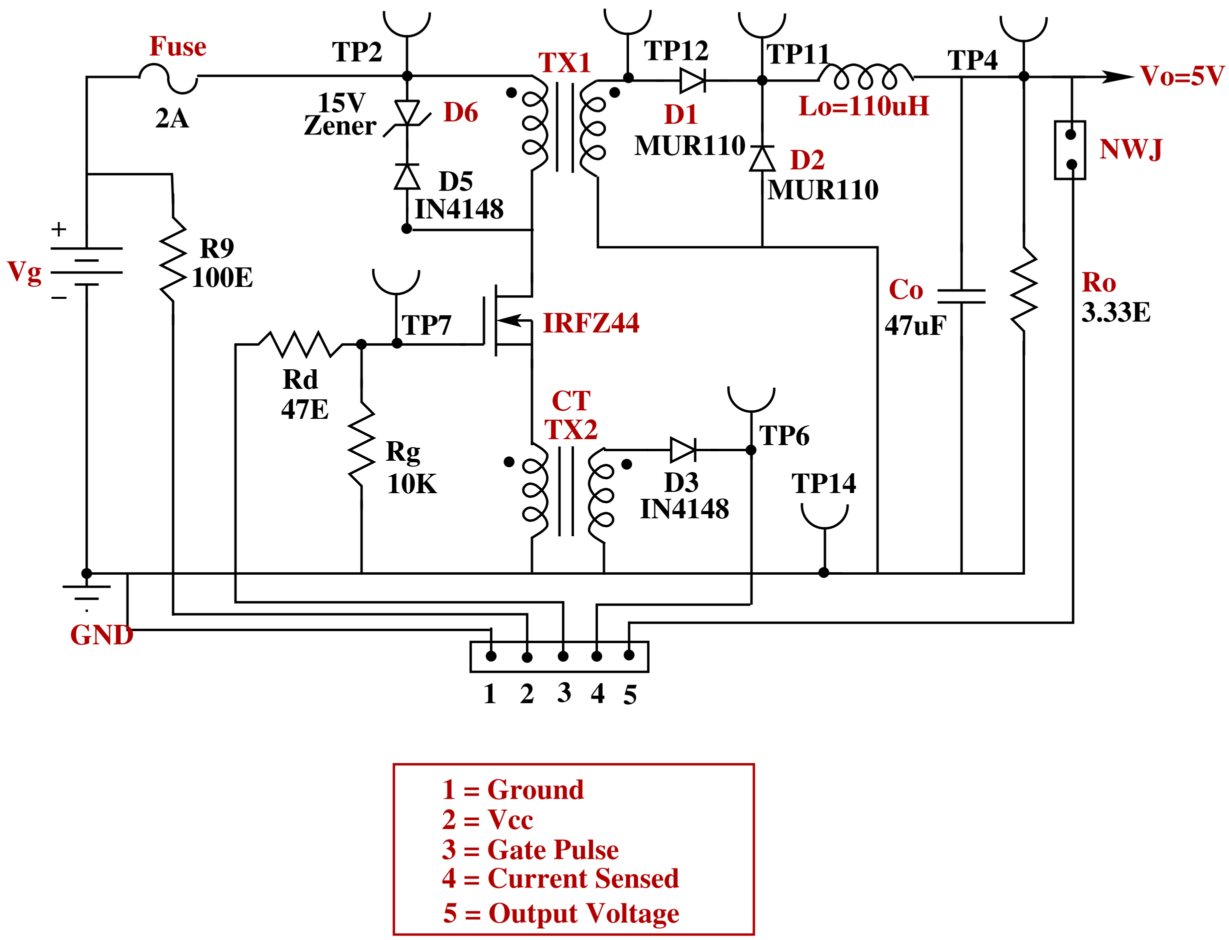


Figure 8.2: Power Circuit for Current Mode Control of Forward Converter

8.3 Practical Bode Plot using Network Analyser

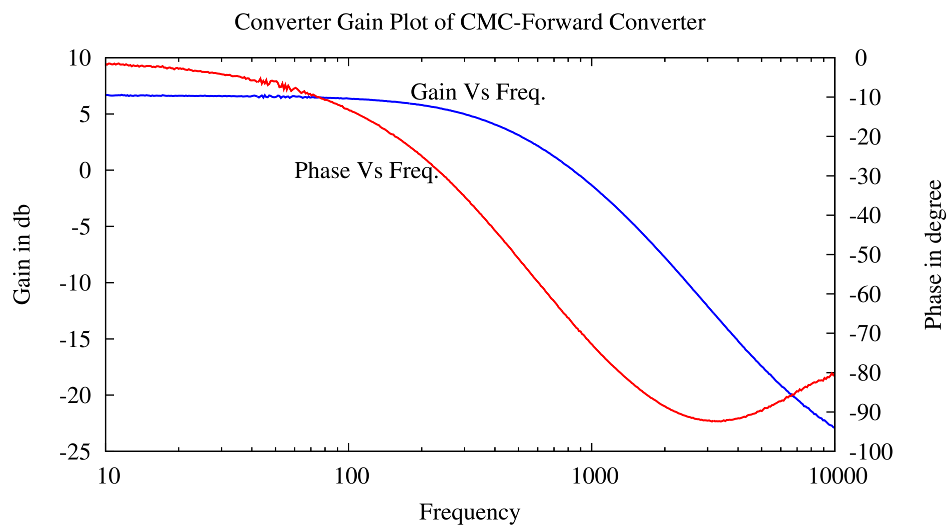


Figure 8.3: Converter Gain Bode Plot of CMC-Forward Converter

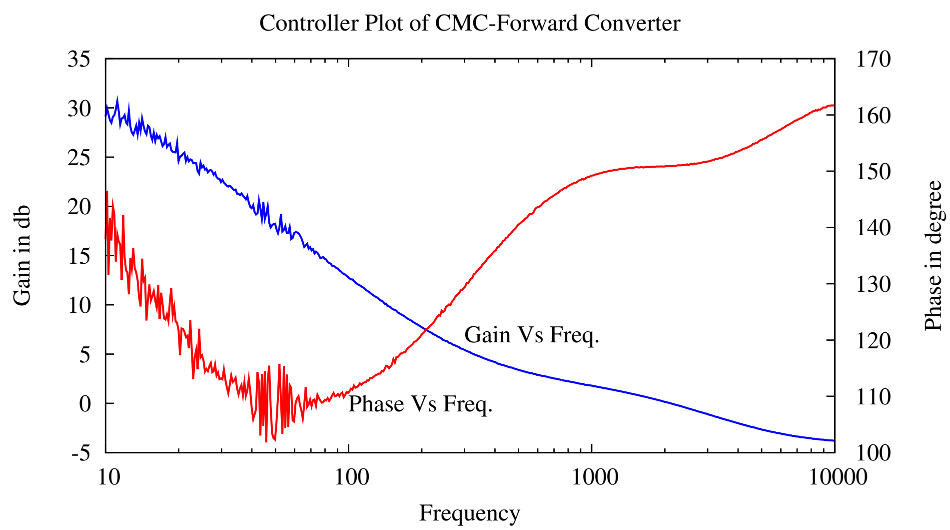


Figure 8.4: Controller Gain Bode Plot of CMC-Forward Converter

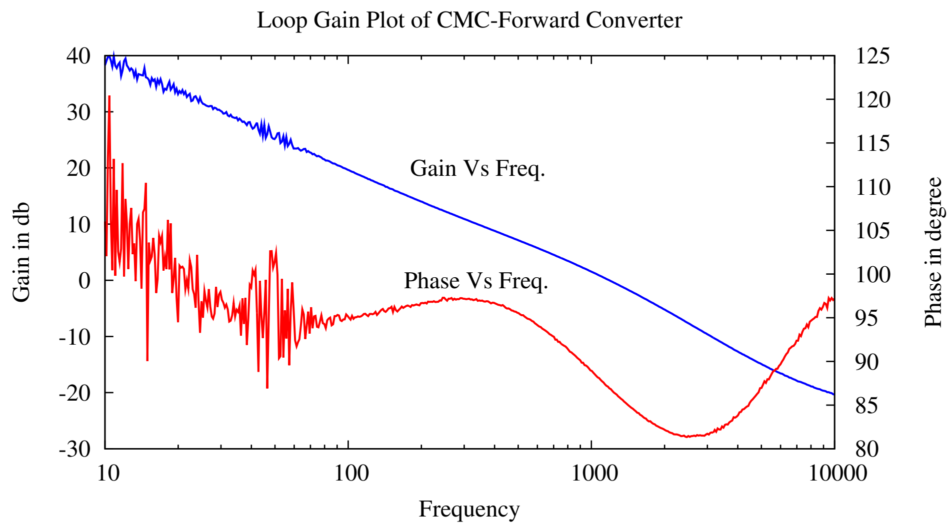
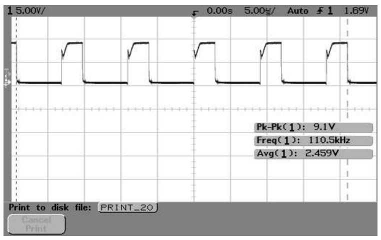
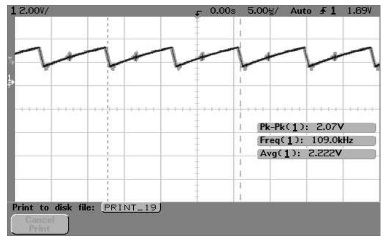


Figure 8.5: Closed Loop Gain Bode Plot of CMC-Forward Converter

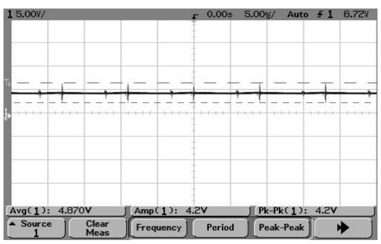
8.4 Pratical Waveform of the CMC-Forward Converter



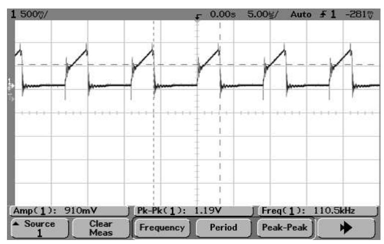
(a) GateVoltage



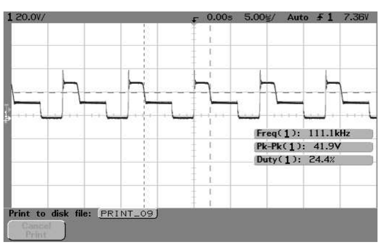
(b) Ramp Voltage



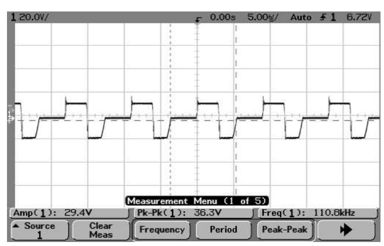
(c) Output Voltage



(d) Current Sensed



(e) Primary Transformer Voltage



(f) Secondary Transformer voltage

8.5 Mounted and Bare PCB Boards

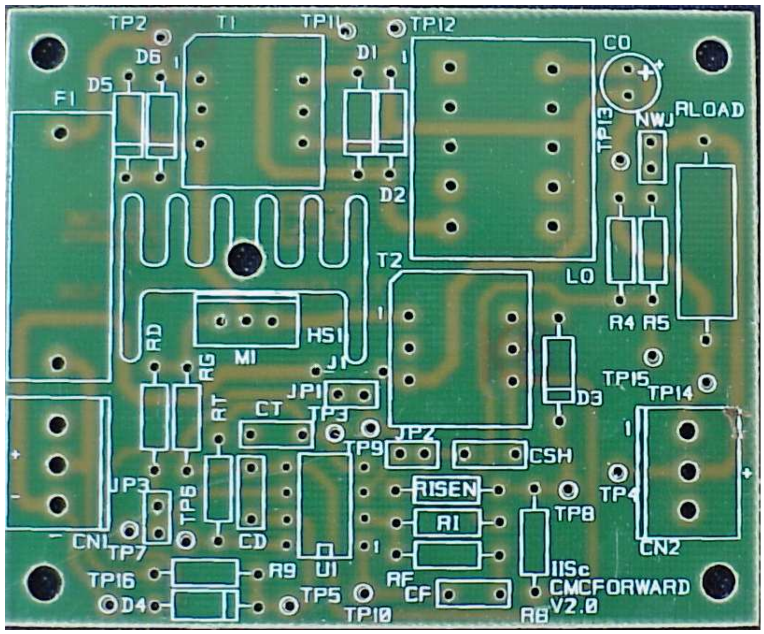


Figure 8.6: Bare PCB Board of CMC-Forward Converter

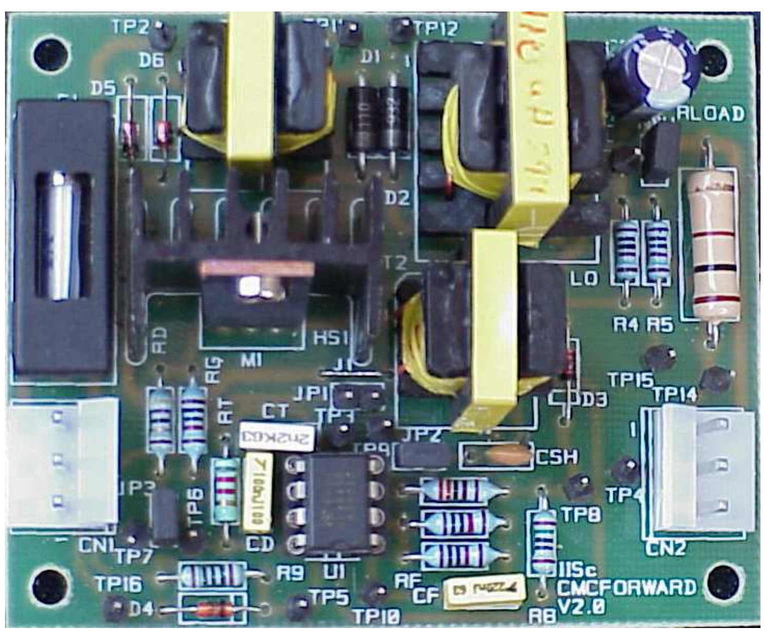


Figure 8.7: Mounted PCB Board of CMC-Forward Converter

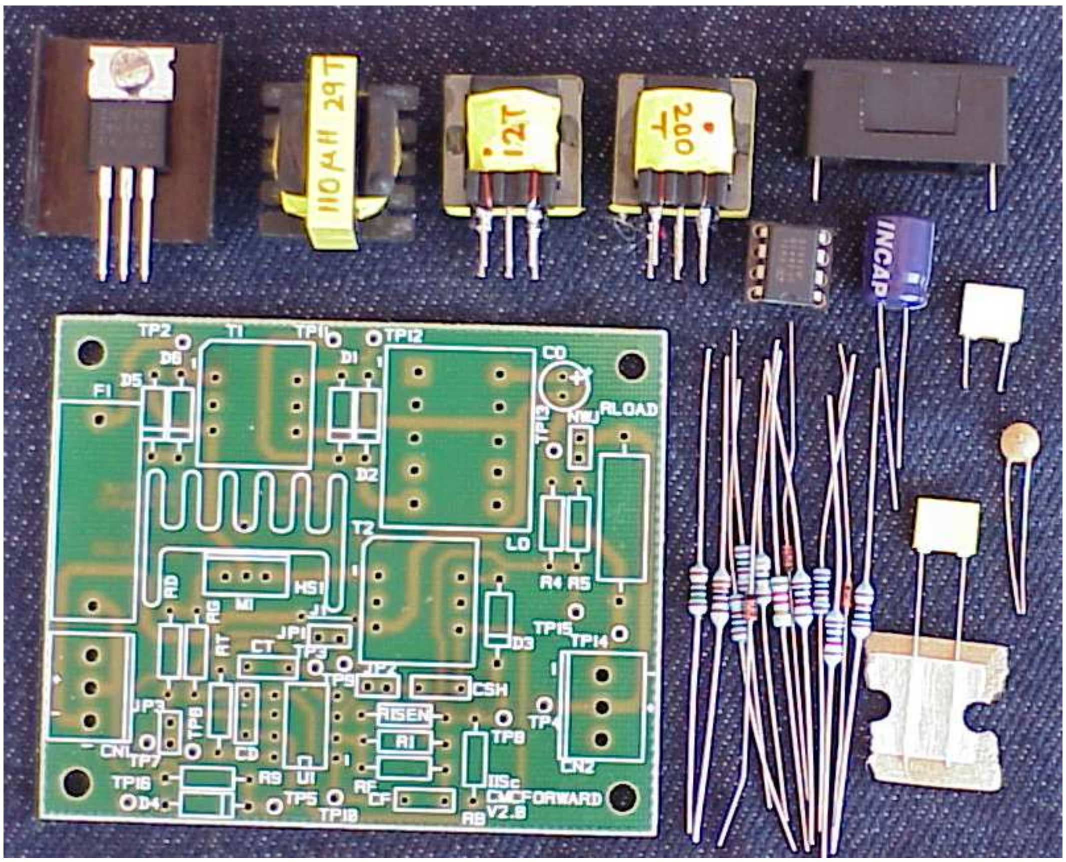


Figure 8.8: Components used in CMC-Forward Converter

8.6 PCB Films for Solder and Components Side

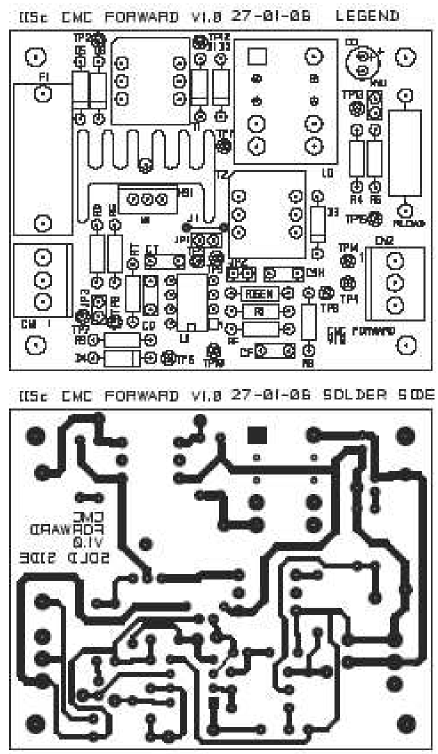


Figure 8.9: Solder and Component Side of CMC-Forward Converter

8.7 Bill of Materials

Table 8.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg,Rf,Ri	$10k\ \Omega$	3	0.35	1.05
2	Resistor	Rt	$8.2\ \Omega$	1	0.35	0.35
3	Resistor	R9	$100\ \Omega$	1	0.35	0.35
4	Resistor	Rb	$150\ \Omega$	1	0.35	0.35
5	Resistor	Rd	$47\ \Omega$	1	0.35	0.35
6	Resistor	Risense	$3.3k\ \Omega$	1	0.35	0.35
7	Resistor	R5,R4	$1k\ \Omega$	2	0.35	0.75
8	Resistor	Rload	$3.3\ \Omega$	1	3.00	3.00
9	Capacitor	Csh	$560pF$	1	2.00	2.00
10	Capacitor	Cin	$0.22\ \mu F$,63V	1	2.50	5.00
11	Capacitor	Co	$220\ \mu F$,25V	1	2.00	2.00
12	Capacitor	Cf	$0.022\ \mu F$,50V	2	2.50	5.00
13	Capacitor	Ct	$0.002\ \mu F$,50V	1	2.50	2.50
15	Current Transformer	T2	1:200	1	15.00	15.00
16	Mosfet	M1	IRFZ44N	1	16.00	16.00
17	Inductor	L1	$110\ \mu H$	1	25.00	25.00
18	Transfomer	T1	E 16/8/5,1:1	1	16.00	16.00
19	Diode	D3,D6	IN4148	2	0.40	0.80
20	Diode	D1,D2	MUR110	2	8.00	16.00
21	Linear IC	U1	UC3843	1	7.00	7.00
22	Test Points	T1-T10	Berg Stick	20	0.10	2.00
23	Jumpers	NMJ,GJ,IS, SCJ,PSJ,ISG		6	0.10	0.60
24	8 Pin IC Base	U1b		1	5.00	5.00
25	Terminal Connector	T1,T2		2	3.00	6.00
26	Heat Sink	HS1	P149	2	5.00	5.00
27	Diode	D6,D4	Zener Diode (15V)	2	2.00	4.00
28	PCB	CMC Forward V1.0		1	25.00	25.00
					TOTAL	166.75

Chapter 9

7.5W Quasi-Resonant Converter ZVS - Boost Converter

9.1 Circuit Specification

This section covers a simple closed loop controlled boost converter with the following specifications.

- Input: 10V to 15V
- Output: 15V, 0.5A, 7.5W
- Topology: Non-isolated Boost Converter
- Controller: 555 Timer(555 Timer)
- Switching Frequency: 80 to 120 kHz
- Protection: None
  Figure 9.1 and 9.2 shows the full circuit diagram of the zvs boost converter operating from 15V battery (10V to 15V) providing regulated output power at 15V (0.5 A). The controller used is 555 Timer.

9.2 Principle of Operation

1. The Major advantage of ZCS and ZVS quasi-resonant converters is thhat the power switch is turned on and off at zero voltage and zero current, respectively. In ZCS topologies the rectifying diode has ZVS, where as ZVS topologies the rectifying diode has ZCS. The Second advantage is that both ZVS and ZCS converter utilize Transformer leakage inductors and diode junction capacitor and the ouput parasitic capacitor of the power switch.
2. The major disadvantage of ZCS and ZVS techniques is that they require variable frequency control to regulate the output. This is undesirable

since it complicates the control circuit and generate unwanted EMI harmonics expecially under wide load variation.In ZCS the power switch turns off at zero current, but at turn on converter still suffers from the capacitor turn on loss caused by the output capacitor of power switch.

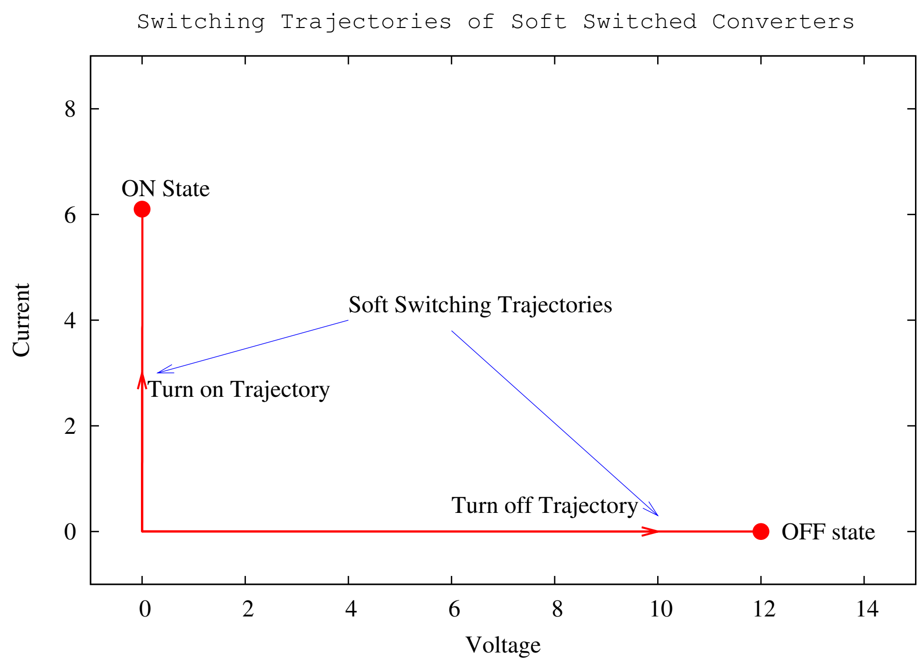


Figure 9.1: Switching Loci

3. Most regulator converters switches need to turn on or turn off the full load current at high voltage, resulting in what is known as hard switching. The figure 10.1 shows the typical switching loci for a hard switching converter without and with snubber circuit.

4. In soft switching topologies, an LC resonant network is added to shape the switching devices voltage or current waveform into a quasi-sinewave in such a way that a zero voltage or zero current condition is created. This technique eliminates the turn on or turn off losses associated with the charging or discharging of the energy stored in mosfets's parasitic junction capacitors.

9.3 Circuit Discription

1. The Controller used is 555 Timer.

2. For the Zero Voltage Switching Operation, the Off time is fixed and the Frequency variation is done by varying the ON time only.

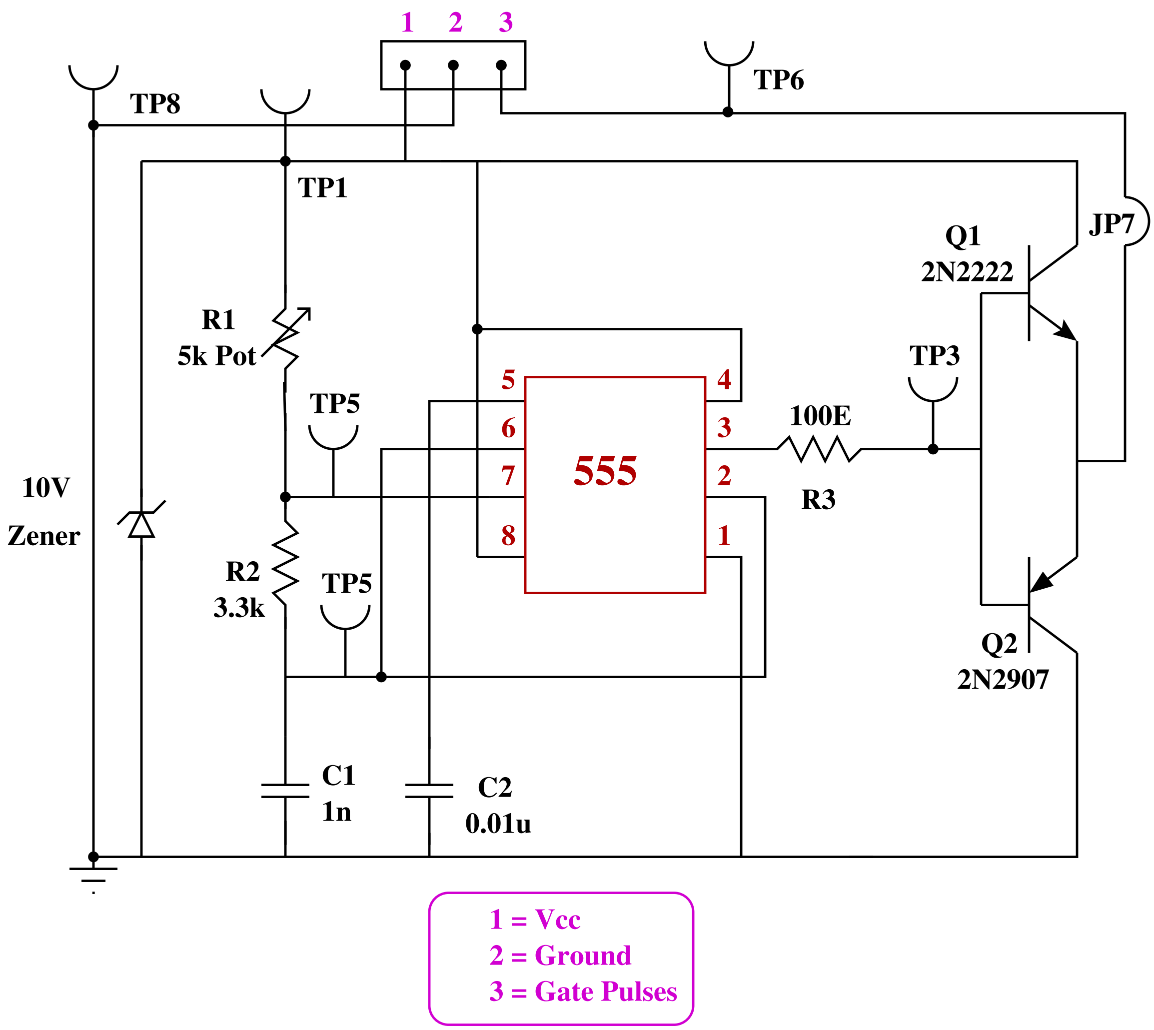


Figure 9.2: Control Circuit of ZVS-Boost Converter

3. The Frequency varied from 80 to 120 KHz.
4. The ON Time and OFF time equation for the 555 Timer is given,

$$T_{on} = 0.693[R_a + R_b]C \tag{9.1}$$

$$T_{off} = 0.693[R_a]C \tag{9.2}$$

5. The Frequency variation is done by keeping a Trim pot for the R_a and the ON time is varied.
6. The OFF time is fixed to be 3.6 μsec.The C,R_a and R_b are calculated from the above equation.

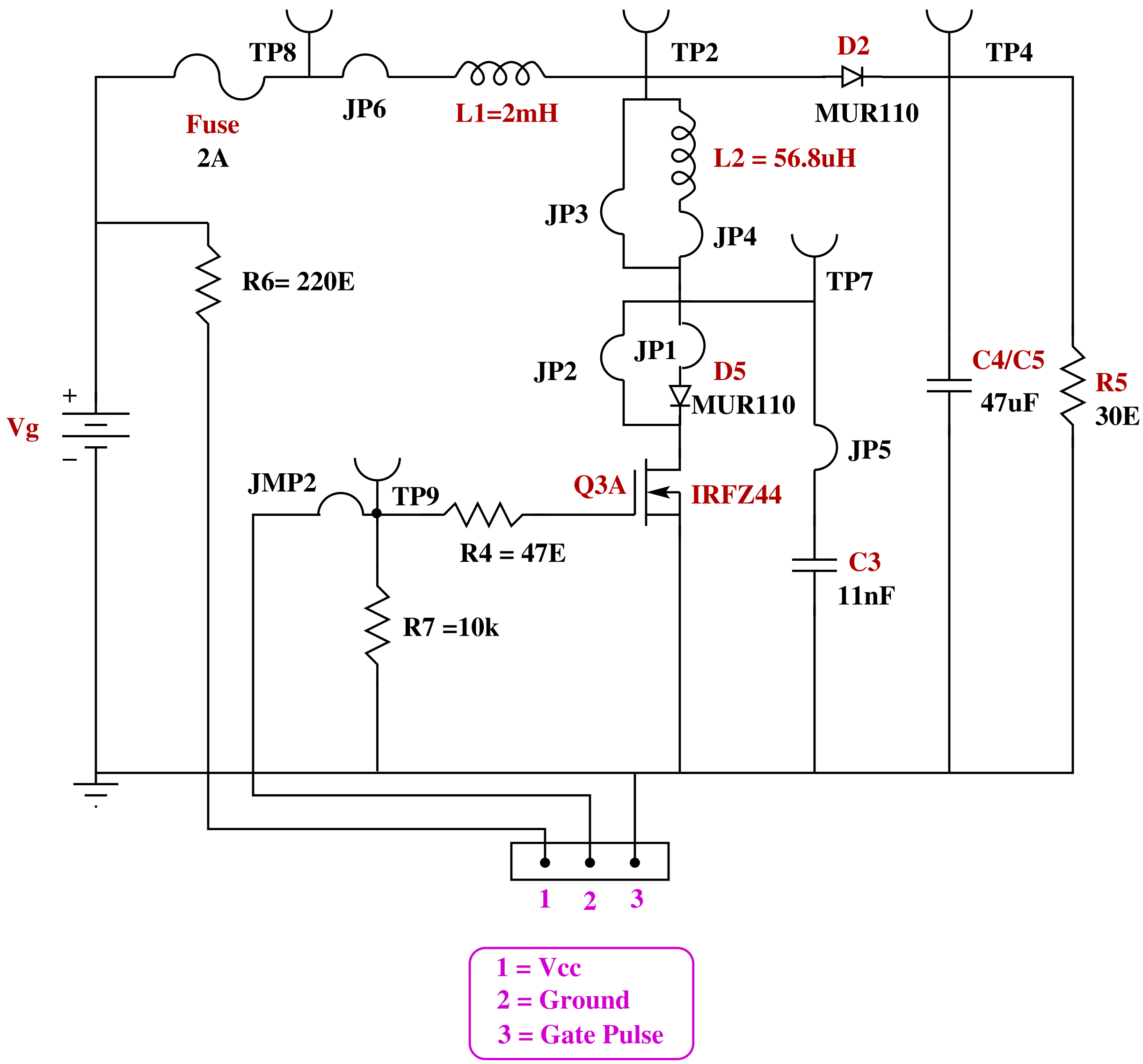


Figure 9.3: Power Circuit of ZVS-Boost Converter

7. For Zero VS,

$$V_o = Ig\sqrt{\frac{L_r}{C_r}} \tag{9.3}$$

8. The Resonant Frequency is selected to be 200KHz and then from equation 9.3, the $L_r = 56.84\ \mu H$ and C_r=0.01 μF values are obtained. The L_r and Cr in figure 9.2 form the resonant circuit.

9. Here in Zero Voltage Switching, when the switch voltage reaches zero then the switch is turned on.

9.4 Pratical Waveform of the ZVS-Boost Converter

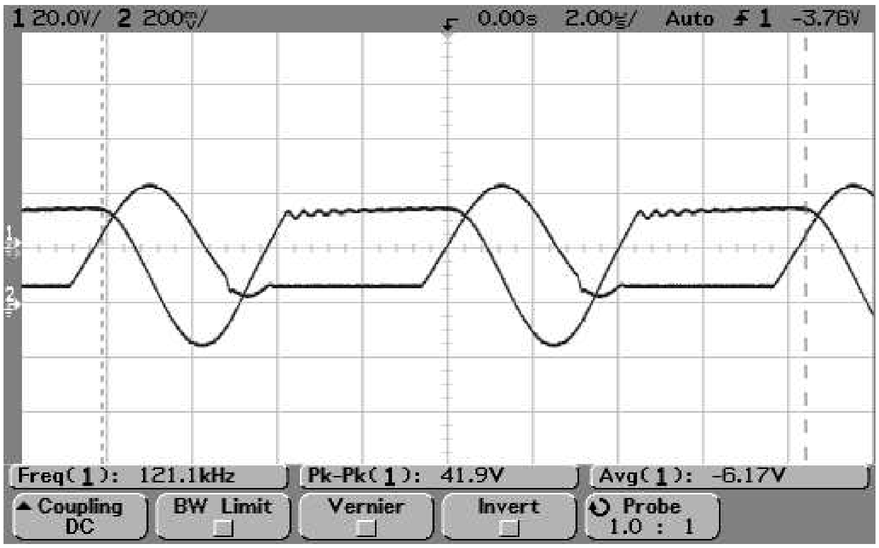


Figure 9.4: Resonant Inductor Current and Capacitor Voltage-Full Wave

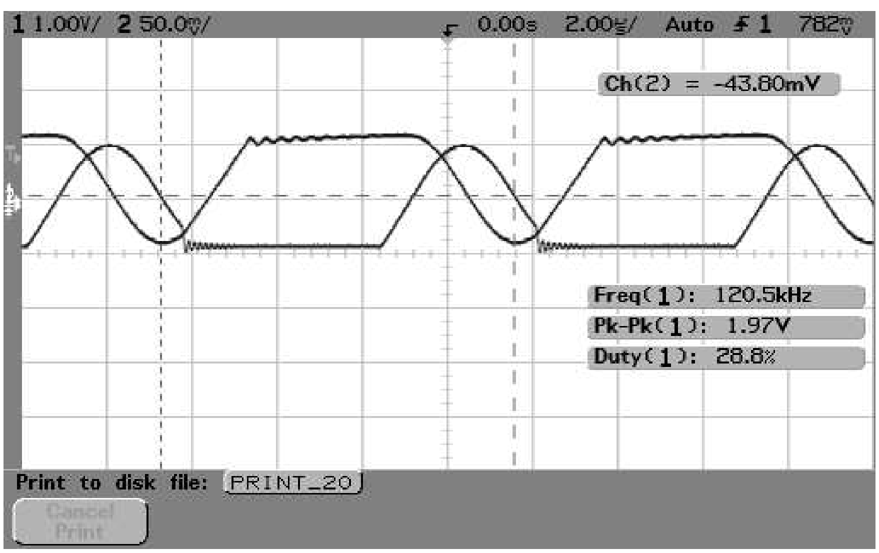


Figure 9.5: Resonant Inductor Current and Capacitor Voltage-Half Wave

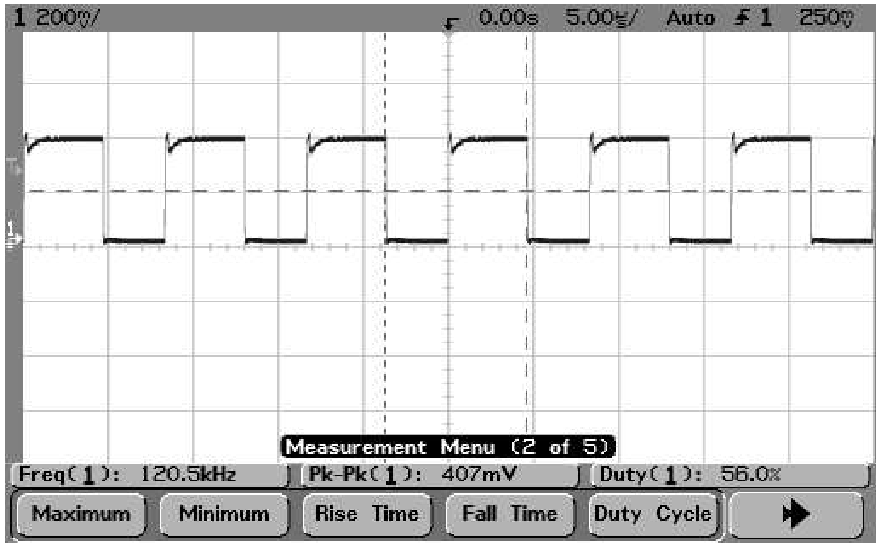


Figure 9.6: Gate Pulse form Control Circuit

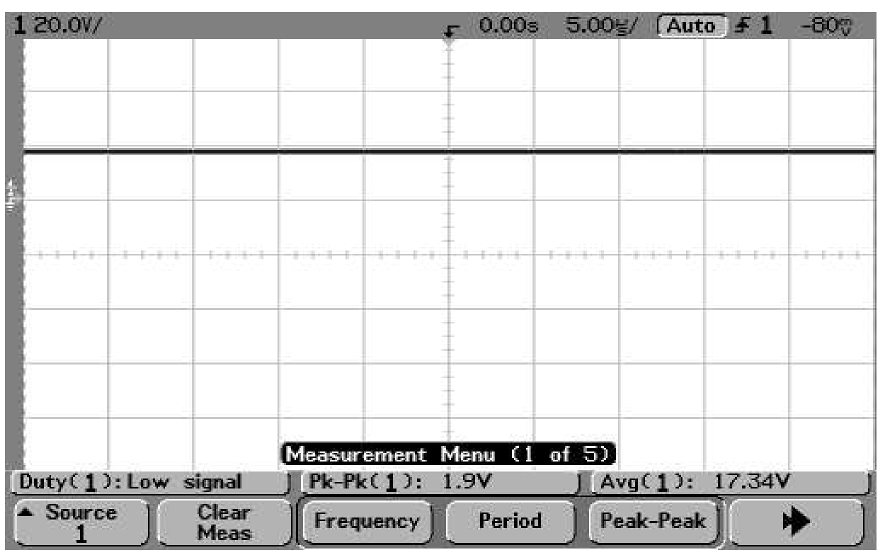


Figure 9.7: Output Voltage

9.5 Mounted and Bare PCB Boards

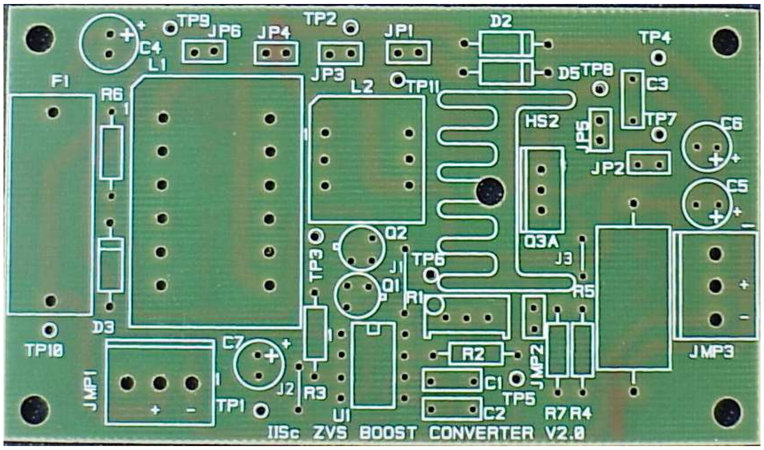


Figure 9.8: Bare PCB Board of ZVS-Boost Converter

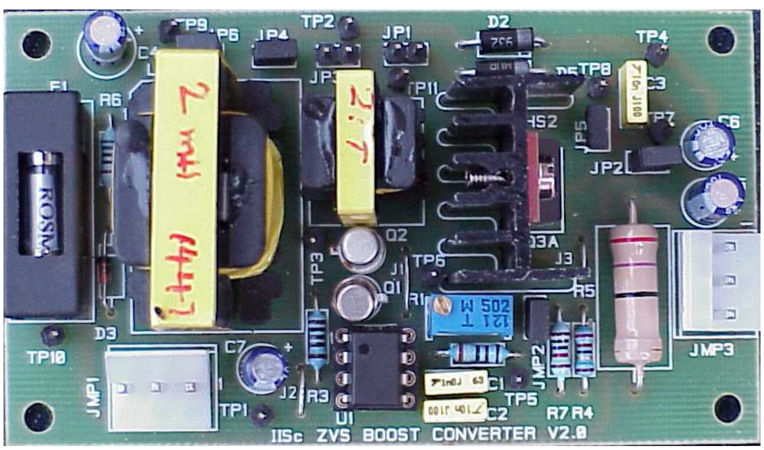


Figure 9.9: Mounted PCB Board of ZVS-Boost Converter

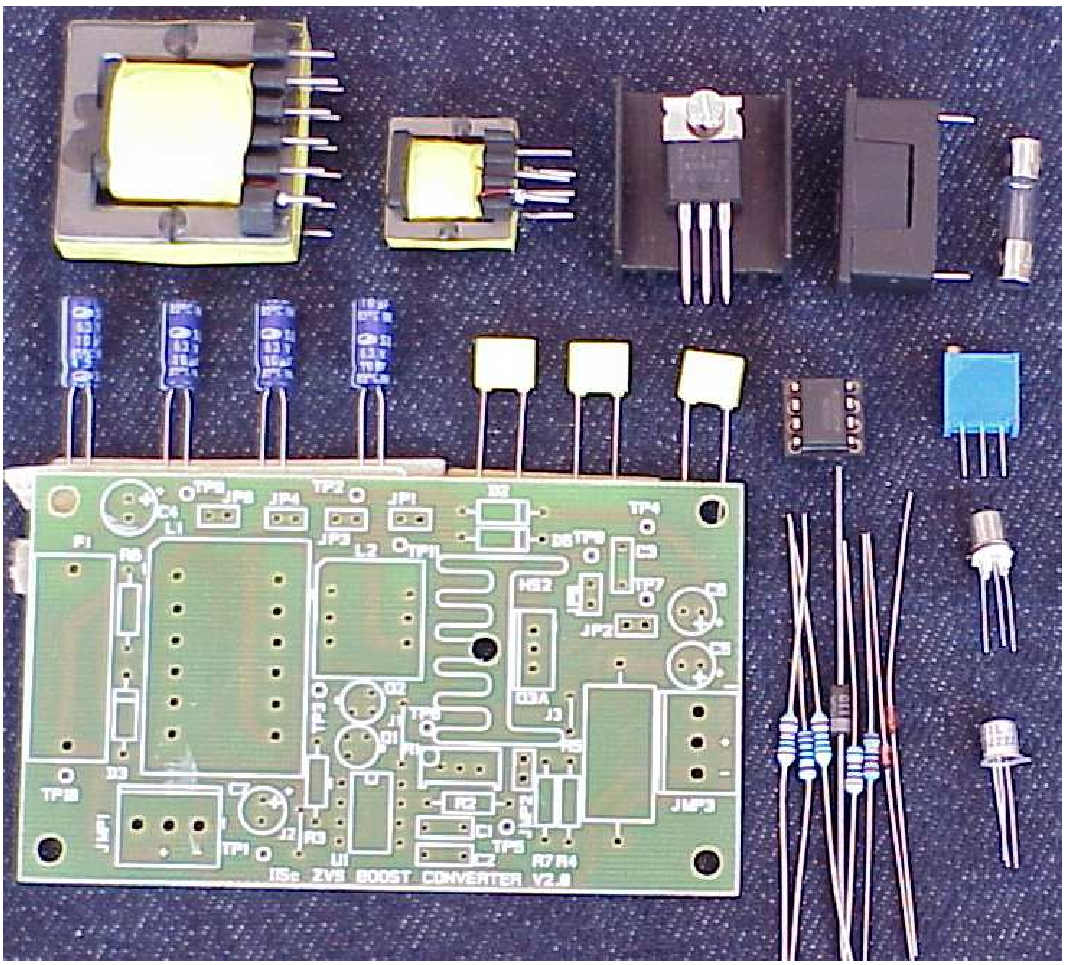


Figure 9.10: Components used in ZVS-Boost Converter

9.6 PCB Films for Solder and Components Side

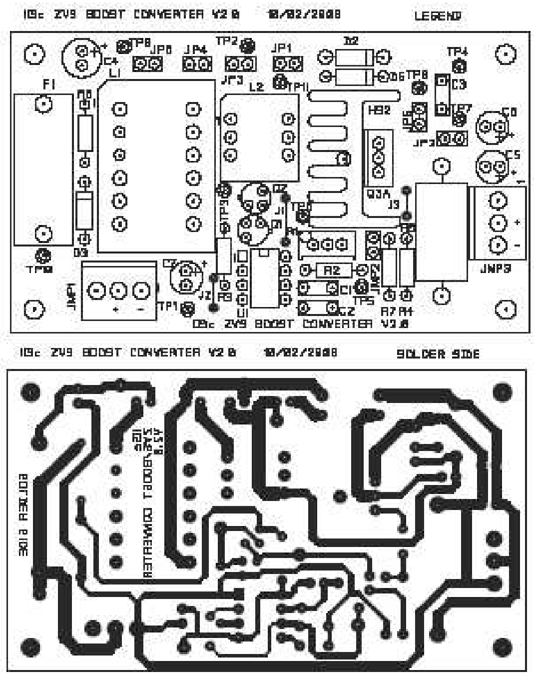


Figure 9.11: Solder and Component Side of ZVS-Boost Converter

9.7 Bill of Materials

Table 9.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1	$5k\ \Omega$ pot	1	2.00	2.00
2	Resistor	R2	$3.3k\ \Omega$	1	0.35	0.35
3	Resistor	R3	100 Ω	1	0.35	0.35
4	Resistor	R4	22 Ω	1	0.35	0.35
5	Resistor	R5	30 Ω,5W	1	2.00	2.00
6	Resistor	R6	560 Ω	1	0.35	0.35
7	Resistor	R7	$10k\ \Omega$	1	0.35	0.35
9	Capacitor	C1	$1nF$	1	0.50	0.50
10	Capacitor	C2,C3	0.01 μF,63V	2	0.50	1.00
11	Capacitor	C4,C5	10 μF,25V	2	2.00	4.00
12	Filter Inductor	L1	2000 μH	1	20.00	20.00
13	Mosfet	M1	IRFZ44N	1	16.00	16.00
14	Resonant Inductor	L2	56.8 μH	1	20.00	20.00
15	Tranisitor	Q1,Q2	2N2222,2N2907	2	4.50	9.00
16	Diode	D2,D5	MUR110	2	8.00	16.00
17	Linear IC	U1	555 TIMER	1	5.00	5.00
18	Test Points	T1-T10	Berg Stick	20	0.10	2.00
19	Jumpers	JP1-JP6		6	0.10	0.60
20	8 Pin IC Base	U1b		1	3.00	3.00
21	Terminal Connector	T1,T2		2	3.00	6.00
22	Heat Sink	HS1	P149	2	5.00	5.00
23	Diode	D3	Zener Diode (10V)	1	2.00	2.00
24	PCB	ZVS-BOOST		1	25.00	25.00
					TOTAL	140.85

Chapter 10

7.5W Quasi-Resonant Converter ZCS - Buck Converter

10.1 Circuit Specification

This section covers a simple zcs buck converter with the following specifications.

