"DESIGN AND IMPLEMENTATION OF ISOLATED HIGH POWER DC-DC BOOST CONVERTER USING DSP"

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Apparatus & Systems)

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CERTIFICATE

This is to certify that the Major Project Report entitled **"Design and Implementation of Isolated High Power DC-DC Boost Converter Using DSP"**submitted by **Mr.Pravinkumar Dhanjibhai Patel (Roll No: 06MEE012)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Apparatus & Systems of Nirma University of Science and Technology is the record of work carried out by him/her under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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ABSTRACT

A DC-DC converter can be considered as DC equivalent to an AC transformer with variable turns ratio. DC converter is widely used for traction motor control trolley cars, marine hoists, forklift trucks, mine haulers and DC/AC drives and DC voltage regulators. They provide smooth acceleration control, high efficiency and fast dynamic response.

Power supplies, which are used extensively in industrial application. The main aim of this project is to meet industrial needs like isolation between source and load, smooth control of power flow, high conversion efficiency, lower distortion in output voltage and current.

Different isolated converter topologies such as forward converter, fly back converter, push pull converter, half bridge converter, full bridge converter. The report mainly covers full bridge converter topology. The effects of various control techniques on the transient response of switching power supply have been discussed and compared. The full bridge converter topology is designed and simulated using PSIM6.0 software tool. This report contains full bridge converter design, control of full bridge converter, transformer design, transformer core selection, transformer development, simulation results, experimental results are also discussed.

A dc-dc converter of 10 KW capacity for converting 144 V DC voltage available as a battery supply to 600 V DC for feeding battery back up AC drive is presented in this report. The converter uses full bridge inverter - transformer -rectifier scheme to provide galvanic isolation between input and output and uses IGBTs to switch at 6 kHz. The constant voltage (CV) mode control is simulated with conventional control scheme and phase shift control scheme and checked for varying duty cycle and hence varying output voltage. The proposed scheme is illustrated and experimentally verified by prototype module.

Index Terms: Full bridge converter, Isolated converter and Phase shifted control scheme.

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NOMENCLATURE

Vo	Output voltage
Vin	Input voltage
Np	Transformer Primary voltage
Ns	Transformer Secondary voltage
Dr	Duty Ratio
Lo	Output Filter Inductor
Co	Filter Capacitor
Iq(rms)	Rms current of IGBT
Iq(avg)	Average current of IGBT
Iq(pk)	Peak Current of IGBT
Kp	Proportional gain of PI controller
Ti	Integral gain of PI controller
Po	Output Power
Vo	Output voltage
Vind	Inductor voltage drop
Vd	Diode voltage drop
Io	Output current
Ap	Area product
Kw	Window area
J	Current density
f	Switching frequency
Bm	Maximum flux density
Wa.Ac	Area product
Ac	Core area
Np	Primary turns
Ns	Secondary turns
Dmax	Maximum duty cycle
awg	American wire guage

ABBREVIATIONS

DC	Direct current
AC	Alternating current
DSP	Digital Signal Processor
PI	Proportional plus Integral
DLL	Dynamic Link Library
PWM	Pulse Width Modulation
IGBT	Insulated Gate Bipolar Transistor
CC	Constant current
CV	Constant voltage
kVA	Kilo Volt Ampere
D	Duty cycle
avg	Average
ADC	Analog to digital converter
Kp	Proportional gain
Ti	Time constant for integration
IGBT	Insulated gate bipolar transistor

CONTENTS

CHAPTER-1
INTRODUCTION

1.1 GENERAL

Power supplies are extensively used in industrial application. Some critical application cannot tolerate failure of power supply as well as variation in supply. The critical applications involving electric drives require continuous drives performance at all the time irrespective of supply situation, load variation and internal drive condition. Hence it requires battery back up supply.

There are many DC-DC power conversion applications where the voltage source has to be converted to a high output voltage. The utilization of dc-dc switching converters have been extensively increased in many different applications in recent years due to their compactness, low weight, high efficiency and other advantages. . The High power DC converter has a wide spectrum of the applications in the medical, industrial and military areas.[1]Such applications are power supplies for semiconductor fabrication equipment, ultrasound and X-ray equipment[2], photovoltaic systems and Battery back up AC drive. The dc-dc converters are commonly used in space stations, ships and airplanes, as well as in computer and telecommunication equipment. It is expected that modern portable wireless communication and signal processing systems will use variable supply voltages to minimize power consumption and to extend battery life. Low-output voltage converters in these applications utilize the synchronous rectification arrangement. However, in large power systems wherever the input line voltage and output current may have fast and large variations, the role of control strategy selection on dynamic response becomes more essential.[3]

Isolation is required in some of important industrial applications. Switch mode power regulators do not provide the necessary isolation. Hence two stage conversion DC-AC and AC – DC is required. The isolation is provided by inter stage transformer.

1.2 SCOPE OF THE WORK

The major aim of this project work is of setting up of hardware model of high power isolated converter. Literature of various commercial available high power isolated converter has to be studied and features desired in the converter needs to be decided. Provisions of protective features like under voltage protection, over voltage protection, over current protection, heat sink temperature protection etc.,is also made as a part of the work. Initial part of the study need to be focused on various types of high power converter topologies. The work is divided in to four parts; in the first part choose the topology of isolated converter and design of converter. In the second part simulation is done using various control schemes with analog as well as DLL blocks and the results need to be compared. In the third part hardware component design is required and hardware module set up. In the fourth part software is need to implement using DSP based control.

1.3 OBJECTIVES:

To design and implement a high power DC/DC converter with a regulated output voltage with isolation using DSP. Main objectives are to design a converter with the following requirements:

- Cost efficient DC/DC converter
- Output power:10 kW
- DC output voltage: 600V
- Input DC voltage: 144 V (Battery supply)
- Switching frequency of inverter: 6000Hz
- Output voltage regulation: ±5%
- Output current tolerance: ±10%
- Galvanic isolation between input and output: 2.5kv
- Efficiency >90%

1.4 BASIC BLOCK DIAGRAM OF BATTERY BACK UP AC DRIVE

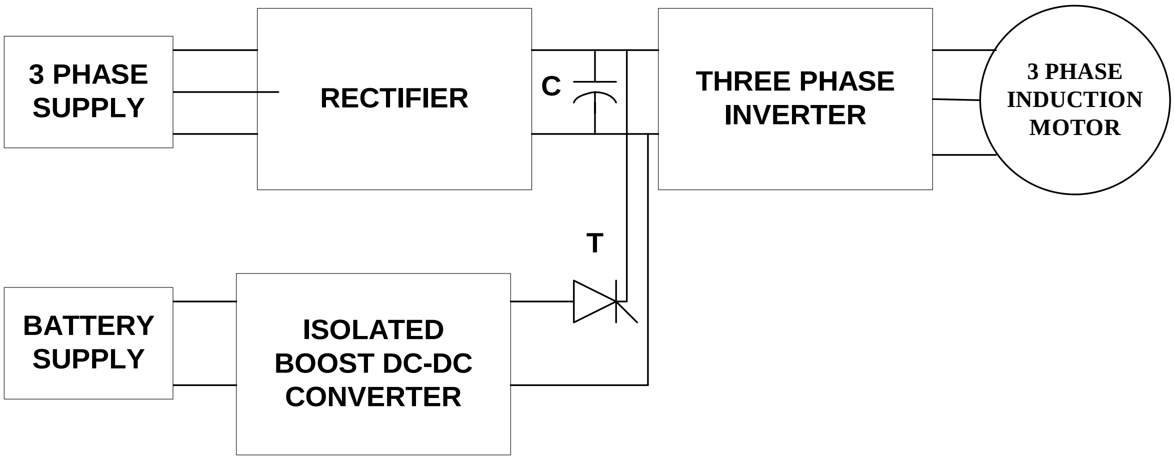

Fig.1.1 Basic block diagram of battery back up ac drive

Fig. 1.1 shows the one of the application of isolated high power dc-dc boost converter in ac drive. The critical applications involving electric drives require continuous drives performance at all the time irrespective of supply situation, load variation and internal drive condition. Hence battery back up supply is needed for drive.

CHAPTER-2
LITERATURE SURVEY

Literature survey plays important role in project. Literature survey consists of power topology, control topology and application of power converter related information. Some important information about full bridge converter, push pull topology, active clamping and transformer design were studied. Papers were taken from IEEE conference proceedings and other standard publication.

2.1 BASIC ISOLATED CONVERTER TOPOLOGY

Here the basic isolated converter topologies like fly back converter, forward converter, push pull converter, half bridge converter, full bridge converter are explained and compared. The most suitable converter topology is found from them for the high power application.

2.1.1 Fly back converter

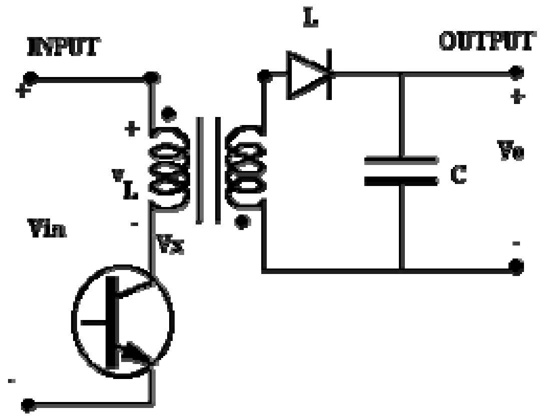

Fig 1.2 fly back converter topology

Fly back converter operates like the buck-boost converter, but using a transformer to store the energy instead of a single inductor.

When Transistor is switched on, current flows from the source through primary winding L1 and energy is stored in the transformer’s magnetic field. When transistor is turned off, the transformer tries to maintain the current flow through primary winding (L1) by suddenly reversing the voltage across it generating a fly back pulse of back-emf.

Fly back converter is use mostly in discontinues mode conduction.

2.1.2 Forward converter

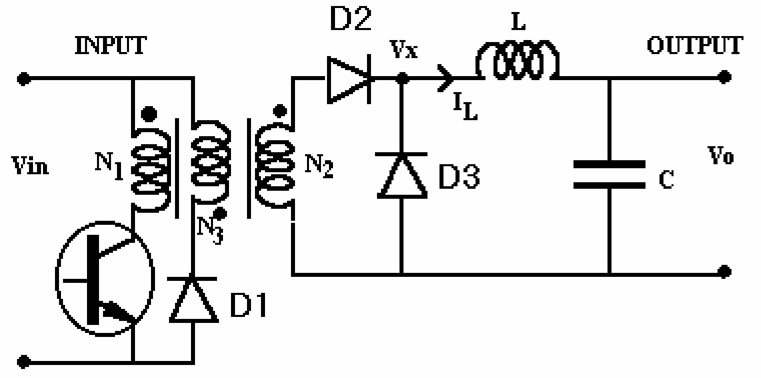

Fig.1.3 forward converter topology

In the forward converter one of the transistors of push pull has been replaced by the diode D1.When transistor is on the dot end primary winding N1 and secondary N2 goes positive with respect to their no dot end. Hence power flows through rectifier, filter and output. Here note that power flows to the load when the transistor is on thus it is known as a forward converter. The transformer core is reset by reset winding. When energy stored in transformer core is return to the supply and the efficiency increased than fly back converter. Unlike the fly back, the forward converter is operated in continuous mode.

The forward converter does not store energy in transformer, for the same out put power level, the size of the transformer can be made smaller than that required for the fly back.

2.1.3 Push pull converter Topology

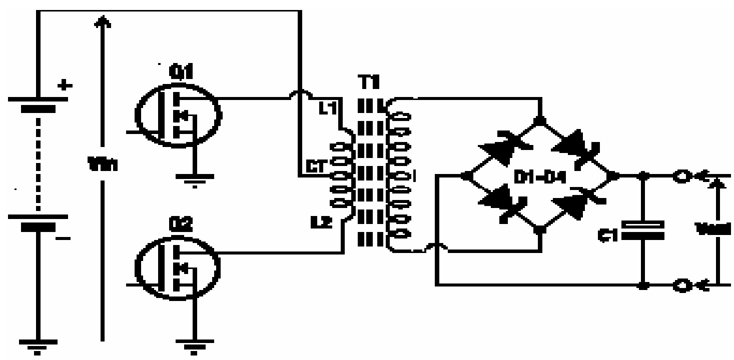

Fig.1.4 Push pull converter topology

This is an oldest topology and still valuable one.

There are two switching MOSFETs, Q1 and Q2, connected to either end of a center-tapped primary winding on the transformer. The positive side of the input voltage source is connected to the center tap. Transistor Q1 and Q2 operate with a 50% duty cycle.

The input voltage is first connected across one half of the primary winding, and then across the other. So current flows first in L1 then in L2.

If one transistor has a slightly larger volt second product than the other, it will start the core drifting slightly of centered towards saturation. This will cause that the transistor to draw slightly more current than the other as it a run away condition is arises and which quickly drives the core in to the saturation and destroys the transistor.

2.1.4 Half Bridge converter

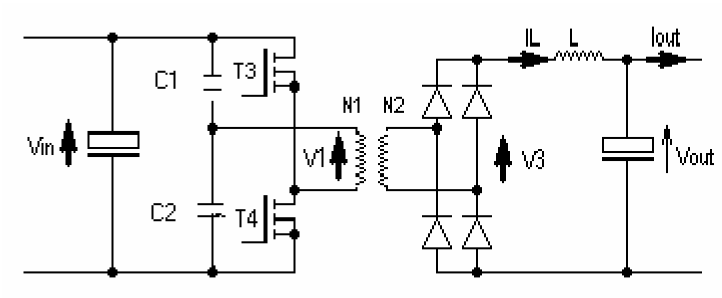

Fig1.5 Half Bridge converter

T3 and T4 are switch on alternatively at each half cycle. When T3 is on and T4 is off, The dot end of n1 have positive voltage as C1. When T4 is on and T3 is off, The dot end of n1 have negative voltage as C2.This Ac square wave primary voltage produce full wave square wave shapes on all secondary.

2.1.5 Full Bridge converter

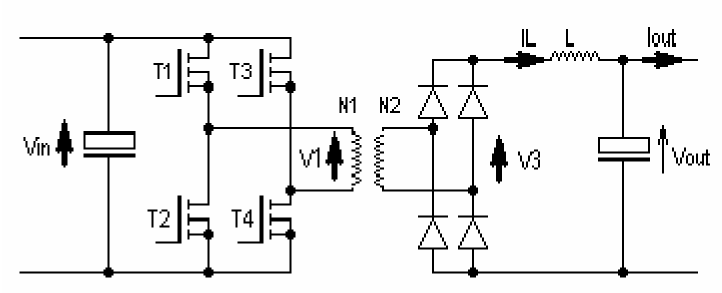

Fig.1.6 full bridge converter

The H bridge inverter is use to convert dc voltage in to square wave ac. This Ac square wave primary voltage produce full wave square wave shapes on all secondary. [4]

2.2 SELECTION OF TOPOLOGY OF DC-DC CONVERTERS

Selection of a topology of dc-dc converters is determined not only by input-output voltages, which can be additionally adjusted with the turns ratio in isolated converters, but also by power levels, voltage and current stresses of semiconductor switches, and utilization of magnetic components. The low part-count flyback converter is popular in low power applications (up to 200W). Its main deficiencies are a large size of the fly back transformer core and high voltage stress on the semiconductor switch. The forward converter is also a single switch converter. Because its core size requirements are smaller, it is popular in low-medium- (up to several hundreds of watts) power applications. Disadvantages of the forward converter are the need for demagnetizing winding, and a high voltage stress on the semiconductor switch. The push pull converter is also used at medium-power levels. Due to bi-directional excitation, the transformer size is small. An advantage of the push-pull converter is also a possibility to refer driving terminals of both switches to the ground, which greatly simplifies the control circuitry. A disadvantage of the push-pull converter is potential core saturation in the case of asymmetry. The half-bridge converter has a similar range of applications as the push-pull converter. There is no danger of transformer saturation in the half-bridge converter. It requires, however, two additional input capacitors to split in half the input dc source. The full-bridge converter is used at high (several kilowatts) power and voltage levels. The voltage stress on power switches is limited to the input voltage source value. A disadvantage of the full-bridge converter is a high number of semiconductor devices. [5]

2.2.1 COMPARISONS OF DIFFERENT TOPOLOGY

Table 1.1 Comparisons of different topology of isolated converter

Forward converter	Fly back converter	Push pull converter
Max of voltage stress across switch is twice the supplied voltage.	Max of voltage stress across switch is the supplied voltage.	Max of voltage stress across switch is twice the applied voltage.
Note that the "dot" convention for the tertiary winding is opposite those of the other windings.	Secondary winding has current flow in reverse direction than the primary winding.	If one switch has a slightly larger volt. Second produced than other it will select drifting slightly off center toward saturation. Thus run away condition destroys switch
Use for 150-200W.	Mostly application below 100w.	Use up to 100-150 W.
Cheap, efficient, smaller in size than other converter.	Transformer design required more cost.	For the same power rating of transformer, size is more than other.

Half Bridge converter	Full Bridge converter
Max of voltage stress across switch is the supplied voltage	Max of voltage stress across switch is the supplied voltage.
Two switches are used.	Four switches are used.
Use up to 400-500W.	Use for 1Kw and above.
Primary supports half the voltage of the full bridge.	Primary supports twice the voltage of the half bridge.
Primary turns must be twice of transformer as full bridge.	Primary turns must be twice of transformer as half bridge.

Full bridge converter is widely use for high power application. One should kept in mind that it has more cost than other topology because maximum switches are use. [6]

2.3 IEEE PUBLICATIONS BASED SURVEY

Some important information about full bridge converter, push pull topology, active clamping and transformer design were studied. Papers were taken from IEEE conference proceedings and other standard publication.

2.3.1 Papers related to power topology

In the paper titled, “A state-of-the-art 50 kW-10 kHz soft-switching assisted pwm DC-DC converter for x-ray power generator”[2], described about PWM DC-DC high power converter using IGBTs**,** which makes the most parasitic LC parameters of high-voltage transformer link, for diagnostic X-ray power generator. A constant frequency phase shift pulse width modulated series & parallel resonant full-bridge DC-DC power converter with resonant poles is practically applied to this equipment. This technique bring about dramatic decreases in the switching losses of' IGBTs and their electrical stresses as compared with the common used hard-switching PWM DC-DC power converter.

In the paper titled, “18 kW dc-dc converter using push-pull inverter with lossless snubber circuits “[16], described about a DC-DC converter of 18 KW capacity for converting ll0V DC voltage available in railway coaches to 675 V DC for feeding variable frequency inverter The converter uses push-pull inverter - transformer - rectifier scheme to provide galvanic isolation between input and output and uses IGBTs along with lossless snubber circuits to switch at 8 KHZ.

In the paper titled, “Design and Technology of Compact High-Power Converters”[17], described new material technologies such as Silicon Carbide (Sic) are promising in the development of compact high-power converters for next-generation power electronics applications. This paper presents an optimized converter design approach that takes into consideration non-linear interactions among various converter components, source and load. It is shown that with the development of high-temperature, high-power Sic power module technology, magnetic components and capacitors become important technology challenges, and cannot be ignored. A 50% improvement in power density is calculated for a 100V-2kV, 7kW SiC DC-DC power converter operating at 150°C compared to a silicon power converter. The SiC power converter can be operated at junction temperatures in excess of 300°C (as compared to 150°C for a silicon power converter) with reasonable efficiency that potentially leads to a significant reduction in thermal management.

In the paper titled," Analysis, Design, and Implementation of an Active Clamp Forward Converter With Synchronous Rectifier"[18], described the system analysis, circuit design, and implementation of active clamp based forward converter with synchronous rectifier. To release the energy stored in the leakage inductor and to minimize the spike voltage at the transformer primary side, active clamp circuit included one clamp switch and one clamp capacitor is adopted in the circuit. Based on the partial resonance with the output capacitor of switch and the leakage inductor of transformer, the main switch is turned on at zero voltage switching (ZVS).

The paper titled, "A Comparison of High-Power DC-DC Soft-Switched Converter Topologies"[19], compare the properties of several soft-switching converter topologies when used to achieve dc-dc conversion at high-power and high-voltage levels. As an example, a 100-kW transformer isolated converter with 700-1400 Vdc input is designed. Converter on conceptual designs and comparisons at the 100 kW level to convert high voltage directly to a lower dc utilization voltage have been performed.

2.3.2 Papers related to control topologies

The paper titled, "Comparison Study of Switching DC-DC Converter Control Techniques"[9], described Normalized small signal model of switching DC-DC converter with voltage mode control, current mode control, V^2 control and V^2C control technique is derived, analyzed and compared in the present paper. It is shown that the transient response character of V^2 control and V^2C control is better than voltage mode control and current mode control, with the transient response character of V^2C control the best. The experiment study performed on buck converter verifies our studies.

The paper titled, "Design and Implementation of a Digital Controller For DC-to-DC Power Converters"[20], described A digital signal processor (DSP) solution is proposed to control an H-bridge DC-DC isolated output power converter.

The multiple mode digital controller is evaluated with an existing Westinghouse 1-kW power stage. This paper documents the elements of a research program to develop a DSP-based digital controller for a high power DC-to-DC converter. The controller developed features a novel architecture in which a CPLD device is used for PWM generation. Separating this converter function from the control DSP eases the DSP's computational load and provides a level of system fault tolerance. Evaluations of the initial selected control strategies show fast transient recovery for load and line disturbances and the potential for stable, tight steady state output voltage regulation.

The paper titled, "High Power DC-DC Converters Under Large Load and Input Voltage Variations: A New Approach."[21], described the Sliding Mode Control based on VSS (Variable Structure System) theory has been examined for all switch mode converter types, whilst Current Mode (CM) control scheme is particularly applied to DC/DC converters. In this paper, a new control strategy by compromising both schemes and derivation of dynamic current reference is proposed, analyzed and simulated. Moreover, considerations for realization with DSP controllers are addressed.

The paper titled, "A Bi-directional Isolated DC–DC Converter as a Core Circuit of the Next-Generation Medium-Voltage Power Conversion System"[22], described a bi directional isolated dc–dc converter considered as a core circuit of 3.3-kV/6.6-kV high power density power conversion systems in the next generation. The dc–dc converter is intended to use power-switching devices based on silicon carbide (SiC) and/or gallium nitride. Which will be available on the market in the near future. A 350-V, 10-kW and 20 kHz dc–dc converter is designed, constructed and tested. It consists of two single-phase full-bridge converters with the latest trench-gate insulated gate bipolar transistors and a 20-kHz transformer with a nano-crystalline soft-magnetic material core and litz wires. The transformer plays an essential role in achieving galvanic isolation.

The paper titled," The Effects of Control Techniques on the Transient Response of Switching DC-DC Converters"[23], described the effects of various control techniques on the transient response of switching power supply have been discussed and compared. To improve the transient response of switching power supply presented by fast load changes, double voltage loop control technique is given. The analysis and simulation results show that double voltage loop control technique has much faster load transient response compared with conventional voltage mode and current mode control techniques.