- Input: 10V to 15V
- Output: 5V, 1.5A, 7.5W
- Topology: Isolated Buck Converter
- Controller: 555 Timer(555 Timer)
- Switching Frequency: 100 to 67 kHz
- Protection: None
  Figure 10.1 and 10.2 shows the full circuit diagram of the zcs buck converter operating from 15V battery (10V to 15V) providing regulated output power at 5V (1.5 A). The controller used is 555 Timer.

10.2 Principle of Operation

1. The Major advantage of ZCS and ZVS quasi-resonant converters is thhat the power switch is turned on and off at zero voltage and zero current, respectively. In ZCS topologies the rectifying diode has ZVS, where as ZVS topologies the rectifying diode has ZCS. The Second advantage is that both ZVS and ZCS converter utilize Transformer leakage inductors and diode junction capacitor and the ouput parasitic capacitor of the power switch.

2. The major disadvantage of ZCS and ZVS techniques is that they require variable frequency control to regulate the output. This is undesirable

since it complicates the control circuit and generate unwanted EMI harmonics expecially under wide load variation.In ZCS the power switch turns off at zero current, but at turn on converter still suffers from the capacitor turn on loss caused by the output capacitor of power switch.

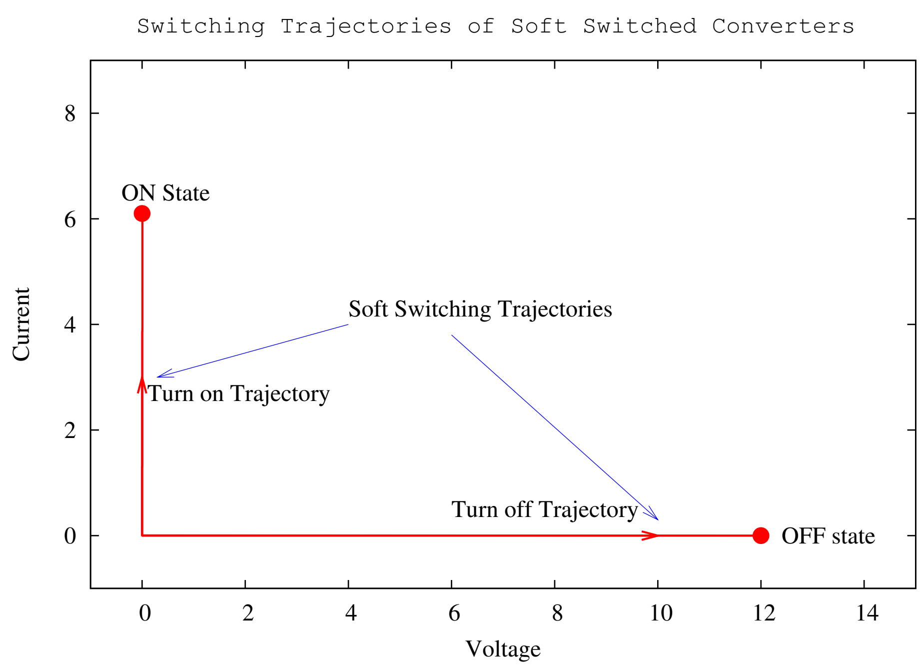


Figure 10.1: Switching Loci

3. Most regulator converters switches need to turn on or turn off the full load current at high voltage, resulting in what is known as hard switching. The figure 10.1 shows the typical switching loci for a hard switching converter without and with snubber circuit.

4. In soft switching topologies, an LC resonant network is added to shape the switching devices voltage or current waveform into a quasi-sinewave in such a way that a zero voltage or zero current condition is created. This technique eliminates the turn on or turn off losses associated with the charging or discharging of the energy stored in mosfets's parasitic junction capacitors.

10.3 Circuit Discription

1. The Controller used is 555 Timer.

2. For the Zero Current Switching Operation, the ON time is fixed and the Frequency variation is done by varying the OFF time only.

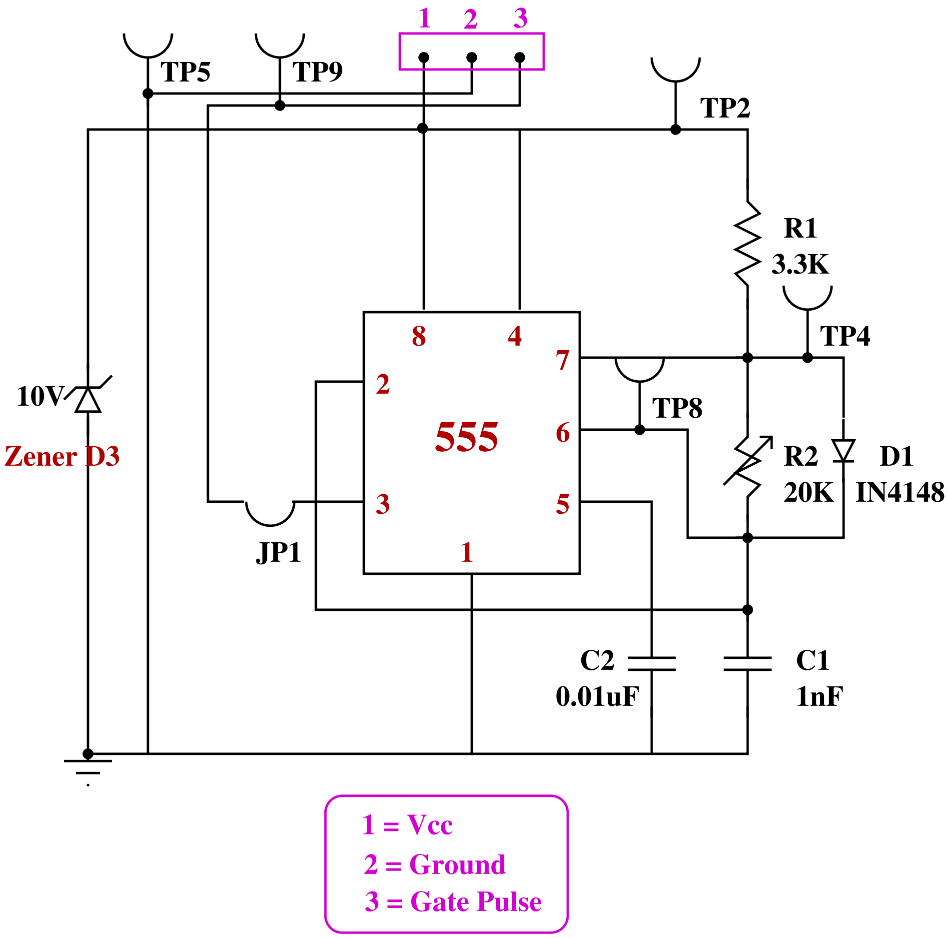


Figure 10.2: Control Circuit of ZCS-Buck Converter

3. The Frequency varied from 67 to 100 KHz.
4. The ON Time and OFF time equation for the 555 Timer is given,

$$T_{on} = 0.693[R_a + R_b]C \tag{10.1}$$

$$T_{off} = 0.693[R_a]C \tag{10.2}$$

5. The Frequency variation is done by keeping a Trim pot for the R_b and a diode in parallel across the R_b to bypass the resistor during the ON time.
6. The ON time is fixed to be 3.6 μsec.The C,R_a and R_b are calculated from the above equation.
7. For Zero Current Switching,

$$I_o = Vin\sqrt{\frac{C_r}{L_r}} \tag{10.3}$$

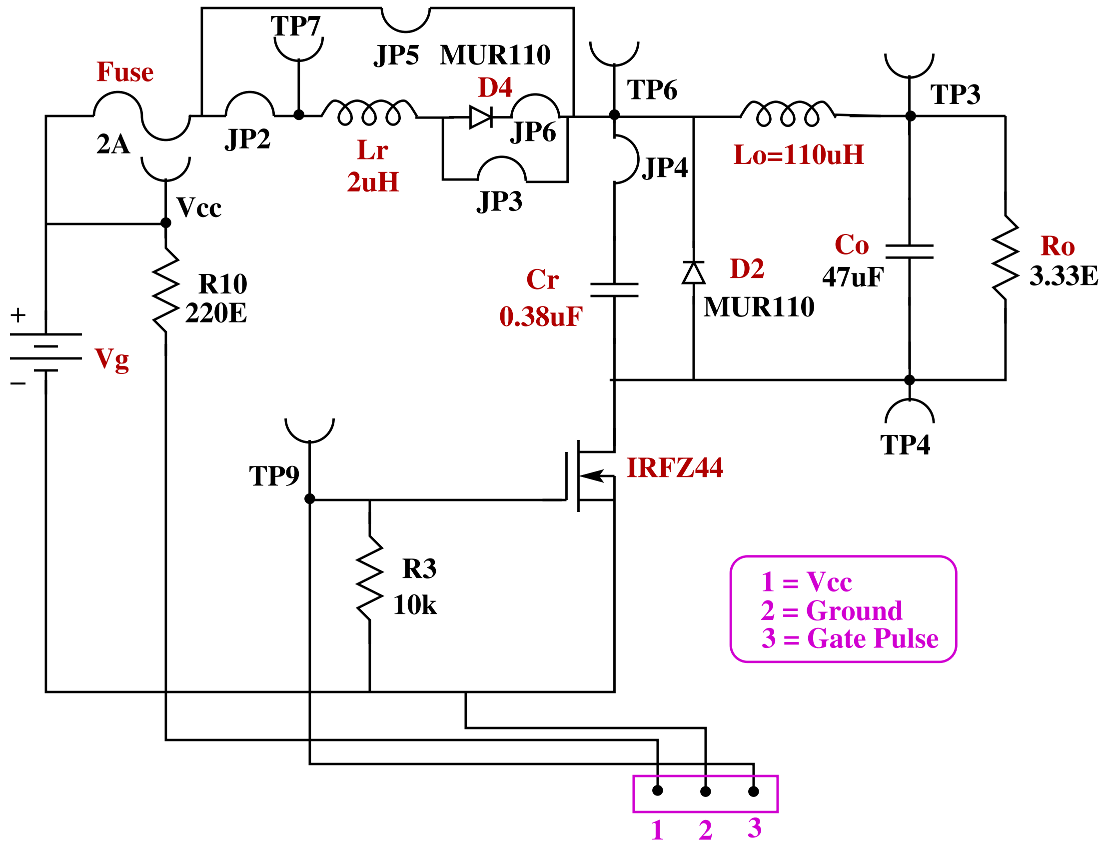


Figure 10.3: Power Circuit of ZCS-Buck Converter

8. The Resonant Frequency is selected to be 200KHz and then from equation 9.3, the $L_r = 2\ \mu H$ and C_r=0.47 μF values are obtained. The L_r and Cr in figure 9.2 form the resonant circuit.

9. Here in Zero Current Switching, when the Resonant Inductor Current reaches zero then the switch is turned OFF.

10.4 Pratical Waveform of the ZCS-Buck Converter

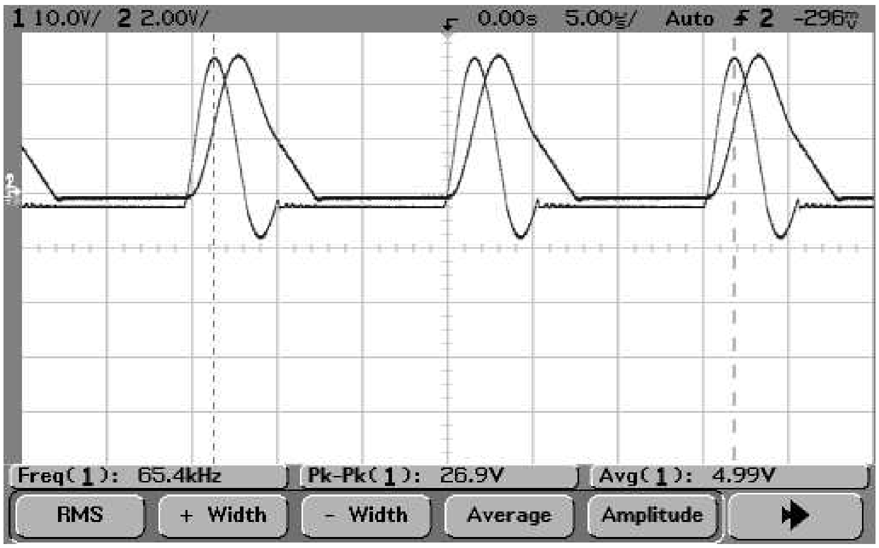


Figure 10.4: Resonant Inductor Current and Capacitor Voltage

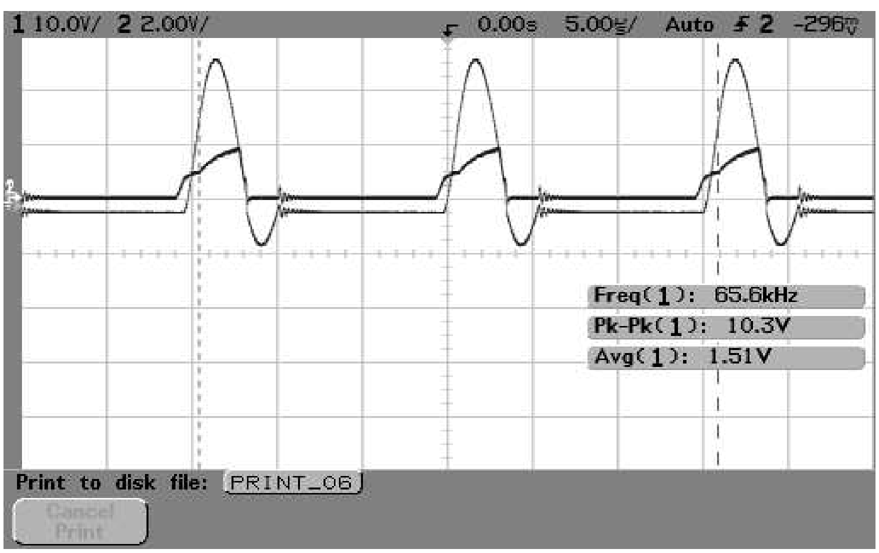


Figure 10.5: Gate Pulse form Control Circuit

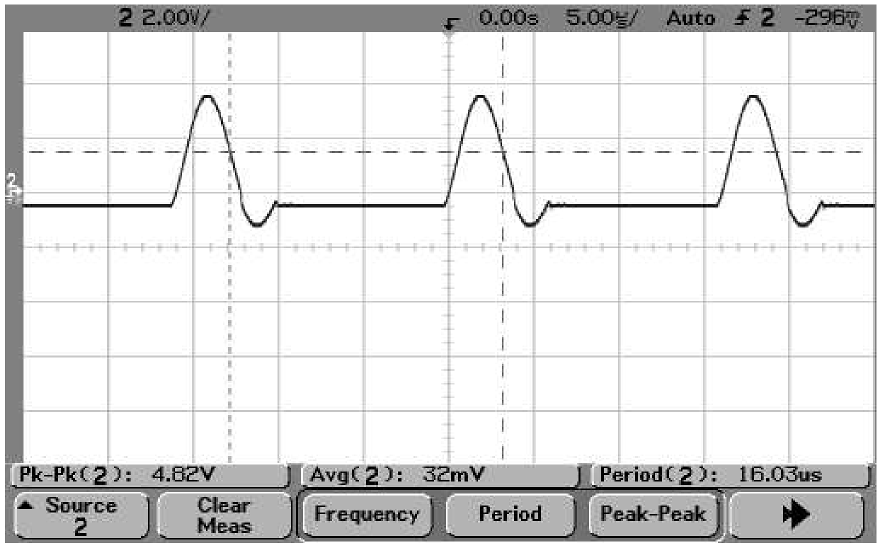


Figure 10.6: Inductor Current

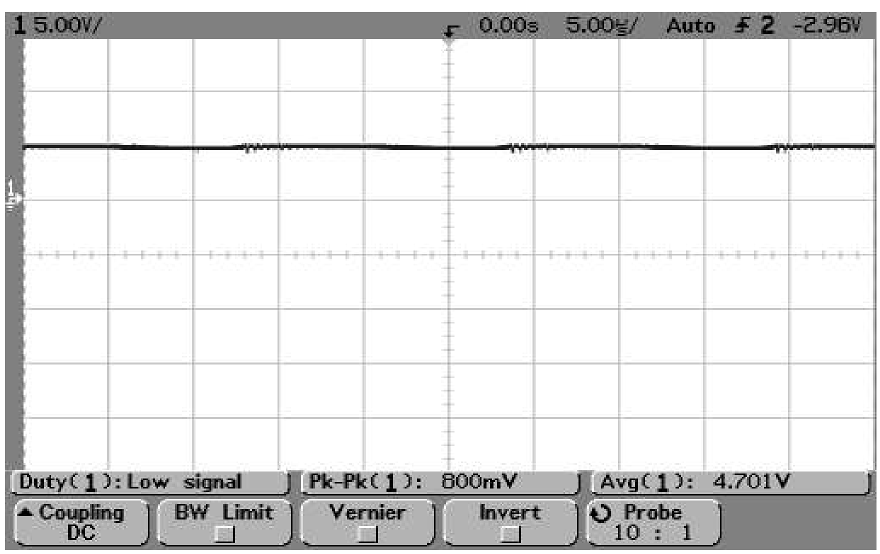


Figure 10.7: Output Voltage

10.5 Mounted and Bare PCB Boards

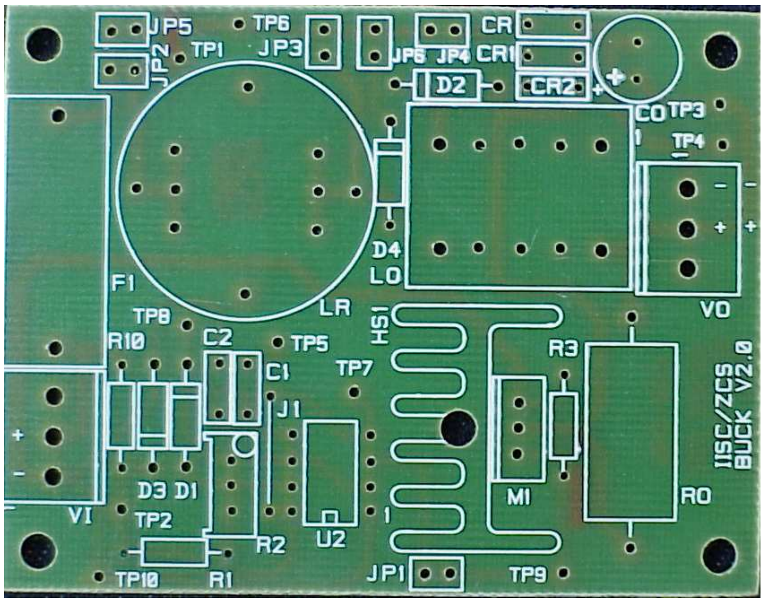


Figure 10.8: Bare PCB Board of ZCS-Buck Converter

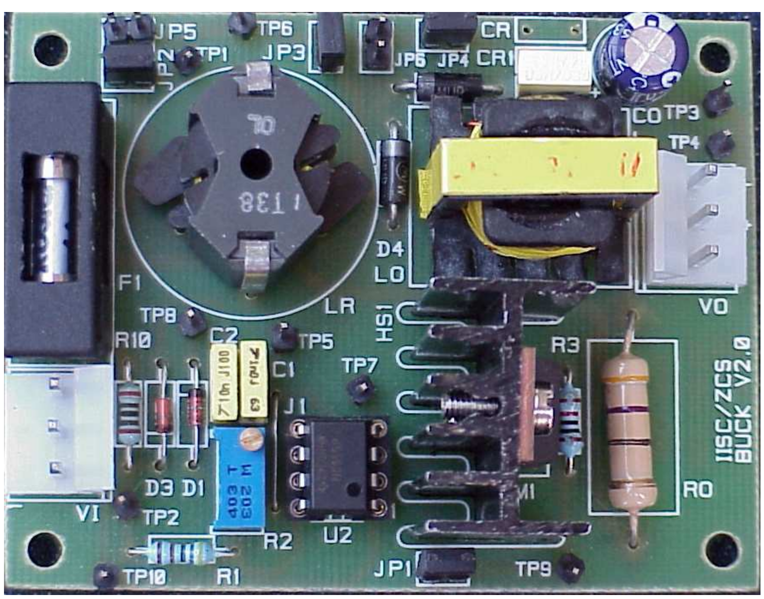


Figure 10.9: Mounted PCB Board of ZCS-Buck Converter

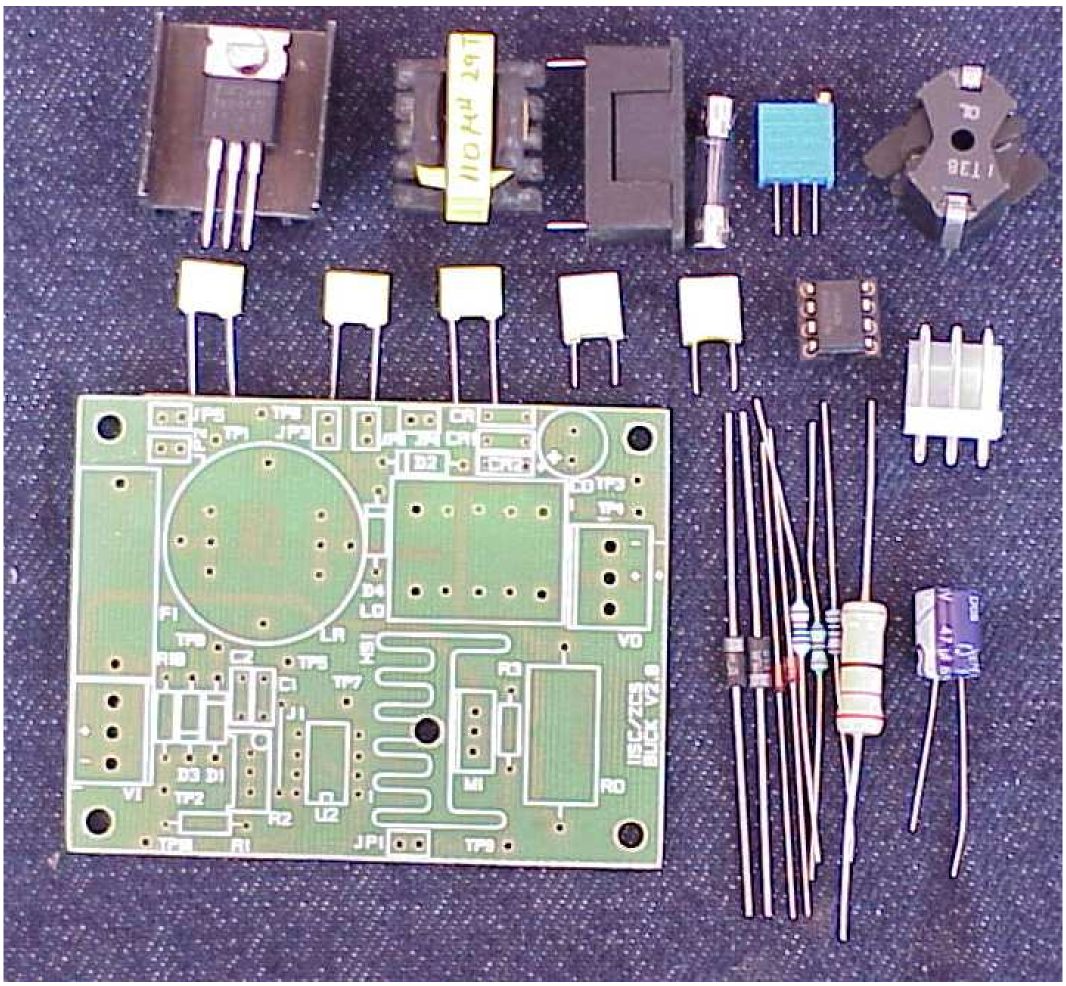


Figure 10.10: Components used in ZCS-Buck Converter

10.6 PCB Films for Solder and Components Side

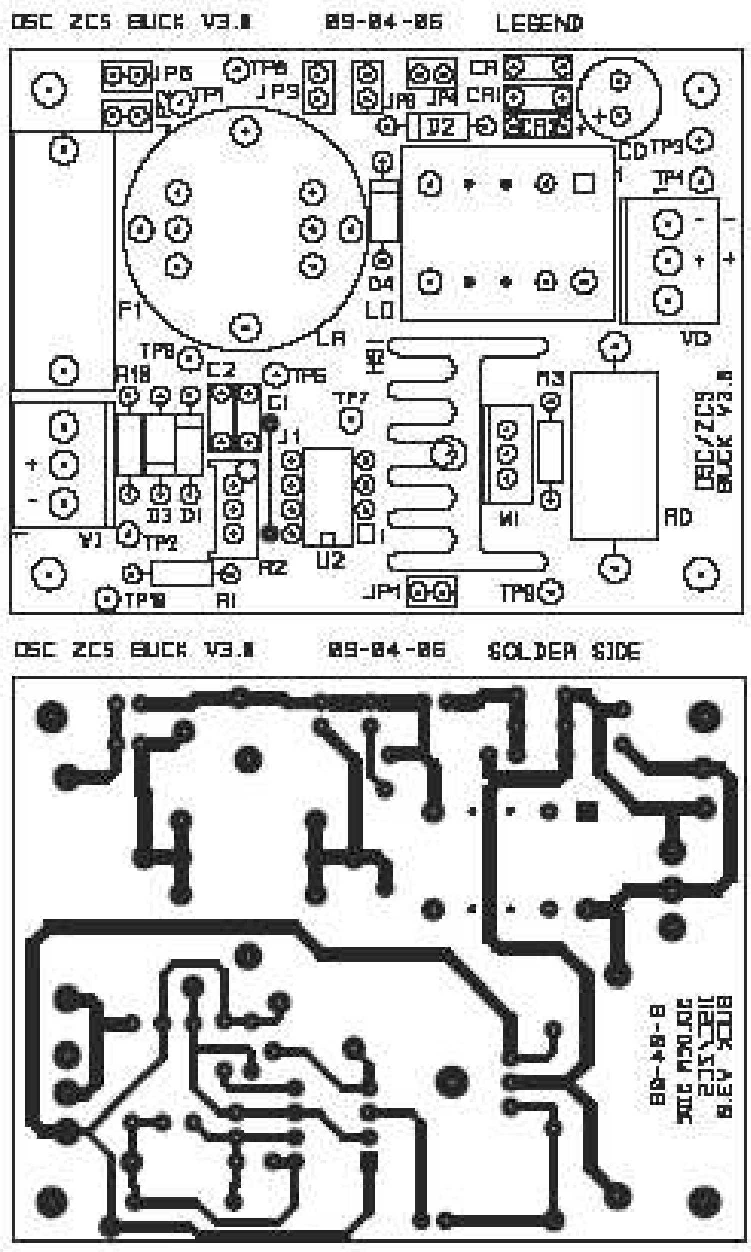


Figure 10.11: Solder and Component Side of ZCS-Buck Converter

10.7 Bill of Materials

Table 10.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R2	$20k\ \Omega$ pot	1	2.00	2.00
2	Resistor	R1	$3.3k\ \Omega$	1	0.35	0.35
3	Resistor	Ro	3.33Ω	1	3.00	3.00
4	Resistor	R10	$10k\ \Omega$	1	0.35	0.35
5	Capacitor	Co	47 μF	1	2.00	2.00
6	Capacitor	C1	$1nF$	1	0.50	0.50
7	Capacitor	C2	0.01 μF,63V	2	0.50	1.00
8	Capacitor	Cr,Cr1	0.47 μF,25V	2	2.00	4.00
9	Filter Inductor	Lo	110 μH	1	20.00	20.00
10	Mosfet	M1	IRFZ44N	1	16.00	16.00
11	Resonant Inductor	Lr	2 μH	1	20.00	20.00
12	Diode	D2,D4	MUR110	2	8.00	16.00
13	Linear IC	U1	555 TIMER	1	5.00	5.00
14	Test Points	T1-T10	Berg Stick	20	0.10	2.00
15	Jumpers	JP1-JP6		6	0.10	0.60
16	8 Pin IC Base	U1b		1	3.00	3.00
17	Terminal Connector	T1,T2		2	3.00	6.00
18	Heat Sink	HS1	P149	2	5.00	5.00
19	Diode	D3	Zener Diode (10V)	1	2.00	2.00
20	PCB	ZCS-BUCK		1	25.00	25.00
					TOTAL	127.8

Chapter 11

7.5W Current Mode Control of Flyback Converter

11.1 Circuit Specification

This section covers a simple closed loop current mode controlled flyback converter with the following specifications.

- Input: 10V to 15V
- Output: 5V, 1.25A, 7.5W
- Topology: Non-isolated flyback Converter
- Controller: UC3843(UC3843)
- Switching Frequency: 100 kHz
- Protection: None
  Figure 11.1 and 11.2 shows the full circuit diagram of the non-isolated flyback converter operating from 15V battery (10V to 15V) providing regulated output power report at 5V (1.25 A). The controller used is UC3843 of Unitrode make.

11.2 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

11.2.1 Control Circuit:

1. Controller: The controller used here is UC3843. It is 8 pin IC with maximum supply voltage is 40V.
2. C_2,C_{sh} are all used for filtering.

3. Reference voltage: IC has a internal reference Voltage of 5V.
4. Oscillator Section: Switching Frequency is determined by R_t and C_t

$$F_s = \frac{1.72}{R_t C_t} = 100KHz \tag{11.1}$$

5. Slope Compensation: Transitor Q_4 and R_v forms the Slope Compensation Circuit.The Slope Compensation circuit is required when the circuit is operating with a duty ratio more then 0.5.
6. Controller: Resistor R_f and Capacitor C_f forms the PI controller circuit.
7. Current Sense: UC3843 IC Pin 3 is the Current Sense Pin, it sense the rectified switch current from the Current Transfomer. This rectified Current gets added with the slope compensation voltage and this the Current Sensed by the IC.
8. R_b is the Bleeder resistance used, based on the value of R_b we decide the current sensed to be less then 1V threshold at pin no.3.

11.2.2 Power Circuit:

1. It Consists of the flyback converter with include a Coupled Inductor, Switch, Diode , Capacitor and Load.
2. Duty Ratio: The input voltage is in the range of 10 to 15 V. The output of the boost converter is designed for 5V. The range of duty ratio is from 0.6 to 0.33.
3. Main Inductor: The rated current is 1.25 A. The ripple current is chosen as 0.15 A. With maximum on time of 12 μs, at input voltage of 10V, this gives an inductor value of approximately 150 μH. Inductor is 150H with 33 Turns on primary and 11 Turns on seconday of 22 SWG.
4. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.
5. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)
6. The capacitor C1 has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 220F.
7. Current Transformer: The CT is used to sense the switch current. The Core used is E 16/8/5 of SWG 28 with 1:200 Turns.
8. The Load Resistor used is 120E.[7.5W]

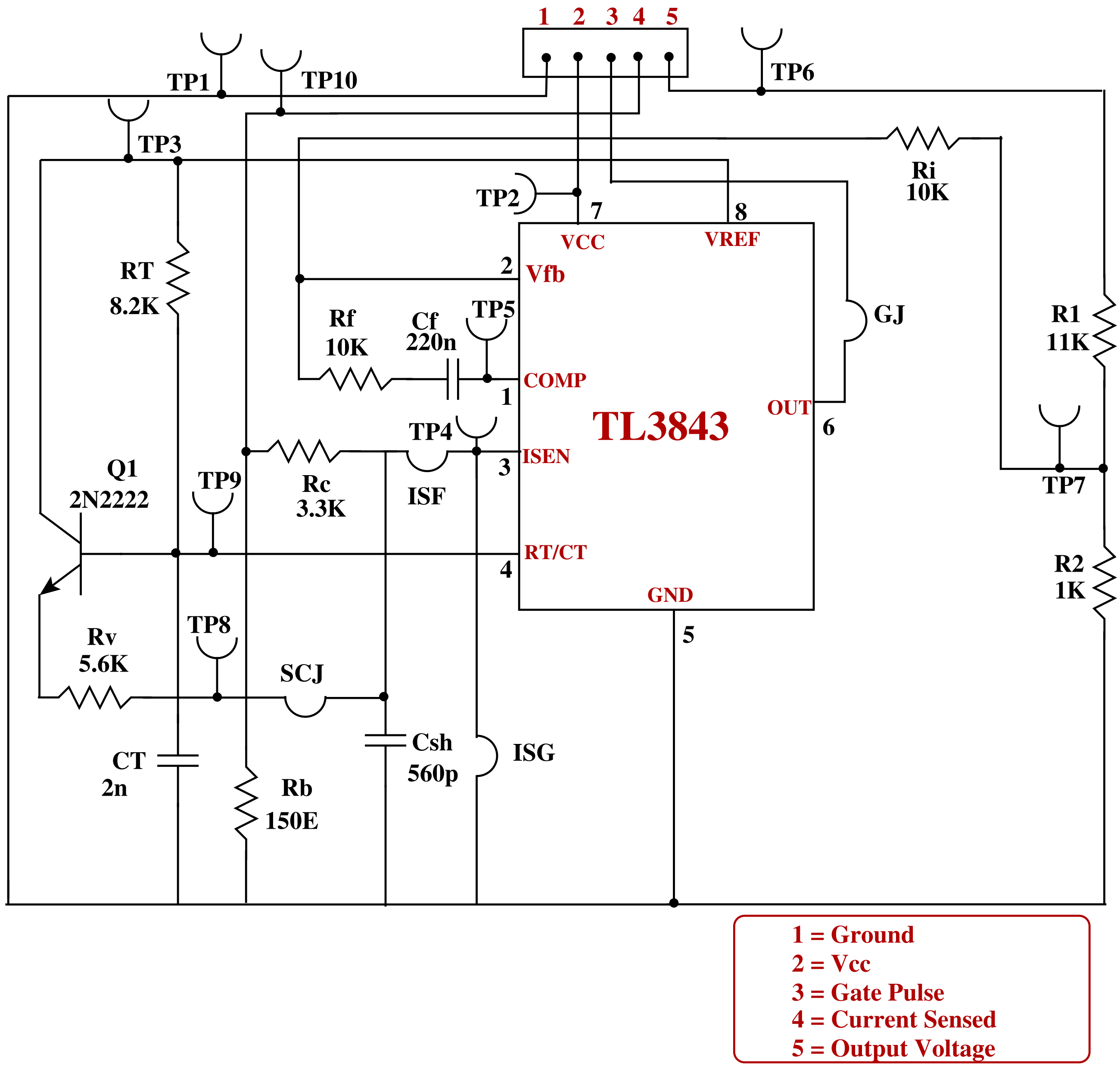
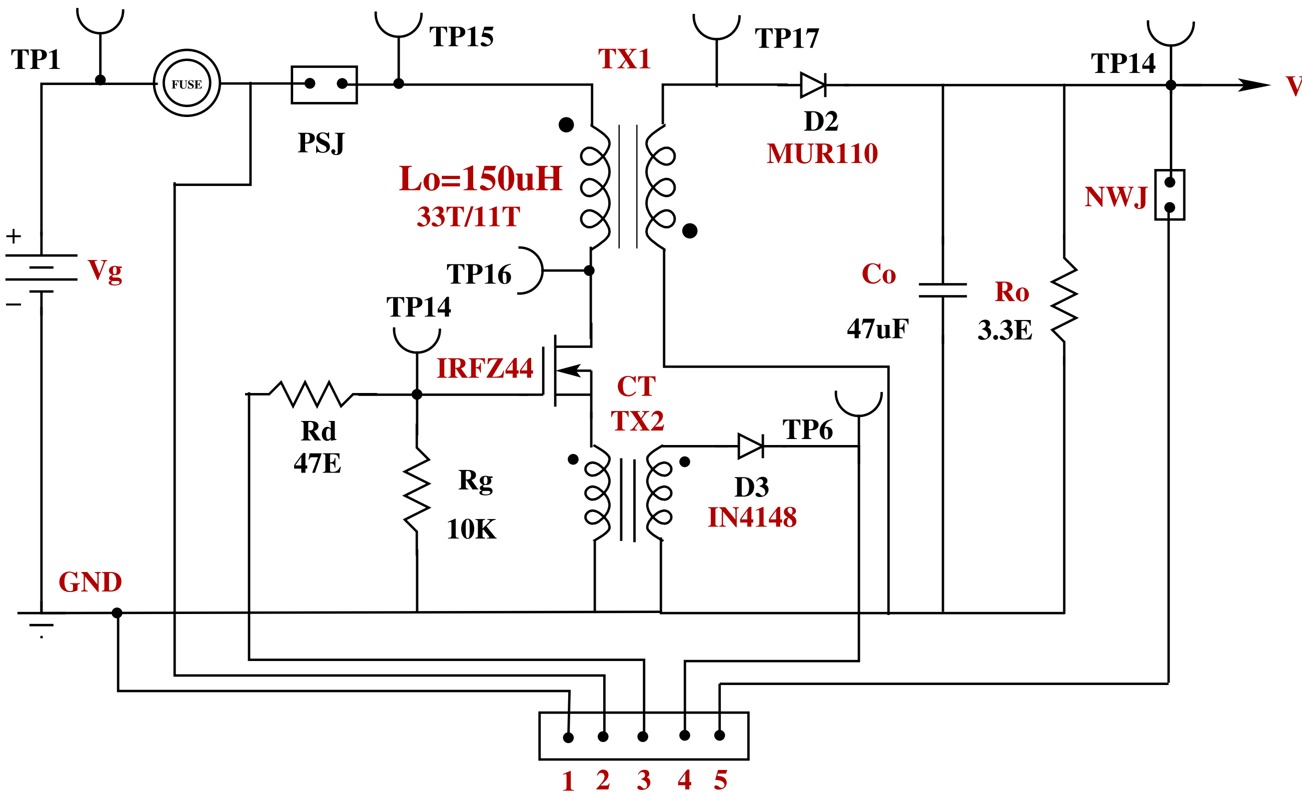


Figure 11.1: Control Circuit for Current Mode Control of Flyback Converter



1 = GND
2 = Vcc
3 = Gate Pulse
4 = Current Sense
5 = Output Voltage

Figure 11.2: Power Circuit for Current Mode Control of Flyback Converter

11.3 Practical Bode Plot using Network Analyser

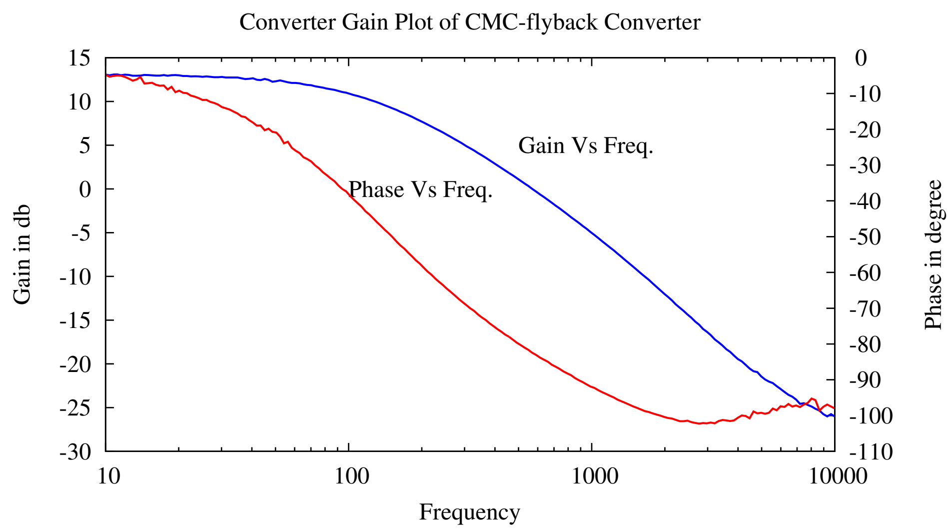


Figure 11.3: Converter Gain Bode Plot of CMC-Flyback Converter

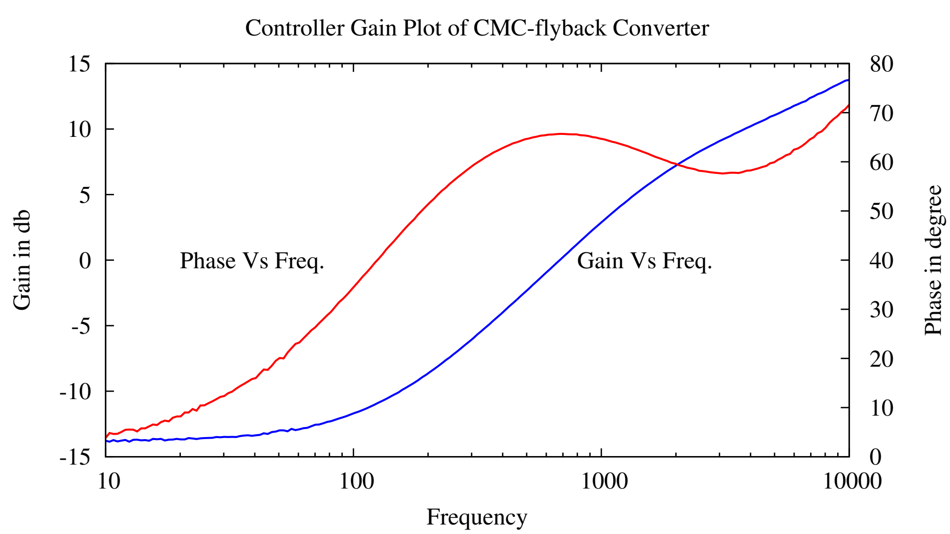


Figure 11.4: Controller Gain Bode Plot of CMC-Flyback Converter

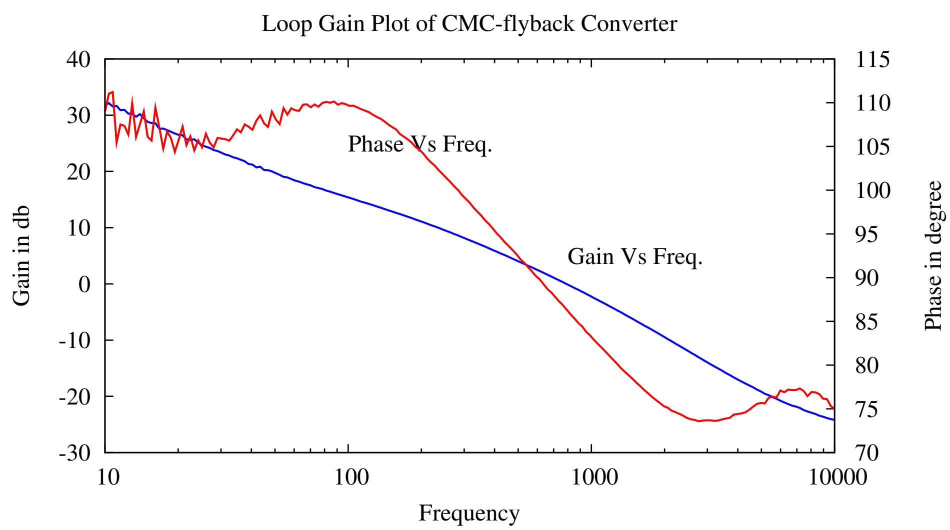
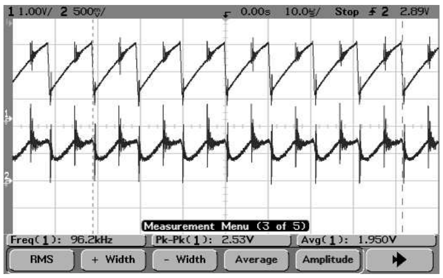
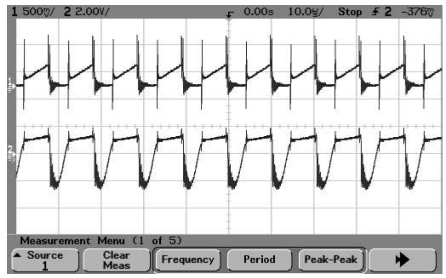


Figure 11.5: Loop Gain Bode Plot of CMC-Flyback Converter

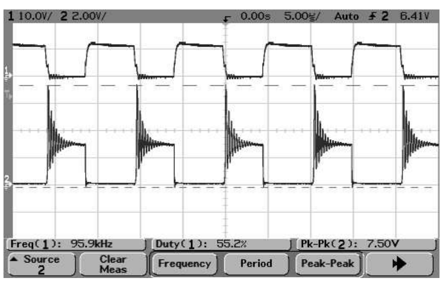
11.4 Pratical Waveform of the CMC-flyback Converter



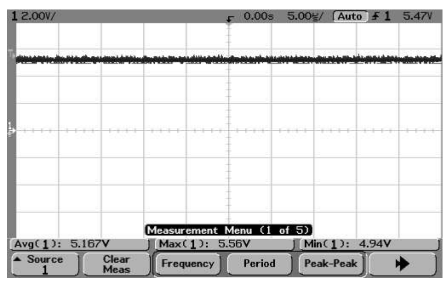
(a) Ramp Voltage and Current sensed with Ramp Compensation



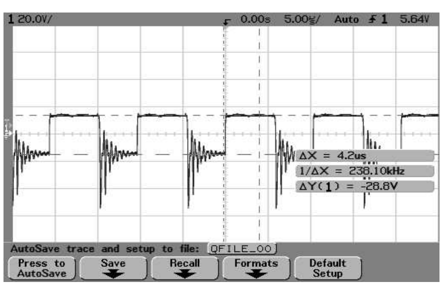
(b) Rectified and Unrectified Switch Current



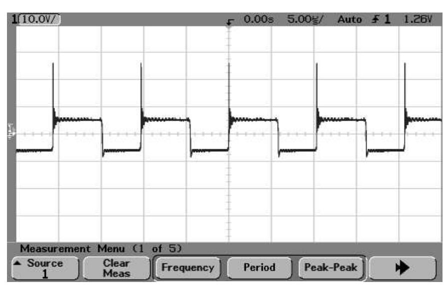
(c) Gate Voltage and Switch Voltage



(d) Output Voltage



(e) Primary Inductor Voltage



(f) Secondary Inductor Voltage

11.5 Mounted and Bare PCB Boards

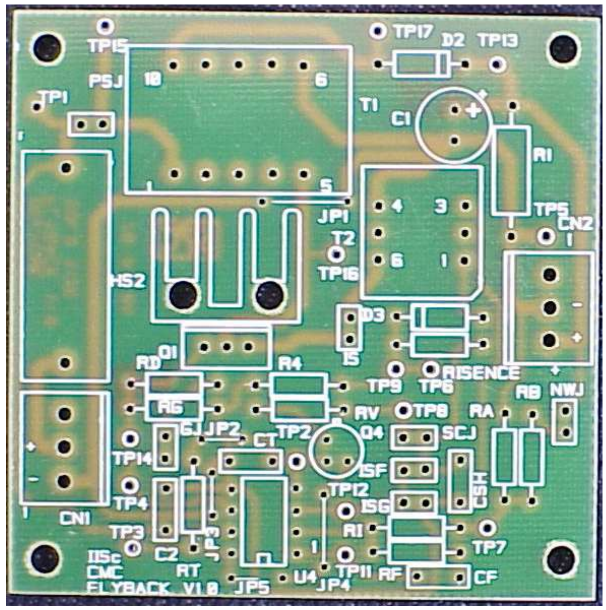


Figure 11.6: Bare PCB Board of the CMC-flyback Converter

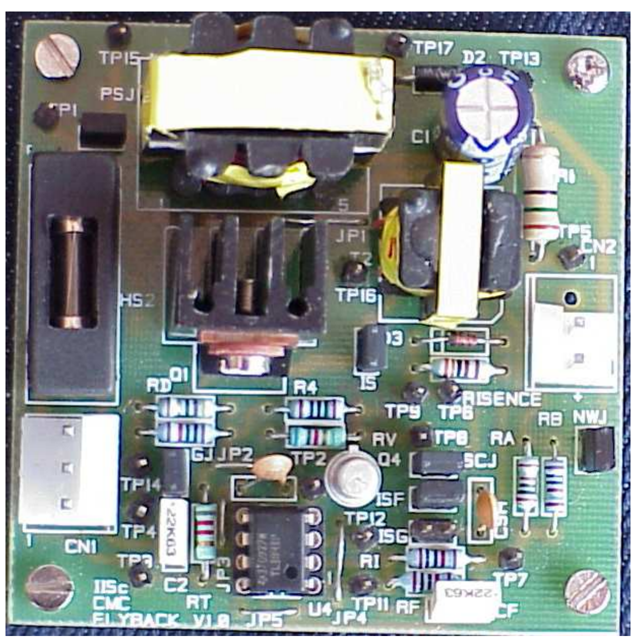


Figure 11.7: Mounted PCB Board of the CMC-flyback Converter

11.6 PCB Films for Solder and Components Side

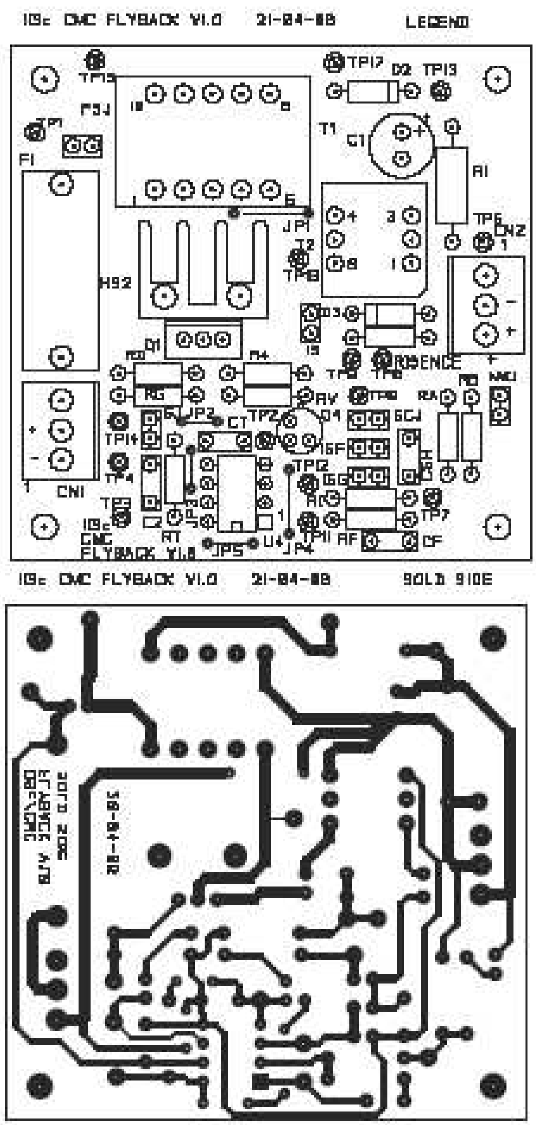


Figure 11.8: Solder and Component Side of CMC-Flyback Converter

11.7 Bill of Materials

Table 11.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg,Rf,Ri	$10k\ \Omega$	3	0.35	1.05
2	Resistor	Rt	$8.2k\ \Omega$	1	0.35	0.35
3	Resistor	Rv	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	R4	$150\ \Omega$	1	0.35	0.35
5	Resistor	Rd	$47\ \Omega$	1	0.35	0.35
6	Resistor	Risen	$3.3k\ \Omega$	1	0.35	0.35
7	Resistor	Ra,Rb	$1k\ \Omega$	2	0.35	0.70
8	Resistor	R1	$5\ \Omega$	1	3.00	3.00
9	Capacitor	Csh	$560pF$	1	2.00	2.00
10	TP Connectors		2pin	6	0.10	0.60
11	Capacitor	C1	$47\ \mu F$,25V	1	2.00	2.00
12	Capacitor	Cf,C2	$0.022\ \mu F$,50V	2	2.50	5.00
13	Capacitor	Ct	$0.0047\ \mu F$,50V	1	2.50	2.50
15	Current Transformer	T2	1:200	1	15.00	15.00
16	Mosfet	M1	IRFZ44N	1	16.00	16.00
17	Coupled Inductor	L1	$150\ \mu H, 33T/11T$	1	25.00	25.00
18	Transisor	Q1	2N2222	1	4.50	4.50
19	Diode	D3	IN4148	1	0.40	0.40
20	Diode	D2	MUR110	1	8.00	8.00
21	Linear IC	U1	UC3843	1	7.00	7.00
22	Test Points	T1-T10	Berg Stick	20	0.10	2.00
23	Jumpers	NMJ,GJ,IS, SCJ,PSJ,ISG		6	0.10	0.60
24	8 Pin IC Base	U1b		1	5.00	5.00
25	Terminal Connector	T1,T2		2	3.00	6.00
26	Heat Sink	HS1	P149	2	5.00	5.00
27	PCB	7.5W CMC flyback		1	25.00	25.00
					TOTAL	138.10

Chapter 12

7.5W Current Mode Control of Isolated Flyback Converter

12.1 Circuit Specification

This section covers a simple closed loop current mode controlled isolated flyback converter with the following specifications.

- Input: 10V to 15V
- Output: 5V, 1.25A, 7.5W
- Topology: Isolated flyback Converter
- Controller: UC3843(UC3843)
- Switching Frequency: 100 kHz
- Protection: None
  Figure 12.1 and 12.2 shows the full circuit diagram of the Isolated flyback converter operating from 15V battery (10V to 15V) providing regulated output power report at 5V (1.25 A). The controller used is UC3843 of Unitrode make.

12.2 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

12.2.1 Control Circuit:

1. Controller: The controller used here is UC3843. It is 8 pin IC with maximum supply voltage is 40V.
2. C_2,C_{sh} are all used for filtering.

3. Reference voltage: IC has a internal reference Voltage of 5V.
4. Oscillator Section: Switching Frequency is determined by R_t and C_t

$$F_s = \frac{1.72}{R_t C_t} = 100KHz \tag{12.1}$$

5. Slope Compensation: Transitor Q_4 and R_v forms the Slope Compensation Circuit. The Slope Compensation circuit is required when the circuit is operating with a duty ratio more then 0.5.
6. Controller: Resistor R_f and Capacitor R_i form the gain of the error amplifier.
7. Current Sense: UC3843 IC Pin 3 is the Current Sense Pin, it senses the rectified switch current from the Current Transfomer. The rectified Current gets added with the slope compensation voltage and the current obtained is then given to the isense pin of IC.
8. R_b is the Bleeder resistance used, based on the value of R_b we limit the voltage at Isense pin, since it is having a threshold of 1V.

12.2.2 Power Circuit:

1. It Consists of the flyback converter which include a Coupled Inductor, Switch, Diode , Capacitor, Load, Precision Shunt Regulator and a Opto-coupler.
2. Duty Ratio: The input voltage is in the range of 10 to 15 V. The output of the boost converter is designed for 5V. The range of duty ratio is from 0.6 to 0.33.
3. Main Inductor: The rated current is 1.25 A. The ripple current is chosen as 0.15 A. With maximum on time of 12 μs, at input voltage of 10V, this gives an inductor value of approximately 150 μH. Inductor is 150H with 33 Turns on primary and 11 Turns on seconday of 22 SWG.
4. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.
5. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)
6. The capacitor C1 has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 220F.

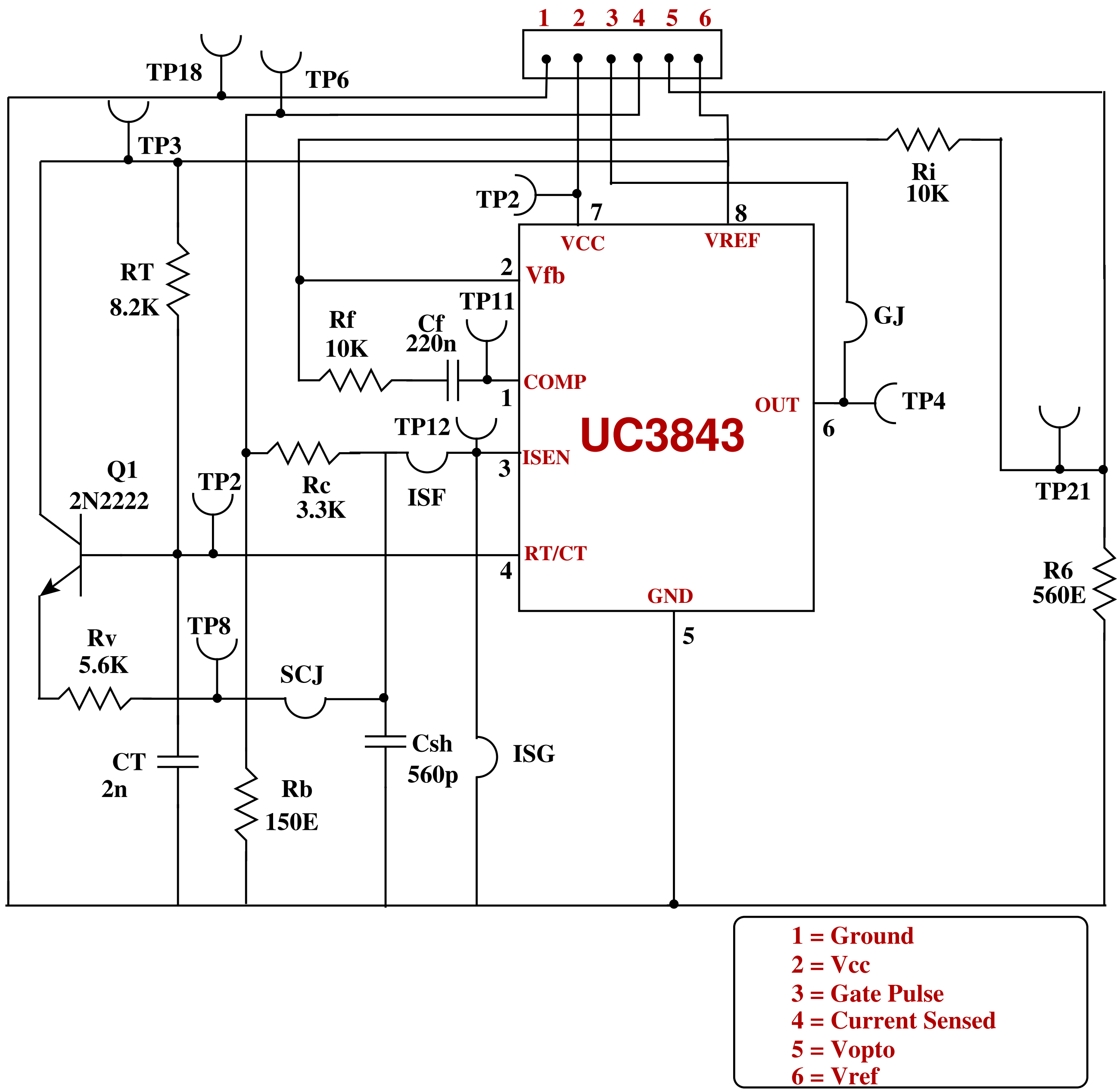
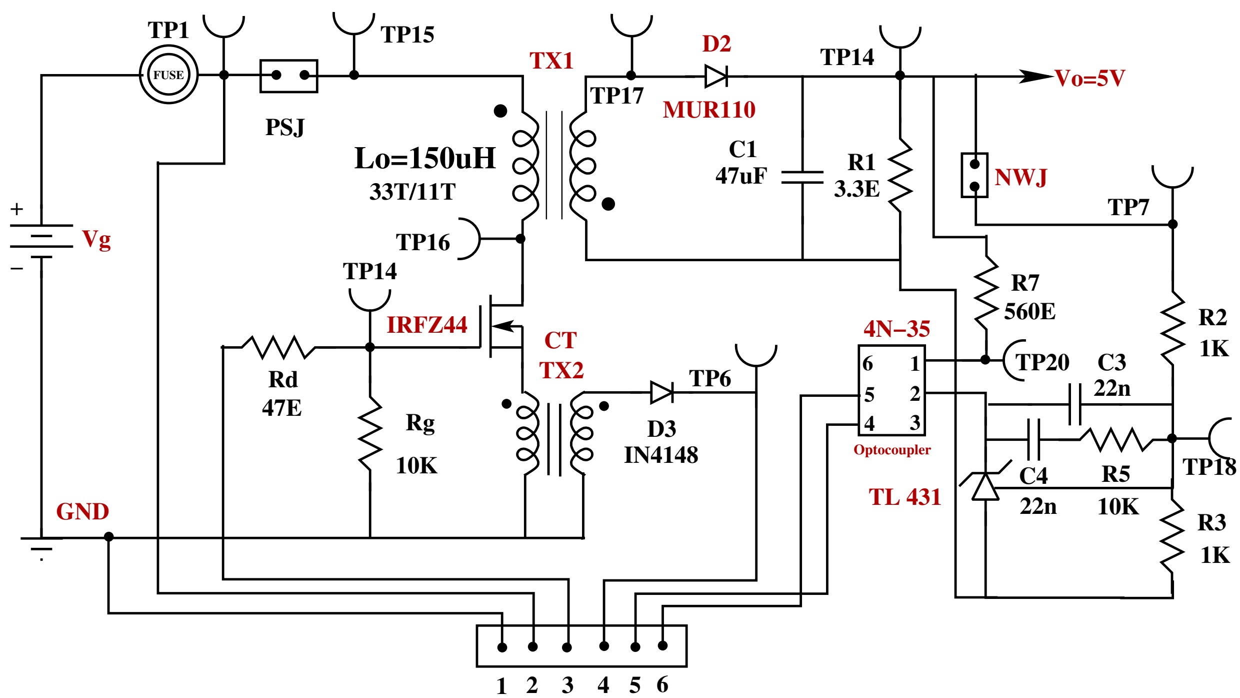


Figure 12.1: Control Circuit for Current Mode Control of Flyback Converter

7. Current Transformer: The CT is used to sense the switch current. The Core used is E 16/8/5 of SWG 28 with 1:200 Turns.

8. R_5,C_4 and C_3 for the PI controller circuit.

9. The isolation is provided by using an optocoupler.(4N-35)



1 = GND
2 = Vcc
3 = Gate Pulse
4 = Current Sense
5 = Vopto
6 = Vref

Figure 12.2: Power Circuit for Current Mode Control of Flyback Converter

10. TL431 is used a fixed 2.5V reference regulator. (tl431)

11. The Load Resistor used is 120E.[7.5W]

12.3 Practical Bode Plot using Network Analyser

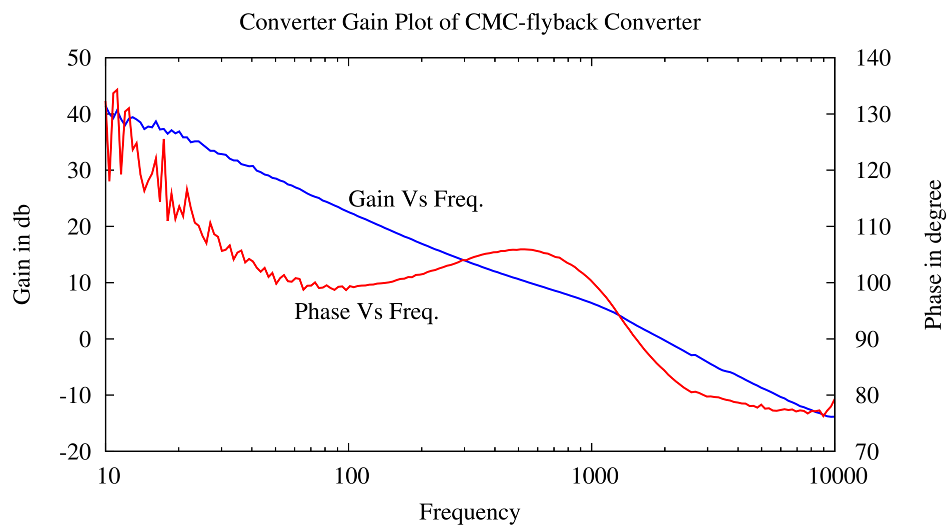
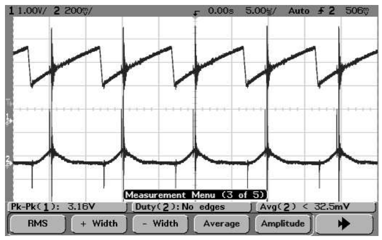
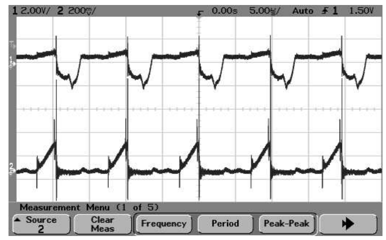


Figure 12.3: Loop Gain Bode Plot of CMC-Isolated Flyback Converter

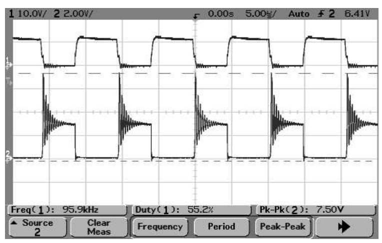
12.4 Pratical Waveform of the CMC Isolated Flyback Converter



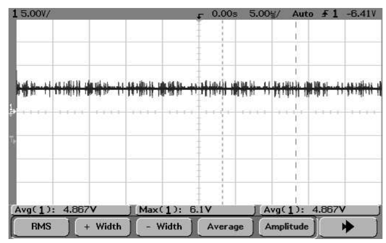
(a) Ramp voltage and Current Sensed



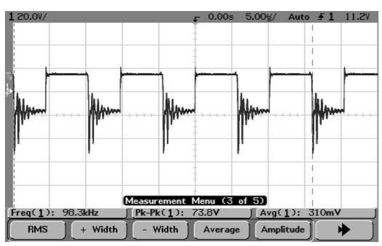
(b) Unrectifed and Rectifed Switch Current



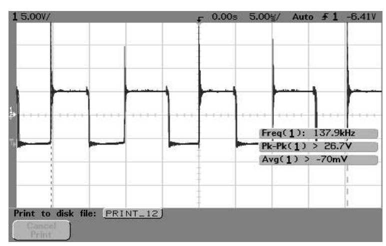
(c) Gate Pulse and Switch Voltage



(d) Output Voltage



(e) Primary Inductor Voltage



(f) Secondary Inductor Voltage

12.5 Mounted and Bare PCB Boards

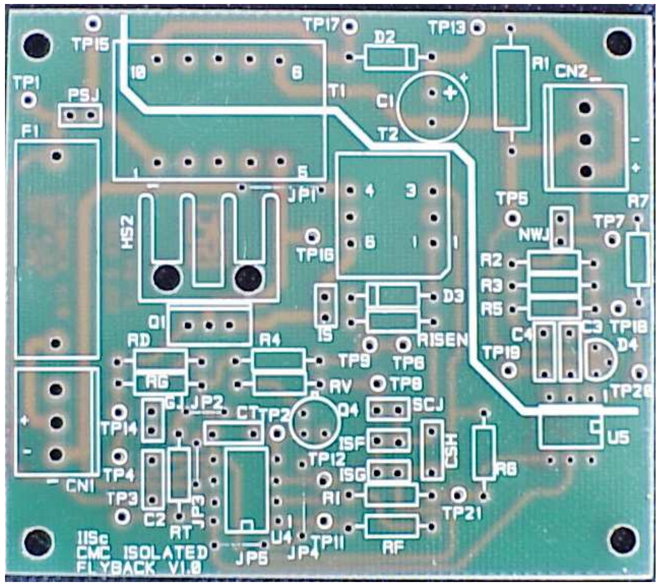


Figure 12.4: Bare PCB Board of the Isolated Flyback Converter

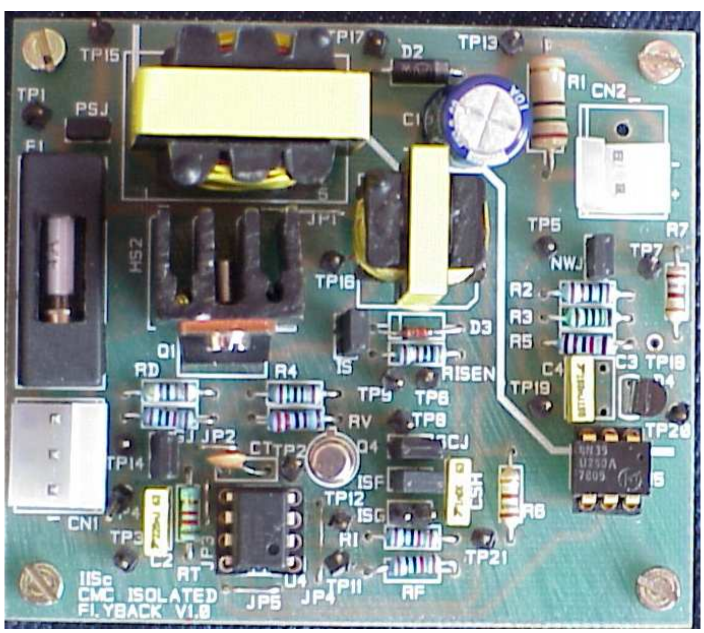


Figure 12.5: Mounted PCB Board of the Isolated Flyback Converter

12.6 PCB Films for Solder and Components Side

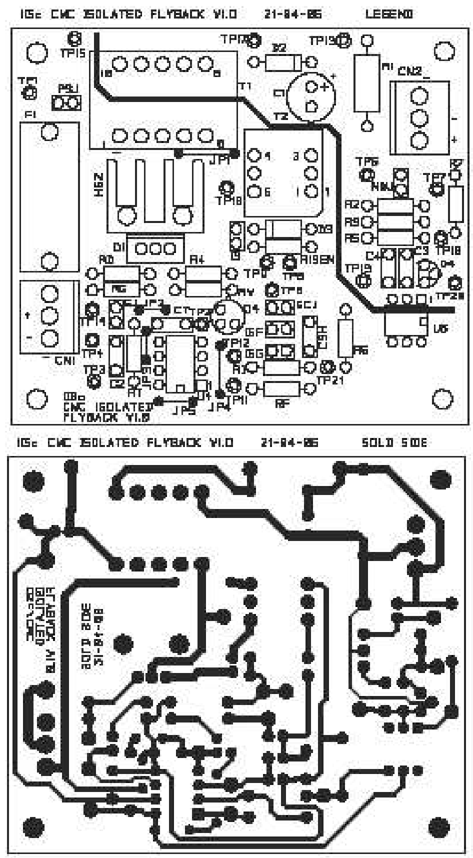


Figure 12.6: Solder and Component Side of Isolated Flyback Converter

12.7 Bill of Materials

Table 12.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg,Rf,Ri,R5	$10k\ \Omega$	4	0.35	1.40
2	Resistor	Rt	$8.2k\ \Omega$	1	0.35	0.35
3	Resistor	Rv	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	R4	$150\ \Omega$	1	0.35	0.35
5	Resistor	Rd	$47\ \Omega$	1	0.35	0.35
6	Resistor	Risen	$3.3k\ \Omega$	1	0.35	0.35
7	Resistor	R2,R3	$1k\ \Omega$	2	0.35	0.70
8	Resistor	R1	$5\ \Omega$	1	3.00	3.00
9	Resistor	R7,R6	$470\ \Omega$	2	0.35	0.70
10	Capacitor	Csh	$560pF$	1	2.00	2.00
11	Capacitor	C2,C3	0.22 μF,63V	1	2.50	5.00
12	Capacitor	C1	47 μF,25V	1	2.00	2.00
13	Capacitor	Cf	0.022 μF,50V	2	2.50	5.00
14	Capacitor	Ct	0.0047 μF,50V	1	2.50	2.50
15	Current Transformer	T2	1:200	1	15.00	15.00
16	Mosfet	M1	IRFZ44N	1	16.00	16.00
17	Coupled Inductor	L1	$150\ \mu H, 33T/11T$	1	25.00	25.00
18	Transisor	Q1	2N2222	1	4.50	4.50
19	Diode	D3	IN4148	1	0.40	0.40
20	Diode	D2	MUR110	1	8.00	8.00
21	Linear IC	U1	UC3843	1	7.00	7.00
22	Optocoupler	U5	4n35	1	8.00	8.00
23	Diode	D4	TL431	1	3.00	3.00
24	Test Points	T1-T10	Berg Stick	20	0.10	2.00
25	Jumpers	NMJ,GJ,IS, SCJ,PSJ,ISG		6	0.10	0.60
26	8 Pin IC Base	U1b		1	5.00	5.00
27	6 Pin IC Base	U1b		1	5.00	5.00
28	Terminal Connector	T1,T2		2	3.00	6.00
29	Heat Sink	HS1	P149	2	5.00	5.00
30	PCB	CMC Flyback Isolated		1	25.00	25.00
					TOTAL	159.55

Chapter 13

7.5W Current Mode Control of Isolated Forward Converter

13.1 Circuit Specification

This section covers a simple closed loop current mode controlled forward converter with the following specifications.

- Input: 10V to 15V
- Output: 5V, 1.25A, 7.5W
- Topology: Isolated forward Converter
- Controller: UC3843(UC3843)
- Switching Frequency: 100 kHz
- Protection: None
  Figure 13.1 and 13.2 shows the full circuit diagram of the Isolated forward converter operating from 15V battery (10V to 15V) providing regulated output power report at 5V (1.25 A). The controller used is UC3843 of Unitrode make.

13.2 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

13.2.1 Control Circuit:

1. Controller: The controller used here is UC3843. It is 8 pin IC with maximum supply voltage is 40V.
2. C_2,C_{sh} are all used for filtering.

3. Reference voltage: IC has a internal reference Voltage of 5V.

4. Oscillator Section: Switching Frequency is determined by R_t and C_t

$$F_s = \frac{1.72}{R_t C_t} = 100KHz \tag{13.1}$$

5. Slope Compensation: The Slope Compensation circuit is not required, since the circuit is operating at a duty less than 0.5.

6. Current Sense: UC3843 IC Pin 3 is the Current Sense Pin, it senses the rectified switch current from the Current Transfomer. The rectified Current gets added with the slope compensation voltage and the current obtained is then given to the isense pin of IC.

7. R_b is the Bleeder resistance used, based on the value of R_b we limit the voltage at Isense pin, since it is having a threshold of 1V.

13.2.2 Power Circuit:

1. It Consists of the forward converter which include a Transformer, witch, Diode , Capacitor, Load, Precision Shunt Regulator and a Optocoupler.

2. Duty Ratio: The input voltage is in the range of 10 to 15 V. The output of the boost converter is designed for 5V. The range of duty ratio is from 0.6 to 0.33.

3. Main Inductor: The rated current is 1.25 A. The ripple current is chosen as 0.15 A. With maximum on time of 12 μs, at input voltage of 10V, this gives an inductor value of approximately 150 μH. Inductor is 150H with 33 Turns on primary and 11 Turns on seconday of 22 SWG.

4. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.

5. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)

6. The capacitor C1 has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 220F.

7. Transformer: The Transformer has a turns ratio of 1. With SWG 22 used for the primary winding and SWG 23 used for the secondary winding. Core used is EE 16/8/5.The primary turns is 12 and secondary turns is 12.

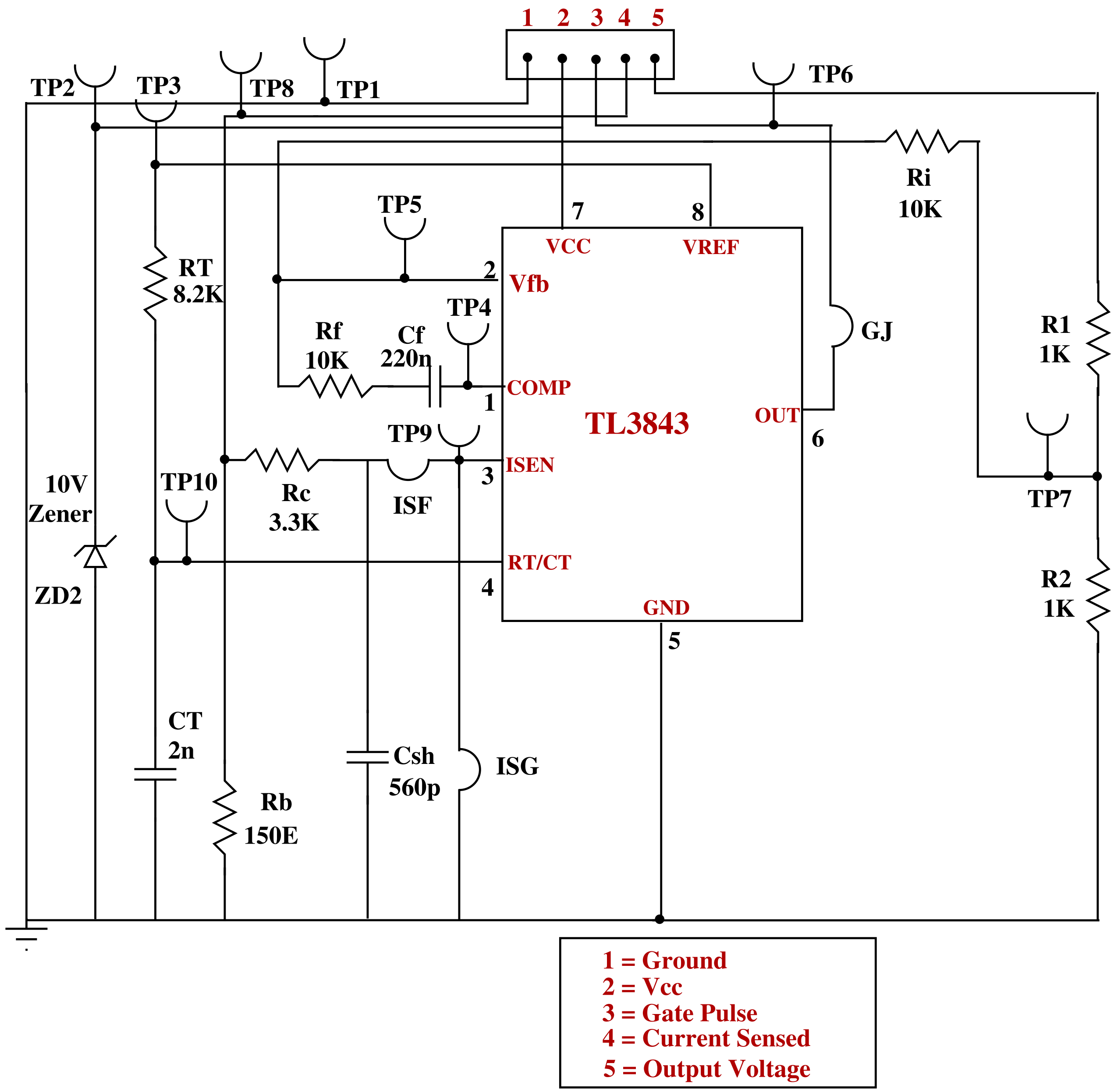


Figure 13.1: Control Circuit for Current Mode Control of Forward Converter

8. Current Transformer: The CT is used to sense the switch current. The Core used is E 16/8/5 of SWG 28 with 1:200 Turns.

9. The Load Resistor used is 120E.[7.5W]

10. R_5,C_4 and C_3 for the PI controller circuit.

11. The isolation is provided by using an optocoupler.(4N-35)

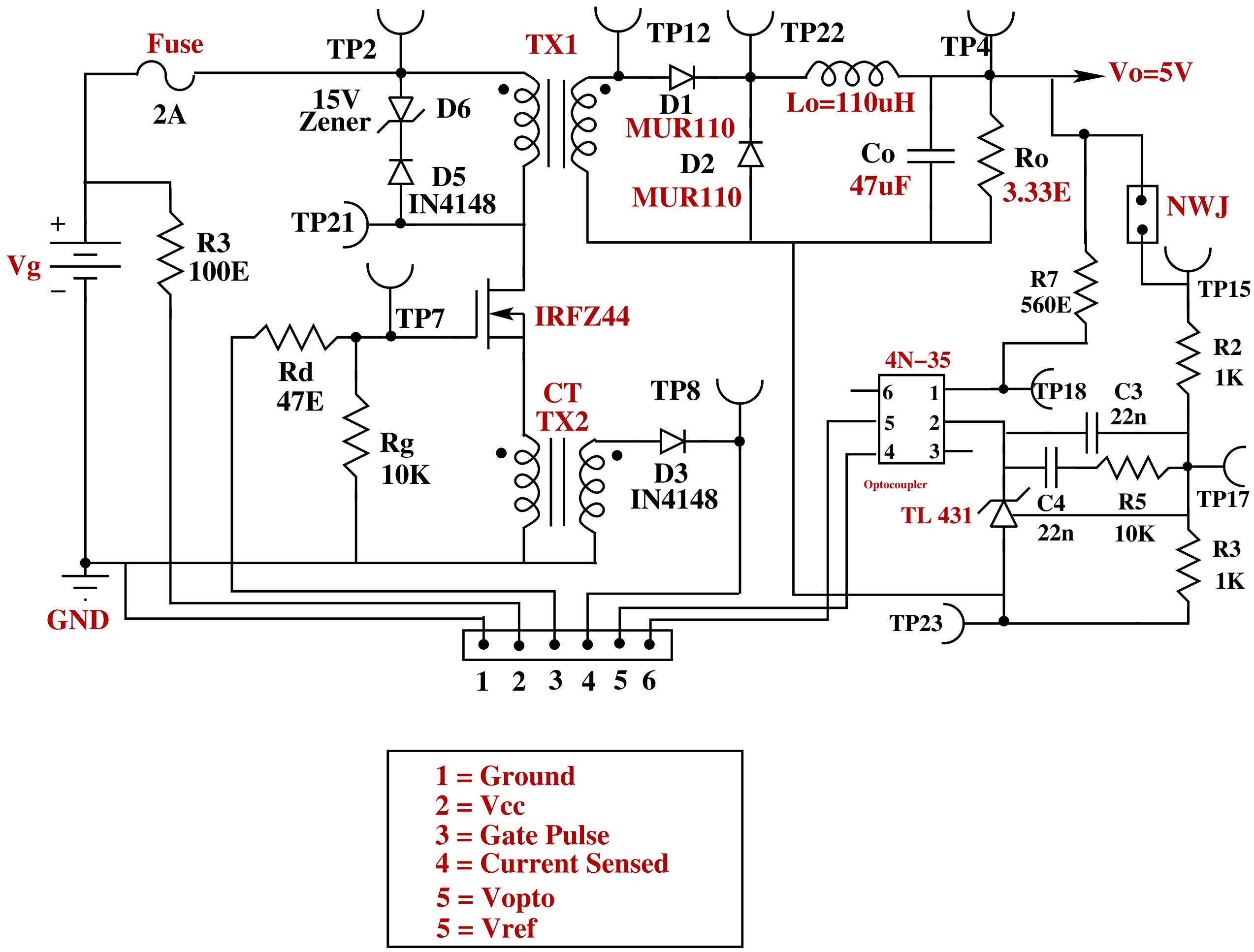


Figure 13.2: Power Circuit for Current Mode Control of Forward Converter

12. TL431 is used a fixed 2.5V reference regulator. (tl431)

13.3 Practical Bode Plot using Network Analyser

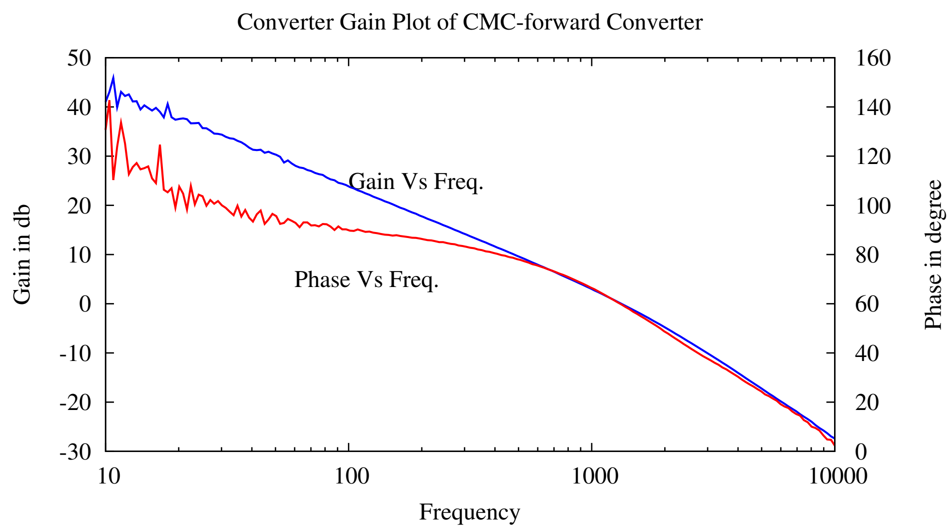
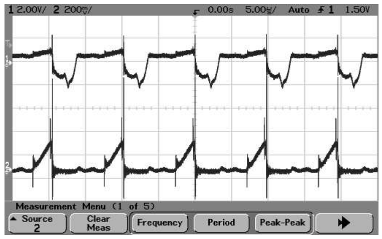
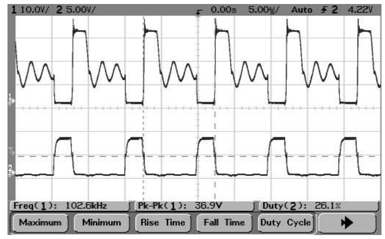


Figure 13.3: Loop Gain Bode Plot of CMC-Isolated Forward Converter

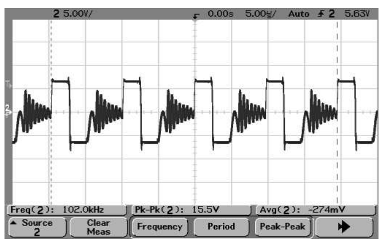
13.4 Pratical Waveform of the CMC-Isolated Forward Converter



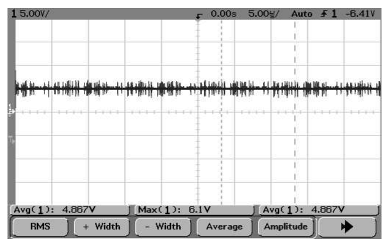
(a) Unrectifed and Rectifed Switch Current



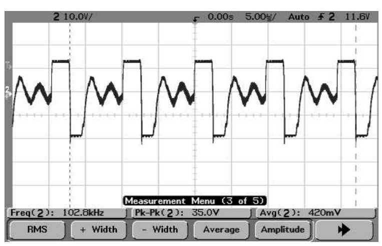
(b) Gate Pulse and Switch Voltage



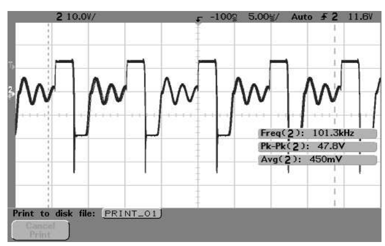
(c) Inductor Voltage



(d) Output Voltage



(e) Primary Transformer Voltage



(f) Secondary Transformer voltage

13.5 Mounted and Bare PCB Boards

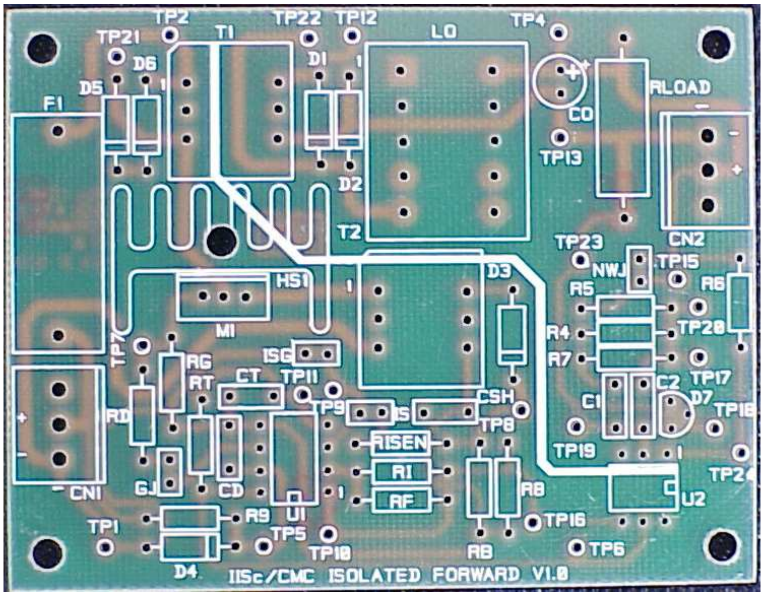


Figure 13.4: Bare PCB Board of the CMC-forward Converter

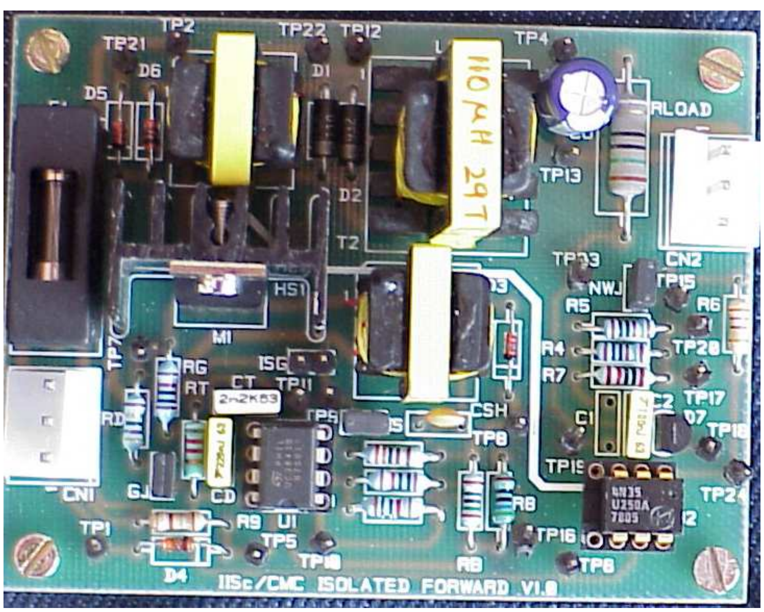


Figure 13.5: Mounted PCB Board of the CMC-forward Converter

13.6 PCB Films for Solder and Components Side

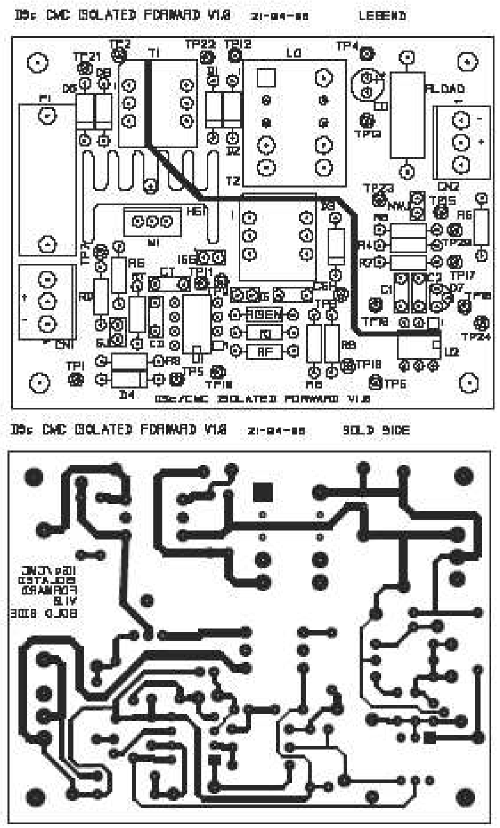


Figure 13.6: Solder and Component Side of CMC-Forward Converter

13.7 Bill of Materials

Table 13.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg,Rf,Ri,R5	$10k\ \Omega$	4	0.35	1.40
2	Resistor	Rt	$8.2k\ \Omega$	1	0.35	0.35
3	Resistor	R9	220 Ω	1	0.35	0.35
4	Resistor	R4	150 Ω	1	0.35	0.35
5	Resistor	Rd	47 Ω	1	0.35	0.35
6	Resistor	Risen	$3.3k\ \Omega$	1	0.35	0.35
7	Resistor	R2,R3	$1k\ \Omega$	2	0.35	0.70
8	Resistor	R1	5 Ω	1	3.00	3.00
9	Resistor	R7,R6	470 Ω	2	0.35	0.70
10	Capacitor	Csh	$560pF$	1	2.00	2.00
11	Capacitor	C2,C3	0.22 μF,63V	1	2.50	5.00
12	Capacitor	C1	47 μF,25V	1	2.00	2.00
13	Capacitor	Cf	0.022 μF,50V	2	2.50	5.00
14	Capacitor	Ct	0.0047 μF,50V	1	2.50	2.50
15	Current Transformer	T2	1:200	1	15.00	15.00
16	Mosfet	M1	IRFZ44N	1	16.00	16.00
17	Transformer	T1	$12T/12T$,N=1	1	25.00	25.00
18	Zener	D6,D4	15V	2	4.50	9.00
19	Diode	D3,D5	IN4148	2	0.40	0.80
20	Diode	D1,D2	MUR110	2	8.00	16.00
21	Linear IC	U1	UC3843	1	7.00	7.00
22	Optocoupler	U2	4n35	1	8.00	8.00
23	Diode	D7	TL431	1	3.00	3.00
24	Test Points	T1-T10	Berg Stick	20	0.10	2.00
25	Jumpers	NMJ,GJ,IS, SCJ,PSJ,ISG		6	0.10	0.60
26	8 Pin IC Base	U1b		1	5.00	5.00
27	6 Pin IC Base	U1b		1	5.00	5.00
28	Terminal Connector	T1,T2		2	3.00	6.00
29	Heat Sink	HS1	P149	2	5.00	5.00
30	PCB	CMC Forward Isolated		1	25.00	25.00
					TOTAL	173.8

Chapter 14

7.5W Active Clamped Boost Converter

14.1 Circuit Specification

This section covers a simple Active Clamped Boost Converter with the following specifications.

- Input: 8V to 12V
- Output: 15V, 0.5A, 7.5W
- Topology: Active Clamped Boost Converter
- Controller: UC495(UC495)
- Switching Frequency: 250 kHz
- Protection: None

14.2 Circuit Discription

The Circuit consists of a power circuit, delay circuit and a control circuit.

14.2.1 Control Circuit:

1. Controller: The controller used here is UC495. It is 8 pin IC with maximum supply voltage is 40V.
2. Reference voltage: IC has a internal reference Voltage of 5V.
3. Oscillator Section:
   R_{osc} ($4.7k\ \Omega$) and C_{osc} (1 nF) determine the switching frequency. The

switching frequency is given by

$$F_s = \frac{1.11}{R_t C_t} = 250KHz \tag{14.1}$$

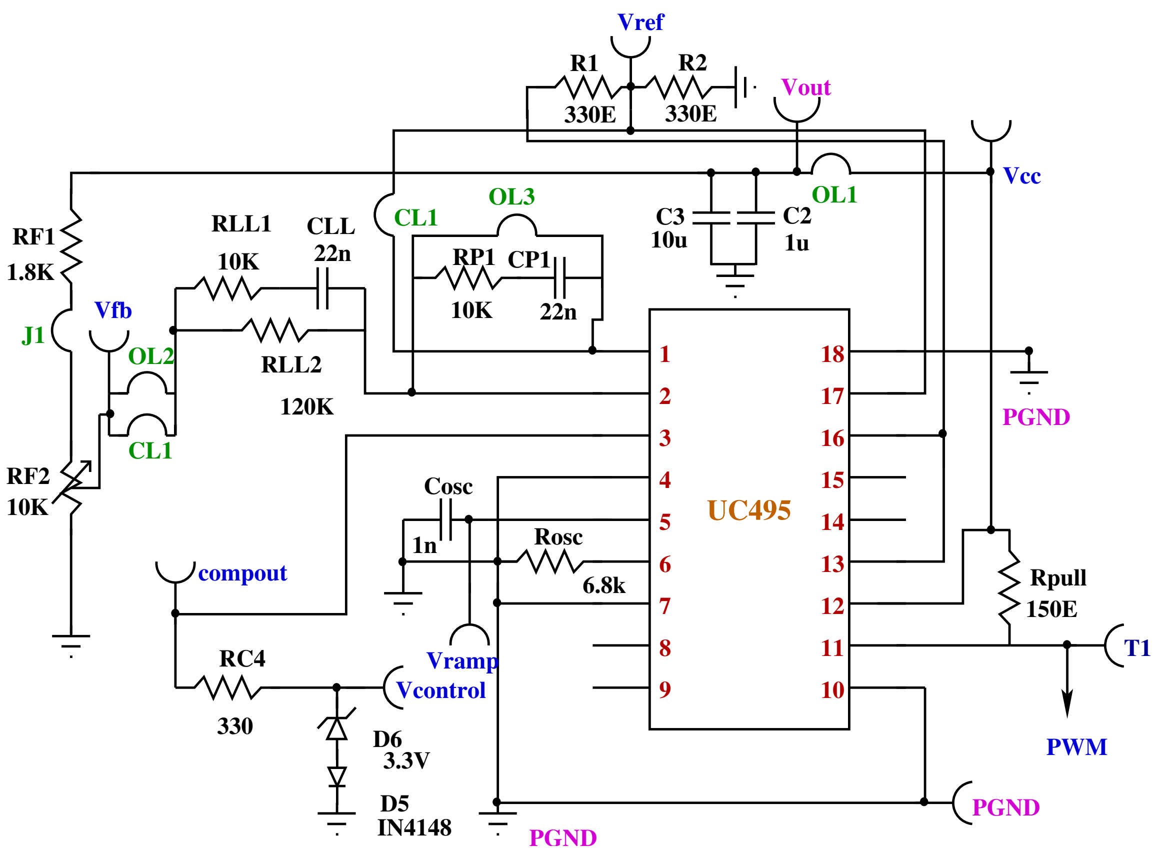


Figure 14.1: Control Circuit of Active Clamped Boost Converter

The selected switching frequency is approximately 250 kHz.