From the above referred papers and comparison study, one can get idea of different topologies on which people had worked so far. Author has decided the full bride converter topology for high power isolated converter because numerous advantage as discussed.

CHAPTER-3

DESIGN OF FULL BRIDGE CONVERTER

3.1 GENERAL

The full bridge converter is one of the isolated converter topology that use in high power rating. The block diagram of it is shown in Fig 3.1.The battery supply is given to IGBT based full bridge inverter which converts dc to square wave ac, which is supply to high frequency step up transformer, that will again rectified by fast recovery diodes. The rectified dc is filtered and get smooth dc high voltage. This will given to the load and the feedback signal is given to the DSP control card for control and protection purpose.

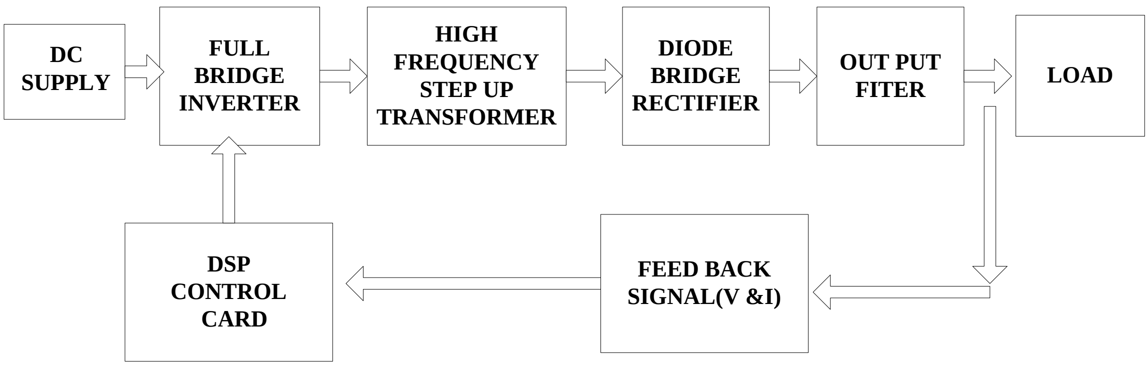

Fig.3.1 full bridge dc- dc converter (block diagram)

3.2 OVERALL SYSTEM DESIGN CALCULATION

Input Data:

P_o=10000W

V_o =600V

V_{in}=144V

Design:

Duty ratio(Dr) = $T_{on} \div T/2$ (assume Dr = 0.8)

$$P_O = V_O \times I_O \Rightarrow I_O = P_O/V_O$$

$$= 10000/600$$

$$= 16.66A$$

$$\text{Rload} = \text{P}_\text{O} \div (\text{Io})^2$$
$$= 10000 / 16.662$$
$$= 36\Omega$$

Secondery voltage of transformer $V_{sec} = (600 + 2(0.8)) / 0.8$

Primary voltage of transformer $V_{pri} = 144$

Turns ratio Ns/Np $= 752 \div 144 = 5.3$

$$\text{I diode(avg)} = \text{Dr} \times \text{Io}/2$$
$$= .8 \times 16.66 / 2$$
$$= 6.66\text{A}$$

$$\text{Rms diode current} = \text{Idiode(rms)} = \sqrt{\text{Dr}/2} \times \text{Io}$$
$$= \sqrt{0.4} \times 16.66\text{A}$$
$$= 10.53\text{A}$$

$$\text{Transformer Secondary VA} = \text{Vsec} \times \text{Idiode(rms)}$$
$$= 752 \times 10.53 = 7918.56\text{VA}$$

$$\text{Transformer Primary VA} = V_{pri} \times \sqrt{2} \times \text{Idiode(rms)} \times \text{Ns/Np}$$
$$= 144 \times \sqrt{2} \times 10.53 \times 5.3$$
$$= 11113.17\text{VA}$$

$$\text{Avg. Diode loss} = 4 \times \text{Idiode(avg)} \times \text{Dr}$$
$$= 21.3\text{W}$$

$$\text{Primary power required} = v_1 \times I_1 = \text{Po} + \text{Avg. Diode loss} + \text{Avg. Switch loss}$$
$$144 \times I_1 = 10000 + 21.3 + (4 \times 1\text{V} \times I_Q)$$
$$= 10000 + 21.3 + (2 \times I_1)$$

$$\therefore \quad I_1 = 70.57\text{A}$$

$$\text{Avg.switch loss} = (4 \times 1\text{V} \times I_Q) = 2 \times I_1 = 2 \times 70.57 = 141.14\text{w}$$

Current through IGBT

$$I_{Q(avg)} = I_1 \div 2 = 35.28\text{A}$$

$$I_{Q(peak)} = I_1 \div Dr = 88.21\text{A}$$

$$I_{Q(rms)} = I_{Q(peak)} \times \sqrt{\text{Dr}/2} = 88.21 \times \sqrt{.4} = 55.78\text{A}$$

Open circuit voltage of switch (IGBT) $= 144\text{V}$

$$\text{Efficiency} = \text{Po} \div \text{Pin}$$
$$= 10000 \div (10000 + 21.3 + 141.14)$$
$$= 98.4\%$$

(Here transformer loss and load ripple current and filter inductor dc voltage drop is not considered)

Filter design

$$\mathrm{Lo} = 0.8 \times .03 \times \mathrm{VO} \div (0.1 \times \mathrm{IO} \times f)$$

$$= 1.73mH$$

$$Co = 0.8 \times \mathrm{IO} \div (0.03 \times \mathrm{VO} \times f)$$

$$= 123\mu F$$

3.2.1 FULL BRIDGE CONVERTER DESIGN USING EXCEL SHEET

Table 3.1 Full bridge converter design sheet

INPUT	QUANTITY	UNIT
Po(Out put power)	10000	W
Vo(Output voltage)	600	V
Vin(Input voltage)	144	V
f(Switching frequency)	6000	Hz
Dr(Max.Duty ratio)	0.8	
OUTPUT		
Io(Load current)	16.66	A
R load	36	ohm
Vsec	752	V
Vpri	142	V
Ns/Np(Turns ratio)	5.3	
Id(avg)	6.66	
Id (rms)	10.54	
Secondary VA	7926.77	VA
Primary VA	11176.75	VA
Avg diode loss	21.33	W
I1	70.57	A
avg switch loss	141.14	W
I_q(avg)	35.28	A
I_q(pk)	88.21	A
I_q(rms)	55.79	A
open ckt voltage of switch	144	V
Efficiency	98	%
L_f(10% of load current variation)	1.73E-03	H
C_f(10%vo variation)	1.481E-04	F

Using this excel design sheet for different input battery voltage and power the analysis is done on which output voltage and on what power the design become more economical and cost effective. The data collected is shown in the table 3.2

Table 3.2 full bridge converter design comparison for different input voltage and load

DESIGN OF FULL BRIDGE CONVERTER
V0=600V

Vin	freq.	Ns/Np	Vsw (max)	Idiode (avg)	Irms (diode)	Transformer		Iqavg	Iq(pk)	Iqrms	Pi	efficiency
Volt	Hz		Volt	Amp	Amp	Pri.VA	Sec.VA	Amp	Amp	Amp	Watt	%
10kw load(Z=36 ohm,Io=16.66A)												
12	6000	75.2	12	6.66	10.53	11133	7896	500.53	1252	791	12013	83
24	6000	34.13	24	6.66	10.53	11133	7896	227.51	569	359	10932	91.47
36	6000	22.08	36	6.66	10.53	11133	7896	147.21	368	232	10611	94.24
48	6000	16.34	48	6.66	10.53	11133	7896	108.92	266.25	168.8	10456	95
60	6000	12.94	60	6.66	10.53	11133	7896	86.39	215	136	10366	96.46
72	6000	10.72	72	6.66	10.53	11133	7896	71.5	178	113	10307	97
84	6000	9.15	84	6.66	10.53	11133	7896	61.04	152	96	10265	96.41
96	6000	7.98	96	6.66	10.53	11133	7896	53.24	266.2	168.4	10234	97.71
120	6000	6.36	120	6.66	10.53	11133	7896	42.41	212.05	134.1	10180	97.51
144	6000	5.29	144	6.66	10.53	11133	7896	35.24	106	68	10192	98
20kw load(Z=18ohm,Io=33.33A)												
48	6000	16.34	48	13.32	21.07	22266	15792	217.4	544	344	20914	95.62
60	6000	12.96	60	13.32	21.07	22266	15792	172.42	431	272	20733	96
72	6000	10.74	72	13.32	21.07	22266	15792	142.86	357	226	20615	97
84	6000	9.17	84	13.32	21.07	22266	15792	121.96	305	193	20531	97.41
96	6000	8	96	13.32	21.07	22266	15792	106.39	531.55	336.2	20469	97.7
120	6000	6.37	120	13.32	21.07	22266	15792	84.75	212	134	20382	98.12
144	6000	5.29	144	13.32	21.07	22266	15792	70.42	176	111	20324	98.4
30kw load(Z=12 ohm,Io=50A)												
48	6000	16.34	48	20	31.62	33400	23688	326.43	817	516	31371	95.63
60	6000	12.96	60	20	31.62	33400	23688	258.89	648	409.5	31100	96.46
72	6000	10.74	72	20	31.62	33400	23688	214.51	536	339	30922	97.01
84	6000	9.17	84	20	31.62	33400	23688	183.12	915.6	579.1	30764	97.51
96	6000	8	96	20	31.62	33400	23688	159.74	400	252	30703	97.12
120	6000	6.37	120	20	31.62	33400	23688	127.25	318	201	30573	98.22
144	6000	5.29	144	20	31.62	33400	23688	105.74	264	167	30487	98.4

As seen from the table calculated above one can observed, as we increase the input voltage the switch current rating is decrease so one has to select one topology such that it will moderate the size of the battery and cost of switch.

3.3 COMPONENT DESIGN AND SELECTION

Component design is one of the most important criteria in any Project. Each and every component requires the special attention according to the required rating of the prototype, which is needed to be made. To Design the isolated boost converter following designing criteria should be keep in mind.

3.3.1 BATTERY

From the above practice of doing system level design, battery is selected to use of 144V. Below it battery takes more current for high power and the IGBT's current rating will goes much higher, that is not preferable because high cost in the market.

3.3.2 IGBT SELECTION FOR H-BRIDGE INVERTER

The inverter contains four IGBTS. The selection of IGBT rating is one of the most important design aspects in this project. The current rating of the IGBT should be 1.5 times the maximum harmonic compensation capacity. Voltage rating of IGBT can be selection on the basis of the supply voltage and ultimately based on the maximum allowable DC link voltage.

3.3.3 TRANSFORMER

Transformer is a major contributor to the weight and volume of a power supply .Major area of transformer design consideration of high power and high frequency dc-dc converter are core material selection, copper loss minimization, skin effect, leakage inductance, temperature. Transformer design is shown in next chapter.

3.3.4 RECTIFIER SECTION

The single-phase rectifier has four diode. As it has high frequency square wave ac input, the diode should have fast reverse recovery time in terms of neno second.

3.3.5 FILTER INDUCTOR AND CAPACITOR

The filter component should be select such that the current ripple and voltage ripple is within limits as per the project requirement definition.

3.4 FINALIZED COMPONENT RATING FOR MODULE

Finally, the component rating is decided which is shown in Fig.1.2.