4. Minimum Pulse-Width:
   The minimum ON time is decided by the dead time control circuit R_{osc}. On a ramp voltage of 3V, and an internal additional bias voltage of 0.1 V, this is selected to be 15%.

5. Maximum Pulse-width limit:
   The amplifier output (Compensation pin) is compared with the internal ramp to generate the duty ratio. The amplifier output requires to be clamped below the peak of the ramp in order that the maximum duty ratio is well below 3 V, which is the peak of the ramp. For this Purpose, a 3.3V Zener Diode is connected at the output of error amplifier.

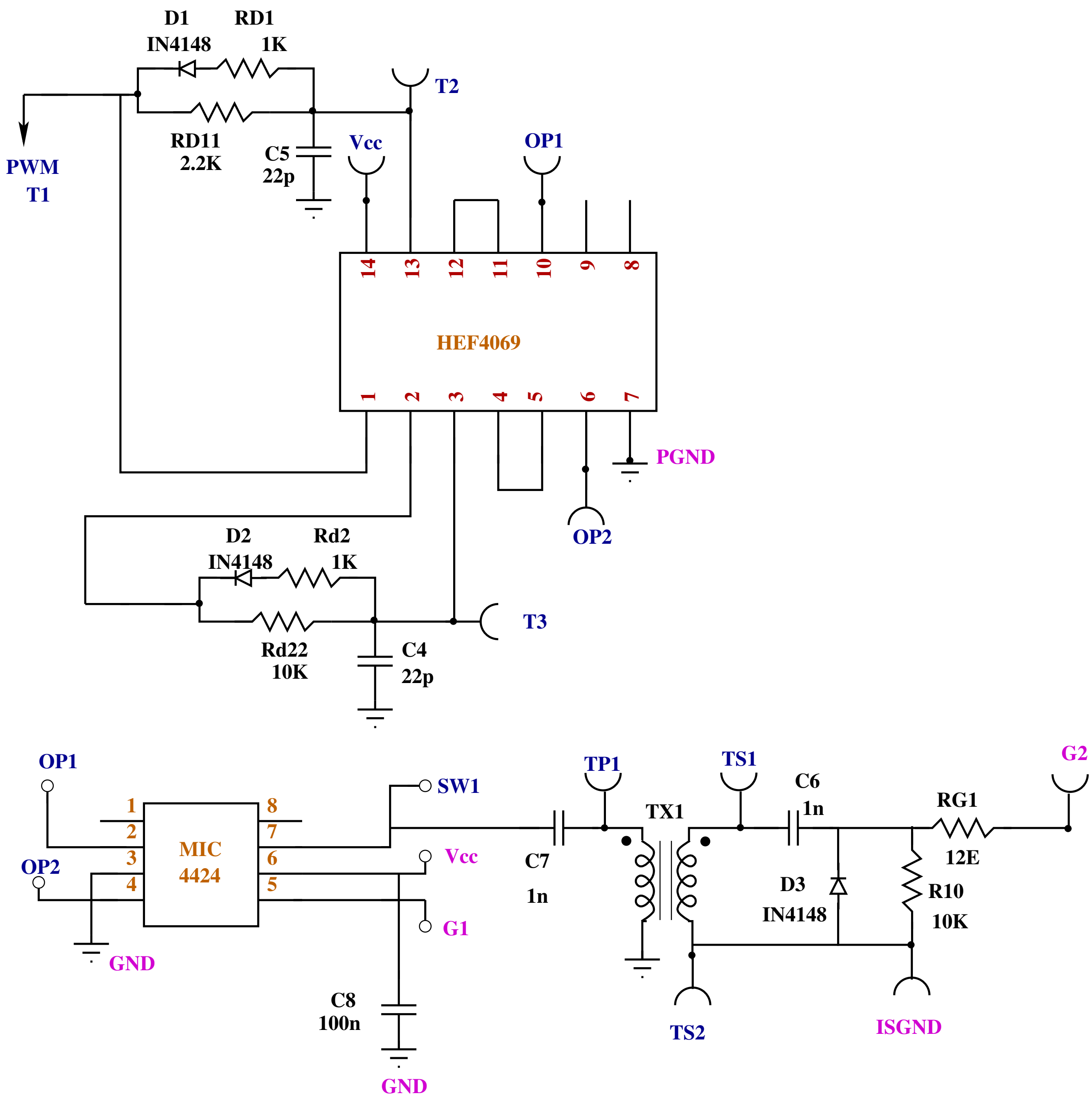


Figure 14.2: Delay Circuit of Active Clamped Boost Converter

6. Here, there are jumpers provided to work the converter in Open Loop operation and Closed Loop operation. The Open Loop operation is done by connector jumerper OL1,J1,OL2, and OL3. The Closed Loop operation is done by conecting J1,CL1, and CL2.

7. The Delay circuit consist of HEF4069, MIC4425N, and Isolation Trans-

former.

8. HEF4069 is a general purpose hex inverter. Each of the six inverters are of Single Stage. (HEF4069)

9. The PWM pulse obtained from UC495 is given as input to this hex inverter. Two delay circuit is connected to inputs. R_{d2},R_{d1}, R_{d22},R_{d12}, C_4 and C_5 forms the delay circuit. The delay time is taken to be 200ns.

10. The two output from HEF4069 is given to MIC4425N.(mic4424) MIC4424 is a Dual 3A-peak Low side Mosfet Driver.

11. MIC4424 produces two output. One pulse is isolated using a isolation transformer and filter capacitor.

14.2.2 Power Circuit:

1. It Consists of the boost converter which include a inductor, switch, Diode , Capacitor, and Load..The resonant circuit consists of resonant inductor, switch and capacitor.

2. Main Inductor: The rated current is 1.25 A. The ripple current is chosen as 0.15 A. With maximum on time of 2 μs, at input voltage of 10V, this gives an inductor value of approximately 150 μH. Inductor is 70H with 37 Turns on primary and 11 Turns on seconday of 22 SWG.

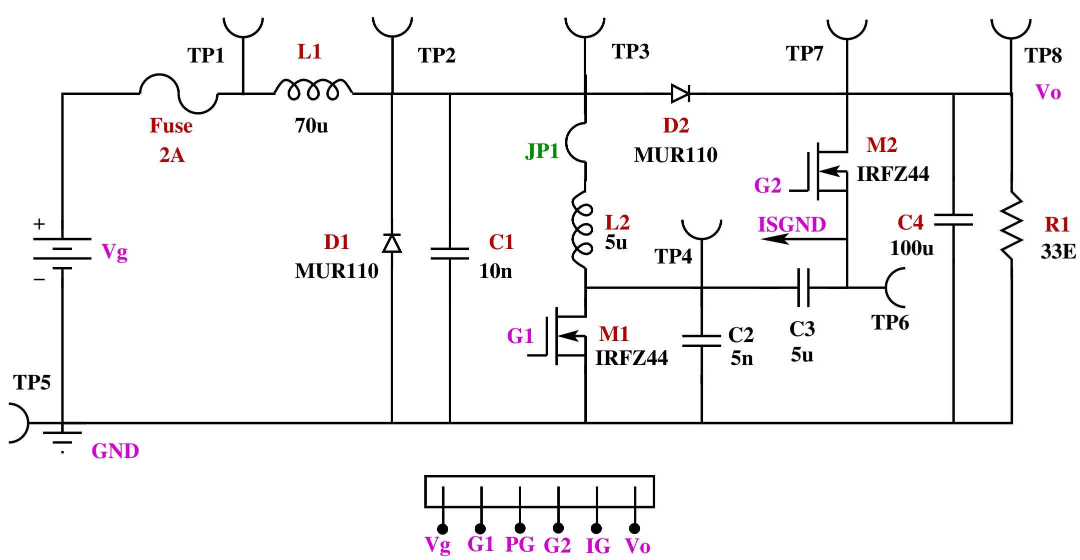


Figure 14.3: Power Circuit for Active Clamped Boost Converter

3. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.

4. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 50KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)
5. The capacitor C1 has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 100F.
6. The Load Resistor used is 33E.[7.5W]

14.3 Pratical Waveform of the Active Clamped-Boost Converter

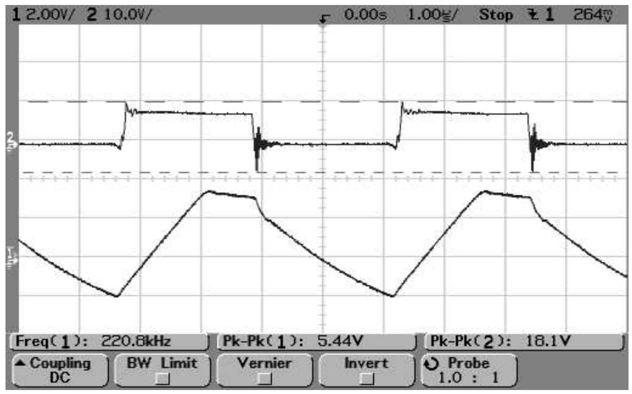


Figure 14.4: Gate Pulse of Main Switch and Inductor Current

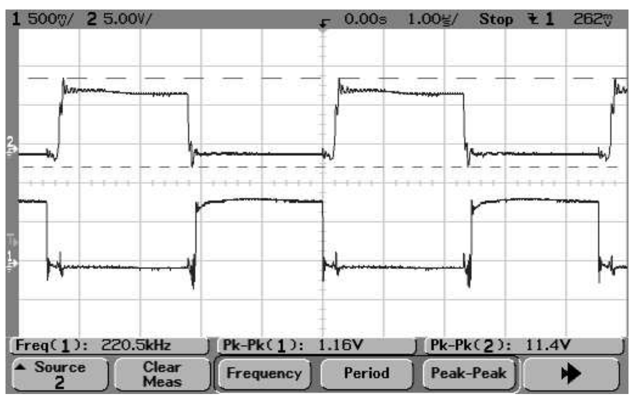


Figure 14.5: Auxillary and Main Switch Gate Pulses

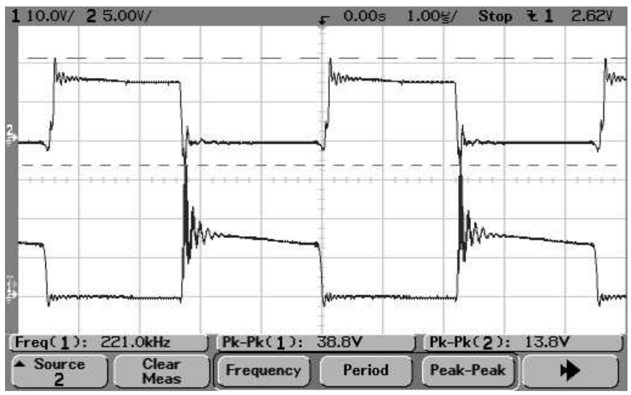


Figure 14.6: Gate Voltage and Switch Voltage of Main Switch

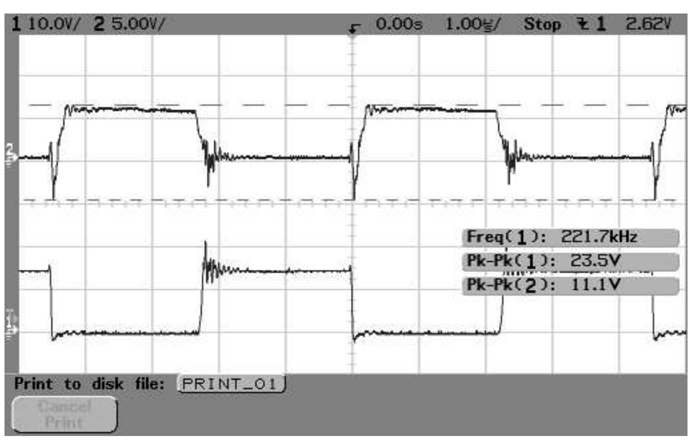


Figure 14.7: Gate Voltage and Switch Voltage of Auxillary Switch

14.4 Mounted and Bare PCB Boards

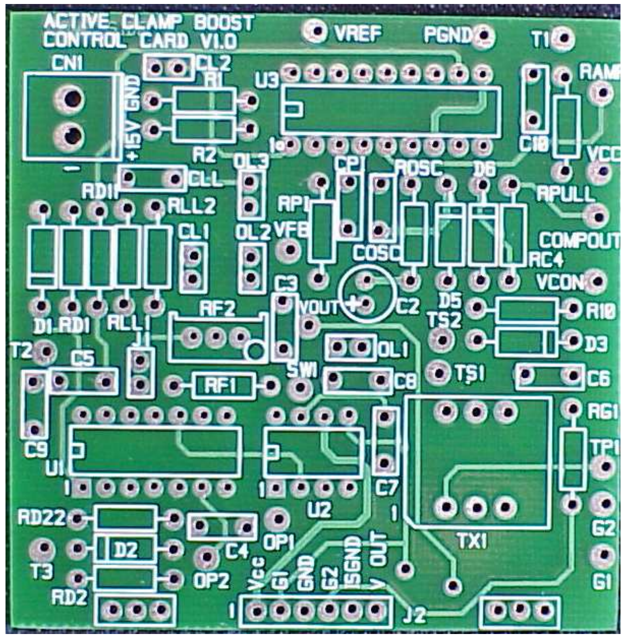


Figure 14.8: Bare Control Board of the Active-Boost Converter

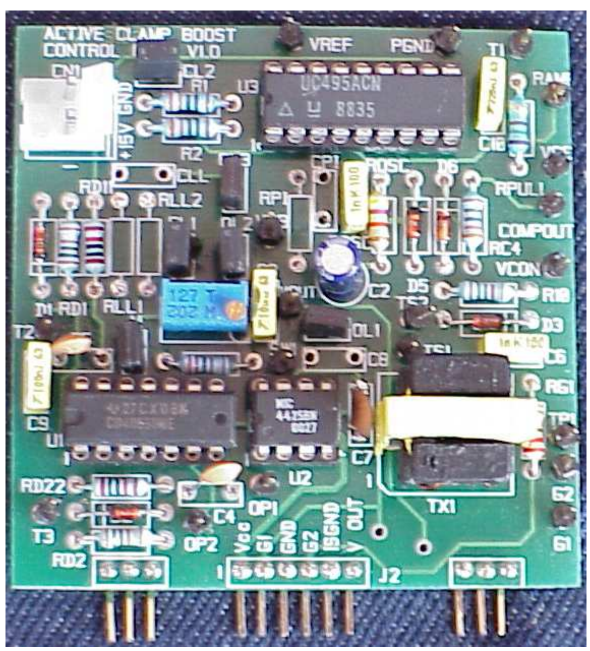


Figure 14.9: Mounted Control Board of the Active-Boost Converter

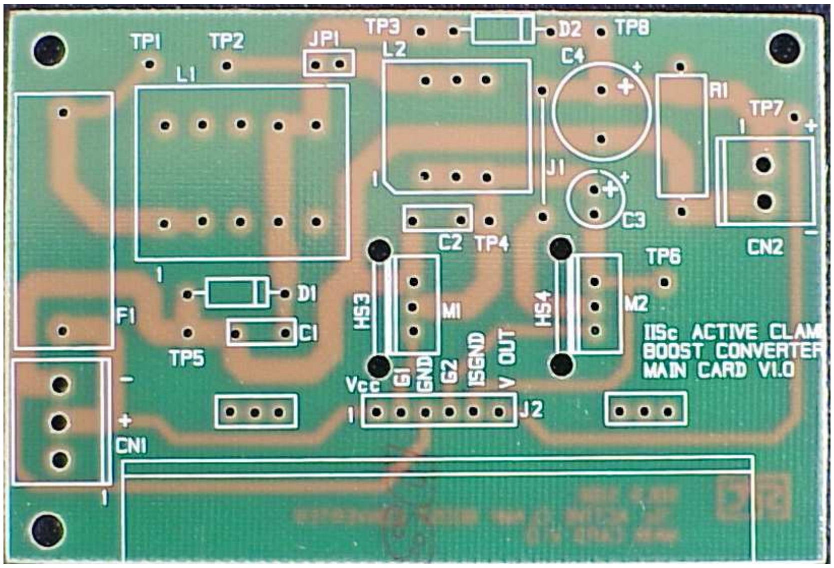


Figure 14.10: Bare Power Board of the Active-Boost Converter

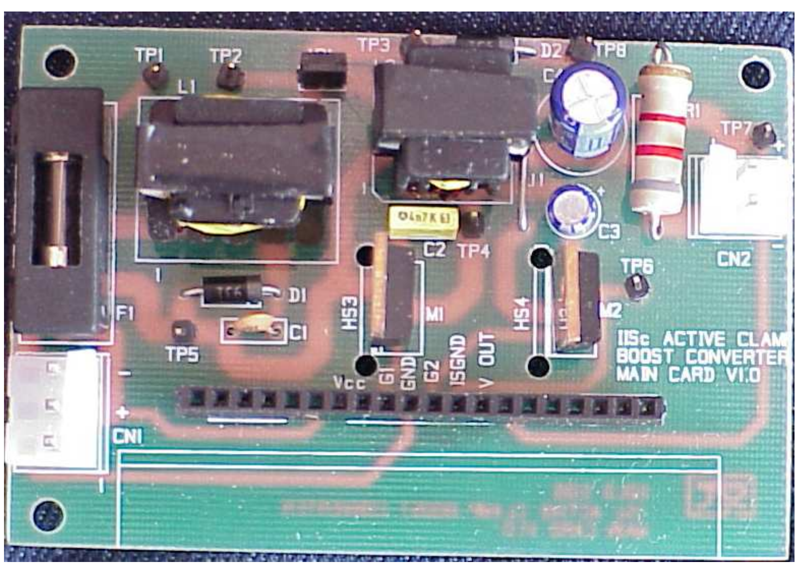


Figure 14.11: Mounted Power Board of the Active-Boost Converter

14.5 PCB Films for Solder and Components Side

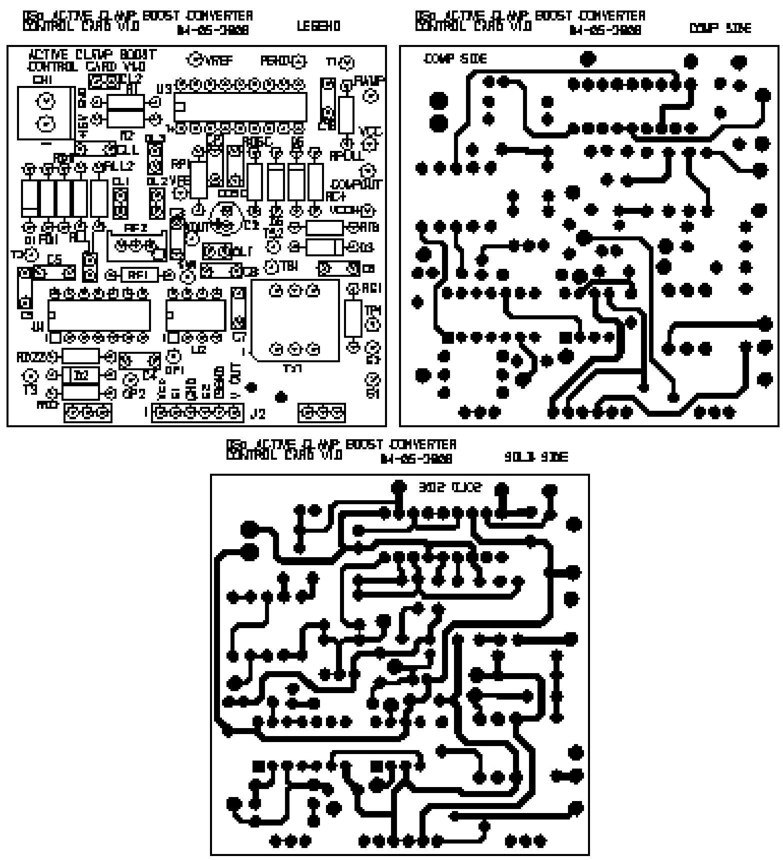


Figure 14.12: Solder and Component Side of Active-Boost Converter Control Circuit

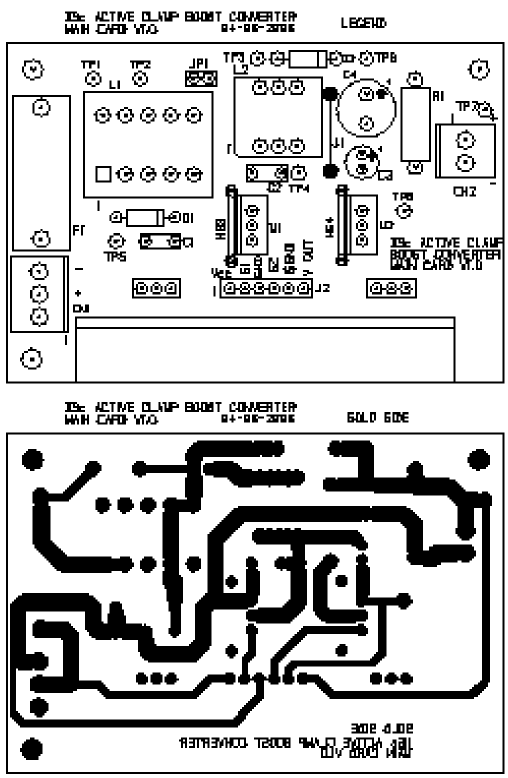


Figure 14.13: Solder and Component Side of Active-Boost Converter Power Circuit

14.6 Bill of Materials

Table 14.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1,R2,RC4	330 Ω	3	0.35	1.05
2	Resistor	Rf1	$1.8k\ \Omega$	1	0.35	0.35
3	Resistor	Rosc	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	Rpull	150 Ω	1	0.35	0.35
5	Resistor	RLL1,RLL2,RP1	$10k\ \Omega$	3	0.35	1.05
6	Resistor	RF2	$5k\ \Omega$POT	1	3.00	3.00
7	Resistor	Rd1,Rd2	$1k\ \Omega$	2	0.35	0.70
8	Resistor	Rd11,R10	$10k\ \Omega$	2	0.35	0.70
9	Resistor	Rd22	$2.2k\ \Omega$	1	0.35	0.35
10	Resistor	Rg1	12 Ω	1	0.35	0.35
11	Resistor	R1	33 Ω	1	3.00	3.00
12	Capacitor	C2	10 μF	1	2.00	2.00
13	Capacitor	C3,C8	0.22 μF,63V	1	1.00	2.00
14	Capacitor	C4	100 μF	1	2.00	2.00
15	Capacitor	Cosc,C7,C8	0.001 μF,25V	3	1.00	3.00
16	Capacitor	C10,C1	0.01 μF,50V	2	1.50	3.00
17	Capacitor	C3 POWER	10 μF	1	2.00	2.00
18	Capacitor	C4,C5	$22pF$	2	2.50	5.00
19	Isolation TRANSF	Tx1	1:1,20Turns	1	15.00	15.00
20	Mosfet	M1	IRFZ44N	2	16.00	32.00
21	Boost Inductor	L1	$70\ \mu H, 37T$	1	25.00	25.00
22	Resonant Inductor	L2	$4\ \mu H, 5T, 2strand$	1	15.00	15.00
23	Zener	Z6	3.3V	1	2.00	2.00
24	Diode	D5,D3,D1,D2	IN4148	4	0.40	1.60
25	Diode	D2,D1	MUR110	2	8.00	16.00
26	Linear IC	U1	HEF4069	1	8.00	8.00
27	Linear IC	U3	UC495	1	15.00	15.00
28	Linear IC	U2	MIC4424	1	120.00	120.00
29	18/14 Pin IC Base	U1,U3		2	5.00	10.00
30	Test Points		Berg Stick	20	0.10	2.00
31	Jumpers			10	0.10	1.00
32	8 Pin IC Base	U1b		1	5.00	5.00
33	Terminal Connector	T1,T2		3	3.00	9.00
34	Heat Sink	HS1	P149	2	5.00	10.00
35	PCB	7.5W Active Boost	Control and Boost	2	25.00	50.00
					TOTAL	306.00

Chapter 15

7.5W ARCP Boost Converter

15.1 Circuit Specification

This section covers a simple ARCP Boost Converter with the following specifications.

- Input: 8V to 12V
- Output: 16V, 0.468A, 7.5W
- Topology: Axillary Resonant Commutated Pole Boost Converter
- Controller: UC495(UC495)
- Switching Frequency: 250 kHz
- Protection: None

15.2 Introduction

The proposed circuit achieves loss-less switching for both the main and auxiliary switches without increasing the main device current/voltage rating. A tapping in the pole inductor is added for the purpose of commutation. The proposed circuit is capable of operation at elevated switching frequencies of several hundreds of KHz, high and low power levels with wide range of load variations. In the sections that follow, theoretical analysis and operating principle of the proposed circuit is outlined through the example of buck converter. Simulation and experimental results of 7.5 watt, 250KHz boost converter are presented. The proposed circuit is applicable to all isolated and non-isolated DC-DC converters. The performance and the design equations of the ZVS are identical for all types of DC-DC converters when the throw voltage and the pole current are properly defined.

15.3 Circuit Discription

The Circuit consists of a power circuit and a control circuit.

15.3.1 Control Circuit:

1. Controller: The controller used here is UC495. It is 8 pin IC with maximum supply voltage is 40V.
2. Reference voltage: IC has a internal reference Voltage of 5V.
3. Oscillator Section:
   R_{osc} (2.2k Ω) and C_{osc} (2 nF) determine the switching frequency. The switching frequency is given by
   $$F_s = \frac{1.11}{R_t C_t} = 250KHz \qquad (15.1)$$

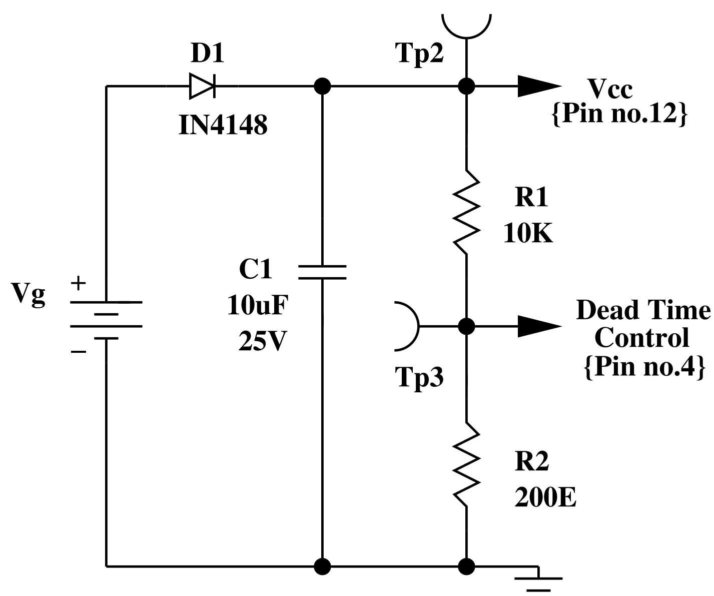


Figure 15.1: Startup and Dead Time Control Circuit

4. Minimum Pulse-Width:
   The minimum ON time is decided by the dead time control circuit R_{osc}. On a ramp voltage of 3V, and an internal additional bias voltage of 0.1 V, this is selected to be 15%.

   Reference Voltage:
   The internal reference is 5 V. The circuit uses a reference voltage of 2.5 V through the potential divider R_{10} (10k Ω) and R_{11} (10k Ω).

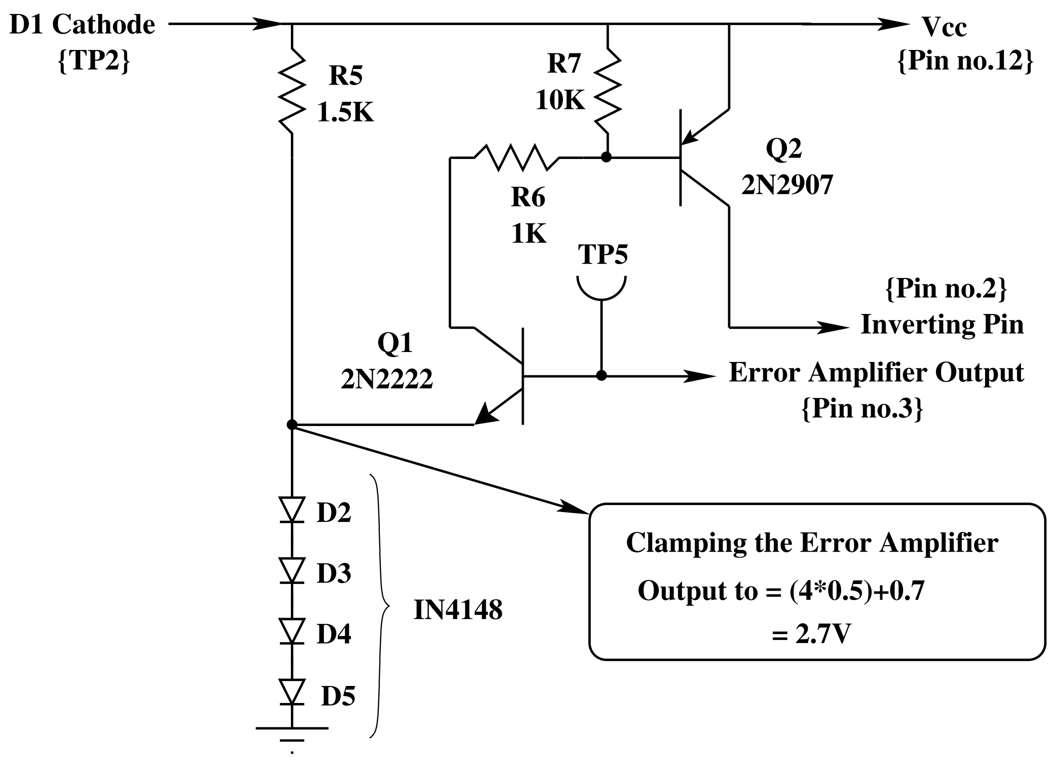


Figure 15.2: Maximum Pulse Width Circuit

5. Biasing-out the unused amplifier:
   The controller has two internal amplifiers a and b. The amplifier outputs are wired such that the higher of the two outputs will prevail (wired OR). The amplifier b is not used and hence it is biased (non-inverting input to ground and inverting input to 2.5 V) such that its output is low.

6. Maximum Pulse-width limit:
   The amplifier output (Compensation pin) is compared with the internal ramp to generate the duty ratio. The amplifier output requires to be clamped below the peak of the ramp in order that the maximum duty ratio is well below 3 V, which is the peak of the ramp. For this Purpose, a 3.3V Zener Diode is connected at the output of error amplifier.

7. Duty ratio:
   The input voltage is in the range of 8 to 12 V. The output of the boost converter is designed for 16V. The range of duty ratio is from 0.25 to 0.50.

8. The natural frequency of the converter is

$$Natural\ Frequency = \frac{1-d}{\sqrt{\{LC\}}} \tag{15.2}$$

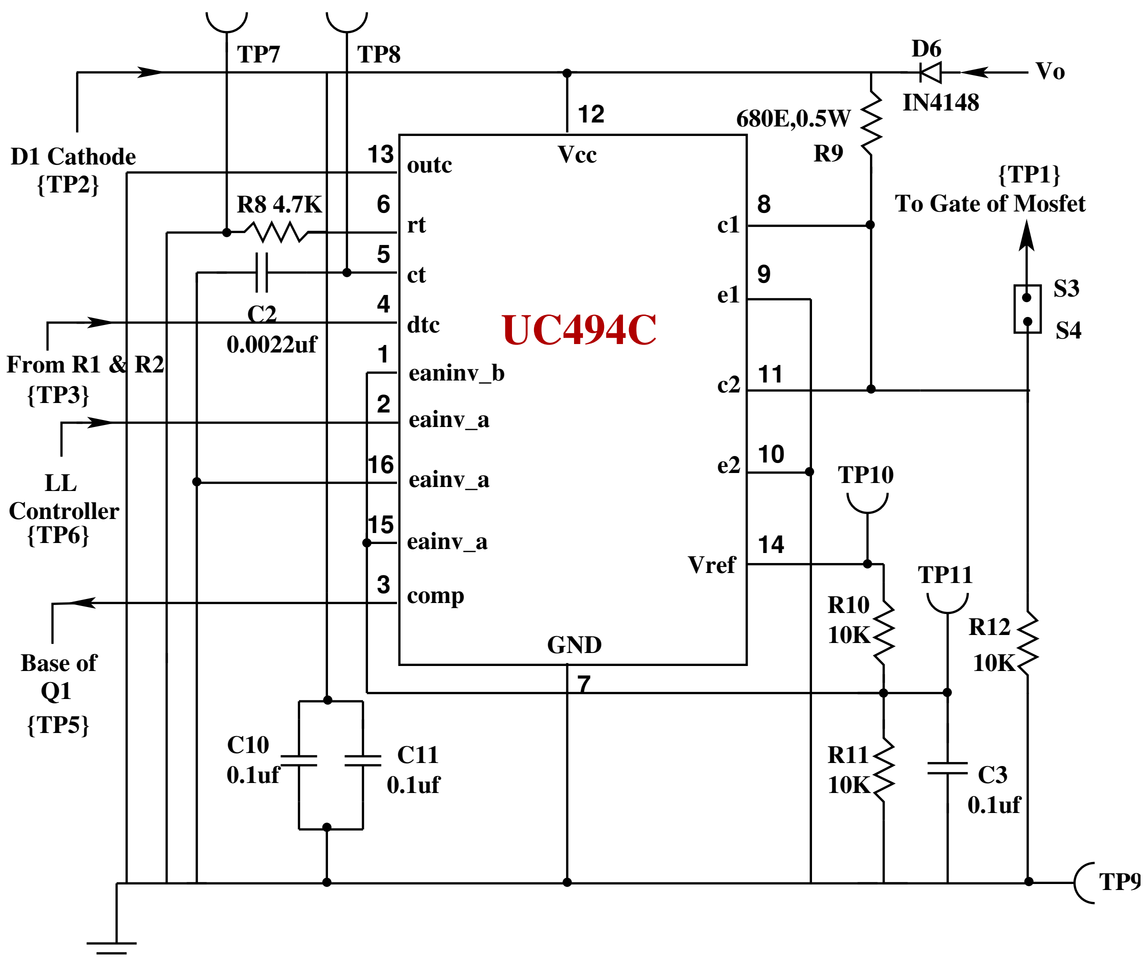


Figure 15.3: Controller Circuit

which is ranging from 2757 rad/sec to 4135 rad/sec. The higher frequency is at higher voltage.

9. The dc gain from duty ratio to output voltage consists of modulator gain and converter gain. The modulator gain is the reciprocal of the ramp peak in the modulator. In UC494, it is 1/3.5. The converter dc gain is

$$DCGain = \frac{V_G}{[1-d]^2} \tag{15.3}$$

This gain varies from 32 to 16. The overall gain is therefore 9.14 to 4.57 for the converter. The lower gain is at higher voltage.

10. The closed loop control used is a PI controller with lead/lag compensator. The PI corner frequency $[1/(R_{16}C_8)]$ is chosen at 658 rad/sec The

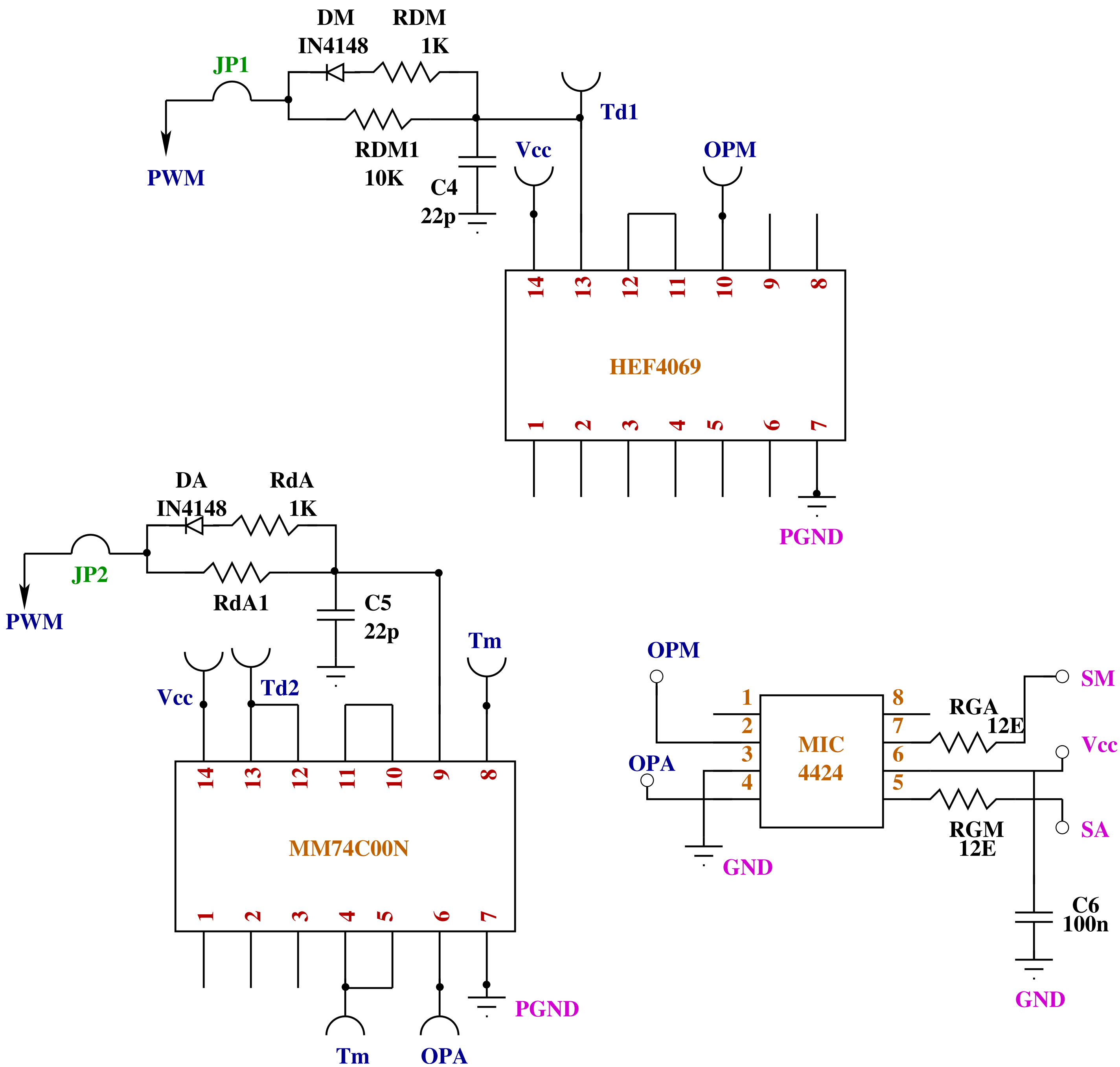


Figure 15.4: Delay Circuit of ARCP Boost Converter

lead/lag compensator frequencies are chosen as $[1/(R_{15}C_7)]$ 658 rad/sec and $[1/(C_7(R_3||R_4||R_{15})]$ 6580 rad/sec .

11. The loop gain band-width on unity feedback will be 1990 rad/sec. The

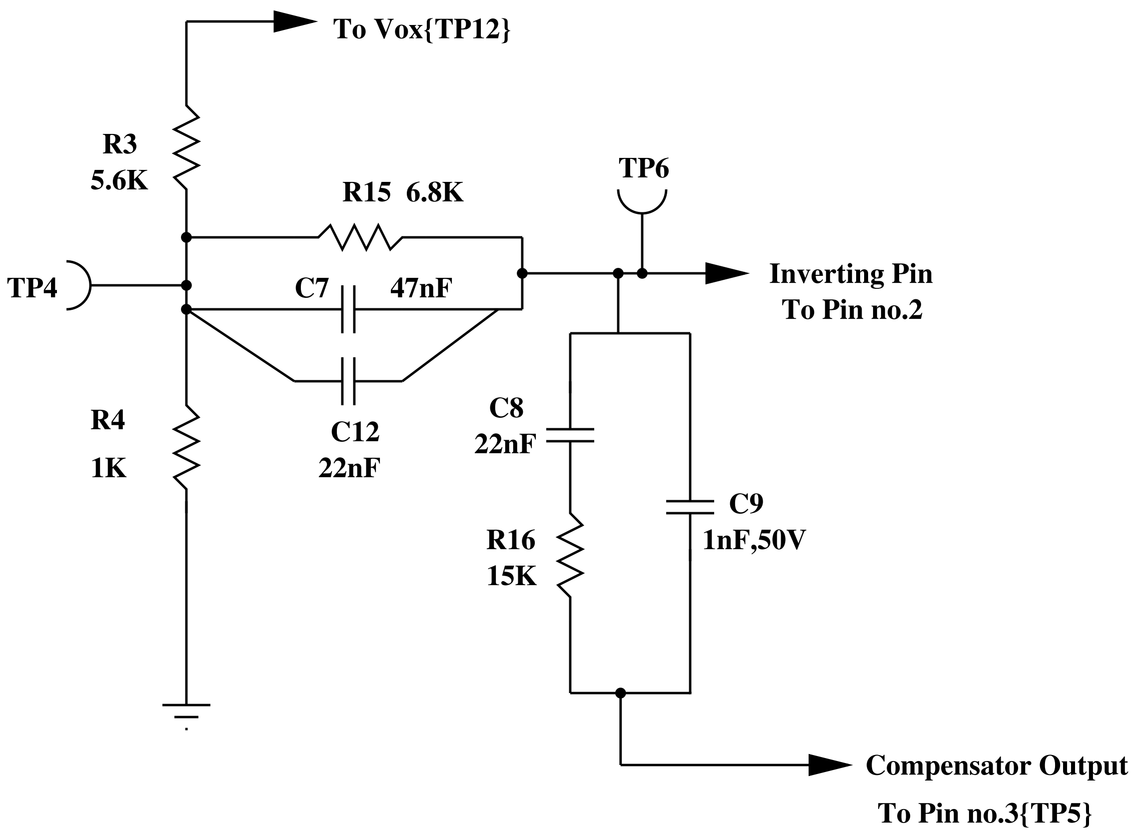


Figure 15.5: Feedback Circuit

dc feedback gain is

$$DC\ Feedback\ Gain = \frac{16}{7.65} \tag{15.4}$$

12. The loop-gain cross-over frequency is 7160 rad/sec to 10500 rad/sec.

13. Here, there are jumpers provided to work the converter in Open Loop operation and Closed Loop operation. The Open Loop operation is done by connector jumerper OL1,J1,OL2, and OL3. The Closed Loop operation is done by conecting J1,CL1, and CL2.

14. The Delay circuit consist of HEF4069, MIC4425N.

15. HEF4069 is a general purpose hex inverter. Each of the six inverters are of Single Stage. (HEF4069)

16. The PWM pulse obtained from UC495 is given as input to this hex inverter. Two delay circuit is connected to inputs. R_{d2},R_{d1}, R_{d22},R_{d12}, C_4 and C_5 forms the delay circuit. The delay time is taken to be 200ns.

17. The two output from HEF4069 is given to MIC4425N.(mic4424) MIC4424 is a Dual 3A-peak Low side Mosfet Driver.

18. MIC4424 produces two output. One pulse is given to main switch and another pulse is given to the auxillary switch.

15.3.2 Power Circuit:

1. It Consists of the boost converter which include a inductor, switch, Diode , Capacitor, and Load..The resonant circuit consists of resonant inductor, switch and capacitor.

2. Main Inductor: The rated current is 1.25 A. The ripple current is chosen as 0.15 A. With maximum on time of 2 μs, at input voltage of 10V, this gives an inductor value of approximately 70 μH with 37 Turns on primary and 11 Turns on seconday of 22 SWG.

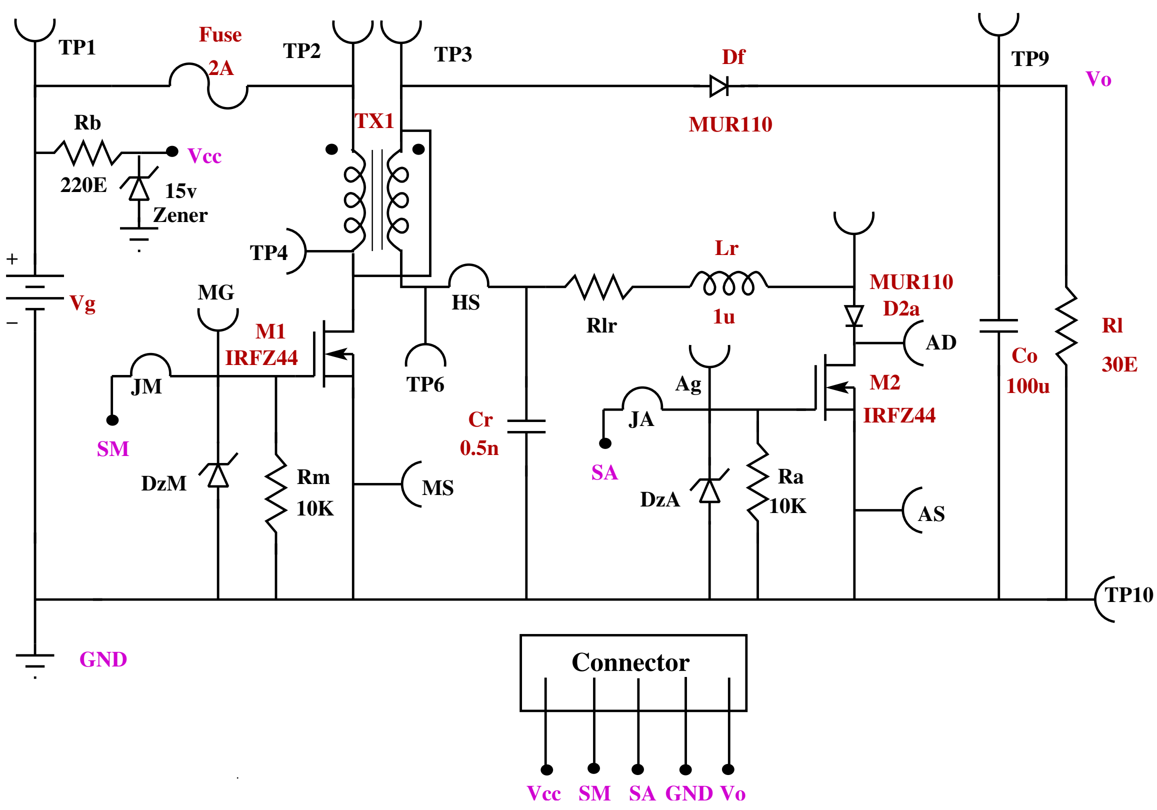


Figure 15.6: Power Circuit for ARCP Boost Converter

3. The power MOSFET has to carry about 1A and block about 20V. The device chosen is IRFZ44.(IRFZ44) Mosfet drive is through the R_g and R_d.

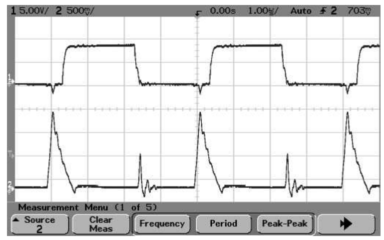
4. The Diode Carries about 0.5A Average Current and Blocks about 20V and suitable for 250KHz switching. The recovery time has to be better than 50ns. Therefore MUR110 is selected.(MUR110)

5. The capacitor Co has to limit the voltage ripple to about 1percent. This Capacitor is selected to be 470F.

6. The Load Resistor used is 33E.[7.5W]

15.4 Pratical Waveform of the ARCP-Boost Converter

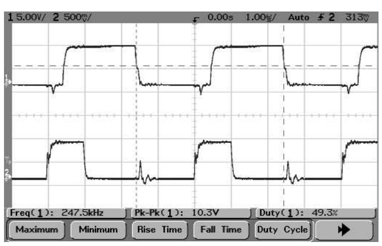
(a) Resonant Inductor Current



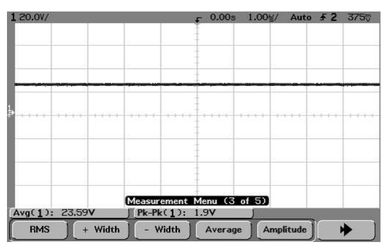
(b) Resonant Inductor Current and Main Switch Pulse

(c) Main Switch's Gate and Switch Voltage

(d) Auxillary Switch's Gate and Switch Voltage



(e) Auxillary and Main Switch Gate Voltage



(f) Output Voltage

15.5 Practical Bode Plot using Network Analyser

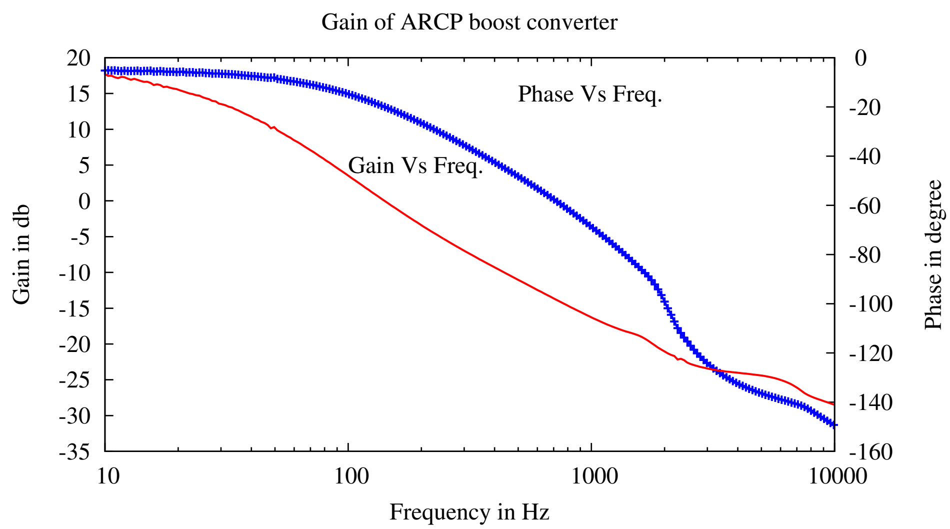


Figure 15.7: Converter Gain Bode Plot of Boost Converter

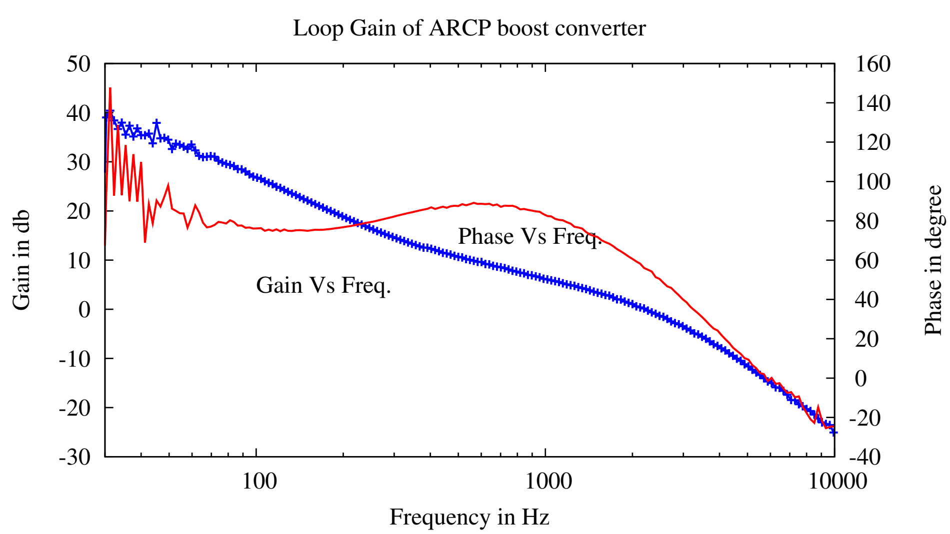


Figure 15.8: Closed Loop Gain Bode Plot of Boost Converter

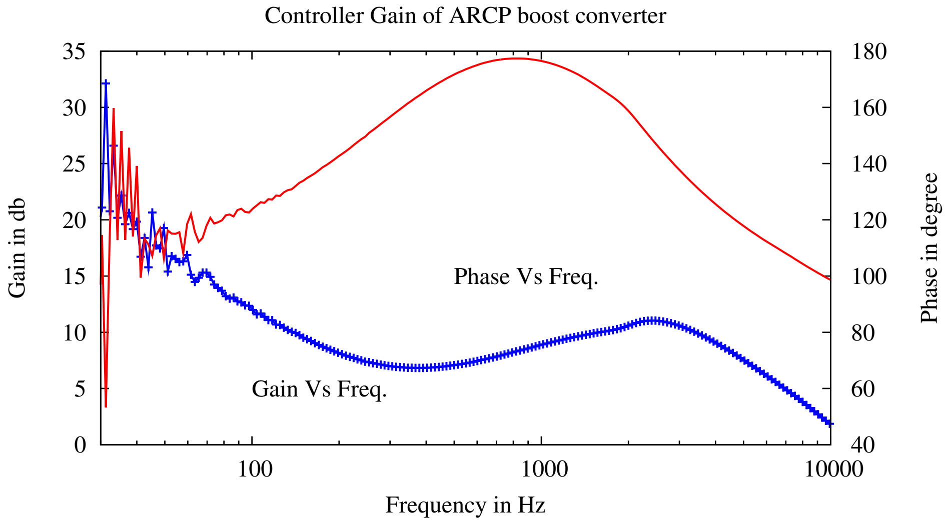


Figure 15.9: Controller Gain Bode Plot of Boost Converter

15.6 Mounted and Bare PCB Boards

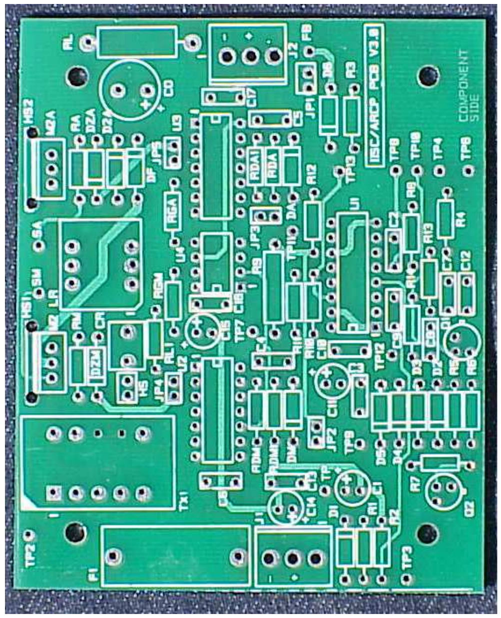


Figure 15.10: Bare Board of the ARCP-Boost Converter

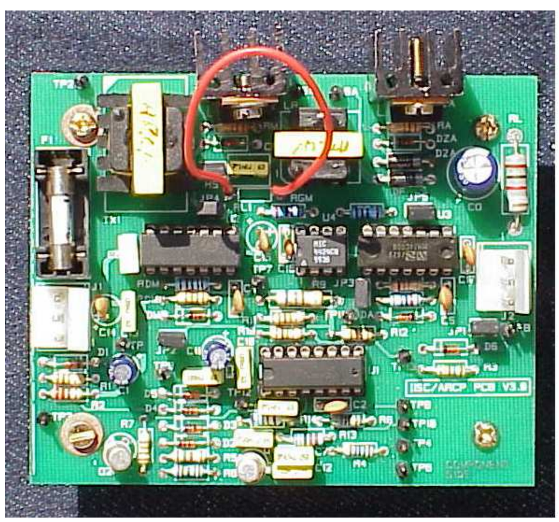


Figure 15.11: Mounted Board of the ARCP-Boost Converter

15.7 Bill of Materials

Table 15.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	R1,R2,RC4	330 Ω	3	0.35	1.05
2	Resistor	Rf1	$1.8k\ \Omega$	1	0.35	0.35
3	Resistor	Rosc	$5.6k\ \Omega$	1	0.35	0.35
4	Resistor	Rpull	150 Ω	1	0.35	0.35
5	Resistor	RLL1,RLL2,RP1	$10k\ \Omega$	3	0.35	1.05
6	Resistor	RF2	$5k\ \Omega$POT	1	3.00	3.00
7	Resistor	Rda,Rdm	$1k\ \Omega$	2	0.35	0.70
8	Resistor	Rda1,Ra,Rm	$10k\ \Omega$	3	0.35	1.05
9	Resistor	Rdm1	$27k\ \Omega$	1	0.35	0.35
10	Resistor	Rga,Rgm	12 Ω	2	0.35	0.70
11	Resistor	RL	33 Ω	1	3.00	3.00
12	Capacitor	C2	10 μF	1	2.00	2.00
13	Capacitor	C3	0.22 μF,63V	1	1.00	2.00
14	Capacitor	Co	100 μF	1	2.00	2.00
15	Capacitor	Cosc,C6,C7,C8	0.001 μF,25V	4	1.00	4.00
16	Capacitor	C10,C1	0.01 μF,50V	2	1.50	3.00
17	Capacitor	Cr	$0.5nF$	1	2.00	2.00
18	Capacitor	C4,C5	$22pF$	2	2.50	5.00
19	Zener		15V	2	2.50	5.00
20	Mosfet	M1	IRFZ44N	2	16.00	32.00
21	Boost Inductor	L1	$70\ \mu H, 37T$	1	25.00	25.00
22	Resonant Inductor	L2	$4\ \mu H, 5T, 2strand$	1	15.00	15.00
23	Zener	Z6	3.3V	1	2.00	2.00
24	Diode	DA,DM,D5	IN4148	3	0.40	1.20
25	Diode	Df,D2a	MUR110	2	8.00	16.00
26	Linear IC	U2	HEF4069	1	8.00	8.00
27	Linear IC	U1	UC495	1	15.00	15.00
28	Linear IC	U4	MIC4424	1	120.00	120.00
29	18/14 Pin IC Base	U1,U2,U3		3	5.00	15.00
30	Test Points		Berg Stick	20	0.10	2.00
31	Jumpers			10	0.10	1.00
32	8 Pin IC Base	U1b		1	5.00	5.00
33	Terminal Connector	T1,T2		3	3.00	9.00
34	Heat Sink	HS1	P149	2	5.00	10.00
35	Linear IC	U3	MM7400CN	1	5.00	5.00
36	PCB	7.5W Active Boost	Control and Boost	2	25.00	50.00
					TOTAL	311.00

Chapter 16

Digital Controller For SMPC

16.1 Circuit Specification

This section covers a simple Digital controller for SMPC with the following specifications.

- Input: 15V
- Controller: Pic (18f2331)
- Duty Cycle: 0.1 to 0.8
- Switching Frequency: 20 to 40 kHz
- Protection: None

16.2 Digital Board

Figure 16.1 shows the block diagram of the Digital Board. It has the Following blocks which are described below.

16.2.1 CPU

PIC 18f2331 microcontroller is acting as a CPU. It is a 28 pin IC with inbuilt Flash memory, PWM and ADC channels.

16.2.2 LCD

A LCD with inbuilt controller is used for display purpose. It is a 16 pin module with 8 data lines (DB0-DB7), 3 control signals (R/W, E, RS). The contrast of the display can be adjusted by giving appropriate voltage level at the pin Vo(3 pin) of the LCD. For 8-bit data to be displayed on LCD, it can be sent either in 4-bit mode (2 operations) or 8-bit mode (1 operation) . Here 4-bit mode is used. Four buses of LCD (DB4-DB7) are interfaced to PortC (RC4-RC7) of the microcontroller. The control signals are interfaced to PortA (RA2-RA4) of the microcontroller.

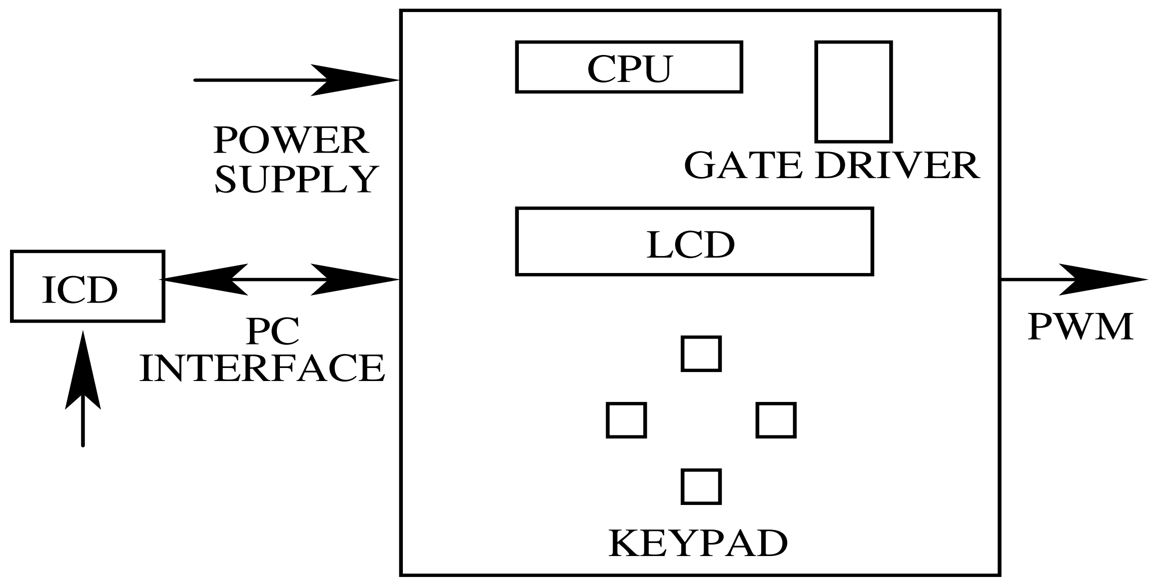


Figure 16.1: Digtal Board

16.2.3 Keypad

Four push buttons are interfaced to the microcontroller. Push buttons can be used to set the duty ratio and the frequency of the converter. These switches are interfaced to ports RB4, RC0, RC1, RC3 of the microcontroller.

16.2.4 Gate Driver

The PWM module of microcontroller is used to generate PWM of the required duty ratio and the frequency. These pulses are given to the driver MIC4424 IC. Input power supply of the converter is used to give power to the driver IC. The isolated pulses are obtained by using a pulse transformer.

16.2.5 ICD

ICD connector(JP1 connector) connects the micro controller to the MPLAB-ICD2. MPLABICD2 is used for programming and debugging purposes. ICD connector is connected to the pins 1, 20,19, 28,27 of the microcontroller.

16.3 Interfacing Technique

16.3.1 Interfacing the switch

When the switch is not pressed there is logic high on the port of the microcontroller. When it is pressed it goes to logic low and on its release it again goes to high. This transitions from high to low and low to high are used to interface the switch. Figure 16.2 shows the switching transition for the switch. When the signal goes from high to low it is recognized that the switch is pressed. Then the program waits till the switch is released. The release of the switch is recognized by a transition from low to high. Upon release the duty ratio or frequency is updated.

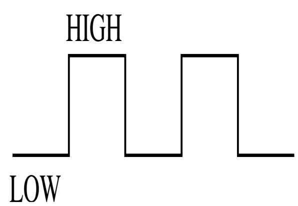


Figure 16.2: Switching Transition

16.3.2 Interfacing the LCD

Four data lines and the three control signals of the LCD are interfaced with the micro controller. To display a character on LCD the ASCII value is to be placed on the data lines. The LCD is interfaced in 4 bit mode. In this mode, data is sent in two operations. First higher 4 bits of the data is transfered and then the lower 4 bit data is transfered. The busy flag (DB7) is checked, when it goes low the next write operation can be performed. The three control signals RS, R/W, enable are either logic high or low depending on the operation being performed. The RS signal is high in case of instruction write and low in case of writing data in DDRAM. The R/W signal is high in case of read operation and low in case of write operation. The enable signal is edge sensitive. The transition of the signal from high to low enables the signal.

16.4 Program and Algorithm

The Program for open loop is written in assembly language and it is checked with power converter. The following Algorithm are used during programming.

16.4.1 Algorithm for PWM generation

Figure 16.3 shows the flowchart for programming the microcontroller to generate PWM waveform. PWM module can be configured by setting the CCPCON,T2CON,CCPR1L,PR2 registers. Here CCPR1L register determines the duty cycle and PR2 register determines the switching frequency.

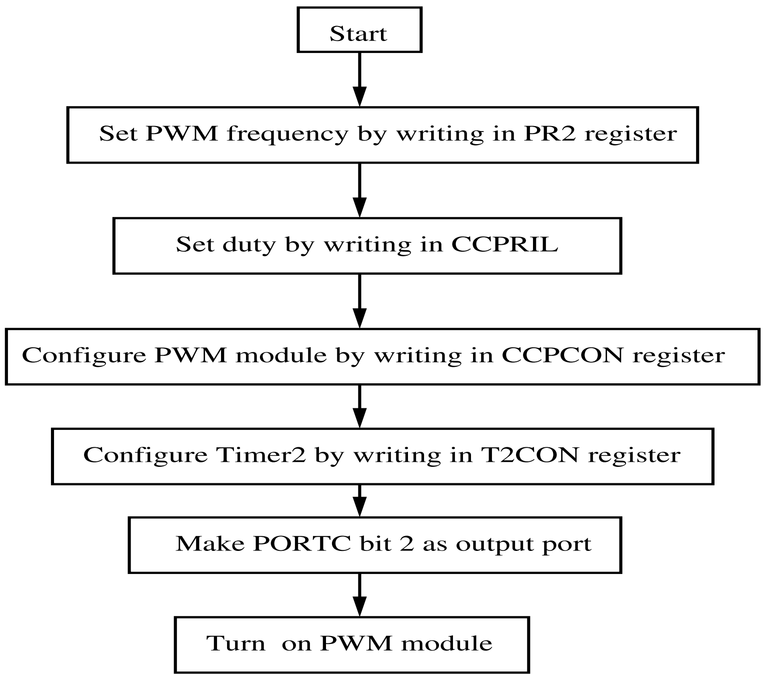


Figure 16.3: Algorithm For PWM Module

16.4.2 Selection of PWM frequency

The required frequency PWM pulses can be generated by writing the value in to PR register. For getting a PWM frequency of 31.25KHz, 7F is to be written in to the PR2 register. This can be obtained using the below equation.

$$PWM\ Period = (PR+1) * 4 * Tosc * TMR2\ Prescaler \tag{16.1}$$

A clock of 4MHz is used with PLL. Therefore, Fosc is 16MHz. TMR2 prescaler value is 1.

16.4.3 Duty cycle of PWM pulse

By writing the appropriate control words in to the register CCPRIL the required duty ratio can be obtained. 34h is to be written in CCPRIL to get a duty ratio of 0.4. This is obtained from the below equation.

$$PWM\ duty\ cycle = (CCPRIL : CCPCON(5:4))*4*Tosc*TMR2\ Prescaler \tag{16.2}$$

The frequency of the switching and the duty ratio can be varied by writing in to PR2 and CCPRIL registers. The Table.16.1 gives the value of PWM frequency for different values of PR2.

Table 16.1: PWM frequency variation with PR2

PR2	*CCPR1L*	*Frequency(KHz)*	*Duty ratio*
FF	$7F$	62.5	0.5
FF	$3F$	62.5	0.25
91	$2F$	38.5	0.45

Figure 16.4 shows the flowchart for the programming the microcontroller. The program has the necessary code to intialize PWM module, display the value of frequency and duty cycle on the LCD. The mode switch is to select either frequency or duty ratio, then the enter key is enter in to the mode. The '+' or '-' switch is to vary either duty ratio or frequency. Consider if the '+' key is pressed the value for either duty or frequency will be incremented by one and similarly when the '-' key is pressed. There is also a minimum and maximum limit for both frequency and duty ratio.
Whenever the circuit gets reset then it starts with default value for both duty ratio and frequency. After that we can vary the duty ratio by Keypad switch.

16.5 Software Development/Requirement

The assembly program for the digital converter is given appendix. Here the assembly program is complied by compiler and then embedded in to chip through ICD-2 debugger.
Microchip ICD-2 is required to embed the program in to the micrcontroller.

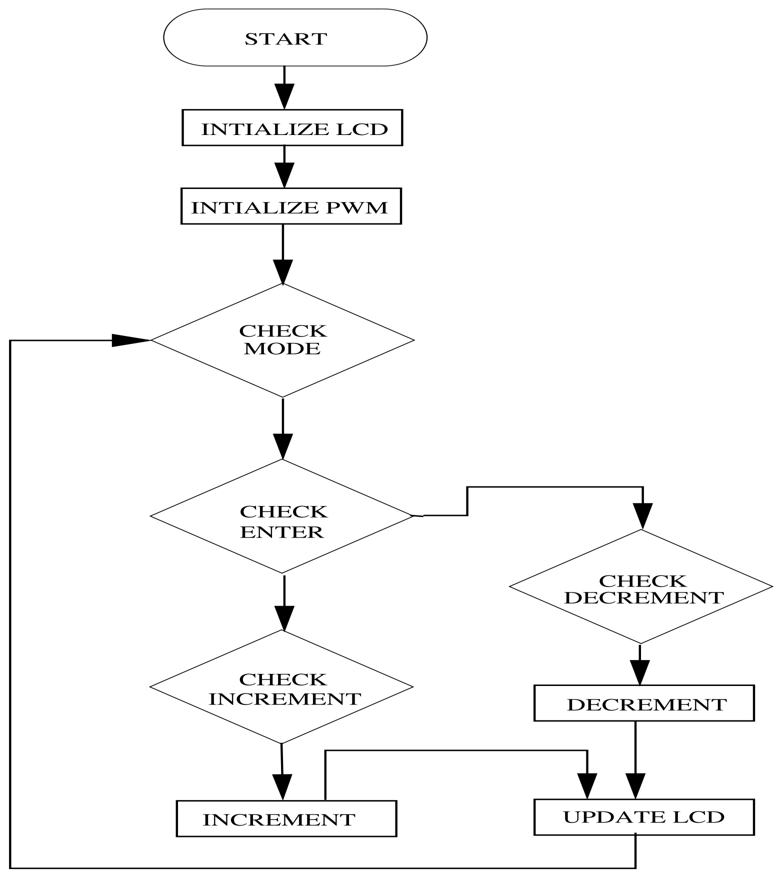


Figure 16.4: Algorithm For Programming

16.6 Mounted PCB Board

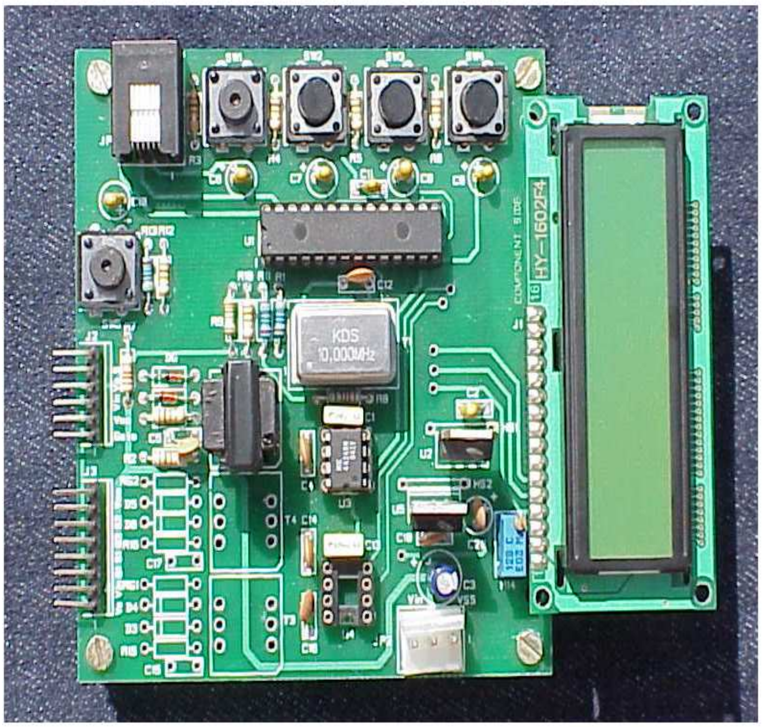


Figure 16.5: Digital Controller for SMPC

Figure 16.5 shows the Hardware model of the Digital Controller for SMPC. The controller board with microcontroller is in the middle. The microcontroller is the 18f2331 (28 pin) ic seen in the middle. The LCD is seen at the right which has 2 Line and 16 characters. The setting switches (4 numbers) are at the top. The reset switch is at the left.

16.7 circuit Layout

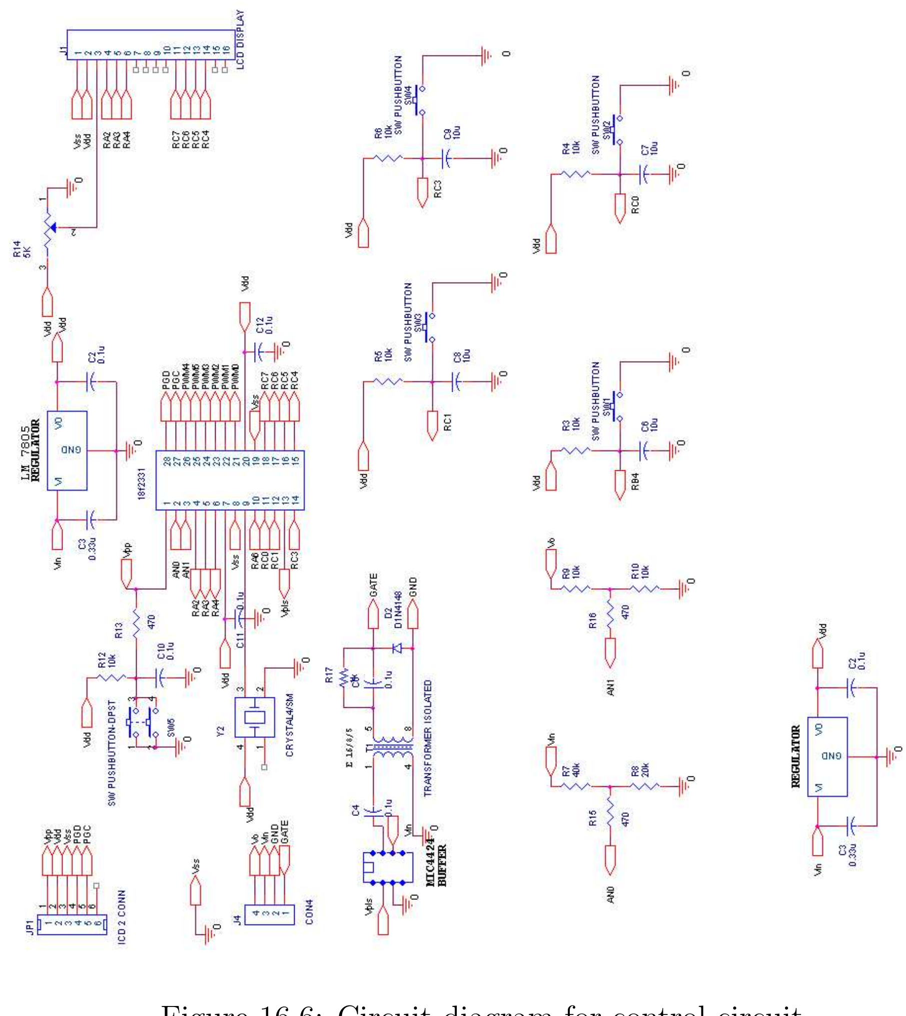


Figure 16.6: Circuit diagram for control circuit

16.8 Bill Of Materials

Table 16.2: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg, R2	$1k\ \Omega$	2	0.35	1.40
2	Resistor	R3, R4, R5, R6, R10, R12	$10k\ \Omega$	6	0.35	2.10
3	Resistor	R7	$40k\ \Omega$	1	0.35	0.35
4	Resistor	R8	$20k\ \Omega$	1	0.35	0.35
5	Resistor	R1, R11, R13	$470\ \Omega$	3	0.35	1.05
6	Resistor	R14	$5k\ \Omega$	1	0.35	0.35
7	Capacitor	C15	$22\ \mu F$	1	2.00	2.00
8	Capacitor	C2, C3,C4,C5,C10,C11,C12,C18	$0.1\ \mu F$,63V	8	0.50	4.00
9	Capacitor	C6, C7,C8,C9	$47\ \mu F$,25V	4	2.00	8.00
10	Capacitor	Cf	$0.022\ \mu F$,50V	1	2.50	2.50
11	Capacitor	Ct	$0.0047\ \mu F$,50V	1	2.50	2.50
12	Transformer	T1	E 16/8/5	3	15.00	45.00
13	Microcontroller IC	U1	18f2331	1	60.00	60.00
14	Voltage regulator	U2	LM 7805	1	8.00	8.00
15	Opto Isolator	U3	MIC 4425	1	8.00	8.00
16	Test Points	T1-T13	Berg Stick	13	0.10	1.30
27	28 Pin IC Base	U1b		1	5.00	5.00
28	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
29	Dip Switch	SW1-SW5		5	5.00	25.00
30	8 Pin IC Base	U3b		1	5.00	5.00
31	Terminal Connector	T1,T2		2	3.00	6.00
32	HD44780 LCD			1	100.00	100.00
33	PCB			1	25.00	25.00
					TOTAL	317.90

Chapter 17

Digital Control of Buck Converter Open Loop

17.1 Circuit Specification

This section covers a simple Digital Control of Buck converter Open loop with the following specifications.

- Input: 15V
- Controller: Pic (18f2331)
- Duty Cycle: 0.1 to 0.8
- Switching Frequency: 20 to 40 kHz
- Protection: None

17.2 Buck Converter

The Buck converter is also called a step down converter as it produces a lower output voltage than the dc input voltage. The average output voltage can be calculated in terms of the switch duty ratio and is found to be:

$$V_o = \frac{1}{T_s} \int_0^{T_S} V_o \, dt \; = \; \frac{1}{T_s} \int_0^{T_{on}} V_g \, dt + \frac{1}{T_s} \int_{T_{on}}^{T_s} 0 \, dt \; = \; V_g \frac{T_{on}}{T_s} \; = \; V_g d \quad (17.1)$$

Figure 21.1 shows a 7.5 W Buck Converter with a resistive load and a low pass filter.All the components used are assumed to be ideal.

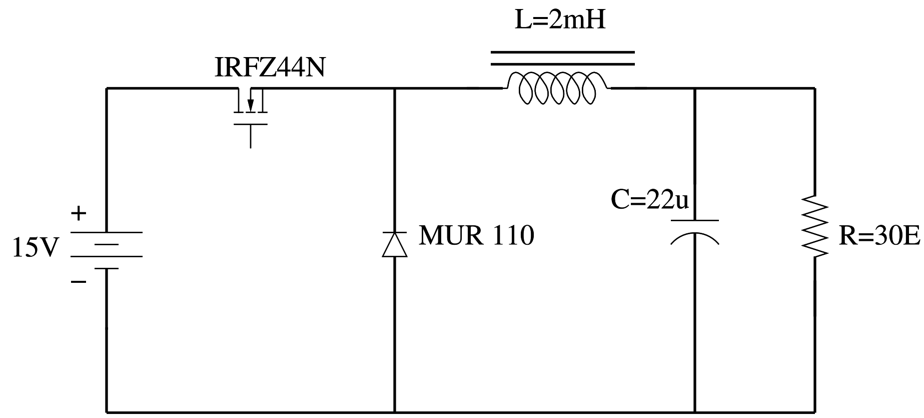


Figure 17.1: Circuit Diagram (Buck Converter)

17.3 Power Circuit Design

17.3.1 Design of inductor

In each sub period [dT_S and $(1-d)T_S$], the rate of change of current is constant. The current ripple can be determined using the following equation.

$$\delta I_o = \frac{V_g d(1-d)T_S}{L} = \frac{V_o(1-d)T_S}{L} \tag{17.2}$$

$$\frac{\delta I_o}{I_o} = \delta_i = \frac{(1-d)RT_S}{L} \tag{17.3}$$

The value of the inductance L is designed such that δ_i is 10% of the output current I_o. The value of L is 0.888 mH. As per the design calculation the follwowing parameters are found out.
Core E 30/15/7
Number of turns 117
lg = 1.157mm
SWG 20

17.3.2 Design of capacitor

The charging and discharging current of the capacitor decides the voltage ripple. We consider that the ac part of the inductor current flows into the capacitor.

$$\delta V_o = \frac{\delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\delta I_o}{2}\frac{T_S}{2} \tag{17.4}$$

$$\delta V_o = \frac{V_o(1-d)T_S^2}{8LC} \tag{17.5}$$

$$\frac{\delta V_o}{V_o} = \delta_v = \frac{(1-d)T_S^2}{8LC} \tag{17.6}$$

The capacitor C is designed for δ_v to be 1% of the output voltage V_o. The value of C is 15 μF/30V.

Selection of active and passive switches

Based on the voltage and current ratings IRFZ44N (50V/10A) and MUR 110 (100V/1A) are used as active and passive switches respectively.

17.4 Hardware Design For Control Circuit

Design of control circuit is same as Digital controller for SMPC. Algortim and program are same as explained in the chapter 16.
The program has the necessary code to intialize PWM module, display the value of frequency and duty cycle on the LCD. The mode switch is to select either frequency or duty ratio, and enter key is to enter in to that mode. The '+' or '-' switch is to vary either duty ratio or frequency. Consider if the '+' key is pressed the value for either duty or frequency will be incremented by one and similarly when the '-' key is pressed. There is also a minimum and maximum limit for both frequency and duty ratio.
Whenever the circuit gets reset then it starts with default value for both duty ratio and frequency. After that duty ratio or we can vary the duty ratio by Keypad switch.

17.5 Mounted PCB Board

Figure 17.2 shows the Hardware model of the Digital Control of SMPC. The controller board with microcontroller is in the middle. The microcontroller is the 18f2331 (28 pin) ic seen in the middle. The LCD is seen at the right which has 2 Line and 16 characters. The setting switches (4 numbers) are at the top. The reset switch is at the left. The board on the left is the 7.5W Buck conveter with a wire wound resistor.

Figure 17.4 a,b shows the practical waveform of the conveter. The input voltage to the converter is set to 15V. We can get the different ranges of output voltage by varying the duty ratio.

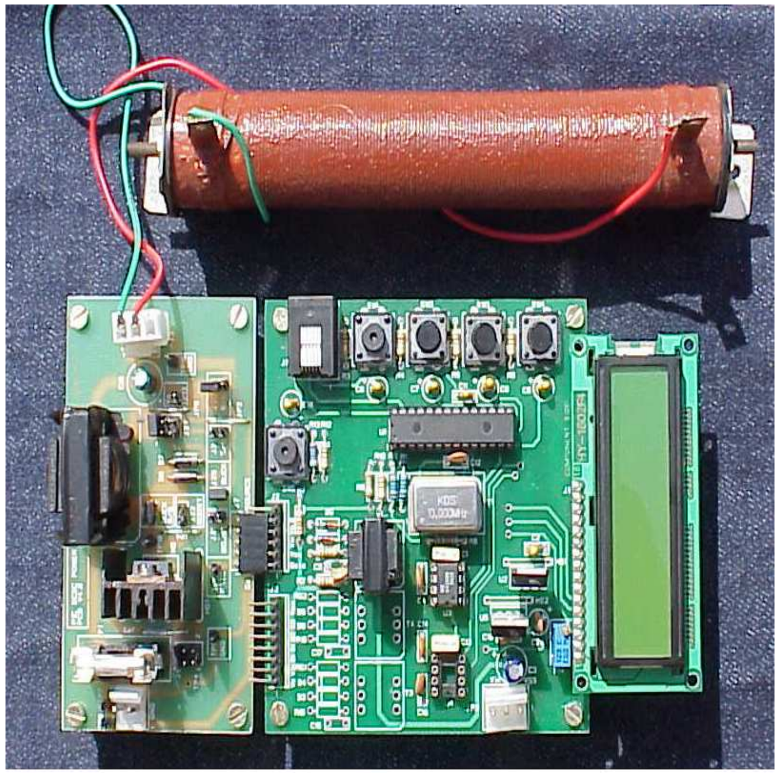
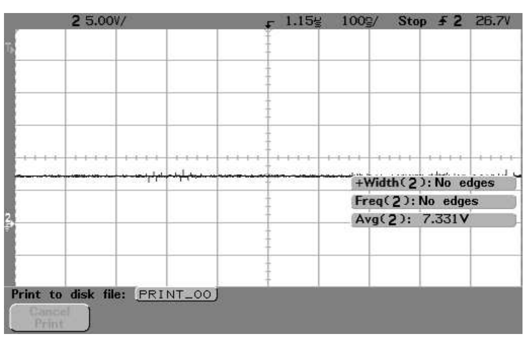
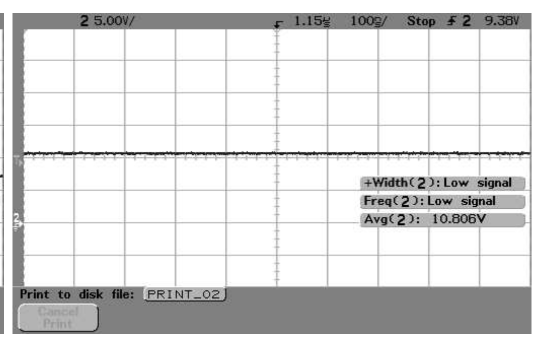


Figure 17.2: Digital Controller for SMPC

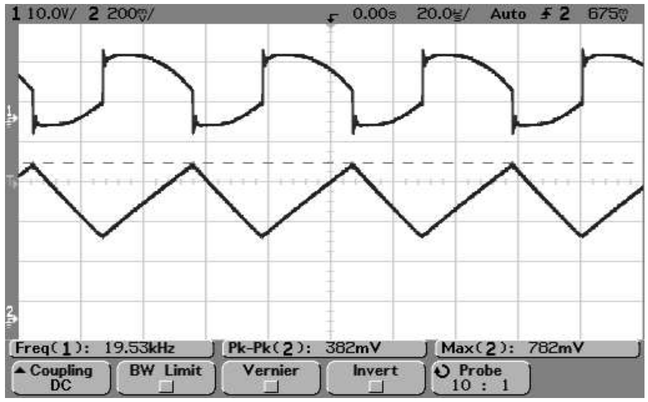


(a) Output waveform across the load when D=0.5

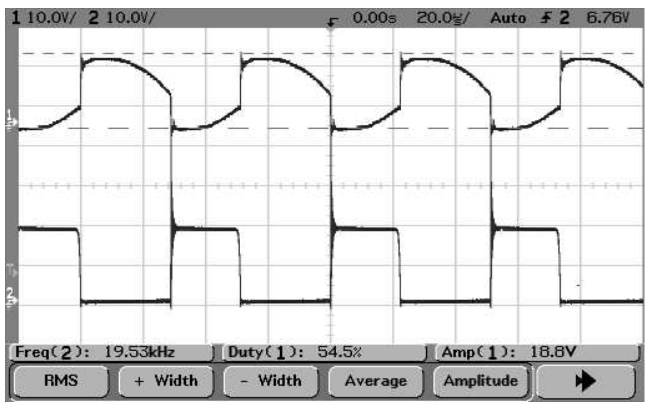


(b) Output waveform across the load when D=0.75

Figure 17.3: Practical Waveform



(a) Gate to Source voltage and Inductor current.



(b) Gate to Source voltage and Drain to Source voltage.

Figure 17.4: Practical Waveform

17.6 Circuit Layout

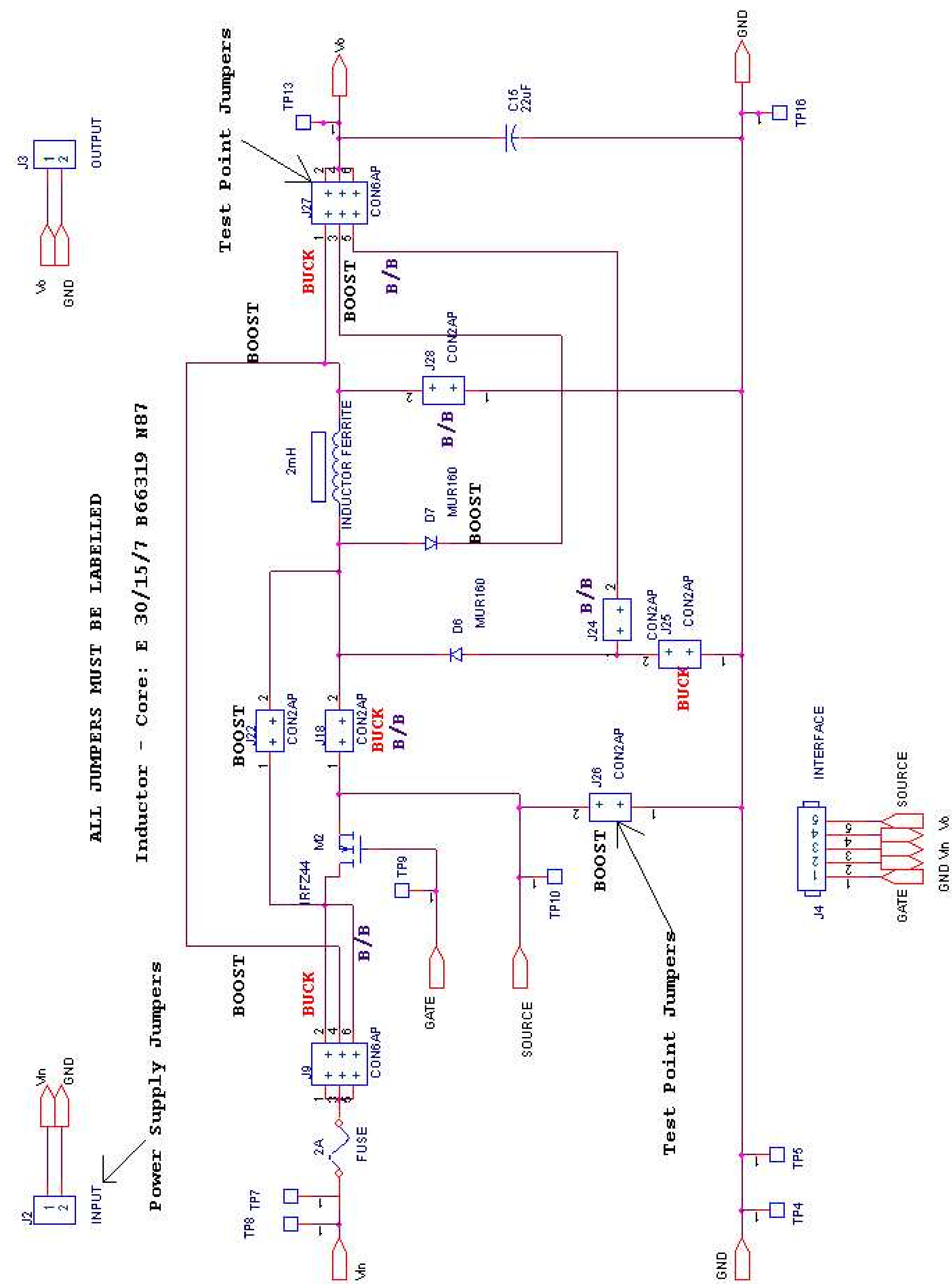


Figure 17.5: Circuit diagram for power circuit

17.7 Bill Of Materials

Table 17.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg, R2	$1k\ \Omega$	2	0.35	1.40
2	Resistor	R3, R4, R5, R6, R10, R12	$10k\ \Omega$	6	0.35	2.10
3	Resistor	R7	$40k\ \Omega$	1	0.35	0.35
4	Resistor	R8	$20k\ \Omega$	1	0.35	0.35
5	Resistor	R1, R11, R13	$470\ \Omega$	3	0.35	1.05
6	Resistor	R14	$5k\ \Omega$	1	0.35	0.35
7	Capacitor	C15	$22\ \mu F$	1	2.00	2.00
8	Capacitor	C2, C3,C4,C5,C10,C11,C12,C18	$0.1\ \mu F$,63V	8	0.50	4.00
9	Capacitor	C6, C7,C8,C9	$47\ \mu F$,25V	4	2.00	8.00
10	Capacitor	Cf	$0.022\ \mu F$,50V	1	2.50	2.50
11	Capacitor	Ct	$0.0047\ \mu F$,50V	1	2.50	2.50
12	Transformer	T1	E 16/8/5	3	15.00	45.00
13	Inductor	L1	E 30/15/7	1	15.00	15.00
14	Mosfet	M1	IRFZ44N	1	16.00	16.00
15	Diode	D1,D2	MUR110	2	8.00	16.00
16	Microcontroller IC	U1	18f2331	1	60.00	60.00
17	Voltage regulator	U2	LM 7805	1	8.00	8.00
18	Opto Isolator	U3	MIC 4425	1	8.00	8.00
19	Test Points	T1-T13	Berg Stick	13	0.10	1.30
20	28 Pin IC Base	U1b		1	5.00	5.00
21	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
22	Dip Switch	SW1-SW5		5	5.00	25.00
23	8 Pin IC Base	U3b		1	5.00	5.00
24	Terminal Connector	T1,T2		2	3.00	6.00
25	Heat Sink	HS1	P149	2	5.00	10.00
26	HD44780 LCD			1	100.00	100.00
27	PCB			2	25.00	50.00
					TOTAL	399.90

Chapter 18

Digital Control of Boost Converter Open Loop

18.1 Circuit Specification

This section covers a simple Digital Control of Boost converter Open loop with the following specifications.

- Input: 10V
- Controller: Pic (18f2331)
- Duty Cycle: 0.1 to 0.8
- Switching Frequency: 20 to 40 kHz
- Protection: None

18.2 Boost Converter

The Boost converter is also called a step up converter as it produces a output voltage higher than the dc input voltage. The average output voltage can be calculated in terms of the switch duty ratio and is found to be:

$$V_0 = \frac{V_g}{1-d} \tag{18.1}$$

Figure 18.1 shows a 7.5 W Boost Converter with a resistive load and a low pass filter.All the components used are assumed to be ideal.