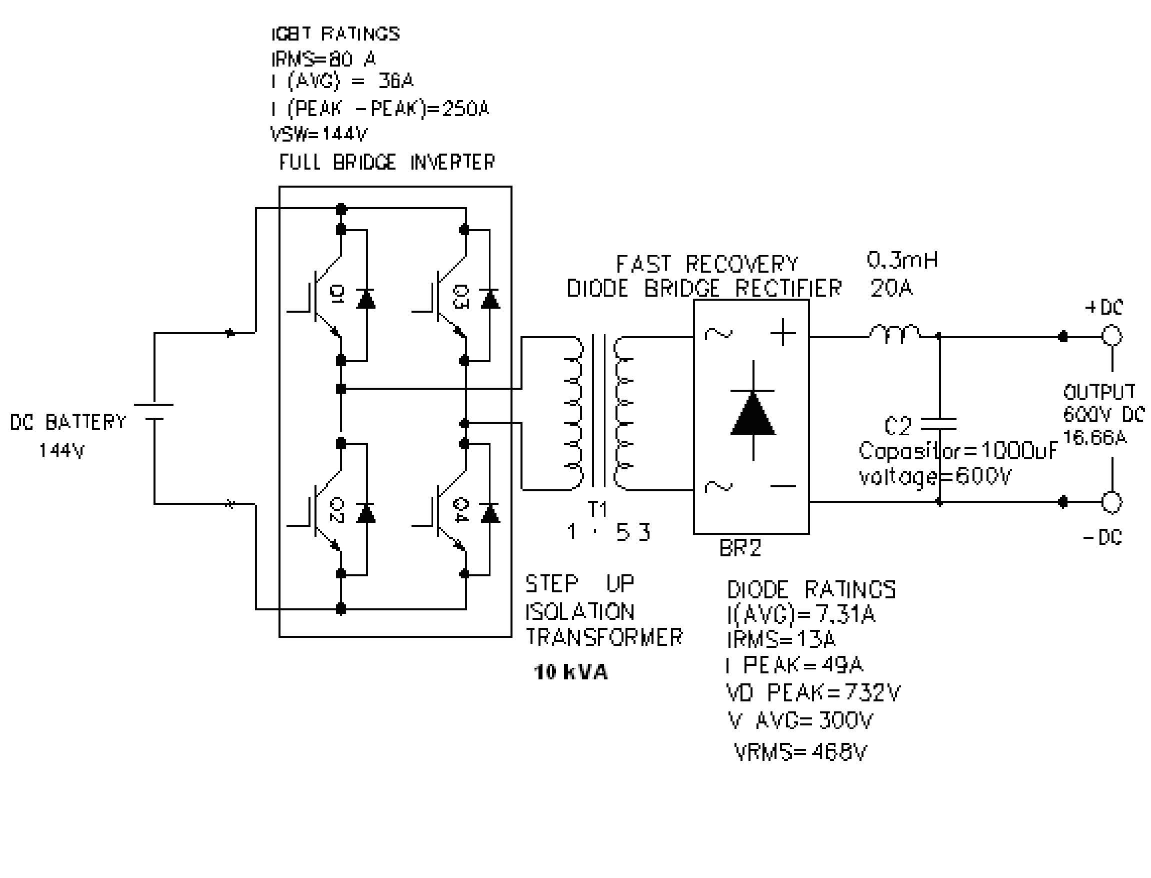

Fig.3.2 Finalized component rating diagram

CHAPTER-4

DESIGN AND DEVELOPMENT OF HIGH FREQUENCY TRANSFORMER

4.1 GENERAL

Transformer is a major contributor to the weight and volume of a power supply. Major area of transformer design considerations of high power and high frequency dc-dc converter are core material selection, copper loss minimization, skin effect, leakage inductance, temperature.

The Characteristics of a good core material include low specific core losses (losses per unit volume) at high frequency, high saturation flux density, high power/weight ratio and good thermal and mechanical properties. Transformer determines about 25% of the overall volume and more than 30% of the overall weight of power supply.

For the most favorable combination of low cost, high Q, high stability, and lowest volume, ferrites are the best core material choice for frequencies from 10 KHz to 50 MHz.

Where typical ferrite cores can only operate up to a flux saturation level (B_{sat}) of 0.49 Tesla, an amorphous metal core can operate at 1.56 Tesla. The C-core also allows for single phase and three phase transformer designs. Amorphous magnetic cores have superior magnetic characteristics, such as lower core loss, when compared with conventional crystalline magnetic materials. Combined with operating at permeability similar to high-end ferrites and the flexibility of manufacturing large cores sizes these cores can be an ideal solution. When comparing Iron Powder to Amorphous core, the amorphous core will tend to be less expensive, and have lower losses, smaller physical size, better heat dissipation, and are mechanically rugged. [7]

The comparison of amorphous core and ferrite core is given in Table 4.1

Table.4.1 Comparison of amorphous and ferrite core

Amorphous core	Ferrite core
Flux saturation level of 1.56 Tesla	Flux saturation level of 0.49 Tesla
Frequency range selection (400 Hz to 500KHz)	Wide frequency range selection (10 KHz to 50 MHz)
Lower losses, smaller physical size, better heat dissipation	Low cost, high Q, high stability, and lowest volume

4.2 TRANSFORMER DESIGN CALCULATIONS

Transformer secondary peak voltage

$$\mathrm{Vsec(peak)} = \frac{\mathrm{Vo} + \mathrm{Vd} + \mathrm{Vind}}{\mathrm{Dmax}}$$

$$= \frac{600 + 2 + 1}{0.8} = 753.75V$$

$$\mathrm{Isec(rms)} = \mathrm{Io(max)} \times \sqrt{\mathrm{Dmax}/2}$$

$$= 21 \times \sqrt{0.4}$$

$$= 13.28A$$

$$\text{Secondary VA of transformer} = \mathrm{V2m} \times D\max \times Io = 602.4 \times 16.66$$

$$= 10035\mathrm{VA}$$

Primary voltage of transformer = Vdc-V (Igbt)

=144-2

=142V

$$\mathrm{Irms(pri)} = \frac{\mathrm{VA\ sec}}{\mathrm{efficiency} \times \mathrm{Vpri}} = \frac{10035}{0.9 \times 142} = 78.52A$$

$$\mathrm{VA(pri)} = \mathrm{Vpri} \times \mathrm{Irms(pri)}$$

$$= 11122\mathrm{V}$$

Area product:

$$\mathrm{WaAc} = \frac{\mathrm{VA\,(sec)} \times 10^8}{4 \times kw \times f \times B\max \times J}(1 + \frac{1}{\eta})$$

Area product = WaAc = $70.43 cm^4$

From amourphous core table select core size.

Here from core data(Appendix - C) , AMCC125 is selected

for AMCC125

Ac=540 mm^2

Aw=2080 mm^2

$$\mathrm{Np} = \frac{\mathrm{Vpri(max)} \times 10^8}{4 \times f \times B\max \times \mathrm{Ac}}$$

$$= \frac{142 \times 10^8}{4 \times 6000 \times 1.2 \times 10^4 \times 5.40}$$

=10 turns

$$\text{wire cross section Area of primary winding} = \frac{\mathrm{Ipri}}{\mathrm{J}}$$

$$= \frac{78.52}{3} = 0.261 = 26.1 mm^2$$

From the wire gauge table AWG3 wire is selected.(APPENDIX-C)

$$\mathrm{Ns} = \frac{\mathrm{Vsec}}{\mathrm{Vpri}} \times Np = \frac{753.75}{142} \times 10 = 53$$

$$\text{wire cross section Area of primary winding} = \frac{\mathrm{Isec}}{\mathrm{J}}$$

$$= \frac{13.28}{3} = 4.42 mm^2$$

From the wire gauge table AWG10 wire is selected.

Total Cu area = $(\mathrm{Np} \times \mathrm{A1}) + (\mathrm{Ns} \times \mathrm{A2})$

=492.116mm^2

Available window area = KwAw

$$= 0.4 \times 1400 = 560 mm^2$$

Total cu Area <Available window area

Hence condition is satisfied.

Table 4.2 Transformer design sheet of full bridge DC-DC converter.

FULL BRIDGE TRANSFORMER DESIGN

INPUT	Specifications	Unit
Po(output power)	10000.00	Watt
Vo(out put voltage)	600.00	V
Io(output current)	16.67	A
F(frequency)	6000.00	Hz
Vin(input voltage)	144.00	V
N2/n1(transformation ratio)	5.30	
Kw(window factor)	0.40	
J(current density)	3000000.00	A/m^2
Dmax(duty ratio)	0.40	
Bm(maximum flux density)	1.20	Tesla
OUTPUT		
Vpri(primary voltage peak)	142.00	V
Vsec(secondary voltage peak)	752.00	V
vo2	603.00	(vo+vrl+vd)
po2	10050.00	Watt
Ap(area product)	70.4375E-07	m^4
Ap	70.43	cm^4
Ap	704375.00	mm^4
vin max	158.40	V
vin min	129.60	V
From ap find core		
N2/n1 calcu	5.30	
i2rms(secondary current)	10.54	A
i1rms(primary current)	88.26	A
area of primary wire	29.42	mm^2
area of secondary wire	3.51	mm^2
to find turns add core area from core table		
Ac(core area)	540.00	(fill this from core table in mm2)
n1(primary turns)	10	
n2(secondary turns)	53	
Aw(window area)	2080.00	(fill this from core table in mm2)
Kwaw	832.00	
A1n1+a2n2	489.18	
CORE SELECTION IS TRUE		

Transformer area product (Ap) is change for different input voltages, power, frequency and current density. Analysis is done for different voltage, power and current density. The economical and efficient transformer design may found out. This is shown in table 4.2.

4.3 TRANSFORMER DESIGN TABLE FOR DIFFERENT FREQUENCY AND VOLTAGE

Table 4.3 Core selection table

J Current Density	Po Output power (kW)	f switching freq.	vin input Battery voltage	Amorphous Ap(Area product)	Amorphous Core	N1 (turns)	N2 (Turns)	Ac mm2	Aw mm2	Pri Wire Area	Sec Wire area	Primary Wire (awg)	Pri Wire DIA(n1)	Sec Wire (Awg)	Sec Wire DIA(n2)
3	10	6000	72	71.44	AMCC 125	5.09	54.71	540	2080	59.6	3.51	00(2/0)	9.266	14	1.628
4	20	6000	72	107.16	AMCC 200	3.53	37.88	780	2080	89.5	5.27	0000(4/0)	11.68	10	2.58
5	20	6000	72	85.73	AMCC 125	5.09	54.71	540	2080	71.6	4.22	000(3/0)	10.4	10	2.58
5	30	6000	72	128.29	AMCC 200	3.53	37.88	780	2080	107	6.32	0000(4/0)	11.68	9	2.9
3	10	6000	144	70	AMCC125	10.19	53.94	540	2080	29.4	3.73	2	6.54	11	2.3
4	20	6000	144	105.65	AMCC 200	7.05	37.34	780	2080	44.1	5.27	0(1/0)	8.25	10	2.58
5	20	6000	144	84.52	AMCC 125	10.19	53.9	540	2080	35.3	4.22	1	7.34	10	2.58
5	30	6000	144	126.78	AMCC 200	7.05	37.34	780	2080	52.9	6.32	0(1/0)	8.25	9	2.9
3	10	6000	48	72.48	AMCC 125	3.4	55.5	540	2080	90.8	3.51	0000(4/0)	11.68	14	1.628
4	10	6000	48	54.36	AMCC 80	3.5	57.64	520	1400	68.1	2.64	000(3/0)	10.4	13	1.82
5	10	6000	48	43.49	AMCC 63	4.7	76.8	390	1400	54.4	2.11	00(2/0)	9.266	13	1.82

Table 4.4 Final core selection table

J Current Density	Po Output power	f switching frequency	vin input battery voltage	Ap(Area product)	Amorphous Core	N1 (turns)	N2 (Turns)	Ac (mm2)	Aw (mm2)	Pri Wire Area	Sec Wire area	Pri. Wire (awg)	Pri Wire DIA(n1)	Sec Wire (Awg)	Sec Wire DIA(n2)
3	10000	6000	48	72.48	AMCC 125	3.4	55.5	540	2080	90.82	3.51	0000(4/0)	11.68	14	1.628
3	10000	6000	72	71.44	AMCC 125	5.09	54.71	540	2080	59.68	3.51	00(2/0)	9.266	14	1.628
3	10000	6000	144	70	AMCC125	10.19	53.94	540	2080	29.4	3.73	2	6.54	11	2.3

Final core selection table give three cores to be selected for transformer. To optimize the design one should has study about characteristic of these cores like Thermal characteristics (permeability→Temp), Magnetizing characteristics (AL→Amp. turns),B-H curve, core loss curve etc.The design of 144V is selected hence AMCC100 is use to design the transformer as shown design details in Table5.6.Under the consideration of temperature AMCC125 is used to made transformer.

4.4 DEVELOPMENT OF TRANSFORMER

To make the transformer following steps one should have to follows.

1.) Make/purchase the bobbin as per dimensions of transformer core selected.

2.) Wound the primary and secondary winding in such a way that gives minimum leakage and maximum coupling between them. Magnetizing inductance should be sufficient.

3.) Between primary and secondary winding take the insulation layer such that it gives desire isolation between them.

4.) Test the designed transformer for isolation.

5.) Measure the magnetizing inductance, primary leakage inductance, secondary leakage inductance, primary resistance, secondary resistance.

4.4.1 Design of Bobbin for the AMCC 125 C-core

The amorphous C core AMCC125 is shown in Fig.4.1.The amorphous C-core top view and cross section is shown in figure 4.2 below. To wound the primary and secondary windings on it one has to make a bobbin.

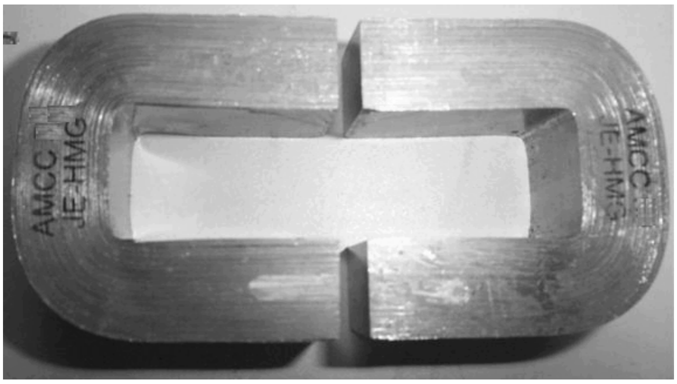

Fig.4.1 Amorphous C core top view

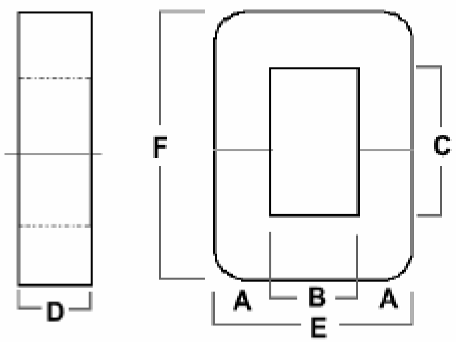

Fig.4.2 Amorphous C core cross sectional view

In the design of the bobbin there are basically three part of design for C-core . One flat A-section, one I- section and one O-section. According to dimension of the bobbin is design as follows.

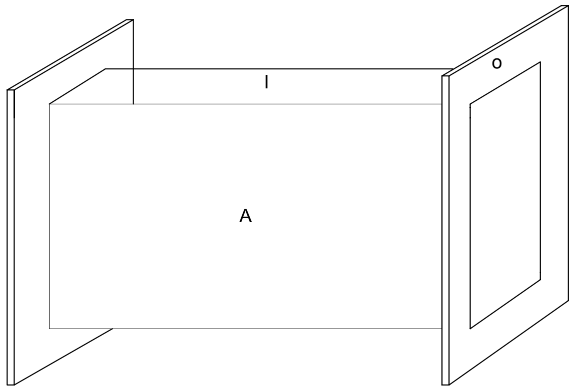

Fig.4.3 Bobbin of the transformer core

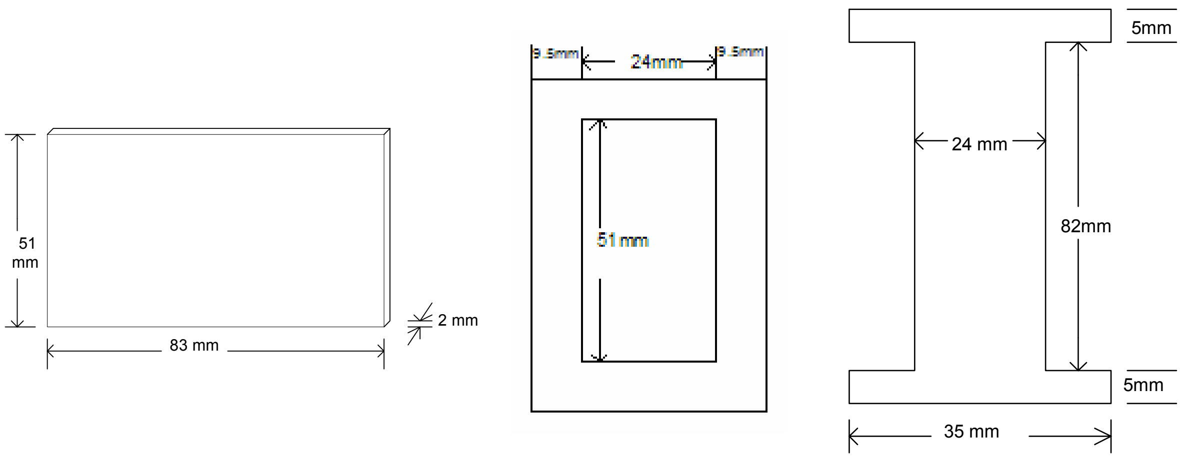

Fig.4.4 A ,O and I – Section of bobbin

Using these sections one should have prepare two bobbins for two C-cores as shown in figure 4.3. Here the sheet used for make bobbin is 2 mm thick. After make bobbins ,wound wire as per the winding data shown in table 1.1. Sandwiching of primary and secondary winding is important for low leakage and good coupling effect. Take insulation between primary and secondary as per requirement of isolation level.

Table 4.5 Winding Data

Windings	Wire size used	No of wire paralled	No.of turns
Primary winding	AWG15(D=1.4mm)	16	13
Secondary winding	AWG15(D=1.4mm)	2	70

The overall view of made transformer (10 KVA) is shown in Fig.4.5

Fig.4.5 HF Transformer

4.4.2 Transformer data measurement

The transformer is passed an isolation test to bare 4.5 kV between primary and secondary. The following data is collected using LCR meter.

Table.4.5 Measured transformer data

Primary resistance	1.73mΩ
Secondary resistance	73 mΩ
Magnetizing inductance	0.4Mh
Primary leakage inductance	2.5µH
Secondary leakage inductance	46µH

CHAPTER-5

SIMULATION OF FULL BRIDGE CONVERTER

5.1 GENERAL

Linear regulator often plays important role in implementing power supply capable of constant voltage/current control. It always provides lots of advantage such as low ripple noise, low EMI, good regulation, ease control strategy. However due to bulky size, low efficiency switch mode technique has become an inevitable development trend for raising the power density, power efficiency and dynamic performance.[8] The full bridge converter is one of the isolated converter topology that use in high power rating. The block diagram of it is shown in figure 3.1. The feedback signal of voltage and current are given to the DSP control card for control and protection purpose.

5.2 CLOSE LOOP CONTROL

Control system should be able to adjust duty cycle in time in order to regulate the output voltage with input voltage and load variation. Voltage-mode and current-mode control techniques are most popular control technique adopted to design switching power supply.

As the speed of the processors increase and the large load changes frequently encountered in system when the system transition from the sleep male to the active mode and vice verse, the faster transient response of DC-DC power supply has been more and more important.[9] The designer must implement a solution to handle this large load step by applying a very fast transient response from the power supply. Improving transient response may be obtained by using a linear regulator, but reducing efficiency renders this solution impractical in high current applications.

5.2.1 Voltage control method (CV mode control)

The transient response of voltage mode control is slow when the input voltage is changing because it has only one feedback loop. It can be seen that the input voltage varying only after the variation of output voltage occurs. In fact, the transient response of voltage mode control is slow for any variations of power stage because voltage mode control doesn't have non-lag feedback loop.[10]

5.2.1.1 Conventional Control Scheme

In Figure 5.1 below represent the switch position of FB-PWM Inverter. SW1 to SW4 each represent IGBTs, which will be connected in parallel to handle the high current. When SW1 and SW4 are closed, the other two switches are open. This produces a positive voltage to the primary terminal of the transformer. Afterward, all switches are opened for a short time period. Following this brief moment, the switches SW2 and SW3 are closed while switches SW1 and SW4 remain open. This produces a negative voltage to the primary terminal of the transformer. In other words, this procedure inverts the input DC voltage. This switching process produces an AC square wave voltage to the primary of the transformer.[11]

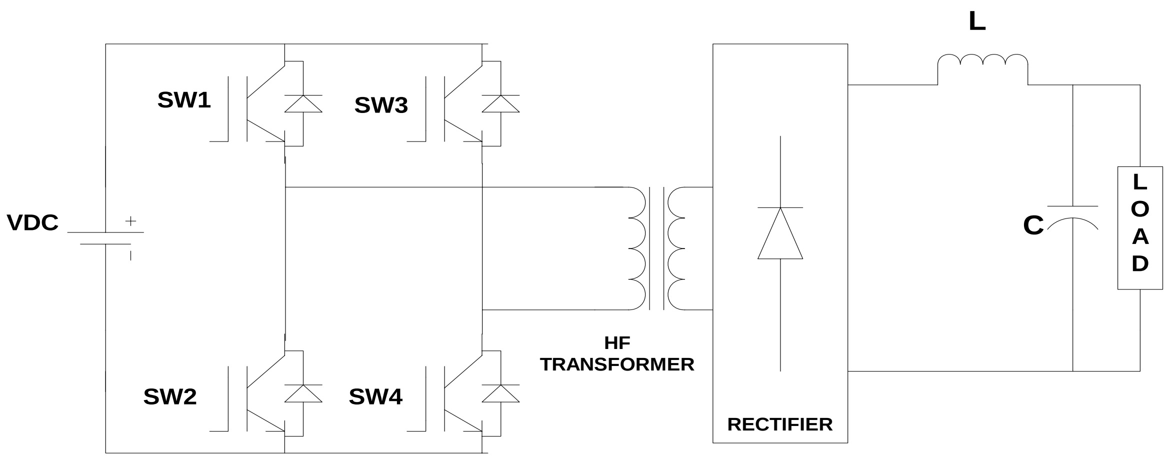

Fig. 5.1 Full Bridge DC-DC converter

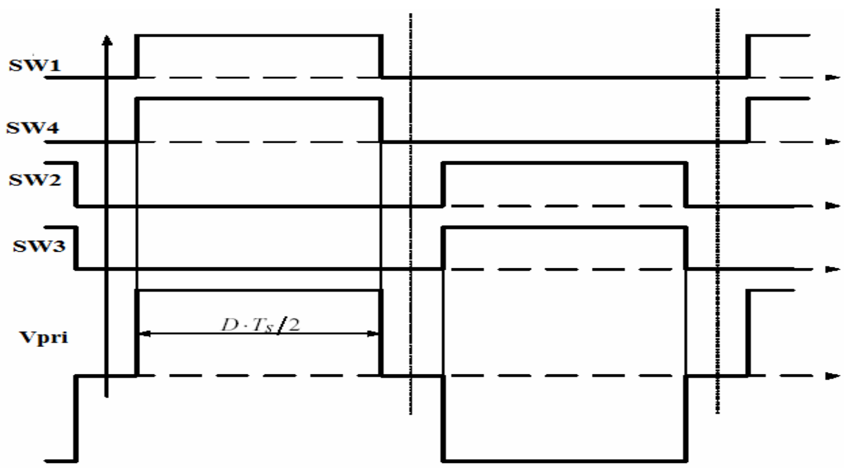

Fig. 5.2 Conventional control scheme for Full Bridge DC-DC converter

The conventional control scheme is shown and simulated. The results were got and discussed.