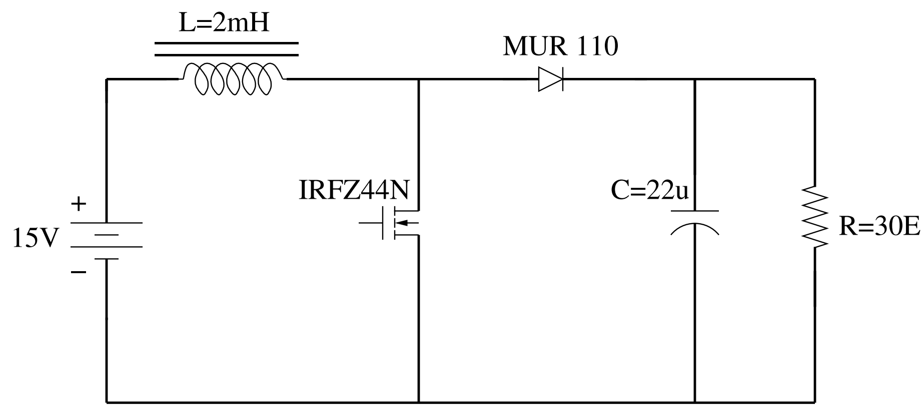


Figure 18.1: Circuit Diagram (Boost Converter)

18.3 Power Circuit Design

18.3.1 Design of inductor

In each sub period [dT_S and $(1-d)T_S$], the rate of change of current is constant. The current ripple can be determined using the following equation.

$$\delta I_o = \frac{V_g d(1-d)T_S}{L} = \frac{V_o(1-d)T_S}{L} \tag{18.2}$$

$$\frac{\delta I_o}{I_o} = \delta_i = \frac{(1-d)RT_S}{L} \tag{18.3}$$

The value of the inductance L is designed such that δ_i is 10% of the output current I_o. The value of L is 0.888 mH. As per the design calculation the follwowing parameters are found out.
Core E 30/15/7
Number of turns 117
lg = 1.157mm
SWG 20

18.3.2 Design of capacitor

The charging and discharging current of the capacitor decides the voltage ripple. We consider that the ac part of the inductor current flows into the capacitor.

$$\delta V_o = \frac{\delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\delta I_o}{2}\frac{T_S}{2} \tag{18.4}$$

$$\delta V_o = \frac{V_o(1-d)T_S^2}{8LC} \tag{18.5}$$

$$\frac{\delta V_o}{V_o} = \delta_v = \frac{(1-d)T_S^2}{8LC} \tag{18.6}$$

The capacitor C is designed for δ_v to be 1% of the output voltage V_o. The value of C is 15 μF/30V.

Selection of active and passive switches

Based on the voltage and current ratings IRFZ44N (50V/10A) and MUR 110 (100V/1A) are used as active and passive switches respectively.

18.4 Hardware Design For Control Circuit

Design of control circuit is same as Digital controller for SMPC. Algortim and program are same as explained in the chapter 16.
The program has the necessary code to intialize PWM module, display the value of frequency and duty cycle on the LCD. The mode switch is to select either frequency or duty ratio, then the enter key is enter in to the mode. The '+' or '-' switch is to vary either duty ratio or frequency. Consider if the '+' key is pressed the value for either duty or frequency will be incremented by one and similarly when the '-' key is pressed. There is also a minimum and maximum limit for both frequency and duty ratio.
Whenever the circuit gets reset then it starts with default value for both duty ratio and frequency. After that we can vary the duty ratio by Keypad switch.

18.5 Mounted PCB Board

Figure 19.2 shows the Hardware model of the Digital Control of SMPC. The controller board with microcontroller is in the middle. The microcontroller is the 18f2331 (28 pin) ic seen in the middle. The LCD is seen at the right which has 2 Line and 16 characters. The setting switches (4 numbers) are at the top. The reset switch is at the left. The board on the left is the 7.5W Boost conveter with a wire wound resistor.

Figure 19.3 a,b shows the practical waveform of the conveter. The input voltage to the converter is set to 10V. We can get the different ranges of output voltage by varying the duty ratio.

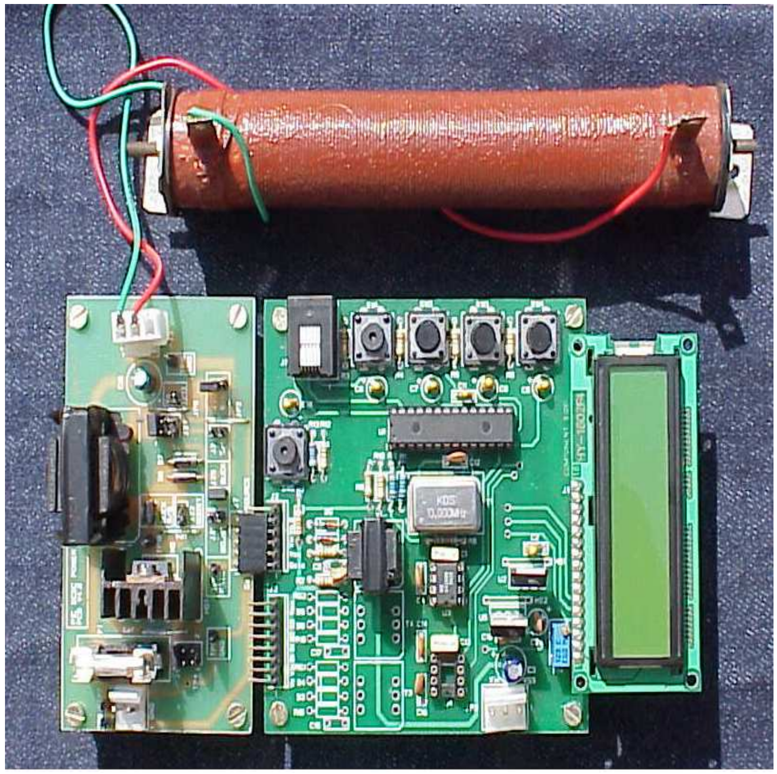
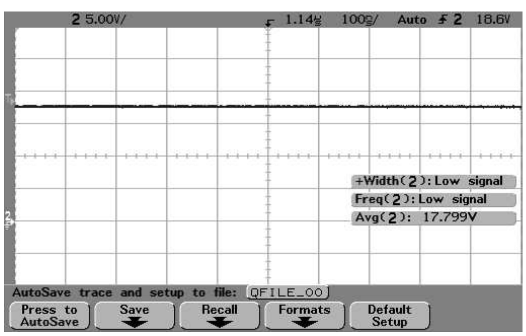
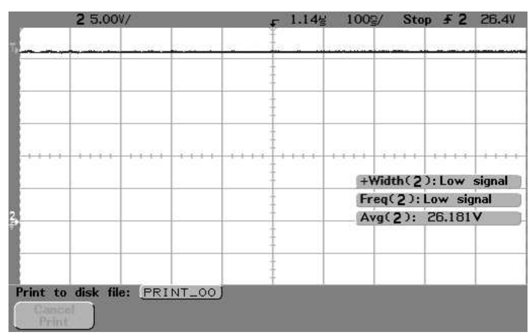


Figure 18.2: Digital Controller for SMPC

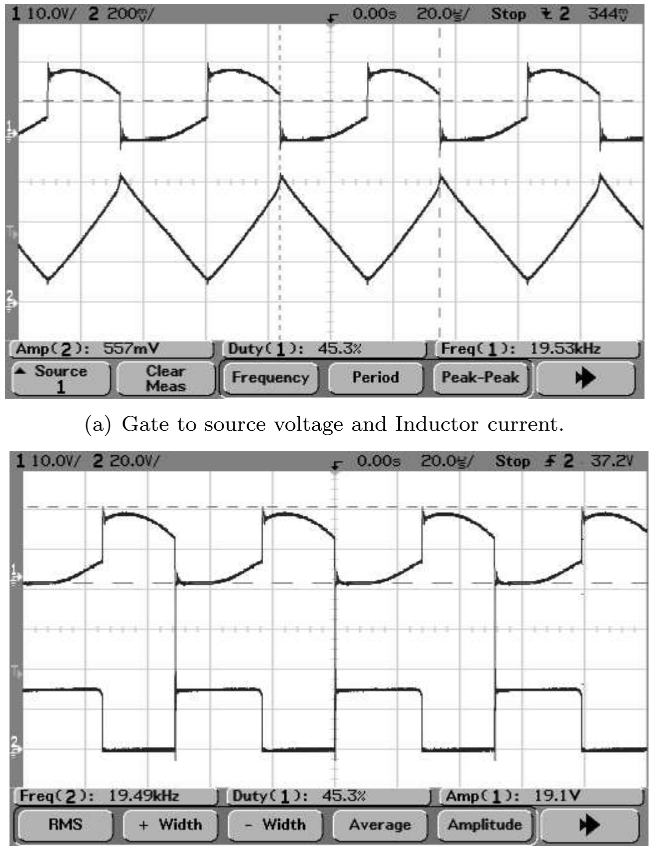


(a) Output waveform across the load when D=0.5



(b) Output waveform across the load when D=0.66

Figure 18.3: Practical Waveform



(a) Gate to source voltage and Inductor current.

(b) Gate to Source voltage and Drain to Source voltage.

Figure 18.4: Practical Waveform

18.6 Circuit Layout

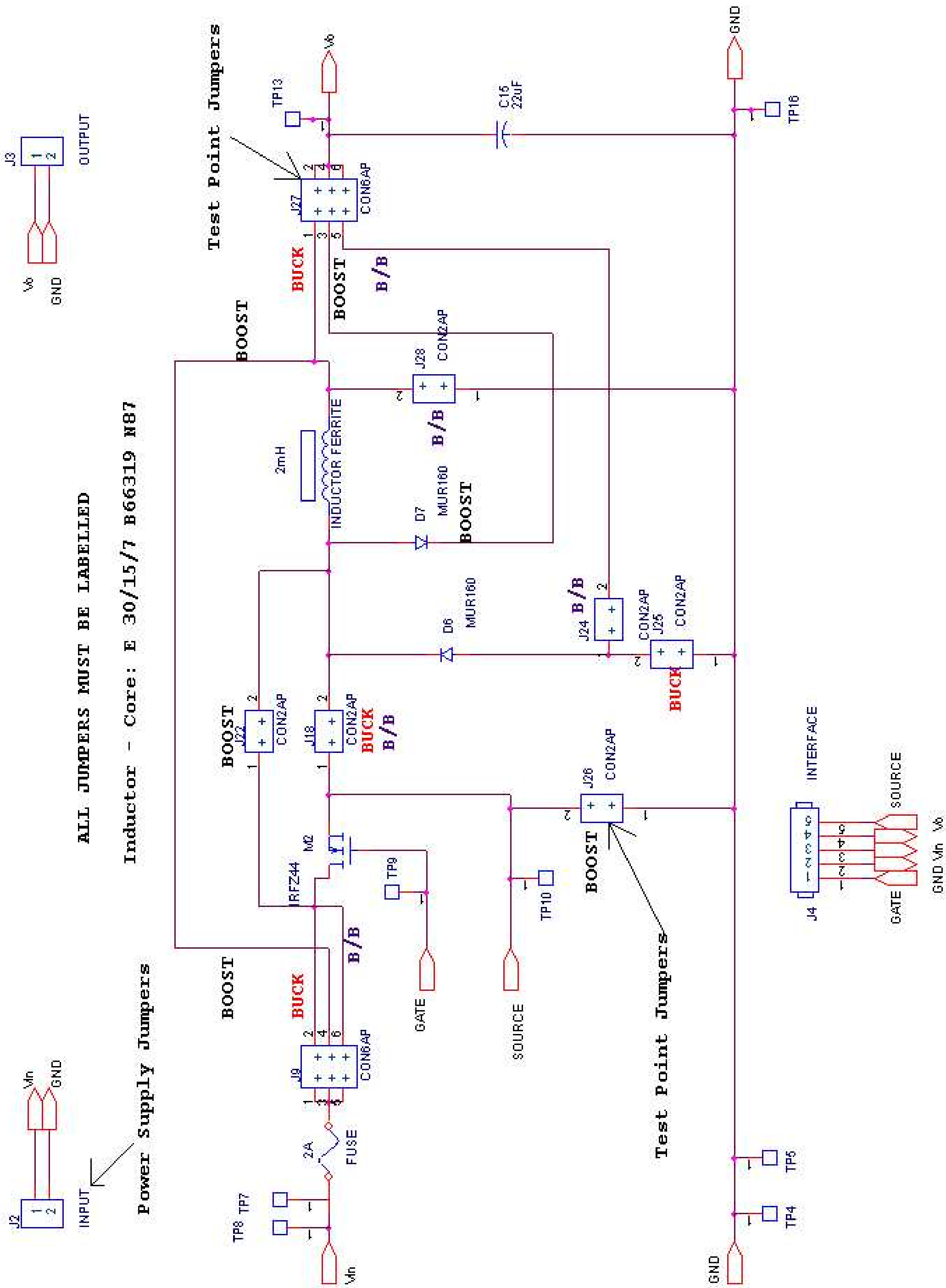


Figure 18.5: Circuit diagram for power circuit

18.7 Bill Of Materials

Table 18.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg, R2	$1k\ \Omega$	2	0.35	1.40
2	Resistor	R3, R4, R5, R6, R10, R12	$10k\ \Omega$	6	0.35	2.10
3	Resistor	R7	$40k\ \Omega$	1	0.35	0.35
4	Resistor	R8	$20k\ \Omega$	1	0.35	0.35
5	Resistor	R1, R11, R13	$470\ \Omega$	3	0.35	1.05
6	Resistor	R14	$5k\ \Omega$	1	0.35	0.35
7	Capacitor	C15	$22\ \mu F$	1	2.00	2.00
8	Capacitor	C2, C3,C4,C5,C10,C11,C12,C18	$0.1\ \mu F$,63V	8	0.50	4.00
9	Capacitor	C6, C7,C8,C9	$47\ \mu F$,25V	4	2.00	8.00
10	Capacitor	Cf	$0.022\ \mu F$,50V	1	2.50	2.50
11	Capacitor	Ct	$0.0047\ \mu F$,50V	1	2.50	2.50
12	Transformer	T1	E 16/8/5	3	15.00	45.00
13	Inductor	L1	E 30/15/7	1	15.00	15.00
14	Mosfet	M1	IRFZ44N	1	16.00	16.00
15	Diode	D1,D2	MUR110	2	8.00	16.00
16	Microcontroller IC	U1	18f2331	1	60.00	60.00
17	Voltage regulator	U2	LM 7805	1	8.00	8.00
18	Opto Isolator	U3	MIC 4425	1	8.00	8.00
19	Test Points	T1-T13	Berg Stick	13	0.10	1.30
20	28 Pin IC Base	U1b		1	5.00	5.00
21	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
22	Dip Switch	SW1-SW5		5	5.00	25.00
23	8 Pin IC Base	U3b		1	5.00	5.00
24	Terminal Connector	T1,T2		2	3.00	6.00
25	Heat Sink	HS1	P149	2	5.00	10.00
26	HD44780 LCD			1	100.00	100.00
27	PCB			2	25.00	50.00
					TOTAL	399.90

Chapter 19

Digital Control of Buck-Boost Converter Open Loop

19.1 Circuit Specification

This section covers a simple Digital Control of Buck-Boost converter Open loop with the following specifications.

- Input: 15V
- Controller: Pic (18f2331)
- Duty Cycle: 0.1 to 0.8
- Switching Frequency: 20 to 40 kHz
- Protection: None

19.2 Buck-Boost Converter

The Buck-Boost converter is also called a step up-down converter as it produces a output voltage higher or lower than the dc input voltage. The average output voltage can be calculated in terms of the switch duty ratio and is found to be:

$$V_0 = \frac{-dV_g}{1-d} \tag{19.1}$$

Figure 21.1 shows a 7.5 W Buck-Boost Converter with a resistive load and a low pass filter.All the components used are assumed to be ideal.

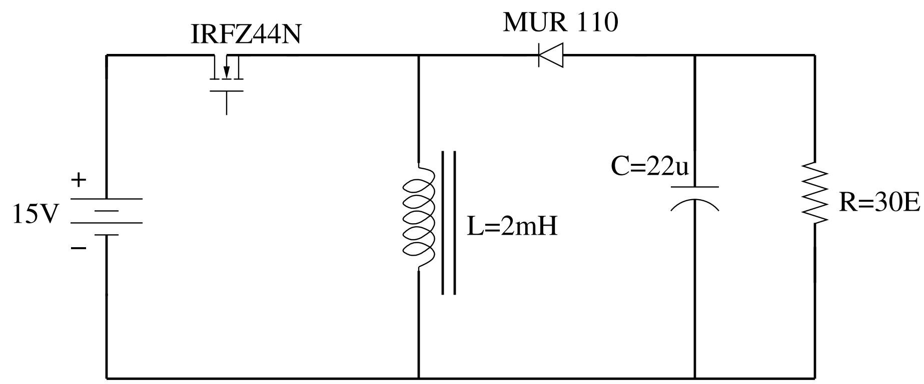


Figure 19.1: Circuit Diagram (Buck-Boost Converter)

19.3 Power Circuit Design

19.3.1 Design of inductor

In each sub period $[dT_S$ and $(1-d)T_S]$, the rate of change of current is constant. The current ripple can be determined using the following equation.

$$\delta I_o = \frac{V_g d(1-d)T_S}{L} = \frac{V_o(1-d)T_S}{L} \tag{19.2}$$

$$\frac{\delta I_o}{I_o} = \delta_i = \frac{(1-d)RT_S}{L} \tag{19.3}$$

The value of the inductance L is designed such that δ_i is 10% of the output current I_o. The value of L is 0.888 mH. As per the design calculation the follwowing parameters are found out.
Core E 30/15/7
Number of turns 117
lg = 1.157mm
SWG 20

19.3.2 Design of capacitor

The charging and discharging current of the capacitor decides the voltage ripple. We consider that the ac part of the inductor current flows into the capacitor.

$$\delta V_o = \frac{\delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\delta I_o}{2}\frac{T_S}{2} \tag{19.4}$$

$$\delta V_o = \frac{V_o(1-d)T_S^2}{8LC} \tag{19.5}$$

$$\frac{\delta V_o}{V_o} = \delta_v = \frac{(1-d)T_S^2}{8LC} \tag{19.6}$$

The capacitor C is designed for δ_v to be 1% of the output voltage V_o. The value of C is 15 μF/30V.

Selection of active and passive switches

Based on the voltage and current ratings IRFZ44N (50V/10A) and MUR 110 (100V/1A) are used as active and passive switches respectively.

19.4 Hardware Design For Control Circuit

Design of control circuit is same as Digital controller for SMPC. Algortim and program are same as explained in the chapter 16.
The program has the necessary code to intialize PWM module, display the value of frequency and duty cycle on the LCD. The mode switch is to select either frequency or duty ratio, then the enter key is enter in to the mode. The '+' or '-' switch is to vary either duty ratio or frequency. Consider if the '+' key is pressed the value for either duty or frequency will be incremented by one and similarly when the '-' key is pressed. There is also a minimum and maximum limit for both frequency and duty ratio.
Whenever the circuit gets reset then it starts with default value for both duty ratio and frequency. After that we can vary the duty ratio by Keypad switch.

19.5 Mounted PCB Board

Figure **??** shows the Hardware model of the Digital Control of SMPC. The controller board with microcontroller is in the middle. The microcontroller is the 18f2331 (28 pin) ic seen in the middle. The LCD is seen at the right which has 2 Line and 16 characters. The setting switches (4 numbers) are at the top. The reset switch is at the left. The board on the left is the 7.5W Buck-Boost conveter with a wire wound resistor.

Figure 19.4 a,b shows the practical waveform of the conveter. The input voltage to the converter is set to 15V. We can get the different ranges of output voltage by varying the duty ratio.

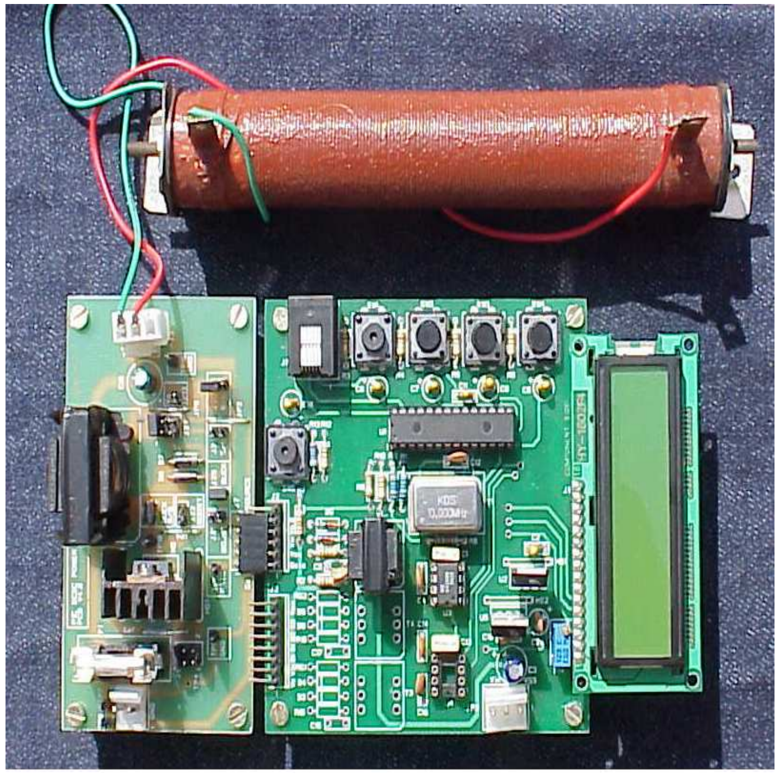
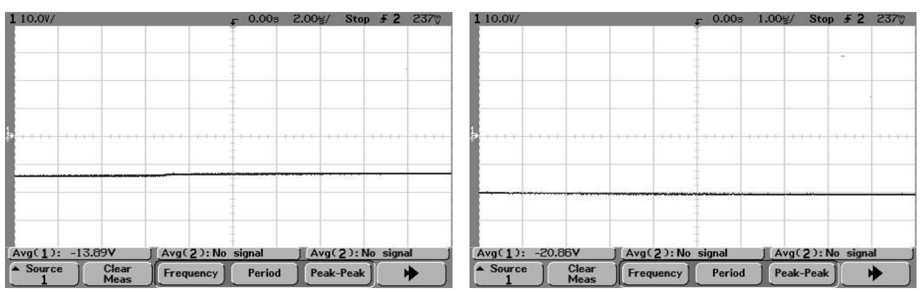


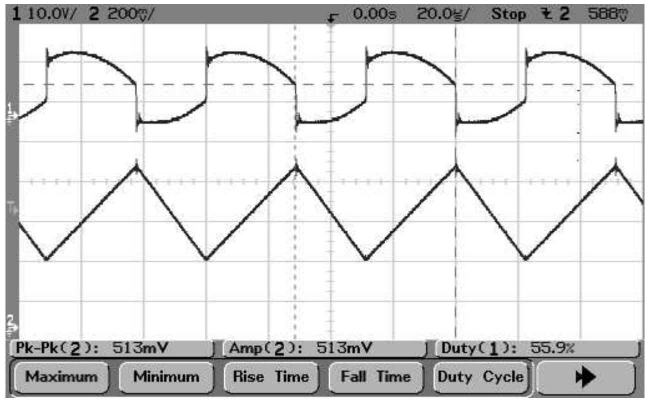
Figure 19.2: Digital Controller for SMPC



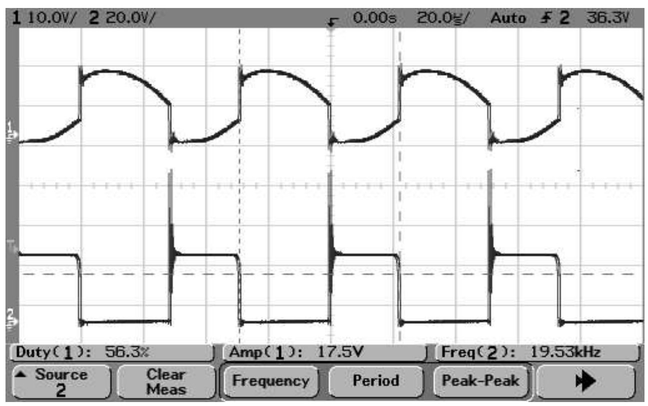
(a) Output waveform across the load when D=0.5

(b) Output waveform across the load when D=0.60

Figure 19.3: Practical Waveform



(a) Gate to source voltage and Inductor current.



(b) Gate to Source voltage and Drain to Source voltage.

Figure 19.4: Practical Waveform

19.6 Circuit Layout

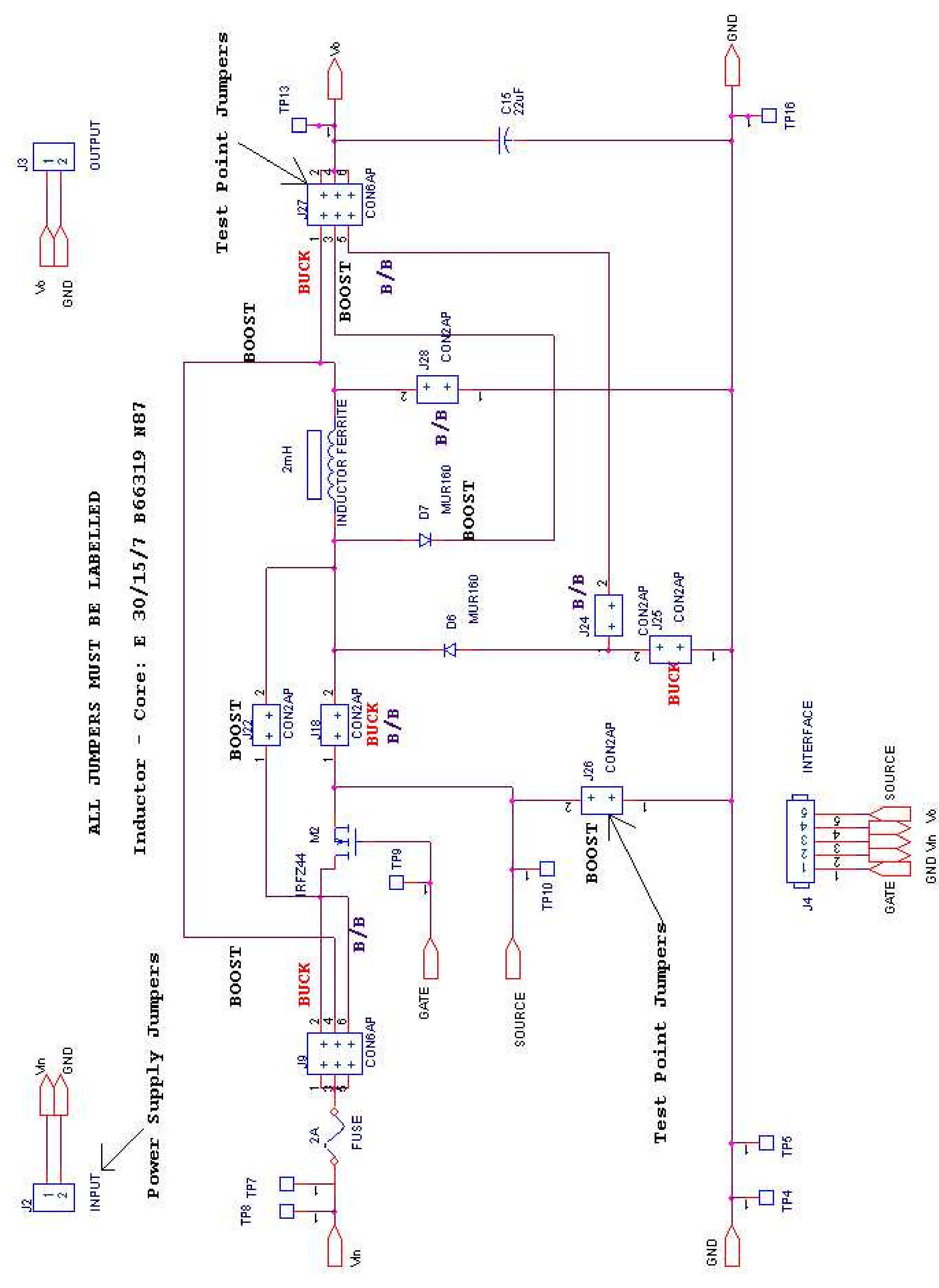


Figure 19.5: Circuit diagram for power circuit

19.7 Bill Of Materials

Table 19.1: Bill of Material Table

Sl.No.	Item	Symbol	Specification	Quantity	Rate	Cost
1	Resistor	Rg, R2	$1k\ \Omega$	2	0.35	1.40
2	Resistor	R3, R4, R5, R6, R10, R12	$10k\ \Omega$	6	0.35	2.10
3	Resistor	R7	$40k\ \Omega$	1	0.35	0.35
4	Resistor	R8	$20k\ \Omega$	1	0.35	0.35
5	Resistor	R1, R11, R13	$470\ \Omega$	3	0.35	1.05
6	Resistor	R14	$5k\ \Omega$	1	0.35	0.35
7	Capacitor	C15	$22\ \mu F$	1	2.00	2.00
8	Capacitor	C2, C3,C4,C5,C10,C11,C12,C18	$0.1\ \mu F$,63V	8	0.50	4.00
9	Capacitor	C6, C7,C8,C9	$47\ \mu F$,25V	4	2.00	8.00
10	Capacitor	Cf	$0.022\ \mu F$,50V	1	2.50	2.50
11	Capacitor	Ct	$0.0047\ \mu F$,50V	1	2.50	2.50
12	Transformer	T1	E 16/8/5	3	15.00	45.00
13	Inductor	L1	E 30/15/7	1	15.00	15.00
14	Mosfet	M1	IRFZ44N	1	16.00	16.00
15	Diode	D1,D2	MUR110	2	8.00	16.00
16	Microcontroller IC	U1	18f2331	1	60.00	60.00
17	Voltage regulator	U2 Flyback	LM 7805	1	8.00	8.00
18	Opto Isolator	U3	MIC 4425	1	8.00	8.00
19	Test Points	T1-T13	Berg Stick	13	0.10	1.30
20	28 Pin IC Base	U1b		1	5.00	5.00
21	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
22	Dip Switch	SW1-SW5		5	5.00	25.00
23	8 Pin IC Base	U3b		1	5.00	5.00
24	Terminal Connector	T1,T2		2	3.00	6.00
25	Heat Sink	HS1	P149	2	5.00	10.00
26	HD44780 LCD			1	100.00	100.00
27	PCB			2	25.00	50.00
					TOTAL	399.90

Chapter 20

Digital Controller For SMPC using PIC Micro Controller

20.1 Circuit Specification

This chapter covers a simple digital controller for SMPC with the following specifications.

- Input: 15V
- Controller: Micro Controller dsPIC30F4011
- Switching Frequency: 15 to 30 KHz
- Protection: None

20.2 Digital Board

Figure 20.1 shows the block diagram of the Control Circuit. It has the following blocks.

20.2.1 CPU

The micro controller dsPIC30F4011 is the Central Processing Unit. It has a 40 pin Ic with in built Flash memory, PWM and ADC modules.

20.2.2 LCD

An LCD with inbuilt controller is used for display purpose. It is a 16 pin module with 8 data lines (DB0-DB7) and 3 control lines (R/W, E, RS). The contrast of the display can be adjusted by giving appropriate voltage level at the pin V_o(pin 3) of the LCD. For 8-bit data to be displayed on LCD, it can be sent either in 4-bit mode (2 operations) or 8-bit mode (1 operation). Here

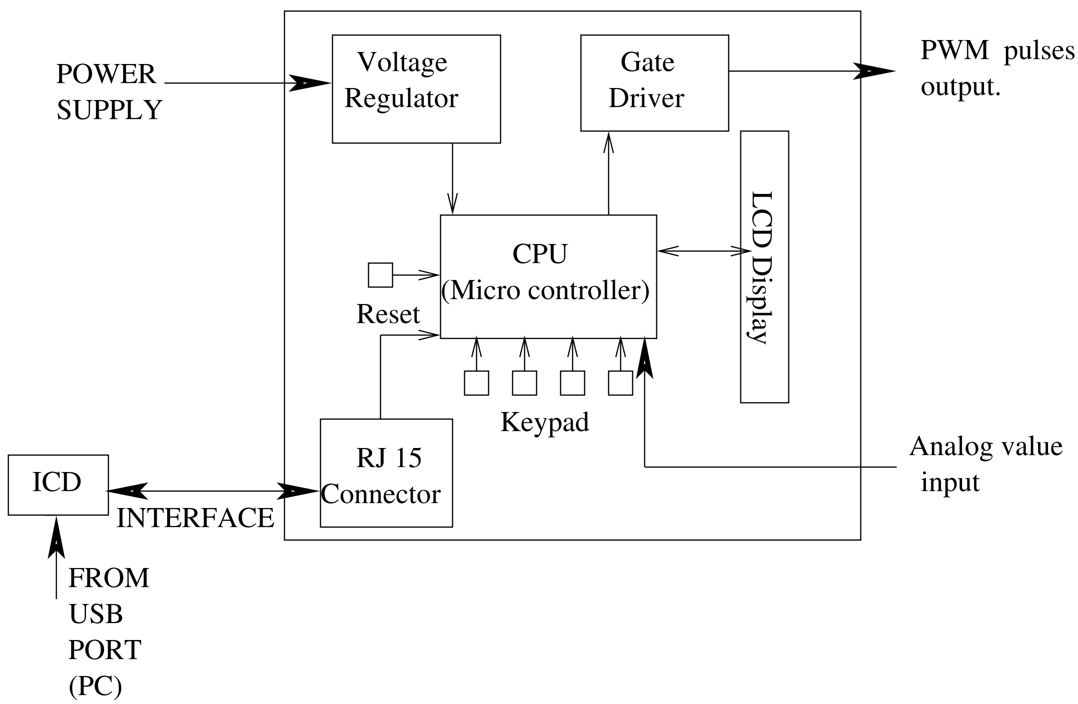


Figure 20.1: Block Diagram

8-bit mode is used. The eight pins of LCD are interfaced to pins of PortF, PortC and PortD. The 3 control pins are connected to PortB.

20.2.3 Keypad

One push button is used to reset the device. It is used to clear the program and data memory and start the program execution from the beginning.

Four other push buttons are connected to RB2, RB3, RB4, RB5 pins of PortB. These buttons can be used to enter the value of frequency and duty ratio into the program. These buttons can also be used to view the input and output voltages in the converter circuit.

20.2.4 Gate Driver

The PWM module of the micro controller is used to generate PWM of the required duty ratio and frequency. These pulses are given to the driver Ic IR2110. Input power supply of the converter is used to give power to the driver Ic. This Ic is capable of taking two inputs and giving two outputs corresponding to each input. One output is isolated with respect to a floating ground while the other is with respect to the common ground.

20.2.5 ICD(In-Circuit Debugger)

The ICD connector (JP1) connects the micro controller to the MPLAB-ICD2 Debugger. The debugger is used for downloading and debugging the program into the Ic. The ICD connector is connected to pins 1, 25, 26 and supply pins (Vdd and Vss) of the micro controller.

20.3 Interfacing Technique

20.3.1 Interfacing the push buttons

When a push button is not pressed there is a logic High at the corresponding pin of the micro controller. When it is pressed it goes to logic Low and upon its release, it again goes to logic High. These transitions High-Low-High are used to interface the push buttons to the controller applications. Figure 20.2 shows the transitions for the switch. When the signal goes from High to Low it is recognised that the switch is pressed. Then the program waits for the switch to be released. The release of the switch is recognised by a transition from Low to High.

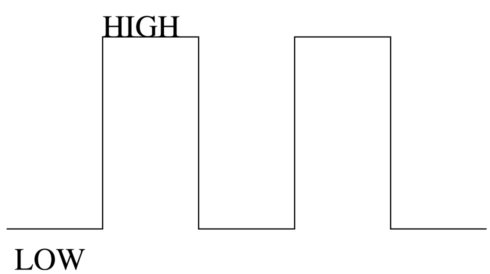


Figure 20.2: Switching States

20.3.2 Interfacing the LCD

Eight data lines and three control lines of the LCD are interfaced with the micro controller. To display a character on the LCD the corresponding ascii value is to be placed on the data lines of the LCD.

The LCD is interfaced in the 8-bit mode. In this mode, data is sent in one single operation itself. The three control signals RS, R/W and E are either logic High or Low depending on the operation being performed. The RS pin stands for register select.

If RS = 0, a command register is selected. The command register is used to perform operations like initialisation of LCD, clearing LCD, moving the cursor from left to right etc. If RS = 1, a data regiter is selected. The data register displays whatever data is written into it, like for example alphabets, numbers or special characters.

The R/W pin, is used for reading from the LCD or writing into the LCD. The signal is High in case of read operation and Low in case of a write operation.

The E pin stands for enable, it is used to enable the display.

20.4 Program and Algorithm

The program is written in assembly level language and is tested with a buck converter. The following algorithms are used during programming.

20.4.1 Algorithm for PWM generation

Figure 20.3 shows the flowchart for programming the micro controller to generate PWM waveform. PWM module can be configured by setting the PWMCON1, PTPER, PDC1, PTMR registers. Here PTPER register determines the switching frequency and PDC1 register determines the duty ratio.

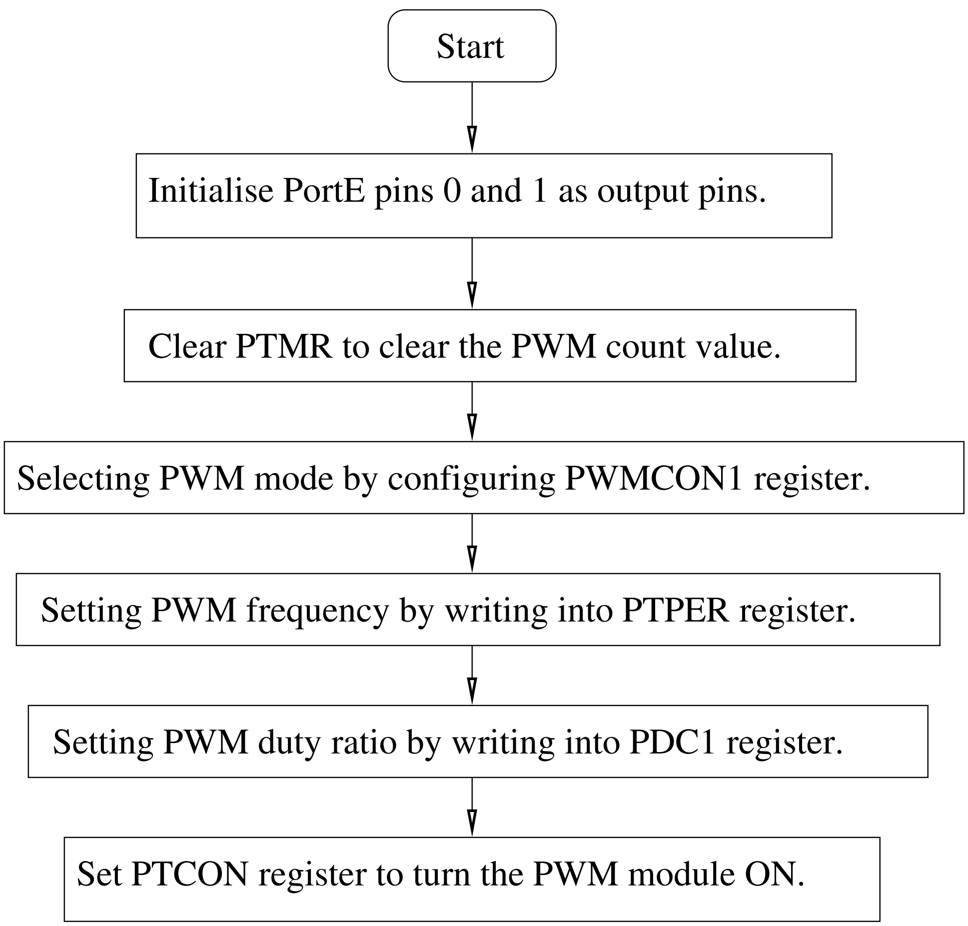


Figure 20.3: Flowchart for PWM Generation

20.4.2 Selection of PWM Frequency

The required frequency of PWM pulses can be generated by writing the value in the PTPER register. For getting a PWM frequency of 20KHz, 1F4 is to be written into the PTPER register. The hexadecimal value for the required frequency can be calculated using the equation given below.

$$PWMPeriod = \frac{F_{CY}}{F_{PWM} * (PTMRPrescaler)} - 1 \qquad (20.1)$$

A clock of 10MHz is used. PTMR Prescale value is 1.

20.4.3 Duty cycle of PWM pulse

By writing the appropriate values into the PDC1 register the required duty ratio of waveforms can be obtained. For a frequency of 20KHz (1F4 - equivalent hex value), 1F4 has to be written for 50% duty ratio. That is, a value equal to the frequency has to be written into PDC1 for 50% duty ratio. It has to be incremented to increase the duty ratio or decremented in order to reduce the duty ratio.

20.4.4 Features of the Controller Circuit

The below figure shows the basic blocks of the control circuit. The micro

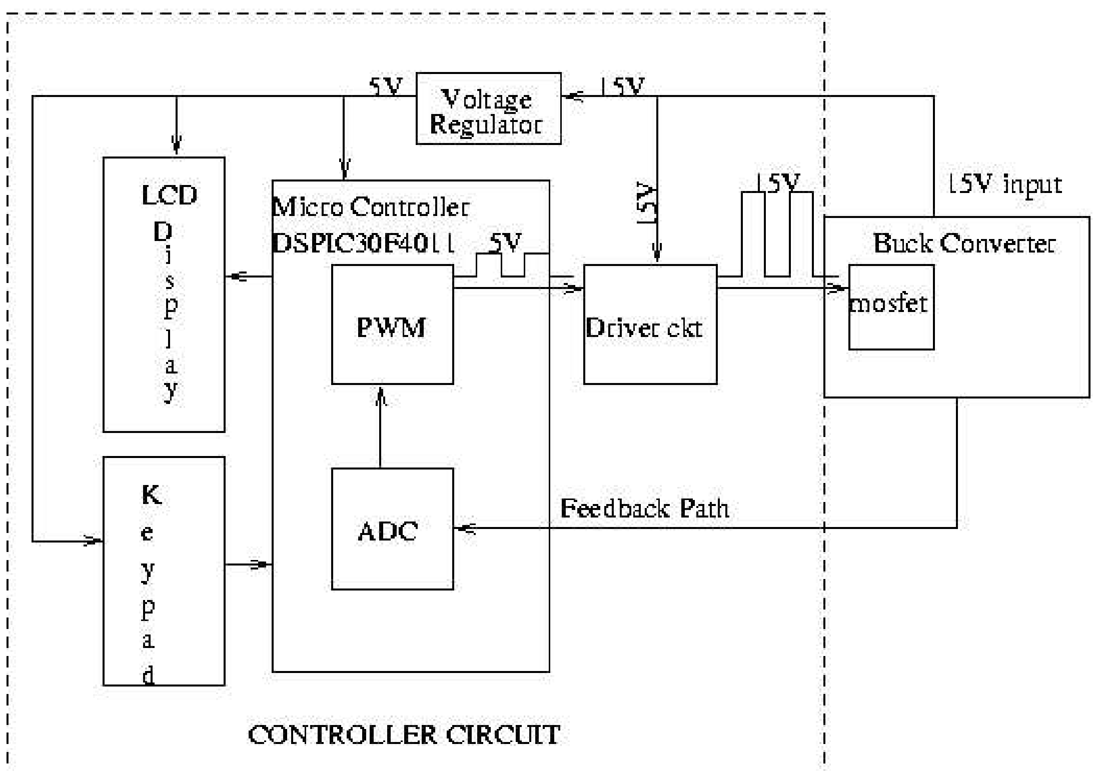


Figure 20.4: Basic Blocks of Control Circuit

controller dspic30f4011 is high performance modified RISC CPU. Some of the important features are,

- Modified Harvard architecture.
- 84 base instructions, 24-bit wide instructions, 16-bit wide data path.
- 48 Kbytes on-chip Flash program space, 2Kb on-chip RAM, 1 Kb EEPROM.
- 16 x 16-bit working register array.
- Upto 30 MIPS operations.

The micro controller has 5, 16-bit timers/counters; PWM module; 10-bit high speed ADC; 3-wire SPI modules; I^2C module; 2 UART modules and 1 CAN module. For our present application we use only ADC and PWM modules.

ADC Module Features

- 10-bit Analog-to-Digital Converter(A/D) with 4 S/H Inputs.
- 500Ksps conversion rate.
- 9 input channels.
- Internal or External reference voltages for conversions.
- Conversions available during Sleep and Idle.

PWM Module Features

- 6 PWM output channels.
- Complementary or Independent Output modes.
- Edge or Center Aligned modes.
- 3 duty cycle generators (one for each pair of output).
- Manual output control.

In our present application we use the pulses generated to trigger only one mosfet hence, of the six PWM outputs only one is selected.

Since the micro controller works on a 5V input the PWM waveforms generated are also of 5V amplitude. This voltage is insufficient to trigger a mosfet hence the PWM signal is given to the driver IC IR2110 which amplifies the output to 15V. This IC can take in two inputs and give two corressponding outputs. One output is isolated and is measured with respect to a floating ground while the other is with respect to a common ground. The isolated output is ideal for circuits like buck converter.

The LCD displays the varying values of frequency, duty cycle, input and output voltages. The LCD has an inbuilt controller which processes the output from the dspic30f4011 IC. Since the display works at a lower speed when compared with the dspic IC we have to incorporate an appropriate delay to make the two devices compatable.

20.5 Mounted PCB

Figure 20.5 shows the hardware model of the Digital Controller for SMPC. The control circuit board is seen in the below image. The micro controller used, dsPIC30F4011 is seen in the middle.The LCD is on the left had side and the push buttons are at the bottom. The reset switch is the first one on the bottom right hand corner.

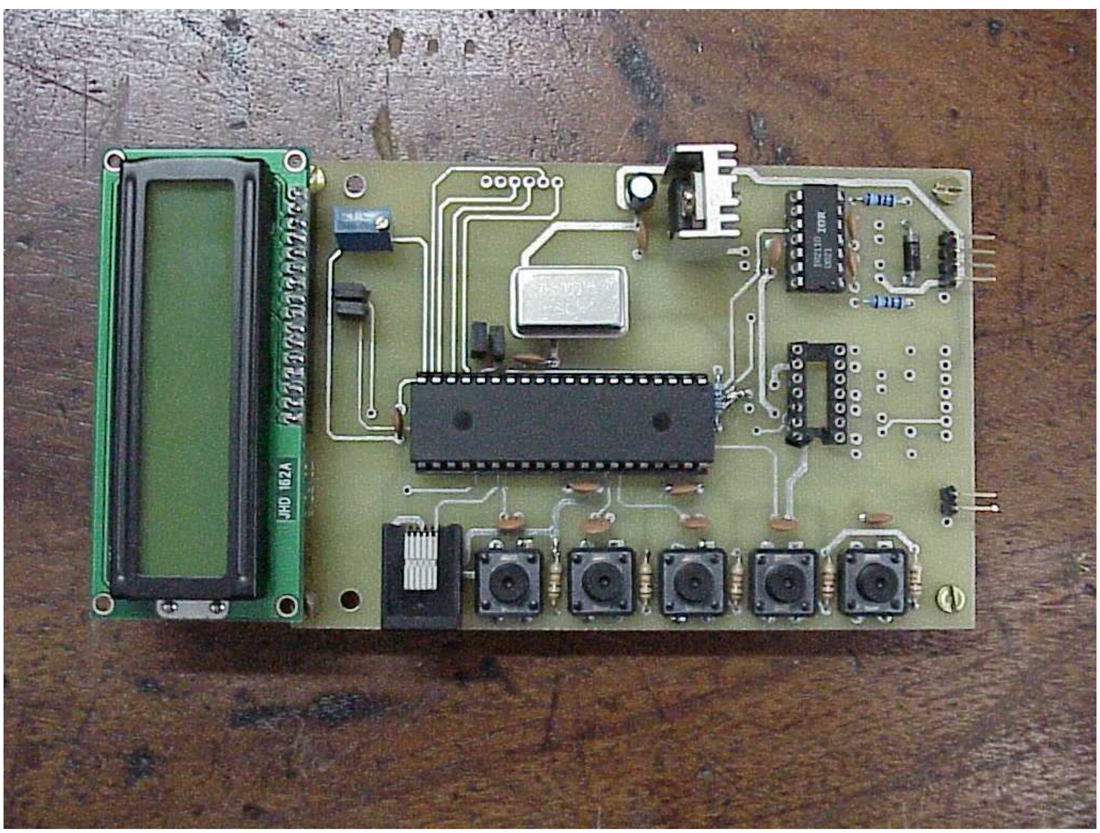


Figure 20.5: Digital Controller

20.6 Practical Waveforms

The below figures show the PWM waveforms of the micro controller and the driver IC.