5.2.1.2 Simulation of conventional control scheme for full bridge converter

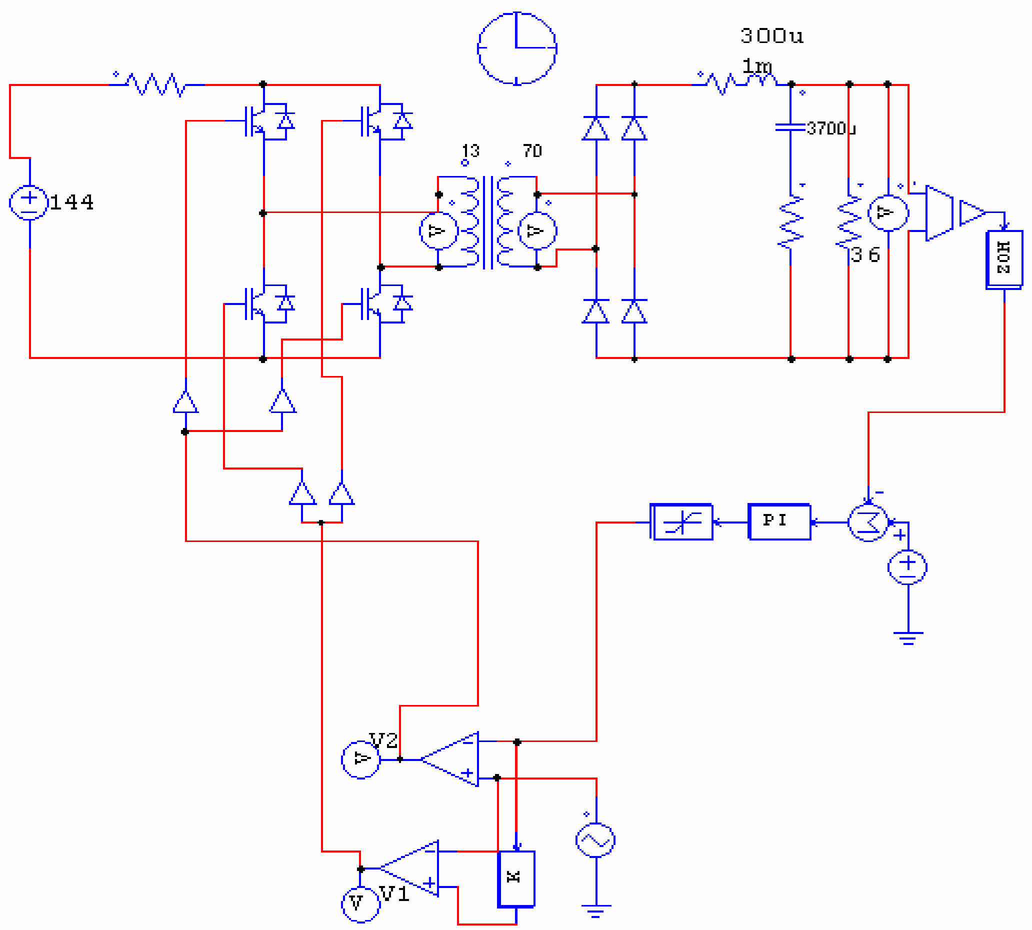

Fig 5.3 Simulation of conventional control scheme for full bridge converter

Figure 5.3 shows a simple PWM controlled full bridge converter operating at 6000Hz frequency. When the output voltage is lower than the nominal dc output value, a high voltage is produced The duty cycle is increased to cause a subsequent increase in output voltage in voltage control mode. Main drawback of this is slow transient response of output voltage.

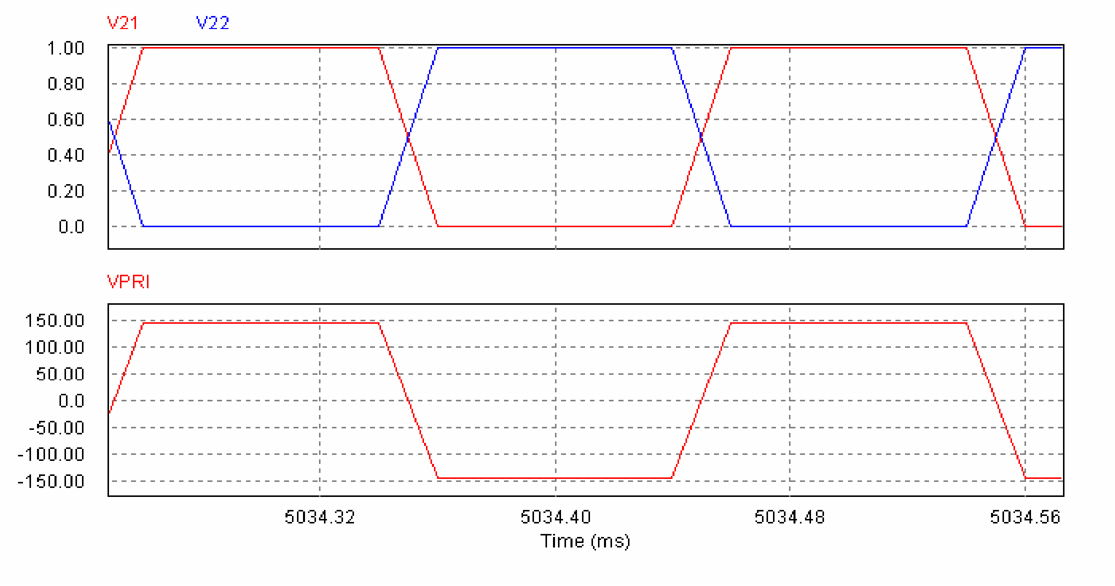

Fig.5.4 Transformer wave form at full Duty cycle(D=90%)

V21,V22= Gate pulses of IGBTS,Vpri= transformer primary voltage wave

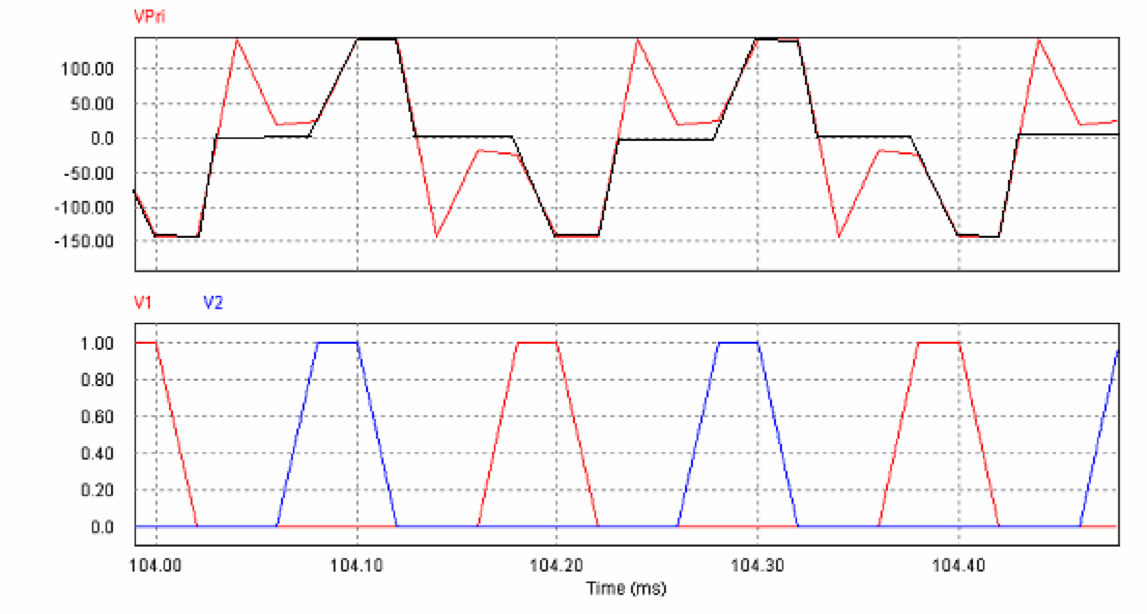

Fig.5.5 Transformer wave form at Duty cycle D=50%

Vpri= transformer primary voltage wave,V1,V2=Gate pulses of IGBTS.

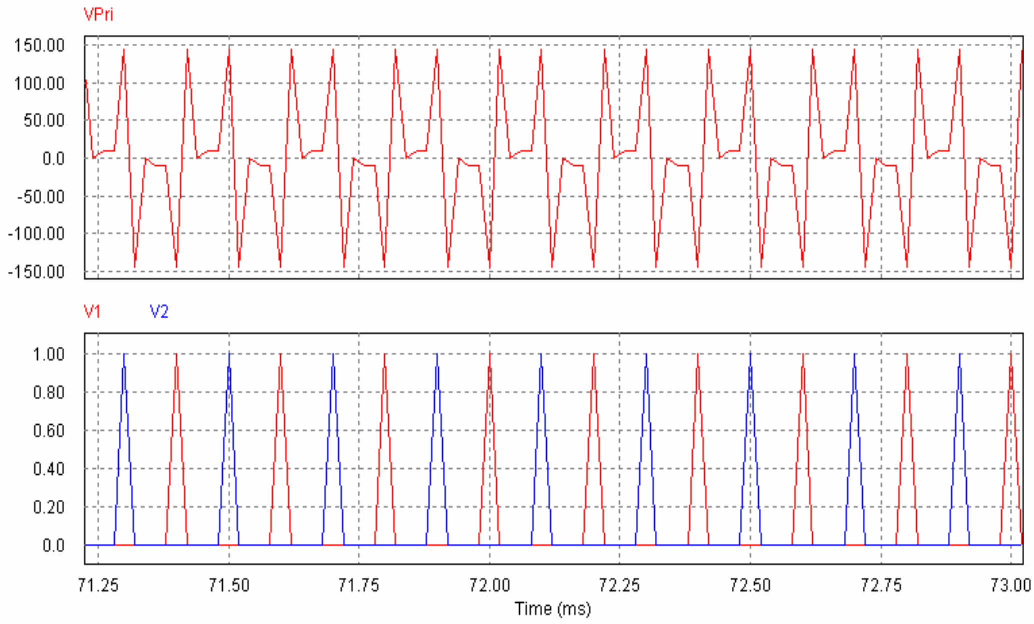

Fig.5.6 Transformer wave form at Duty cycle D=20%

Vpri= transformer primary voltage wave,V1,V2=Gate pulses of IGBTS.

The simulation results of full bridge converter using conventional control scheme, the transformer waveform is some typical other than the normal. Transformer gives energy backs when all switches are off. So the phase shift control scheme is checked using simulation.