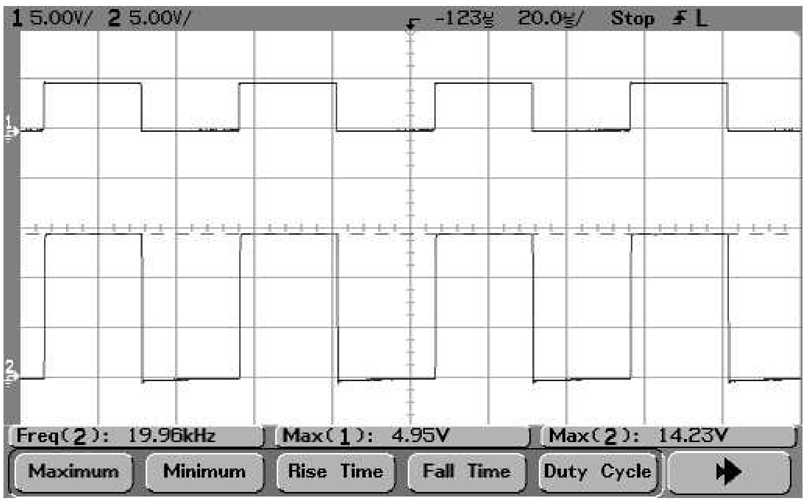


Figure 20.6: Output pulses of micro controller vs.Output of driver IC

20.7 Circuit Layout

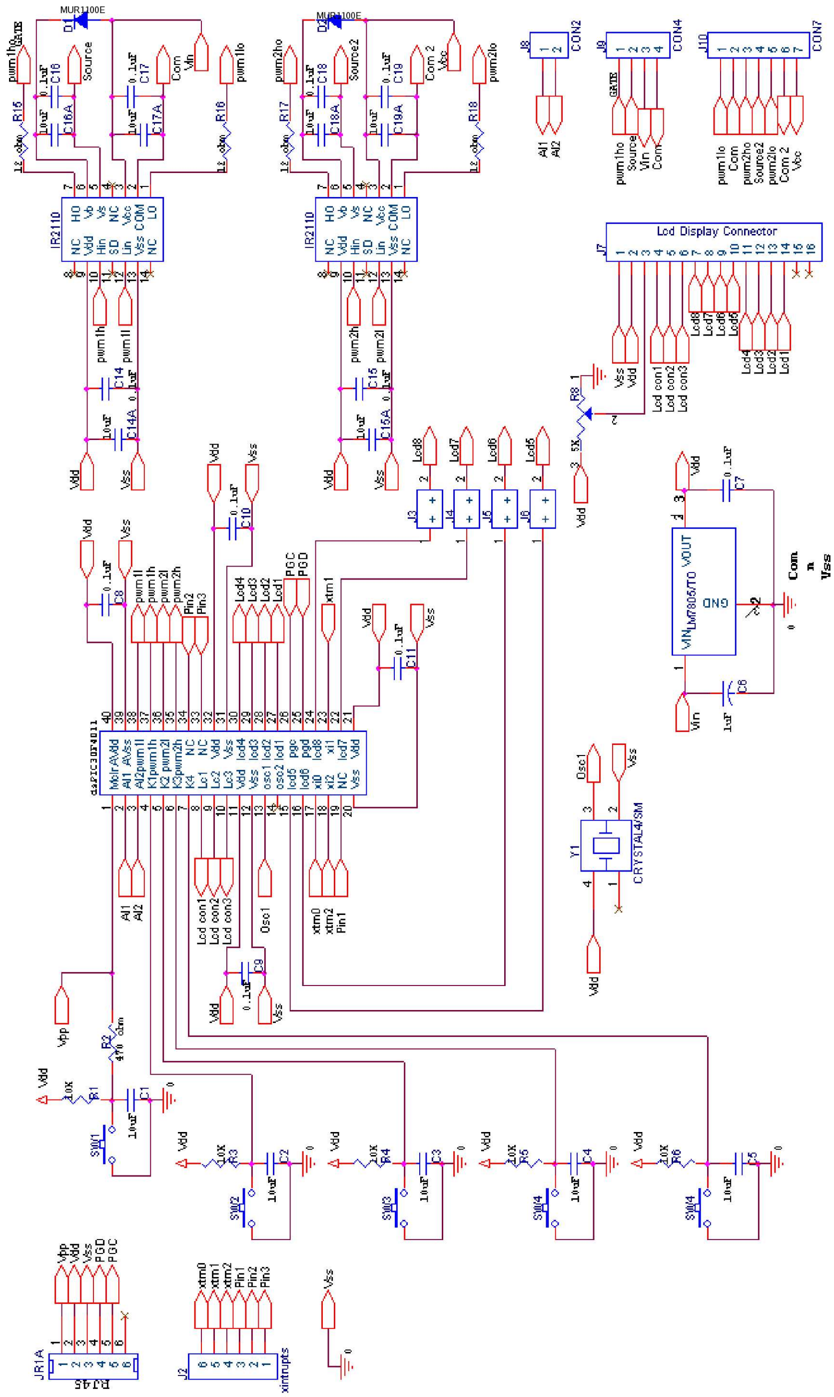


Figure 20.7: Circuit diagram for Control circuit

20.8 Bill of materials

Table 20.1:

Sl.No.	*Item*	*Symbol*	*Specifiation*	*Quantity*	*Rate*	*Cost*
1	Resistor	R1, R3, R4, R5, R6	10kΩ	5	0.35	1.75
2	Resistor	R2	470Ω	1	0.35	0.35
3	Resistor	R15, R16, R17, R18	12Ω	4	0.35	1.40
4	Capacitor	C7 to C11,C14 to C19	0.1μF ,63V	11	0.50	5.50
5	Capacitor	C1, C2, C3, C4, C5	10μF	5	0.50	2.50
6	Capacitor	C6	1μF ,63V	1	2.00	2.00
7	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
8	Micro controller Ic	U23	dsPIC30f4011	1	80	80
9	Voltage Regulator	U24	LM7805	1	8	8
10	Terminal Connector	J2, J7, J8, J9, J10		2	3.00	6.00
11	HD44780 LCD			1	100	100
12	Connector	JR1A	RJ11	1	8.50	8.50
13	Push Button	SW1, SW2, SW3, SW4, SW5		5	3.0	15.0
14	Potentiometer	R8	5kΩ	1	5.0	5.0
15	Driver Ic	U25, U26	IR2110	2	55	110
16	40 pin Ic base			1	10	10
17	14 pin Ic base			3	4	12
18	PCB			2	25.00	50.00
19	TOTAL					423

Chapter 21

Digital Control of Open Loop Buck Converter

21.1 Circuit Specification

This section covers a simple Digital Control of Buck Converter Open Loop with the following specifications.

- Input: 15V
- Controller: dsPIC30F4011
- Duty Cycle: 0.2 to 0.8
- Switching Frequency: 15 to 30KHz
- Output: 5V
- Protection: None

21.2 Buck Converter

The Buck converter is also called a step down converter as it produces a lower output voltage than the dc input voltage. The average output voltage can be calculated in terms of the switch duty ratio and is found to be:

$$V_o = \frac{1}{T_s}\int_0^{T_S} V_o \; dt = \frac{1}{T_s}\int_0^{T_{on}} V_g \; dt + \frac{1}{T_s}\int_{T_{on}}^{T_s} 0 \; dt = \; V_g\frac{T_{on}}{T_s} = V_g d \qquad (21.1)$$

Figure 21.1 shows a 7.5 W Buck Converter with a resistive load and a low pass filter.All the components used are assumed to be ideal.

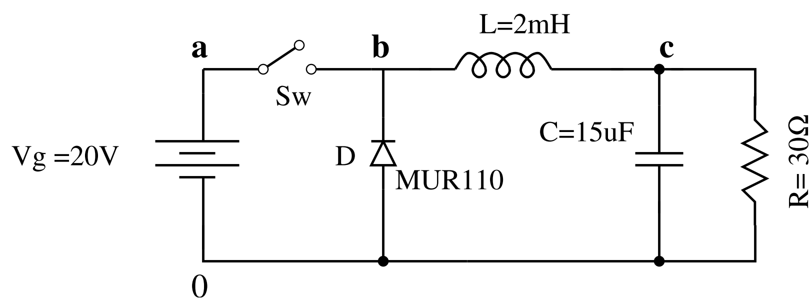


Figure 21.1: Buck Converter

21.3 Power Circuit Design

21.3.1 Design of inductor

In each sub-period [dT_s and $(1-d)T_s$], the rate of change of current is constant. The current ripple (δi) can be determined using the equation 21.3.

$$\delta I_o = \frac{V_g d(1-d)T_s}{L} = \frac{V_o(1-d)T_s}{L} \tag{21.2}$$

$$\frac{\delta I_o}{I_o} = \delta i = \frac{(1-d)RT_s}{L} \tag{21.3}$$

The value of the inductance L is designed such that δi is 10% of the output current I_o. The value of L is 1.5 mH. As per the design calculation the following parameters are found out.
Core E 30/15/7.
Number of turns = 66.
lg = 0.305mm.
SWG = 26.

21.3.2 Design of Capacitance

The charging and discharging current of the capacitor decides the voltage ripple (δv). We consider that the ac part of the inductor current flows into the capacitor.

$$\delta V_o = \frac{\delta Q}{C} = \frac{1}{C}\frac{1}{2}\frac{\delta I_o}{2}\frac{T_s}{2} \tag{21.4}$$

$$\delta V_o = \frac{V_o(1-d)T_s^2}{8LC} \tag{21.5}$$

$$\frac{\delta V_o}{V_o} = \delta v = \frac{(1-d)T_s^2}{8LC} \tag{21.6}$$

The capacitor C is designed for δv to be 1% of the output voltage V_o. The design value of C is 15 μF/30V.

21.3.3 Selection of active and passive switches

Based on the voltage and current ratings IRFZ44N (50V/10A) and MUR 110(100V/1A) are used as active and passive switches respectively.

21.4 Hardware Design For Control Circuit

Design of the control circuit is the same as the digital controller design for SMPC.

The various functions of the program are: initialising the PWM and ADC modules; to display the value of duty cycle, frequency, input and output voltage on the LCD; to perform the operations of a proportional integral controller.

The mode switch is to select between the four modes of display (frequency, duty ratio, input voltage and output voltage). The '+' or '−' switch is to vary either duty ratio or frequency to the required value. Once the required value has been displayed the value is taken into the program by pressing the enter key. Hence the frequency and duty ratio can be entered in by the user using the push buttons.

In open loop operation, the '+' , '−' switches are used to vary both the duty ratio and frequency. But in closed loop operation, the program automatically varies the duty ratio such that the output voltage remains a constant. Hence in closed loop operation, only the frequency can be incremented or decremented, changes made to the duty ratio using the '+', '−' switches will not affect the program. There are also a minimum and maximum value for both duty ratio and frequency.

When the reset button is pressed, the circuit starts with a default value of 20KHz and 50% duty ratio in open loop.

21.4.1 Block Diagram of Open Loop system

The basics blocks of the open loop system are as shown in figure below.

In open loop the control circuit is used to provide the gate pulses for switching the mosfet and to display the frequency and duty ratio of the gate pulses in the LCD. In open loop the LCD is used to display only the frequency and duty ratio. The select mode switch is used to select between the duty ratio and frequency. The increment and decrement buttons are used to increment or decrement the values of the duty ratio or frequency. The enter button is then used to update the software with the altered(incremented or decremented) value of the frequency or duty ratio. The reset buttons are used to clear the registers and restart the program execution.

From the basic equation 21.1 of the buck converter we can see that the output voltage V_o is directly dependent on the input voltage and duty ratio of the gate pulses. Therefore change in the duty ratio changes the output voltage

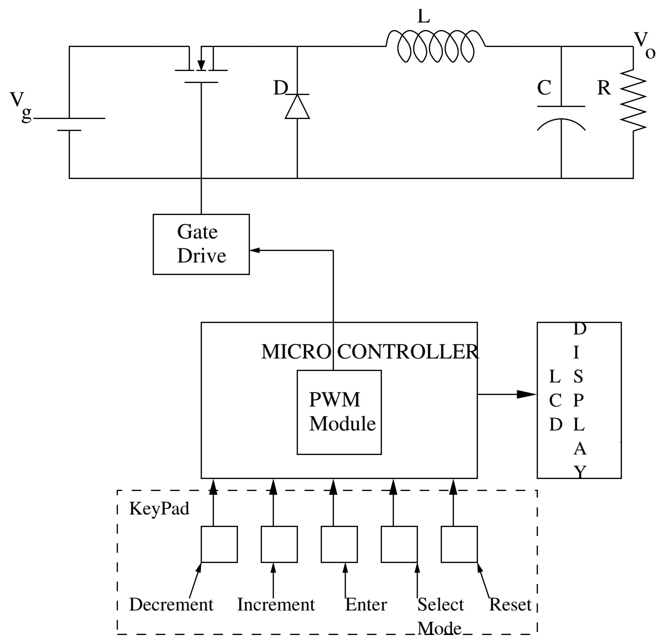


Figure 21.2: Open Loop System

correspondingly. The practical waveforms included with this chapter show the changes in the output dc voltage for changes in the duty ratio.

21.5 Mounted PCB Board

Figure 21.3 shows the hardware model used for digital control of SMPC. The controller board with the micro controller is seen on the left hand side, while on the right the 7.5W Buck Converter with a wire wound resistor is seen.

21.6 Practical Waveforms

The below figures show the open loop waveforms. Figures 21.4, 21.5 and 21.6 show the change in output of the buck converter with respect to change in duty ratio of the gate pulses.

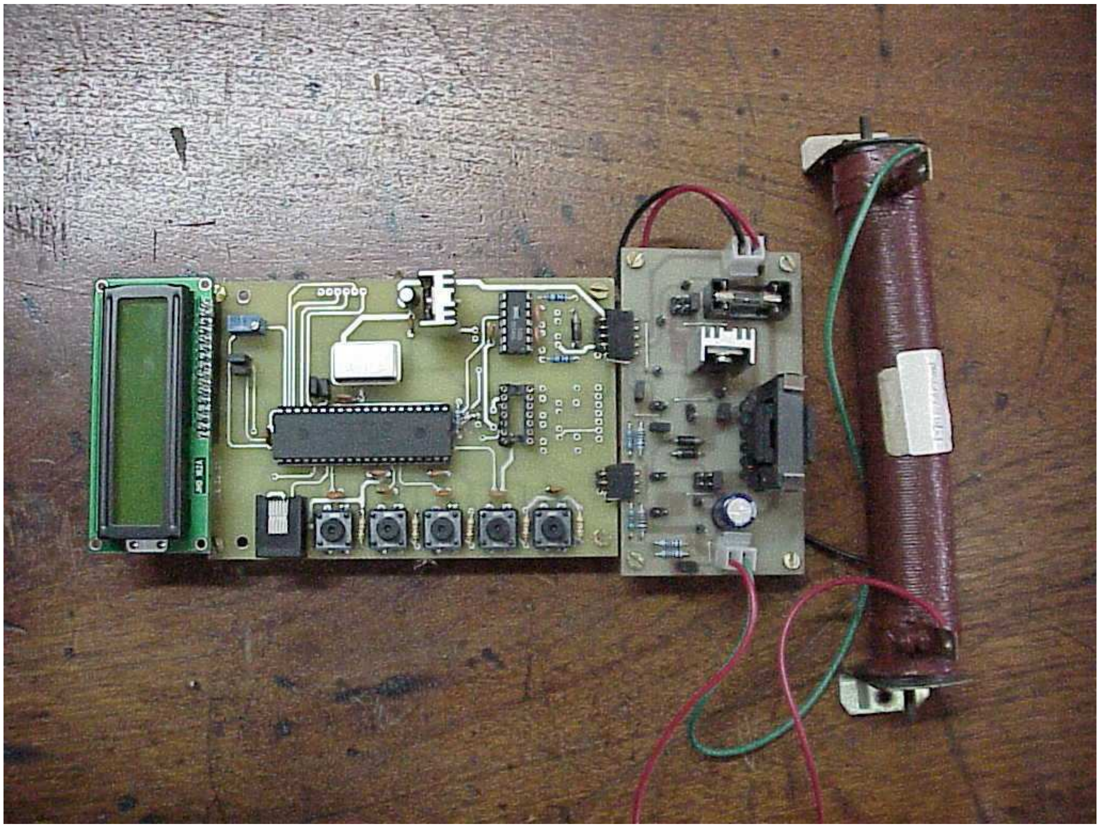


Figure 21.3: Digital Controller for SMPC

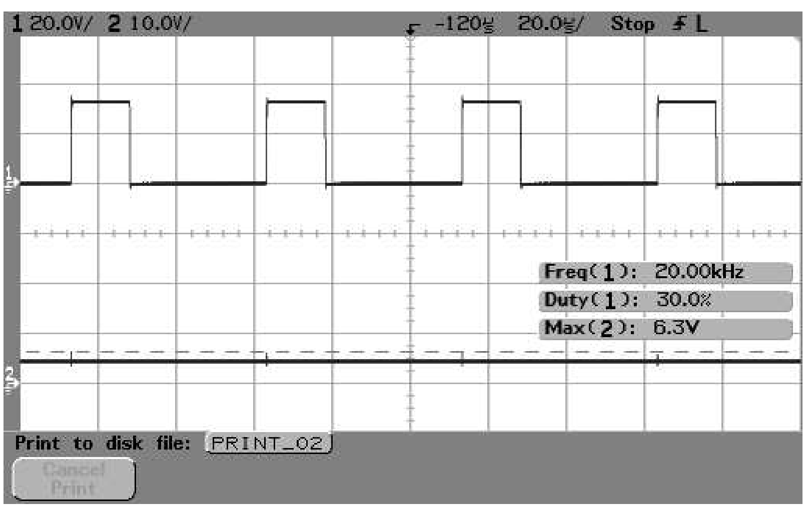


Figure 21.4: Varying duty ratio of input pulses vs. output

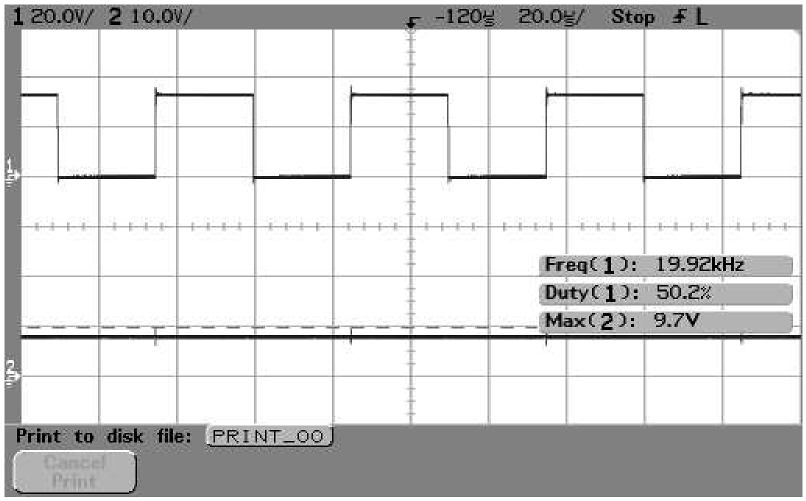


Figure 21.5: Varying duty ratio of input pulses vs. output

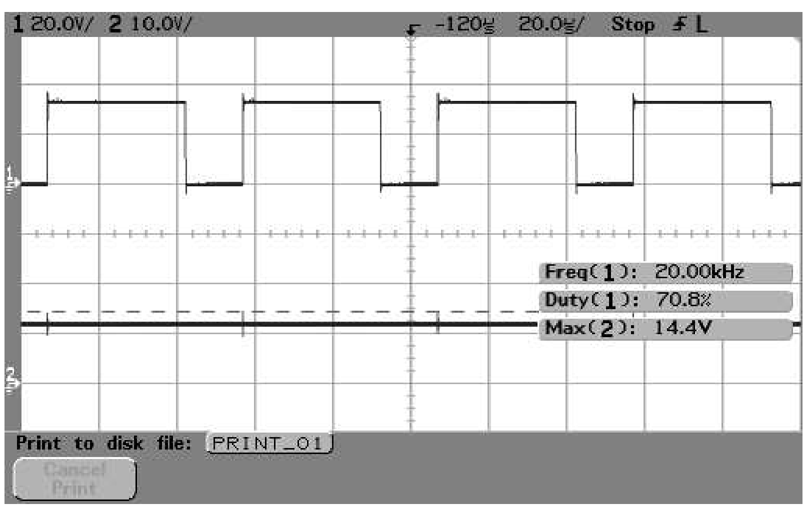


Figure 21.6: Varying duty ratio of input pulses vs. output

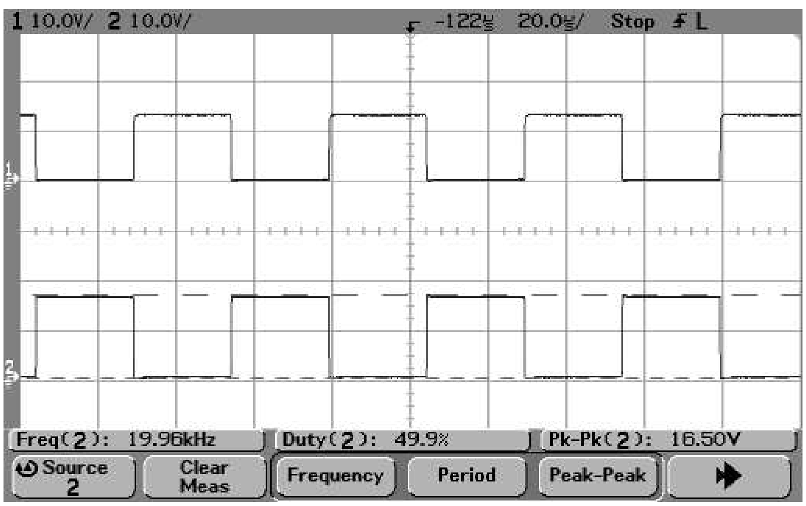


Figure 21.7: Gate to Source and Drain to Source Voltage

21.7 Circuit Layout

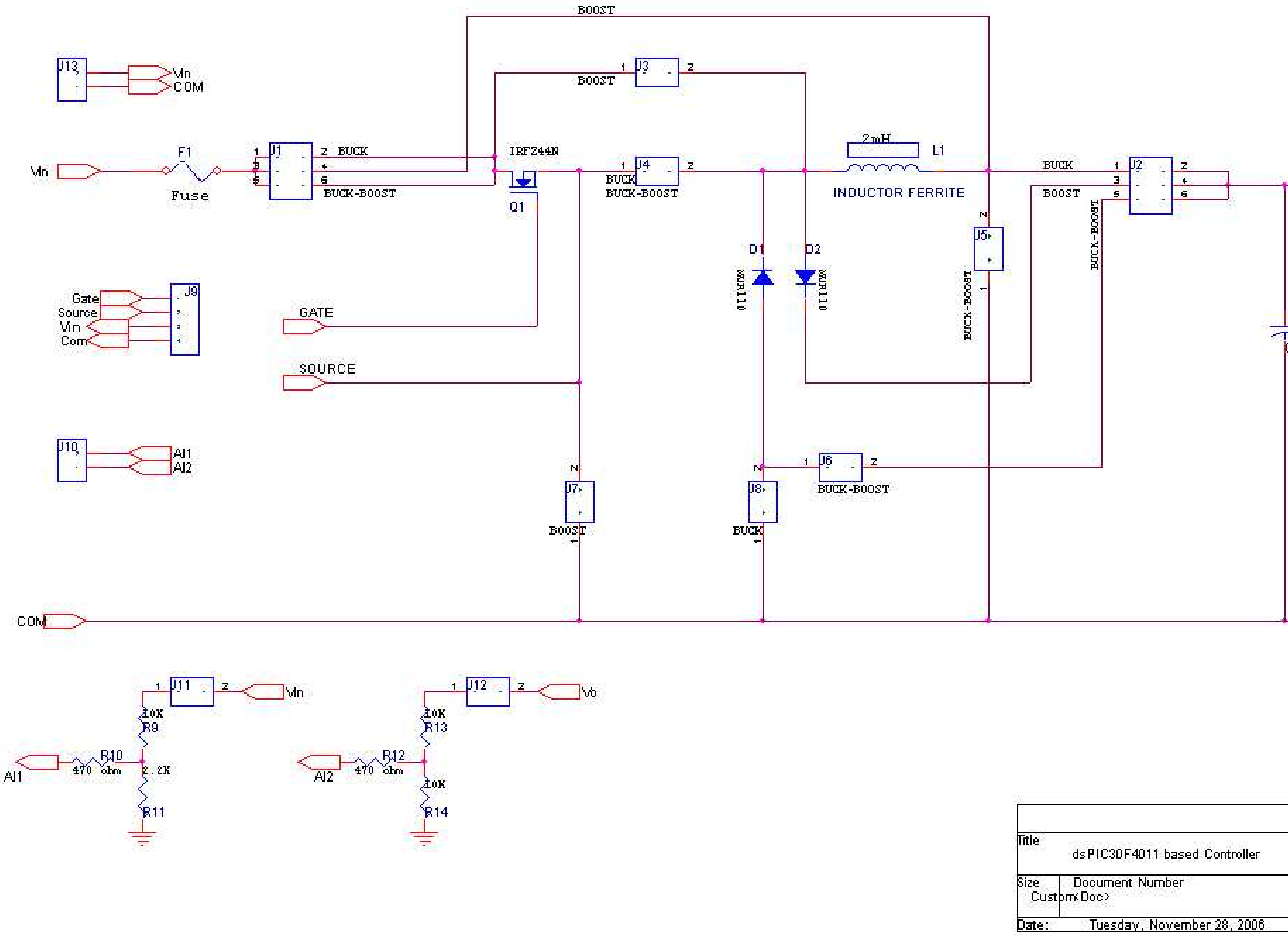


Figure 21.8: Circuit Diagram for power circuit

21.8 Bill of Materials

Table 21.1:

Sl.No.	*Item*	*Symbol*	*Specifiation*	*Quantity*	*Rate*	*Cost*
1	Resistor	R1, R3, R4, R5, R6	10kΩ	5	0.35	1.75
2	Resistor	R2	470Ω	1	0.35	0.35
3	Resistor	R15, R16, R17, R18	12Ω	4	0.35	1.40
4	Capacitor	C7 to C11,C14 to C19	0.1μF ,63V	11	0.50	5.50
5	Capacitor	C1, C2, C3, C4, C5	10μF	5	0.50	2.50
6	Capacitor	C6	1μF ,63V	1	2.00	2.00
7	Crystal Oscillator	Y1	10MHz	1	5.00	5.00
8	Micro controller Ic	U23	dsPIC30f4011	1	80.00	80.00
9	Voltage Regulator	U24	LM7805	1	8.00	8.00
10	Terminal Connector	J2, J7, J8, J9, J10		2	3.00	6.00
11	HD44780 LCD			1	100	100.00
12	Connector	JR1A	RJ11	1	8.50	8.50
13	Push Button	SW1, SW2, SW3, SW4, SW5		5	3.00	15.00
14	Potentiometer	R8	5kΩ	1	5.0	5.00
15	Driver Ic	U25, U26	IR2110	2	55	110.00
16	40 pin Ic base			1	10	10.00
17	14 pin Ic base			3	4	12.00
18	Inductor	L1	E 30/15/7	1	15.00	15.00
19	MOSFET	M1	IRFZ44N	1	16.00	16.00
20	Diode	D1, D2	MUR110	3	8.00	24.00
21	Test Points	T1-T13	Bergstick	13	0.10	1.30
22	Heat Sink	HS1		2	5.00	10.00
23	PCB			2	25.00	50.00
24	TOTAL					483.30

Chapter 22

Digital Control of Closed Loop Buck Converter

22.1 Block Diagram

The block diagram of the closed loop system is as shown below.

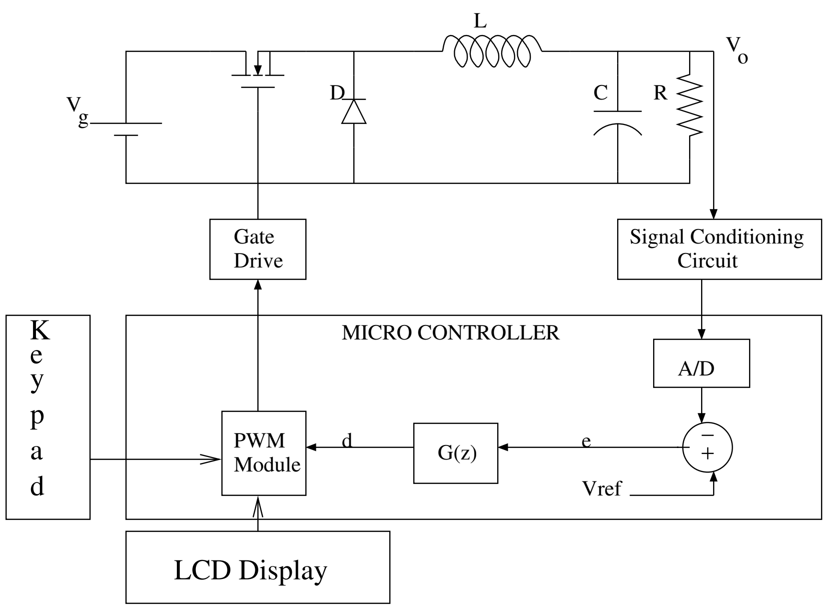


Figure 22.1: Closed Loop System

Along with the functions of displaying data on the LCD and providing gate pulses. The micro controller here also performs the operation of closed loop control.

The output from the buck converter is given to a signal conditioning circuit which makes the output voltage compatible for the micro controller. That is, the output voltage is brought within the micro controller working range (less than 5V).

This voltage is given to the ADC module which converts the analog voltage value into its digital equivalent.

The digital value is then compared with the required output voltage (taken as 5V here). The difference is taken as the error in the output voltage and is fed to the controller equation (design shown below) which then adjusts the duty ratio of gate pulses such that the output voltage is maintained at a constant value of 5V.

22.2 Design of feedback for converter

22.2.1 Basic review

The control specifications of a converter are generally given as,

- Steady state accuracy
- Settling time and allowed transient overshoot

The steady state error is related to the loop gain G(s)H(s) at dc. The steady state error is approximately equal to 1/G(0)H(0). The settling time and transient overshoot are related to gain crossover frequency and phase margin. If w_c is the gain crossover frequency then for a stable system the settling time will be about $3/w_c$ to $4/w_c$ seconds. The more is the phase margin, the lesser is the transient overshoot. For acceptable transient overshoot phase margin ϕ_m can be as low as 45°.

22.2.2 Design of controller

The controller structure is as shown in Figure 22.2. As can be seen from the figure, the control blocks $H_1(s)$ and $H_2(s)$ are cascaded stages of the controller. The controller design is considered in two stages. The first stage $H_1(s)$ of the controller achieves the desired bandwidth w_c and phase margin ϕ_m. The second stage is designed to meet the desired steady state error.

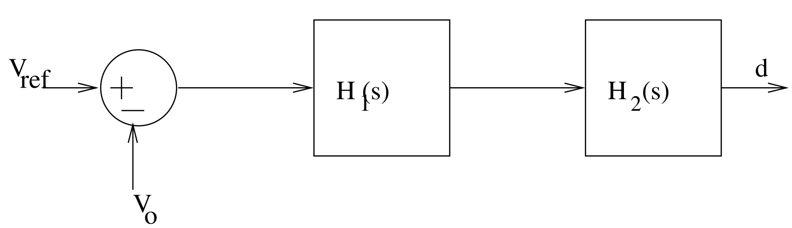


Figure 22.2: Controller Structure

If the loop gain crosses 0dB (unity gain) with a single slope (-20 dB/decade), then the closed loop system will be stable. The reason being, phase margin of a function crossing 0dB with a single slope at a frequency of w_c is equal to -90° which is approximately same as the function K/w_c. This is valid only when the loop gain is a minimum phase function. The actual phase angle will depend on the poles and zeroes nearest to the crossover frequency. Taking this into consideration, $H_1(s)$ chosen as a lead-lag controller.

$$H_1(s) = K1\frac{1+\dfrac{s}{w_{z1}}}{1+\dfrac{s}{w_{p1}}} \tag{22.1}$$

The condtions for determining $H_1(s)$ are,

- If G(s) is a second order system in the vicinity of w_c, then select w_{z1} and w_{p1} such that $w_{z1} < w_c < w_{p1}$.
- If G(s) is a second order system with a complex pole pair w_o then w_{z1} may be taken as w_o and w_{p1} is usually ten times w_{z1}.
- Now K1 may be selected to meet the requirements of w_c and ϕ_m.

The conditions for determining $H_2(s)$ are,

- G(0)$H_1(0)H_2(0)$ = T(0).
- Phase and magnitude gain of $H_2(s)$ must not affect the gain and phase margin already designed.
- Phase and magnitude gain of $H_2(s)$ in the vicinity of $w_c$must be 0.

Taking this into consideration, $H_2(s)$ is selected to be a PI controller.

$$H_2(s) = \frac{1+\dfrac{s}{w_{z2}}}{\dfrac{s}{w_{z2}}} \tag{22.2}$$

The overall controller is,

$$H(s) = K1 * \frac{1+\dfrac{s}{w_{z1}}}{1+\dfrac{s}{w_{p1}}} * \frac{1+\dfrac{s}{w_{z2}}}{\dfrac{s}{w_{z2}}} \tag{22.3}$$

22.2.3 Controller for buck converter

The open loop transfer function of converter is,

$$G(s) = \frac{V_o(s)}{d(s)} = V_{in}\frac{1}{1+s\dfrac{L}{R}+s^2LC} \tag{22.4}$$

We can use different well-known techniques such as bilinear transformation, pole-zero match etc. to discretize the plant transfer function. By writing a MATLAB script as shown below.

```
L=1.5e-3;
C=15e-6;
R=3.33;
ts=50e-6;
num=[15];
den=[L*C L/R 1];
sys=tf(num, den)
sys2=c2d(sys, ts, 'matched')
[Gm, Pm, Wcg, Wcp]=Margin(sys)
bode(num, den)
```

The output of the above program is,

```
Transfer function:
              15
-------------------------------
2.25e-008 s^2 + 0.0004505 s + 1


Transfer function:
  0.5218 z + 0.5218
----------------------
z^2 - 1.298 z + 0.3675

Sampling time: 5e-005

Gm =

   Inf


Pm =

   43.6227


Wcg =

   Inf


Wcp =

  2.2944e+004
```

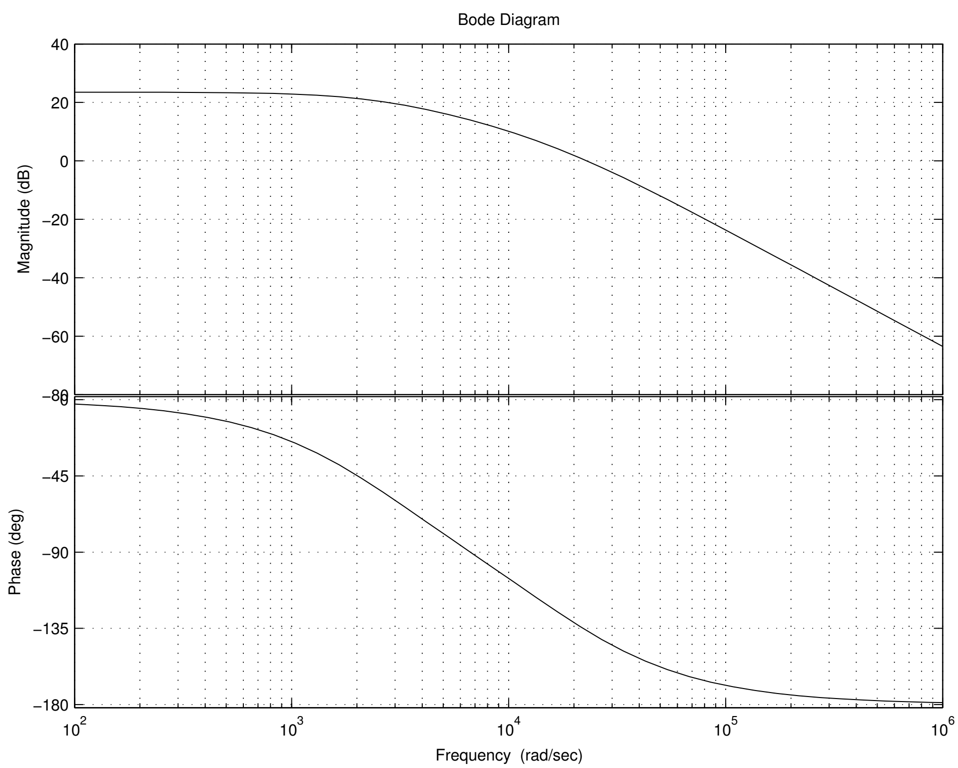


Figure 22.3: Magnitude and Phase plot of open loop transfer function

The open loop transfer function of converter is plotted in Figure 22.3. From plot it can be noticed that the 0dB crossover frequency is about 22.9 x 10^3rad/sec and phase margin with unity feedback is about 43.6°.With a dc gain of 23 (ie $20log_{10}V_{in}$)we get a steady state error of approximately 4%.Therefore, to meet specifications a controller has to be designed. Since, the phase margin and bandwidth requirements are under acceptable limits, there is no need for $H_1(s)$ as the lead-lag controller would only control the phase margin and bandwidth.

Now, to meet steady state specification, let us choose a PI controller of the form,

$$H_2(s) = \frac{1 + \frac{s}{w_{z2}}}{\frac{s}{w_{z2}}} \tag{22.5}$$

where, we choose w_{z2}=1061 rad/sec which is much less than w_c.

The discretised transfer function can be written as,

```
ts=50e-6;
num=[1 1061];
den=[1 0];
sys= tf(num, den)
sys2=c2d(sys,ts,'matched')

Transfer function:
s + 1061
--------
   s


Transfer function:
1.026 z - 0.9733
----------------
     z - 1

Sampling time: 5e-005
```

Using difference equation, this equation can be written as,

$$d(n) = d(n-1) + 1.026e(n) - 0.9733e(n-1) \tag{22.6}$$

where d is the controller output that is the duty ratio of the MOSFET and e is the error voltage.In the equation the quantities with (n) denote the current sampled values wheres quantities with (n-1) denote old sampled values.

The closed loop transfer function can now be written as, $Gc(s) = G(s)H_2(s)$.

$$Gc(s) = V_{in}\frac{1}{1 + s\frac{L}{R} + s^2LC} * \frac{1 + \frac{s}{w_{z2}}}{\frac{s}{w_{z2}}} \tag{22.7}$$

By writing the above equation in the MATLAB script as shown below, we get the discretised transfer function.

```
L=1.5e-3;
C=15e-6;
R=3.33;
ts=50e-6;
num=[15 15915];
den=[L*C L/R 1 0];
sys=tf(num, den)
sys2=c2d(sys, ts, 'matched')
[Gm, Pm, Wcg, Wcp]=Margin(sys)
bode(num, den)
```

The output of the above program is,

```
Transfer function:
          15 s + 15915
---------------------------------
2.25e-008 s^3 + 0.0004505 s^2 + s


Transfer function:
 0.5674 z^2 + 0.02931 z - 0.5381
----------------------------------
z^3 - 2.298 z^2 + 1.665 z - 0.3675

Sampling time: 5e-005

Gm =

   Inf


Pm =

   40.9547


Wcg =

   Inf


Wcp =

  2.2958e+004
```

The bode plot of the above transfer function is as shown in Figure 22.4

Now, implementing the controller equation (22.6) using the micro controller instruction set would complete our aim of implementing digitally controlled dc-dc converter.

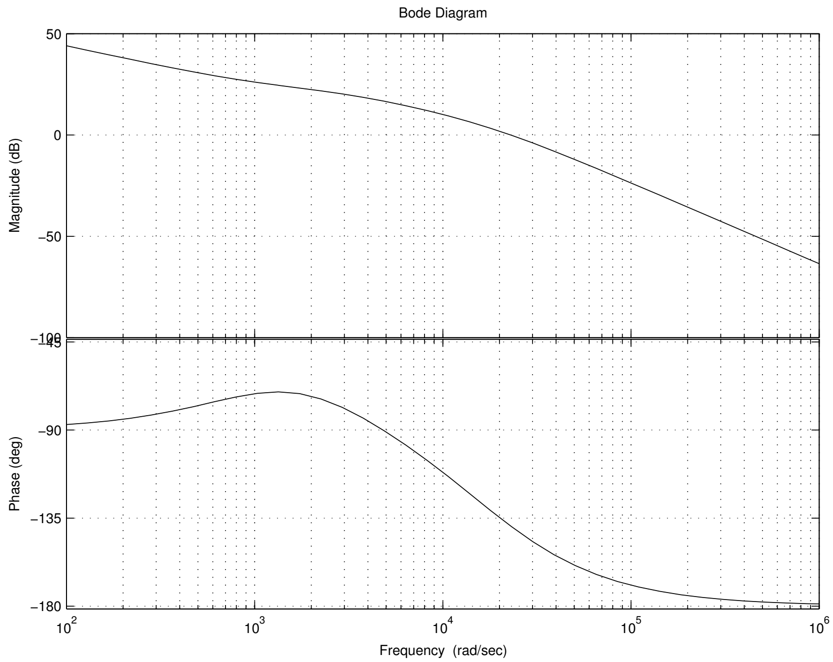


Figure 22.4: Magnitude and Phase plot of closed loop transfer function

As can be seen from the plot the phase margin is around 41° and the gain cross over frequency is about 22.9 x 10^3 rad/sec which are sufficient for a stable closed loop control system. Also the total sampling, hold and computational delay associated with A/D converter and PWM module is in the order of a few micro seconds (approximately 30μs) which is negiligible when compared with the switching frequency (20KHz or 50μs)

22.3 Software Development/Requirement

The assembly level program for the digital converter is given in Appendix B. Here the assembly program is compiled by the compiler and then embedded into the chip using the MPLAB ICD2 Debugger.Figure 22.5 shows the flowchart for the closed loop program.

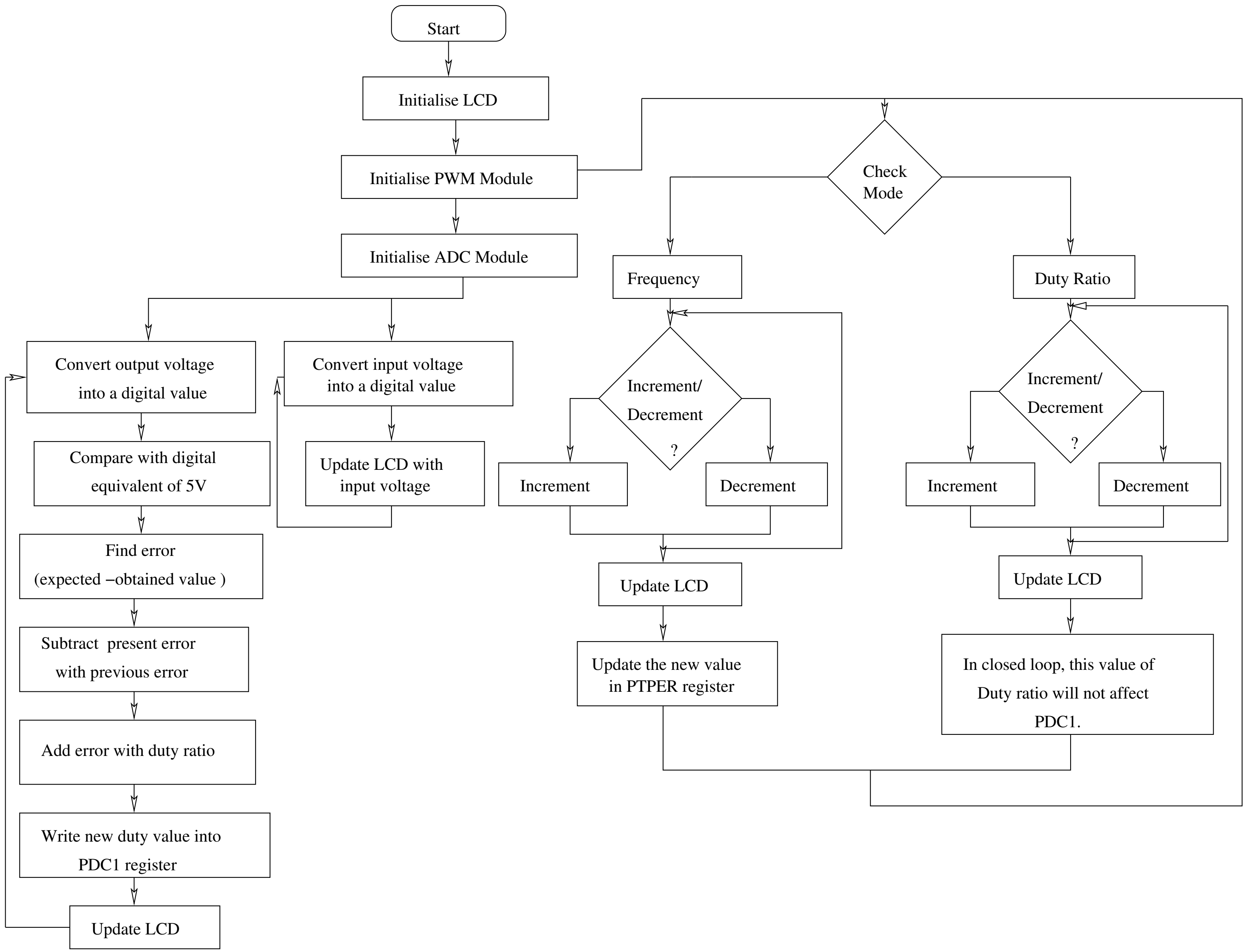


Figure 22.5: Flowchart for closed loop

22.4 Practical Results

22.4.1 Practical Waveforms

The below figures show the practical waveforms of the converter in closed loop.

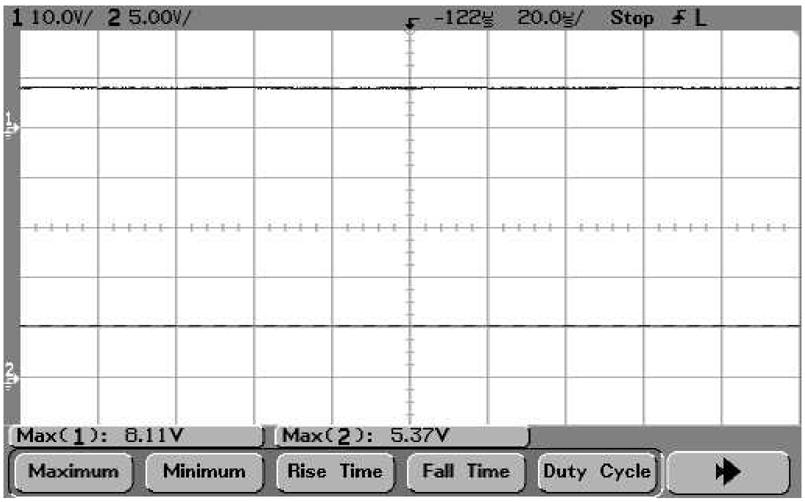


Figure 22.6: Input and Output Voltage at 8V i/p

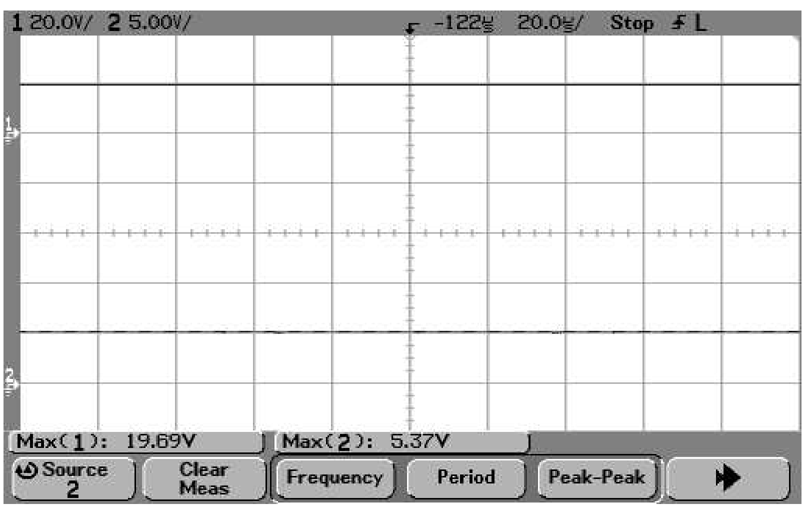


Figure 22.7: Input and Output Voltage at 20V i/p

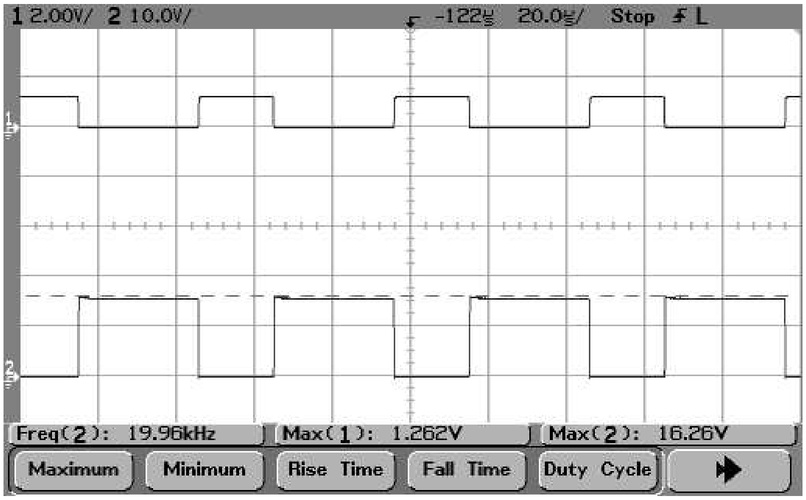


Figure 22.8: Gate to Source and Drain to Source Voltage

22.4.2 Tabular Coloumn

Table 22.1: Load and Line regulation

Sl.No.	*Input Voltage (in V)*	*Duty Ratio (in %)*	*Frequency(in KHz)* (range 15-30KHz)	*Output Voltage (in V)*	*Load (in Ω)*
1	10	47.5	20	5.0	50
2	15	32.9	20	5.0	50
3	20	24	20	5.0	50
4	10	49.5	20	5.0	10
5	15	33.9	20	5.0	10
6	20	25	20	5.0	10
7	10	55.7	20	5.0	5
8	15	39.1	20	5.0	5
9	20	29.7	20	5.0	5

Appendix A

Assembly Program For Openloop

```
------------------------------------------------------------------------------------------------
;;main program
#include <P18F2331.inc>
EXTERN lcd,pwm_module,adc_intialize,int_initialize,dis_freq,dis_duty,freq_ctrl,dis_input,dis_outpu
EXTERN dutyctrl,output,input
#define  timer1Hi 0xFC ;Timer1 timeout defined by timer1Lo & timer1Hi
#define  timer1Lo 0x18 ;this timout is based on Fosc/4

org 0x0000
goto Start

org 0x000008;;;higher priority vector address
goto High_ISR

High_ISR:
btfsc PIR1,TMR1IF
goto TMR1_ISR
retfie

Variables UDATA
sel res 1
temp1 res 1
temp2 res 1
temp3 res 1
temp4 res 1
GLOBAL temp1
GLOBAL temp2
GLOBAL temp3
GLOBAL temp4
GLOBAL sel
GLOBAL mode
GLOBAL enter
```

```
Code
Start:
movlw 0x00
movwf ANSEL0;configuring portA as a digital I/O mode
movlw 0x00
movwf INTCON;disable all interrupts
movlw 0x41;
  movwf ADCON0;
movlw 0x00;
  movwf ADCON1;
call lcd
call int_initialize
call pwm_module
call adc_intialize
;push button operation
step1
btfss PORTB,4;check and skip if portB is set
bra mode;jump to mode selection
btfss PORTC,0;check and skip if portC is set
bra enter
goto step1
GLOBAL step1
mode
btfsc PORTB,4;check and skip if portB is clear
bra mode
mode1
btfss PORTB,4;check and skip if portB is set
bra mode1
;btfss sel,0
movlw 0x00
cpfseq sel
bra c1
bra dis_freq
goto step1
c1 movlw 0x01
cpfseq sel
bra c2
bra dis_duty
goto step1
c2 movlw 0x02
cpfseq sel
bra c3
bra dis_input
goto step1
c3 movlw 0x03
cpfseq sel
goto step1
bra dis_output
clrf sel
goto step1
```

```
enter
btfsc PORTC,0
bra enter
enter1
btfss PORTC,0
bra enter1
movlw 0x01
cpfseq sel
bra d1
bra freq_ctrl;jump to frequency control.

d1 movlw 0x02
cpfseq sel
bra d2
goto dutyctrl;jump to duty ratio control
d2 movlw 0x03
cpfseq sel
bra d3
bra input
d3 movlw 0x00
cpfseq sel
goto step1
bra output

goto step1


TMR1_ISR:


movlw b'00000010'
movwf ANSEL0;configuring analouge inputs
movlw b'11001111'
movwf ADCHS
movlw b'00000101'
movwf ADCON0
bcf PIR1,TMR1IF ;Clear the Timer1 interrupt flag .
movlw timer1Hi ;reload T1 registers with constant time count (user defined)
    movwf TMR1H
movlw timer1Lo
movwf TMR1L


bsf ADCON0,GO;setting adc module
wait
btfsc ADCON0,GO;checking operation is done
goto wait
  movff ADRESH,temp1;storing the higher result
movff ADRESL,temp2;storing the lower result
```

```
movlw b'00000001'
movwf ANSEL0;configuring analouge inputs
movlw b'11111100'
movwf ADCHS
movlw b'00000001'
movwf ADCON0
bcf PIR1,TMR1IF ;Clear the Timer1 interrupt flag .
movlw timer1Hi ;reload T1 registers with constant time count (user defined)
    movwf TMR1H
movlw timer1Lo
movwf TMR1L
bsf ADCON0,GO;setting adc module
wait1
btfsc ADCON0,GO;checking operation is done
goto wait1
  movff ADRESH,temp3;storing the higher result
movff ADRESL,temp4;storing the lower result

retfie

end
------------------------------------------------------------------------------------------


------------------------------------------------------------------------------------------
include P18F2331.inc
;division program
;refer division Algorithm
EXTERN T1,T2
Variables UDATA
num res 1
den res 1
den1 res 1
den2 res 1
n1 res 1
n2 res 1
x1 res 1
x2 res 1
qreg res 1
qreg1 res 1
num1 res 1
num2 res 1
flag res     1
GLOBAL qreg
GLOBAL den
GLOBAL n1
GLOBAL n2
Code
division
movlw 0x00
movwf qreg;qutionent register
movlw 0x32
```

```
mulwf den;denominator register
movff PRODH,x2
movff PRODL,x1
here1
call compare1
movlw 0x00
cpfseq flag
bra mov1
movlw 0x32
addwf qreg
movf x1, W
subwf n1;LSB numerator
movf x2,W
subwfb n2;MSB numerator
goto here1
mov1
movlw 0x0A;checking
mulwf den
movff PRODH,x2
movff PRODL,x1

here2
call compare2
movlw 0x00
cpfseq flag
bra mov2
movlw 0x0A
addwf qreg
movf x1,W
subwf n1
movf x2,W
subwfb n2
goto here2

mov2  movlw 0x01
mulwf den
movff PRODH,den2
movff PRODL,den1

here3
call compare3
    movlw 0x00
cpfseq flag
bra mov3
movlw 0x01
addwf qreg
movf den1,W
subwf n1
movf den2,W
subwfb n2
goto here3
```

```
mov3
movff qreg,qreg1

return;

GLOBAL division

compare1
clrf  flag
   movf x2,W
cpfsgt n2
bra L1
return
L1 cpfseq n2
setf flag
movf x1,W
cpfsgt n1
setf flag
return

compare2
clrf  flag
movf x2,W
cpfsgt n2
bra L2
return
L2 cpfseq n2
setf flag
movf x1,W
cpfsgt n1
setf flag
return

compare3
clrf  flag
movf den2,W
cpfsgt n2
bra L3
return
L3 cpfseq n2
bra L4
L4 movf den1,W
cpfsgt n1
setf flag
return
jump bra jump
end
--------------------------------------------------------------------------------

--------------------------------------------------------------------------------
```

```
;duty ratio control program
#include P18F2331.inc
EXTERN LCDUPDATE,step1,conversion,d_write1,temp_wr
EXTERN val,tent,hund,ones,lcd_duty,n1,n2,qreg,den,division
Variables UDATA
m1 res 1
m2 res 1
m3 res 1
um3 res 1
um4 res 1
um5 res 1
um6 res 1
qreg3 res 1
limit res 1
GLOBAL qreg3
GLOBAL limit
GLOBAL um3
GLOBAL um4
Global um5

Code

dutyctrl
call lcd_duty
call udp_duty
;GLOBAL dutyc
here
;push button operation
btfss PORTB,4
goto step1
btfss PORTC,1
bra inc_check
btfss PORTC,3
bra dec_check
goto here
inc_check
btfsc PORTC,1
bra inc_check
;movlw 0x50
;------------------------------------------------
movff CCPR1L,m1
movlw 0x64
mulwf m1
movff PRODH,n2
movff PRODL,n1
movff PR2,den
call division
movff qreg,limit
movlw 0x50
cpfsgt limit
bra j2
```

```
bra j1

j2 incf CCPR1L
call udp_duty
movlw PR2
movf PR2,W
goto here

j1 goto here
;decrementing operation
dec_check
btfsc PORTC,3
bra dec_check
decf CCPR1L
call LCDUPDATE
call udp_duty
movlw 0x00
cpfseq CCPR1L
bra here
movlw 0x01
movwf CCPR1L
goto here
GLOBAL dutyctrl

udp_duty
call LCDUPDATE
movff CCPR1L,m1
movlw 0x64
mulwf m1
movff PRODH,n2
movff PRODL,n1
movff PR2,den
call division
movff qreg,val
movff qreg,qreg3
call conversion
movlw 0x30
addwf hund
movwf um3
movff um3,temp_wr
call d_write1
movlw 0x30
addwf tent
movff tent,um4
movff um4,temp_wr
call d_write1
movlw 0x30
addwf ones
movff ones, um5
movff um5,temp_wr
call d_write1
```

```
movlw A'%'
movwf um6
movff um6,temp_wr
call d_write1
nop
RETURN
RETURN
GLOBAL udp_duty
loop
bra loop
end
----------------------------------------------------------------------------------------------

----------------------------------------------------------------------------------------------
;frequency control program.
#include P18F2331.inc
EXTERN conversion,qreg,den,division,lcd,LCDUPDATE,udp,n1,n2,step1,lcd_freq,qreg3
;files to be included division1,LCD_UDP,lcd3
Variables UDATA
temp res 1;declaring temporary register
T1 res 1
T2 res 1
qreg1 res 1
duty res 1
GLOBAL T1
GLOBAL T2
GLOBAL duty

;division1 file is to be included,Lcd3 file is to be included
;lcd_udp file is to be included

Code

freq_ctrl

movff PR2,duty
call lcd_freq
CALL udp
;GLOBAL freq
here
;push button operation
btfss PORTB,4
goto step1
movff PR2,duty
btfss PORTC,1
bra inc_check
btfss PORTC,3
bra dec_check
bra here
;incrementing operation
inc_check
```

```
btfsc PORTC,1
bra inc_check
movlw 0x3D
cpfslt PR2
bra k1
bra k2

k1
decf duty
movf qreg3,W
mulwf duty
movff PRODH,n2
movff PRODL,n1
movlw 0x64
movwf den
call division
movff qreg,CCPR1L
call udp
movff duty,PR2
goto here
        k2
movwf PR2
goto here
;decrementing operation
dec_check
btfsc PORTC,3
bra dec_check
movlw 0x7D
cpfsgt PR2
bra s1
bra s2

s1
incf  duty
movf qreg3,W
mulwf duty
movff PRODH,n2
movff PRODL,n1
movlw 0x64
movwf den
call division
movff qreg,CCPR1L
call udp
movff duty,PR2
goto here
s2
movwf PR2
goto here

GLOBAL freq_ctrl
loop
```

```
bra loop
end
-----------------------------------------------------------------------------------------------

-----------------------------------------------------------------------------------------------
;hexadecimal to decimal conversion program
#include P18F2331.inc
EXTERN d_write1,LCDUPDATE,temp_wr,den,division,qreg,n1,n2
;division1 file is to be included,Lcd3 file is to be included
 UDATA
t1 res 1
t2 res 1
t3 res 1
hund res 1
tent res 1
ones res 1
val res 1
ut1 res 1
ut2 res 1
ut3 res 1
ut4 res 1
ut5 res 1
ut6 res 1
cal1 res 1
s1 res 1
s2 res 1



GLOBAL hund
GLOBAL tent
GLOBAL ones
GLOBAL t1
GLOBAL t2
GLOBAL t3
GLOBAL ut1
GLOBAL ut3
GLOBAL ut4
GLOBAL ut5
GLOBAL val
code

udp

call LCDUPDATE
clrf n1
clrf n2
movlw 0x10
movwf n1
movlw 0x27
movwf n2
```

```
movlw 0x01
addwf PR2
movlw 0x4
mulwf PR2
movff PRODH,s1
movff PRODL,s2
bcf STATUS,C
rrcf s1
rrcf s2
bcf STATUS,C
rrcf s1
rrcf s2
movff s2,den
call division
movff qreg,cal1
movff cal1,t2
bcf STATUS,C
rrcf t2
bcf STATUS,C
rrcf t2
movff t2,val
call conversion
movlw 0x30
addwf hund
movff hund,ut3
movff ut3,temp_wr
call d_write1
movlw 0x30
addwf tent
movff tent,ut4
movff ut4,temp_wr
call d_write1
movlw 0x30
addwf ones
movff ones, ut5
movff ut5,temp_wr
call d_write1
movlw A'K'
movwf ut6
movff ut6,temp_wr
call d_write1
movlw A'H'
movwf ut6
movff ut6,temp_wr
call d_write1
movlw A'z'
movwf ut6
movff ut6,temp_wr
call d_write1
nop
RETURN
```

```
GLOBAL udp

conversion
clrf hund
clrf tent
  clrf ones
movff val,ut1

loop5
movlw 0x64
cpfsgt ut1
bra ten
goto hun1
ten movlw 0x0A
cpfsgt ut1
bra l1
goto tens
l1 movlw 0x0A
cpfseq ut1
bra l2
goto p1
l2  movff ut1,ones
return
GLOBAL conversion
hun1
incf hund
movlw 0x64
subwf ut1
bra loop5
tens
incf tent
movlw 0x0A
subwf ut1
bra ten
p1
    incf tent
movlw 0x00
movwf ones
return
GLOBAL p1
end
----------------------------------------------------------------------------------------------

----------------------------------------------------------------------------------------------
;interrupt intialisation program
;adc intialisation program
;pwm module program
#include P18F2331.inc
EXTERN temp1,temp2,temp3,temp4,sel

#define  timer1Hi 0xFC ;Timer1 timeout defined by timer1Lo & timer1Hi
```

```
#define  timer1Lo 0x18 ;this timout is based on Fosc/4

Variables UDATA
code
int_initialize
bsf  RCON,IPEN              ;enable priority interrupts.
bsf  IPR1,TMR1IP            ;set Timer1 as a high priority interrupt source

bsf  INTCON,GIEH            ;set the global interrupt enable bits

bcf PIR1,TMR1IF ;clear T1 flag
bsf PIE1,TMR1IE ;enable T1 interrupt

    clrf    T1CON
movlw b'10000000';configure T1 for Timer operation from Fosc/4
movwf T1CON
movlw timer1Hi ;load T1 registers with 1ms count

movwf TMR1H
movlw timer1Lo
movwf TMR1L
    bsf     T1CON,TMR1ON     ;turn on Timer1
GLOBAL int_initialize
return          ;return back to the main application code

pwm_module

bcf TRISC,2;setting as a output mode for pwm pulse
movlw 0x7f
movwf PR2;determination of frequency
clrf T2CON
bsf T2CON,2;timer start up
clrf CCP1CON;clearing pwm module
bsf CCP1CON,CCP1M3;{setting in pwm mode}
bsf CCP1CON,CCP1M2;()
movlw 0x48
movwf CCPR1L


nop
GLOBAL  pwm_module
return

adc_intialize
clrf sel
bsf TRISA,0;makin portA 0 pin as input for adc module
bsf TRISA,1;makin portA 1 pin as input for adc module
clrf ADRESH
clrf ADRESL
clrf temp1
clrf temp2
```

```
clrf temp3
clrf temp4
movlw b'00011000'
movwf ADCON1
movlw b'10001001';left justification,2TAD
movwf ADCON2
movlw b'11000000'
movwf ADCON3
clrf PIR1;clear the a/d conveter flag
bcf PIE1,ADIE;enable the interrput
bsf INTCON,GIEH;enable the global interruot flag

GLOBAL  adc_intialize
return


end
-------------------------------------------------------------------------------------------


-------------------------------------------------------------------------------------------
;lcd intialisation program.
#include P18F2331.inc
UDATA
count1 res 1
count2 res 1
temp_wr res 1
temp_rd res 1
check res 1
temp1 res 1
temp2 res 1
temp3 res 1
temp  res 1
GLOBAL temp_wr
code
LCDLine_1 ; to display the characters on line1
movlw 0x80
movwf temp_wr
rcall i_write
return
GLOBAL LCDLine_1

LCDLine_2
movlw 0xC0 ;to display characters on line2
movwf temp_wr
rcall i_write
return
GLOBAL LCDLine_2
d_write1
rcall lcd_busy
bsf  check, 1
rcall LCDWrite
```

```
return
GLOBAL d_write1
i_write
rcall lcd_busy
bcf check, 1
rcall LCDWrite
return
GLOBAL i_write

LCDInit

movlw b'00000011'
movwf TRISA
movlw b'00001011'
movwf TRISC
;clrf PORTA



bcf TRISA,2 ;configure control lines
bcf TRISA,3
bcf TRISA,4



rcall delay1

movlw b'00110000';#1 Send control sequence
movwf temp_wr
bcf check, 1
rcall LCDWriteNibble

rcall delay1

movlw b'00110000';#2 Send control sequence
movwf temp_wr
bcf check, 1
rcall LCDWriteNibble

rcall delay2

movlw b'0011000';#3 Send control sequence
movwf temp_wr
bcf check, 1
rcall LCDWriteNibble

rcall delay2

movlw b'00100000';#4 set 4-bit
movwf temp_wr
bcf check, 1
```

```
rcall LCDWriteNibble

rcall lcd_busy ;Busy?

movlw b'00101000';#5   Function set
movwf temp_wr
rcall i_write

movlw b'00001101';#6  Display = ON
movwf temp_wr
rcall i_write

movlw b'00000001';#7   Display Clear
movwf temp_wr
rcall i_write

movlw b'00000110';#8   Entry Mode
movwf temp_wr
rcall i_write

movlw b'10000000';DDRAM addresss 0000
movwf temp_wr
rcall i_write
return
GLOBAL LCDInit
LCDWriteNibble
btfss check, 1 ; Set the register select
bcf PORTA,2
btfsc check, 1
bsf PORTA,2

bcf PORTA,3 ; Set write mode

bcf TRISC,7 ; Set data bits to outputs
bcf TRISC,6
bcf TRISC,5
bcf TRISC,4

NOP ; Small delay
NOP

bsf PORTA,4 ; Setup to clock data

btfss temp_wr, 7 ; Set high nibble
bcf PORTC,4
btfsc temp_wr, 7
bsf PORTC,4
btfss temp_wr, 6
bcf PORTC,5
btfsc temp_wr, 6
bsf PORTC,5
```

```
btfss temp_wr, 5
bcf PORTC,6
btfsc temp_wr, 5
bsf PORTC,6
btfss temp_wr, 4
bcf PORTC,7
btfsc temp_wr, 4
bsf PORTC,7

NOP
NOP

bcf PORTA,4 ; Send the data

return


LCDWrite

rcall LCDWriteNibble
swapf temp_wr,F
rcall LCDWriteNibble
swapf temp_wr,F
return
GLOBAL LCDWrite

delay1
movlw 0xFF
movwf count1
loop1
call delay2
decfsz  count1,1
goto  loop1
return

delay2
movlw 0xFF
movwf count2
loop2
decfsz count2,1
goto loop2
return
lcd_busy
movlw 0x0f
movwf temp1
j3 movlw 0x1f
movwf temp2
j2 movlw 0xff
movwf temp3
j1
decfsz temp3
```

```
bra j1
decfsz temp2
bra j2
decfsz temp1
bra j3
return
end
-----------------------------------------------------------------------------------------------


-----------------------------------------------------------------------------------------------
#include P18F2331.inc
EXTERN LCDInit,LCDLine_1,temp_wr,d_write1,LCDLine_2,i_write,sel,step1


code
lcd
call LCDInit
call LCDLine_1
movlw A'B'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'K'
movwf temp_wr
call d_write1
movlw A'-'
movwf temp_wr
call d_write1
movlw A'B'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'S'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
```

```
movlw A'C'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'N'
movwf temp_wr
call d_write1
movlw A'V'
movwf temp_wr
call d_write1
call LCDLine_2
movlw A'S'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
movlw A'M'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'D'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
return
GLOBAL lcd
NOP
NOP
dis_duty
```

```
call LCDInit
call LCDLine_1
movlw A'D'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
NOP
incf sel
goto step1
GLOBAL dis_duty
 dis_freq
call LCDInit
call LCDLine_1
movlw A'F'
movwf temp_wr
call d_write1
movlw A'R'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'Q'
movwf temp_wr
call d_write1
```

```
movlw A'U'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'N'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
NOP
incf sel
goto step1
GLOBAL  dis_freq

LCDUPDATE ; to display the characters on defined
movlw 0x8A
movwf temp_wr
rcall i_write
return
GLOBAL LCDUPDATE
LCDUPDATE1 ; to display the characters on defined
movlw 0xC8
movwf temp_wr
rcall i_write
return
GLOBAL LCDUPDATE1
lcd_freq
call LCDInit
call LCDLine_1
movlw A'F'
movwf temp_wr
call d_write1
movlw A'R'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'Q'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'E'
```

```
movwf temp_wr
call d_write1
movlw A'N'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
NOP
return
GLOBAL lcd_freq
lcd_duty
call LCDInit
call LCDLine_1
movlw A'D'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'Y'
movwf temp_wr
call d_write1
movlw A'C'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
NOP
bcf sel,0
bsf TRISC,0
return
```

```
GLOBAL lcd_duty
dis_input
call LCDInit
call LCDLine_1
movlw A'I'
movwf temp_wr
call d_write1
movlw A'N'
movwf temp_wr
call d_write1
movlw A'P'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
movlw A'V'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'A'
movwf temp_wr
call d_write1
movlw A'G'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
NOP
incf sel
goto step1
GLOBAL  dis_input

dis_output
call LCDInit
call LCDLine_1
```

```
movlw A'O'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'P'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A' '
movwf temp_wr
call d_write1
movlw A'V'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'A'
movwf temp_wr
call d_write1
movlw A'G'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
NOP
clrf sel
goto step1
GLOBAL  dis_output

inputvolt
call LCDInit
call LCDLine_1
movlw A'I'
```

```
movwf temp_wr
call d_write1
movlw A'N'
movwf temp_wr
call d_write1
movlw A'P'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
call LCDLine_2
movlw A'V'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'A'
movwf temp_wr
call d_write1
movlw A'G'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'-'
movwf temp_wr
call d_write1
NOP
return


GLOBAL inputvolt


outputvolt
call LCDInit
call LCDLine_1
movlw A'O'
movwf temp_wr
```

```
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'P'
movwf temp_wr
call d_write1
movlw A'U'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
call LCDLine_2
movlw A'V'
movwf temp_wr
call d_write1
movlw A'O'
movwf temp_wr
call d_write1
movlw A'L'
movwf temp_wr
call d_write1
movlw A'T'
movwf temp_wr
call d_write1
movlw A'A'
movwf temp_wr
call d_write1
movlw A'G'
movwf temp_wr
call d_write1
movlw A'E'
movwf temp_wr
call d_write1
movlw A'-'
movwf temp_wr
call d_write1
NOP
return
GLOBAL outputvolt

loop bra loop
end
---------------------------------------------------------------------------------


---------------------------------------------------------------------------------
;input voltage and output voltage display program
```

```
#include <P18F2331.inc>
EXTERN outputvolt,LCDUPDATE1,n2,n1,den,division,qreg,um3,um4,um5,step1,temp3,temp4,mode,
EXTERN temp1,temp2,division,hund,ut3,temp_wr,d_write1,tent,ones,val,conversion,inputvolt
variables UDATA
mar1 res 1
mar2 res 1
mar3 res 1
mar4 res 1
volt res 1

code

output
call outputvolt; call output voltage for display
run1  call LCDUPDATE1;call for update the output voltage.
clrf mar1
clrf mar2
movff temp1,mar1
movff temp2,mar2
bcf STATUS,C
rrcf mar1
rrcf mar2
bcf STATUS,C
rrcf mar1
rrcf mar2
movlw 0x09
mulwf mar2
movff PRODH,n2
movff PRODL,n1
movlw 0x8E
movwf den
call division
movff qreg,volt
movff volt,val
call conversion
movlw 0x30
addwf hund
movwf um3
movff um3,temp_wr
call d_write1
movlw 0x30
addwf tent
movff tent,um4
movff um4,temp_wr
call d_write1
movlw 0x30
addwf ones
movff ones, um5
movff um5,temp_wr
call d_write1
movlw A'V'
```

```
movwf temp_wr
call d_write1
btfss PORTB,4;check and skip if portB is set
bra mode;jump to mode selection
btfss PORTC,0;check and skip if portC is set
bra enter
bra run1
return

GLOBAL output


input
call inputvolt; call input voltage for display
run call LCDUPDATE1;call for update the input voltage.
clrf mar3
clrf mar4
movff temp3,mar3
movff temp4,mar4
bcf STATUS,C
rrcf mar3
rrcf mar4
bcf STATUS,C
rrcf mar3
rrcf mar4
movlw 0x0F
mulwf mar4
movff PRODH,n2
movff PRODL,n1
movlw 0x77
movwf den
call division
movff qreg,volt
movff volt,val
call conversion
movlw 0x30
addwf hund
movwf um3
movff um3,temp_wr
call d_write1
movlw 0x30
addwf tent
movff tent,um4
movff um4,temp_wr
call d_write1
movlw 0x30
addwf ones
movff ones, um5
movff um5,temp_wr
call d_write1
movlw A'V'
```

```
movwf temp_wr
call d_write1
;call delay
btfss PORTB,4;check and skip if portB is set
bra mode;jump to mode selection
btfss PORTC,0;check and skip if portC is set
bra enter
bra run

return

GLOBAL input
end
-------------------------------------------------------------------------------------
```

Appendix B

Assembly Program For Closed Loop

```
;main program
.equ __30F4011,1
.include "p30f4011.inc"

.equ SAMPLES,64

.equiv mode, #0x0000
.set mode, #0x0000


config __FOSC, CSW_FSCM_OFF & XT_PLL4
config __FBORPOR, PBOR_ON & BORV_27 & PWRT_16 & MCLR_EN
config __FWDT, WDT_OFF
config __FGS, CODE_PROT_OFF

.global __reset
.global dwrite
.global dwrite1
.global dwrite2
.global dwrite3
.global dwrite4
.global Write
.global L1
.global mode
.global m1
.global LCD

.section .myconstbuffer, code
.palign 2

.section .xbss, bss, xmemory
x_input: .space 2*SAMPLES
```

```
.text
__reset:   mov #__SP_init, W15 ;Initialising the Stack Pointer W15
           mov #__SPLIM_init, W0
  mov W0, SPLIM
Call PWM
LCD:  mov #0x003F, W0  ;Initialisation
 mov W0, TRISB
 mov #0xFFFC, W0
 mov W0, ADPCFG
 mov #0x000C, W0
 mov W0, TRISF
 mov #0x000B, W0
 mov W0, TRISD
 mov #0x8000,W0
          mov W0, TRISC
 mov #0x0000, W0
 mov W0, TRISE
 mov W0, LATE

mov #0x0038, W0 ;Initialize the 2 rows of Lcd Display
call Write

mov #0x000E, W0 ;For cursor
call Write

mov #0x0001, W0 ;Clear Display Screen
call Write

mov #0x0006, W0 ;Increment cursor to the right
call Write

mov #0x0080, W0 ;Start from 0th position of first row of lcd
call Write
Call Start

mov #0x00C0, W0
call Write
Call SelM

L0:
clr W12

L1:
Call ADC1
m1:btss PORTB, #2
   bra m1a
bra L1

m1a:btsc PORTB, #2
    bra m1a
```

```
m1b:btss PORTB, #2
    bra m1b

df: mov W12, W1
    mov #0x0000, W0
    cpseq W0, W1
    bra dc
    Call d_Freq
 dc:mov #0x0001, W0
    cpseq W0, W1
    bra iv
    Call d_Duty
 iv:mov #0x0002, W0
    cpseq W0, W1
    bra o_v
    Call d_IVolt
 o_v:mov #0x0003, W0
     cpseq W0, W1
     bra L0
     Call d_OVolt

bra do

Start:
mov #'B', W0
call dwrite

mov #'U', W0
call dwrite

mov #'C', W0
call dwrite

mov #'K', W0
call dwrite

mov #' ', W0
call dwrite

mov #'C', W0
call dwrite

mov #'O', W0
call dwrite

mov #'N', W0
call dwrite

mov #'V', W0
call dwrite
```

```
mov #'E', W0
call dwrite

mov #'R', W0
call dwrite

mov #'T', W0
call dwrite

mov #'E', W0
call dwrite

mov #'R', W0
call dwrite
return

SelM:
mov #'S', W0
call dwrite

mov #'e', W0
call dwrite

mov #'l', W0
call dwrite

mov #'e', W0
call dwrite

mov #'c', W0
call dwrite

mov #'t', W0
call dwrite

mov #' ', W0
call dwrite

mov #'M', W0
call dwrite

mov #'o', W0
call dwrite

mov #'d', W0
call dwrite

mov #'e', W0
call dwrite

return
```

```
;To display the data
dwrite:bset PORTB, #6 ;Set RS to enable data register
  Call Delay1 ;Delay to properly set RS register
  bclr PORTB, #7 ;R/W=0 to write to LCD
  bset PORTB, #8 ;E=1 for a H-L puls
  bra Convert
return
;To initialise LCD
Write: bclr PORTB, #6 ;RS=0 to enable command register
  Call Delay1 ;Delay to properly clear RS register
  bclr PORTB, #7 ;R/W=0 to write to LCD
  bset PORTB, #8 ;E=1 for a H-L pulse
       bra Convert
return
Convert: btss W0, #7 ;Set o/p pins H or L as per the command
         bclr PORTF, #5
btsc W0, #7
bset PORTF, #5
btss W0, #6
bclr PORTF, #4
btsc W0, #6
bset PORTF, #4
btss W0, #5
bclr PORTF, #1
btsc W0, #5
bset PORTF, #1
btss W0, #4
bclr PORTF, #0
btsc W0, #4
bset PORTF, #0
btss W0, #3
bclr PORTC, #13
btsc W0, #3
bset PORTC, #13
btss W0, #2
bclr PORTC, #14
btsc W0, #2
bset PORTC, #14
btss W0, #1
bclr PORTD, #2
btsc W0, #1
bset PORTD, #2
btss W0, #0
bclr PORTF, #6
btsc W0, #0
bset PORTF, #6

Call Delay
bclr PORTB, #8    ;E=0 for a H-L pulse
return
```

```
Delay: mov #0x007F, W2
   d1: mov #0x003F, W1
   d2: dec W1, W1
       bra NZ, d2
       dec W2, W2
       bra NZ, d1
return
Delay1: mov #0x000F, W2
    d3: mov #0x000F, W1
    d4: dec W1, W1
        bra NZ, d4
        dec W2, W2
        bra NZ, d3
return

dwrite1: mov #0x008B, W0   ;To place LCD cursor at 2nd row 12th position
call Write
mov W6, W0 ;Transferring ascii value of data
Call dwrite
return

dwrite2: mov #0x008A, W0   ;To place LCD cursor at row1, 10th coloumn
call Write
mov W10, W0       ;Transferring ascii value of data
Call dwrite
return

dwrite3: mov #0x0087, W0   ;To place LCD cursor at row1, 10th coloumn
call Write
mov W10, W0       ;Transferring ascii value of data
Call dwrite
return

do: nop
return
.end
```

```
;generating PWM
.global PWM

PWM:       mov #0x0000, W0 ;Set PortE as output port
      mov W0, TRISE
          mov W0, LATE
      mov #0x0003, W0
      mov W0, TRISB

      clr PTCON
      clr PTMR
      clr ADCBUF0
      mov #0x00FF, W0
      mov W0, PWMCON1     ;Enabling PEN<3:1> and PEN<3:1> for o/p
      mov #0x01F4, W8     ;Set Freq = 20Khz
      mov #0x01F4, W9     ;Set DutyCycle = 50%
               mov #0x32, W13

      mov #0x8000, W0    ;Set the PTEN bit and select the Free Running mode for PWM
      mov W0, PTCON
   trial:  mov W8, PTPER      ;Set PWM Time Period reg.= Freq.
   trial1: mov W9, PDC1


return
```

```
;closed loop program, A/D conversion
.global ADC1
.set temps, #0x0000

ADC1:  mov #0x0000, W0
 mov W0, ADCON1   ;Configuring ADC registers.
 mov #0x0000, W0
 mov W0, ADCON2
 mov #0x0002, W0
 mov W0, ADCON3   ;Selecting A/D Conversion Time speed
 mov #0x0001, W0
 mov W0, ADCHS
 mov #0xFFFD, W0
 mov W0, ADPCFG     ;ADPCFG for digital i/p or o/ps
 mov #0x0002, W0
 mov W0, ADCSSL   ;Set Scan Select register for req.


mov W14,temps   ;moving previous value of ADC o/p.
bset ADCON1, #15    ;set ADON bit
bset ADCON1, #1    ;set SAMP bit
Call Delay2   ;Delay of approx 20ms for A/D conversion
bclr ADCON1, #1     ;clear SAMP bit
wait:    btss ADCON1, #0    ;check if DONE bit is set.
bra wait
mov ADCBUF0, W14    ;result in the buffer is moved

mov #0x01FF, W1   ;1FF==2.5V
cpsne W1, W14   ;compare ADC o/p with 2.5V
bra done   ;if equal branch to main program

sub W1, W14, W2   ;if not equal calculate error
btsc SR, #3   ;check if W14 value > 2.5V
bra nega   ;if yes, branch to 'nega'

mov #0xA, W5   ;multiply present error by 10
         mul.uu W2, W5, W2
mov.d W2, W2        ;move it as a double in case of a large number
         mov #0x9, W4
mov temps, W6   ;previous value of ADC is taken in W6
mov #0x0000, W0   ;check if prev val is 0, e(n-1)=0 when device is started
        cpseq W6, W0   ;subtract from 2.5V only after first trial
        sub W1, W6, W6
        btsc SR, #3   ;check if value is negative
        com W6, W6   ;if yes, take complement
        mul.uu W4, W6, W4   ;multiply previous error by 9
        mov.d W4, W4
        sub W2, W4, W2   ;subtract present and past error
        btsc SR, #3   ;check if result is negative
        com W2, W2   ;take complement if yes.
        mov #0xA, W4
```

```
        repeat #17   ;divide the error value by 10
        div.u W2, W4
        mov W9, W7   ;move duty value into W7
        add W7, W0, W7   ;add to get next duty value
        goto N1

nega: com W2, W2
mov #0xA, W5
mul.uu W2, W5, W2
mov.d W2, W2
mov #0x9, W4
mov temps, W6
    mov #0x0000, W0
cpseq W6, W0
sub W1, W6, W6
btsc SR, #3
com W6, W6
mul.uu W4, W6, W4
mov.d W4, W4
sub W2, W4, W2
btsc SR, #3
com W2, W2
mov #0xA, W4
repeat #17
div.u W2, W4
mov W9, W7
sub W7, W0, W7
N1:  mov W7, W9
     mov W9, PDC1 ;moving next duty value

done:   return

Delay2:  mov #0x00FF, W2
    d5:  mov #0x00FF, W1
    d6:   dec W1, W1
         bra NZ, d6
         dec W2, W2
 bra NZ, d5
return

.end
```

```
;display value of frequency
.global d_Freq

d_Freq:
mov #0x0001, W0 ;Clear Display Screen
call Write

mov #0x0006, W0 ;Increment cursor to the right
call Write

mov #0x0080, W0 ;Start from 0th position of first row of display
call Write

mov #'F', W0
call dwrite

mov #'r', W0
call dwrite

mov #'e', W0
call dwrite

mov #'q', W0
call dwrite

mov #'u', W0
call dwrite

mov #'e', W0
call dwrite

mov #'n', W0
call dwrite

mov #'c', W0
call dwrite

mov #'y', W0
call dwrite

mov #'=', W0
call dwrite

trial:nop

Loop:
Call Freqchg
increment1:btss PORTB, #4
  bra inc_2
decrement1:btss PORTB, #5
  bra dec_2
```

```
esc:btss PORTB, #3
    bra esc1
bra Loop

inc_2:btsc PORTB, #4
      bra inc_2
      mov #0x0001, W3
      sub W8, W3, W8 ;Changing frequency
      mov #0x64, W4        ;To maintain the set duty value constant when freq changes
      mov W13, W2  ;The value of duty in terms of percentage is popped into W2 eg.W2=60 or 3C
      mul.uu W8, #0x2, W6
      mul.uu W6, W2, W6
      repeat #17
      div.ud W6, W4 ;(freq*DC%)/100 eg. (7ff*2*3C)/64x=998x
      mov W0, W9

      mov #0x0FF, W3 ;Freq limit
      cpseq W8, W3
      bra trial
      btss PORTB, #5
      bra dec_2
inc_stop2:btss PORTB, #4
 bra inc_stop2

dec_2:btsc PORTB, #5
      bra dec_2
      mov #0x0001, W3
      add W8, W3, W8

      mov #0x64, W4        ;*To maintain the set duty value constant when freq changes
      mov W13, W2  ;The value of duty in terms of percentage is popped into W2 eg.W2=60 or 3C
      mul.uu W8, #0x2, W6
      mul.uu W6, W2, W6
      repeat #17
      div.ud W6, W4 ;(freq*DC%)/100 eg. (7ff*2*3C)/64x=998x
      mov W0, W9
      mov #0x0AA2, W3   ;Freq lower limit
      cpseq W8, W3
      bra trial
      btss PORTB, #4
      bra inc_2

dec_stop2:btss PORTB, #5
 bra dec_stop2

esc1:mov W8, PTPER ;Set PWM Time Period reg.= Freq.
     mov W9, PDC1
     mov #0x0001, W12
     bra L1
return
```

```
;display value of duty ratio
.global d_Duty

d_Duty:
mov #0x0001, W0 ;Clear Display Screen
call Write

mov #0x0006, W0 ;Increment cursor to the right
call Write

mov #0x0080, W0 ;Start from 0th position of first row of display
call Write

mov #'D', W0
call dwrite

mov #'u', W0
call dwrite

mov #'t', W0
call dwrite

mov #'y', W0
call dwrite

mov #' ', W0
call dwrite

mov #'R', W0
call dwrite

mov #'a', W0
call dwrite

mov #'t', W0
call dwrite

mov #'i', W0
call dwrite

mov #'o', W0
call dwrite

mov #'=', W0
call dwrite

trial1:nop

Loop:
call dtyC
increment1:btss PORTB, #4
```

```
  bra inc_1
decrement1:btss PORTB, #5
  bra dec_1
esc:btss PORTB, #3
    bra esc1
bra Loop
inc_1:btsc PORTB, #4 ;Enter Loop if button is pressed.
      bra inc_1 ;Inc/Dec value when button is pressed. Not after release.
      mov #0x0001, W3
      add W9, W3, W9 ;The value of PDC1 reg is incremented for increasing duty.

      mul.uu W8, #0x2, W6
      mov #0x51, W4 ;To set limit of max 80% duty cycle. 0x51=0d81
      mul.uu W6, W4, W2 ;(freq*81)/100=81% duty cycle limit value
is 0xAA2
      mov #0x64, W4
      repeat #17 ;Proper division needs 17 instruction cycles.
      div.ud W2,W4
      mov W0, W3  ;Quotient is stored in W0. Remainder in W1.

      mul.uu W9, W4, W4    ;To get the percentage value of the duty cycle.
      repeat #17
      div.ud W4, W6
      mov W0, W13 ;Store the % value in reg W13
      cpsgt W9, W3 ;Check if limit is reached. If yes, check if other buttons are pressed.
      bra trial1  ;If No, repeat cycle
      btss PORTB, #5 ;If limit is reached this loop gets executed to ensure continuous waveform
      bra dec_1

inc_stop1:btss PORTB, #4
 bra inc_stop1


dec_1:btsc PORTB, #5
      bra dec_1
      mov #0x0001, W3
      sub W9, W3, W9 ;The value of PDC1 reg is decremented for decreasing duty.

      mul.uu W8, #0x2, W6
      mul.uu W6, #0x14, W2 ;To set lower limit of 20% duty ratio.
      mov #0x64, W4 ;(freq*20)/100=20% duty cycle limit value is 0x37C
      repeat #17 ;0x14=0d20; 0x64=0d100
      div.ud W2, W4
      mov W0, W3

      mul.uu W9, W4, W4
      repeat #17
      div.ud W4, W6
      mov W0, W13

      cpslt W9, W3
```

```
      bra trial1
      btss PORTB, #4
      bra inc_1

dec_stop1:btss PORTB, #5
          bra dec_stop1

esc1:
mov W9, PDC1
mov #0x0002, W12
bra L1

return
```

```
;calculate value of frequency
.global Freqchg

Freqchg:mov W8, W3    ;Move PTPER value into W3
   mov #0x9680, W4
   mov #0x0098, W5
   mov.d W4, W6 ;Move 10MHz=0x989680 into W6
   repeat #17
   div.ud W6, W3 ;Divide to get frequency of PWM
   mov W0, W5 ;Move quotient into W5

clr W10
clr W11
clr W12

mov #0x2710, W1 ;Move 0d10000 into W1 for ten thousand's place
mov #0x03E8, W2 ;Move 0d1000 into W2 for thousand's place
mov #0x64, W3 ;Move 0d100 into W3 for hundred's place
;mov #0x0A, W4

L0: cpslt W5, W1 ;Compare W5 with W1 if less than W1 skip
    bra gtl
L1: cpslt W5, W2 ;Compare W5 with W2 if less than W2 skip
    bra gtth
L2: cpslt W5, W3 ;Compare W5 with W3 if less than W3 skip
    bra gth
/*L3: cpslt W5, W4
bra gtt
add #0x30, W5*/
    bra asc

/*To convert from hex to BCD*/
gtl: sub W5, W1, W5 ;If W5>0x2710 then sub W1 from W5 and add 1 to W10
     add #1, W10
     bra L0
gtth: sub W5, W2, W5 ;If W5>0x03E8 then sub W2 from W5 and add 1 to W11
      add #1, W11
      bra L1
gth:  sub W5, W3, W5 ;If W5>0x064 then sub W3 from W5 and add 1 to W12
      add #1, W12
      bra L2
/*gtt: sub W5, W4, W5
  add #1, W12
  bra L3*/

/*To convert from BCD to ascii*/
asc: add #0x30, W10 ;Add 30 to all the bcd values to convert to ascii
     Call dwrite2 ;dwrite2 will place the cursor at required position on the LCD
     add #0x30, W11
     mov W11, W0
     Call dwrite
```

```
     mov #'.', W0
     Call dwrite
     add #0x30, W12
     mov W12, W0
     Call dwrite
     mov #'K', W0
     call dwrite
     /*add #0x30, W12
 mov W12, W0
 Call Dwrite
 mov W5, W0
 Call Dwrite*/
return
.end
```

```
;calculate value of duty ratio.
.global dtyC

dtyC:mov #100, W3           ;To determine the percentage of duty ratio
     mov W9, W4
     mul.uu W3, W4, W4
     mul.uu W8, #2, W6
     repeat #17
     div.ud W4, W6 ;(duty value*0x64)/freq
     mov W0, W5

clr W6
clr W7

mov #0x0A, W4
L1: cpslt W5, W3
    bra gth
L2: cpslt W5, W4
    bra gtt
    add #0x30, W5
    bra asc

gth: sub W5, W3, W5
     add #1, W6
     bra L1
gtt: sub W5, W4, W5
     add #1, W7
     bra L2

asc: add #0x30, W6
     Call dwrite1 ;dwrite1 will place the cursor at required position on the LCD
     add #0x30, W7
     mov W7, W0
     Call dwrite
     mov W5, W0
     Call dwrite
     mov #'%', W0
     Call dwrite
return
.end
```

```
;display input voltage
.global d_IVolt

d_IVolt:
mov #0x0001, W0 ;Clear Display Screen
call Write

mov #0x0006, W0 ;Increment cursor to the right
call Write

mov #0x0080, W0 ;Start from 0th position of first row of display
call Write

mov #'I', W0
call dwrite

mov #'n', W0
call dwrite

mov #'p', W0
call dwrite

mov #'u', W0
call dwrite

mov #'t', W0
call dwrite

mov #'=', W0
call dwrite

 mov #0x0000, W0
 mov W0, ADCON1 ;Configuring ADC registers.
 mov #0x0000, W0
 mov W0, ADCON2
 mov #0x0002, W0
 mov W0, ADCON3 ;Selecting A/D Conversion Time speed
 mov #0x0000, W0
 mov W0, ADCHS
 mov #0xFFFE, W0
   mov W0, ADPCFG   ;ADPCFG for digital i/p or o/ps
 mov #0x0001, W0
 mov W0, ADCSSL ;Set Scan Select register for req. Channels

 bset ADCON1, #15 ;ADON
 bset ADCON1, #1  ;SAMP
 Call Delay2
 bclr ADCON1, #1
    wait:         btss ADCON1, #0  ;DONE
 bra wait
 mov ADCBUF0, W11
```

```
 mov #0x1F, W2
 mov #0x1BC, W1
 cpslt W11, W1
 sub W11, W2, W11
 mov #0x1E, W2
          mul.uu W11, W2, W2
          mov.d W2, W2

mov #0x3FF, W4
repeat #17
div.ud W2, W4
mov W0, W5

clr W10
clr W12
mov #0x1, W2
mov #0xA, W3

L: cpslt W5, W3
    bra gt0
L0: cpslt W5, W2
    bra gt1
    bra asc

gt0: sub W5, W3, W5
add #1, W10
bra L
gt1: sub W5, W2, W5
add #1, W12
bra L0

asc: add #0x30, W10
mov W10, W0
call dwrite3
add #0x30, W12
mov W12, W0
call dwrite
mov #'V', W0
call dwrite

mov #0x0003, W12
bra L1

Delay2: mov #0x00FF, W2
    d5: mov #0x00FF, W1
    d6: dec W1, W1
        bra NZ, d6
        dec W2, W2
   bra NZ, d5
return
```

```
;calculate and display output voltage
.global d_OVolt

d_OVolt:
mov #0x0001, W0 ;Clear Display Screen
call Write

mov #0x0006, W0 ;Increment cursor to the right
call Write

mov #0x0080, W0 ;Start from 0th position of first row of display
call Write

mov #'O', W0
call dwrite

mov #'u', W0
call dwrite

mov #'t', W0
call dwrite

mov #'p', W0
call dwrite

mov #'u', W0
call dwrite

mov #'t', W0
call dwrite

mov #'=', W0
call dwrite

mul.uu W14, #0x5, W2
mov #0x03FF, W3
repeat #17
div.s W2, W3
mul.uu W0, #0x5, W0
mov W0, W5

clr W10
mov #0x1, W2

L0: cpslt W5, W2
    bra gt1
    bra asc

gt1: sub W5, W2, W5
     add #1, W10
     bra L0
```

```
asc: add  #0x30, W10
     call dwrite3
     mov #'V', W0
     call dwrite

mov #0x0000, W12
bra L1

return
```