5.2.2 Phase shift control scheme

When conventional PWM converters are operated at high frequencies, the circuit parasitic has negative effects on the converter performance Switching losses increase in high power applications and snubbers and/or other means of protection are required, which introduce significant losses and lower the efficiency. In the case of the conventional full bridge converter, the diagonally opposite switches (SW1 and SW4, or SW2 and SW3) are turned on and off simultaneously as shown in Figure 1.In the Full Bridge converter, when all four switches are turned off, the load current freewheels through the rectifier diodes. In this case the energy stored in the leakage inductance of the power transformer causes severe ringing with parasitic capacitances of IGBT. This creates the need for using snubbers that increase the overall losses bringing down the efficiency. If snubbers are not used, the selection of the devices becomes more difficult as the voltage rating for these switches has to be much higher. As the voltage rating goes up, so do the conduction losses and as a result the overall losses increase. At the same time the cost increases as well. In order to minimize the parasitic ringing, the gate signals of SW2 and SW4 are delayed (phase-shifted) with respect to those of SW1 and SW3, as shown in Figure 2, so that the primary of the transformer is either connected to the input voltage or shorted. The leakage inductance current is never interrupted, thus solving the problem of parasitic ringing associated with the conventional full-bridge DC converter.[12]

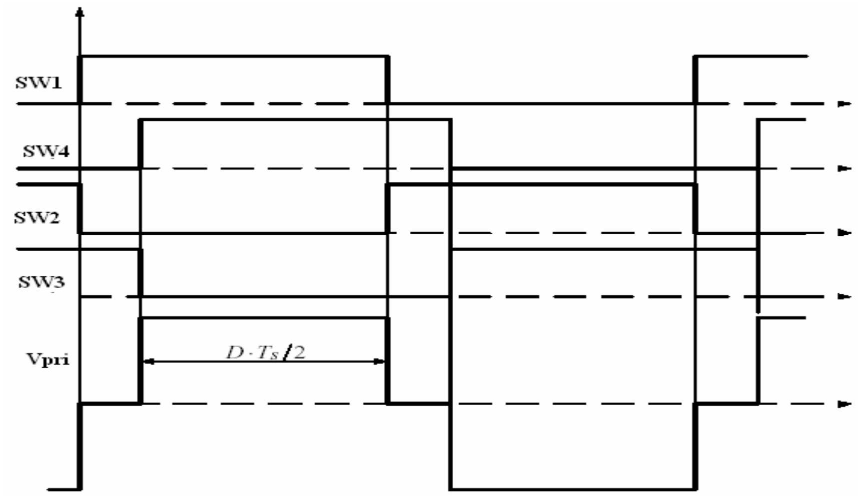

Fig.5.7 Transformer wave according to phase shifted gate pulse.

5.2.2.1 Simulation of Phase shift control scheme

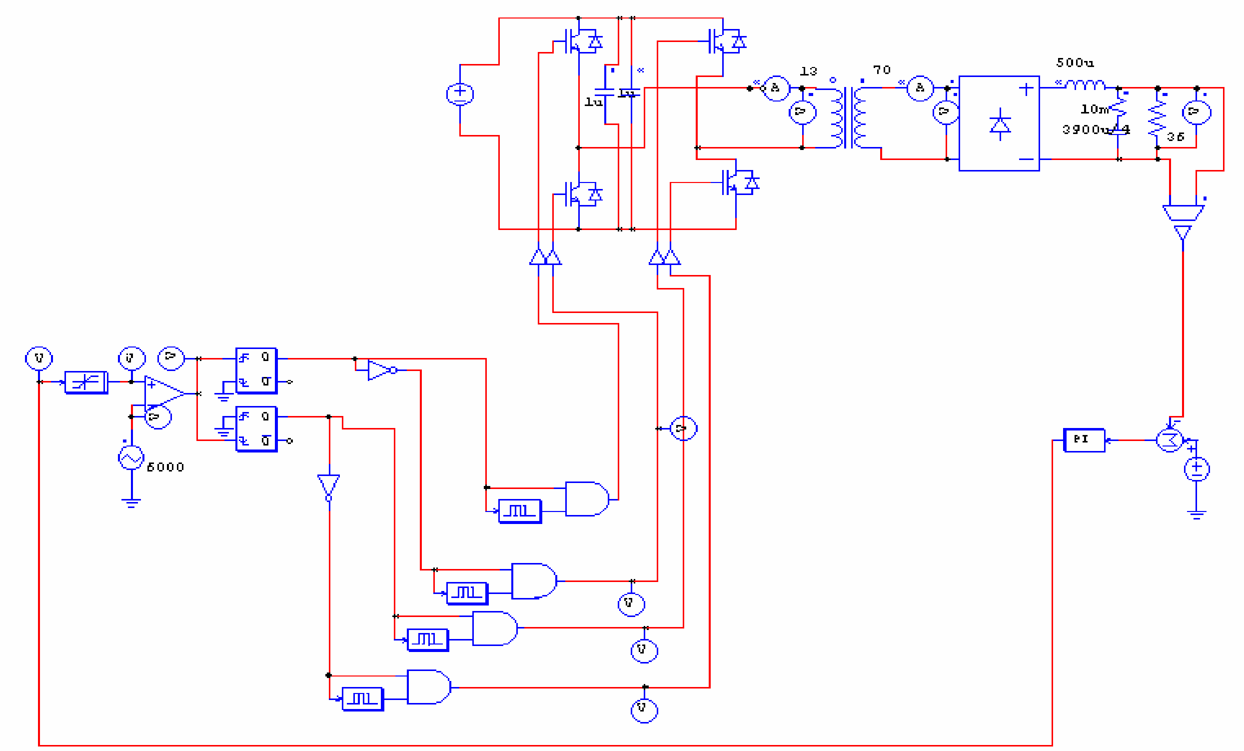

Fig.5.8 Simulation circuit with Phase shift control scheme

The simulation of the full bridge converter has been perform with simulation tool PSIM5.0 for Phase shift control topology and the results obtained are presented in this chapter.

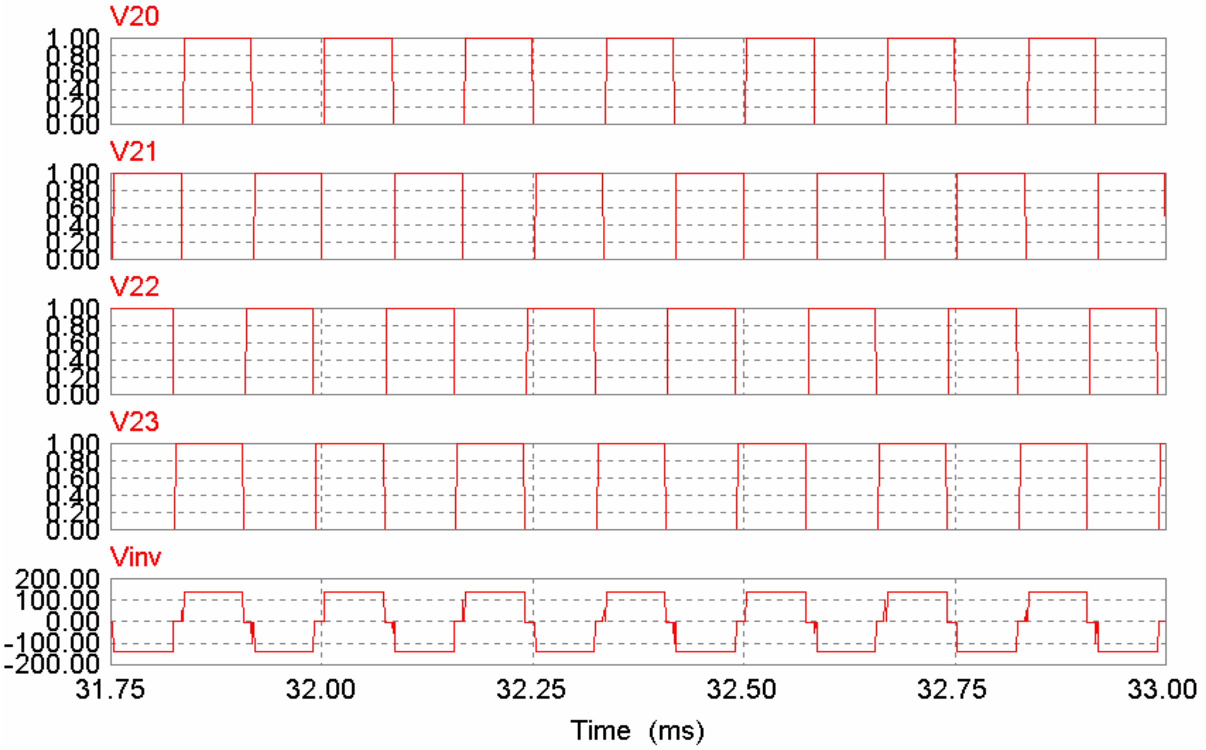

Fig.5.9 Wave formsV20,V21,V22,V23 are Phase shifted Gate pulse of IGBTS,Vinv is Transformer primary voltage.

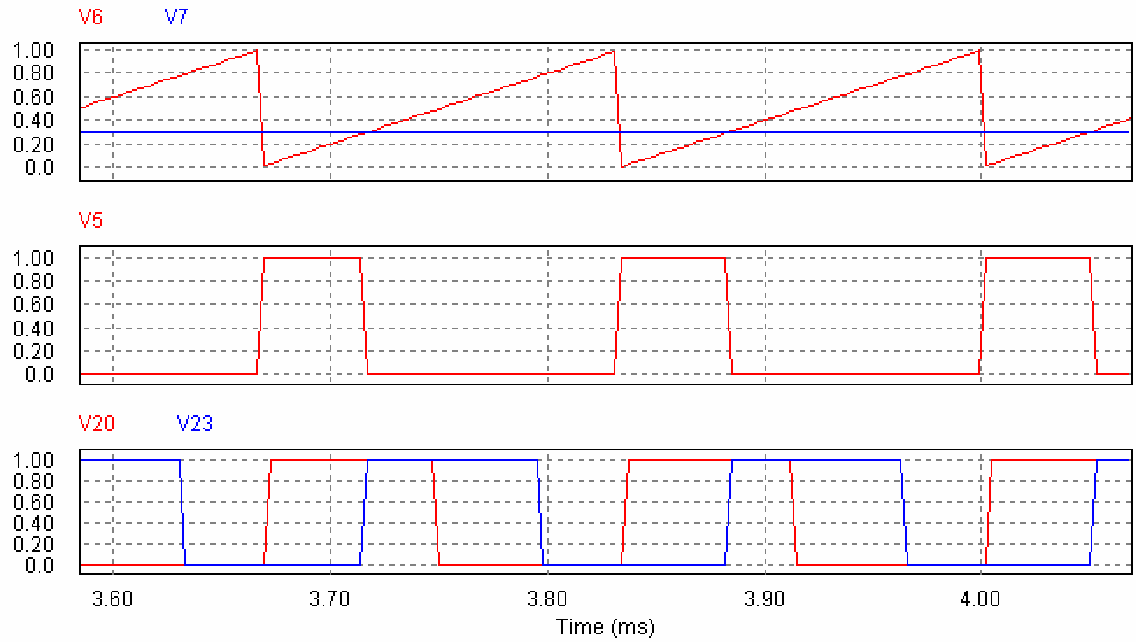

Fig.5.10 Waveform V6 is Carrier wave,V7 is error signal,V5 is compared PWM pulse and V20,V23 are phase shifted gate pulses of SW-1 and SW3.

As shown in Fig.5.10 the carrier wave of 6 KHz is generated. The error signal is compared with the carrier saw tooth wave and produce the PWM pulse as shown in trace V5.On the rising edge and falling edge of the pulse V5 independent pulses is generated of time T/2.this is shown by trace V20 and V23.

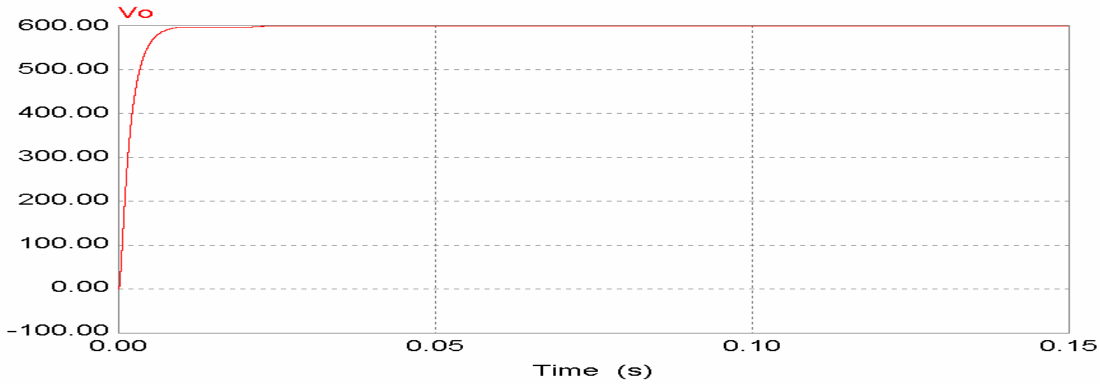

Fig.5.11 Output voltage at full duty cycle.

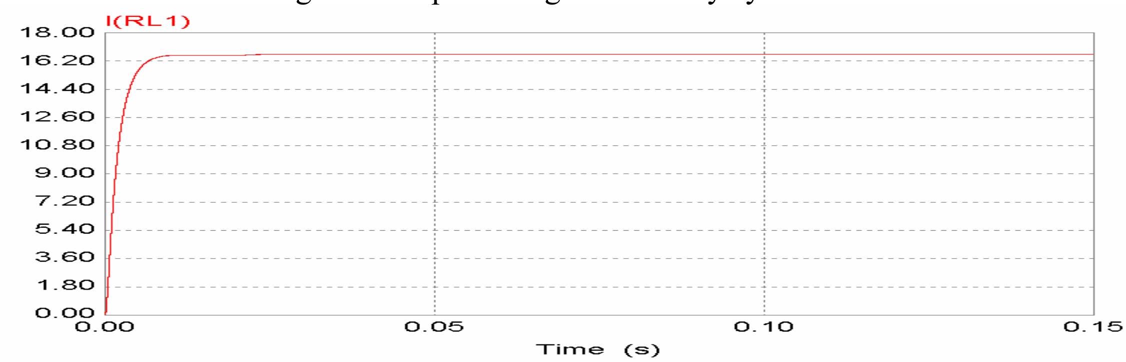

Fig.5.12 Output current at full duty cycle.

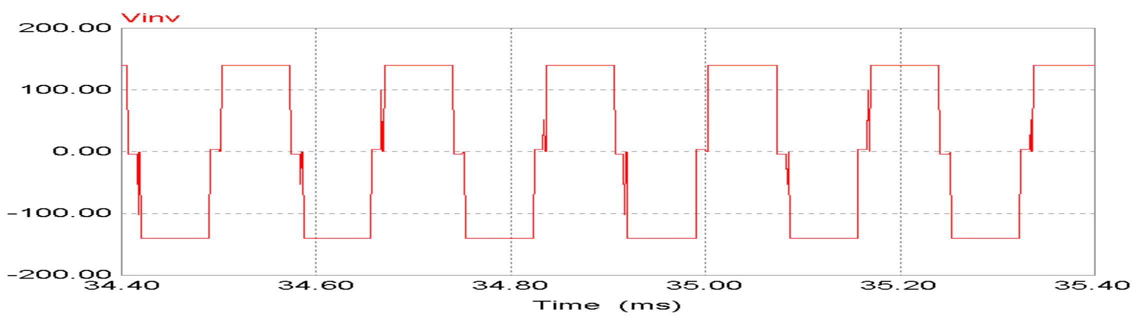

Fig.5.13 Transformer Primary voltage

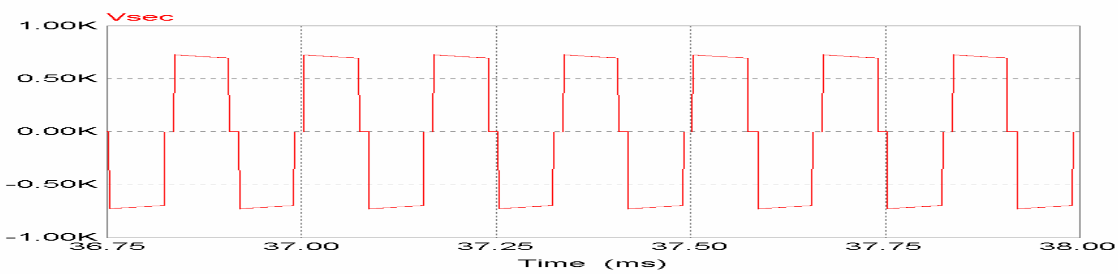

Fig.5.14 Transformer secondary voltage

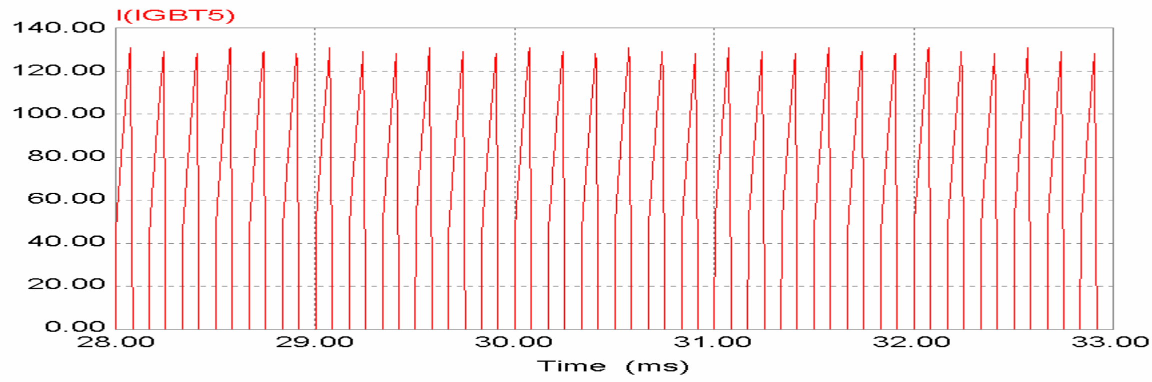

Fig 5.15 IGBT current (Average I_G= 41A)

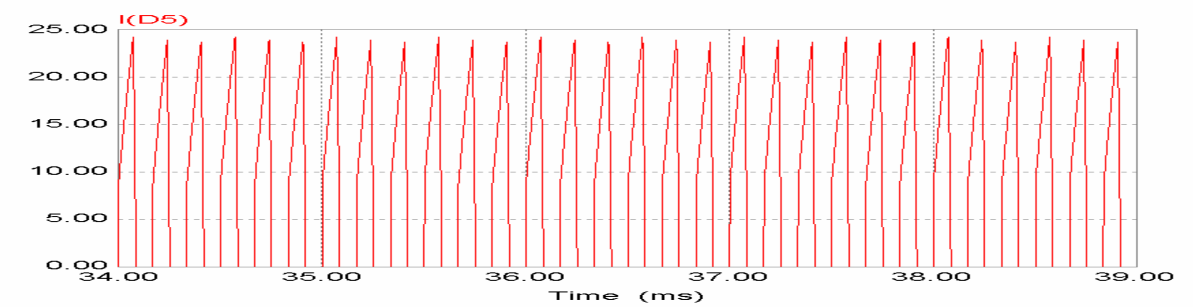

Fig.5.16 Diode current (Average Id=8A)

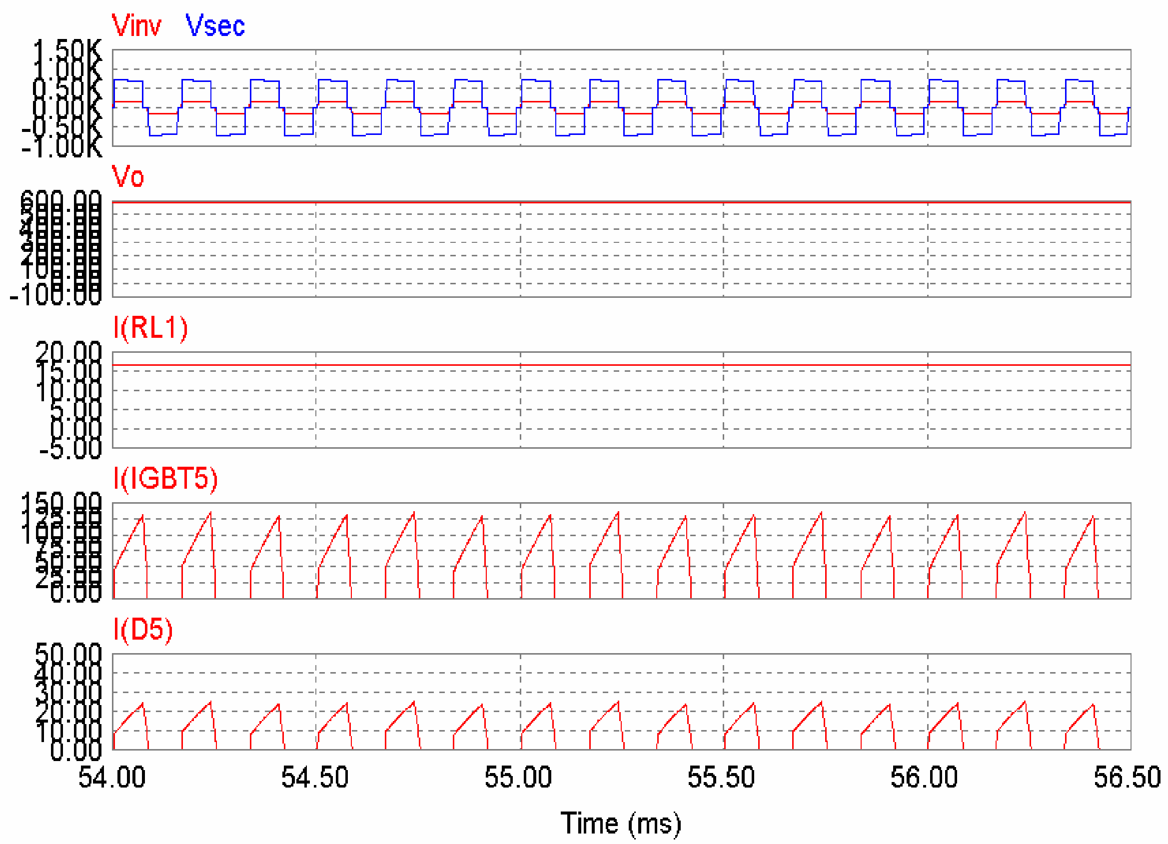

Fig.5.17 Vinv=Transformer primary voltage,Vsec=Transformer sec.voltage, Vo=Output voltage, I(IGBT5)=IGBT current(avg. current=44A),I(D5)=Diode current(Idavg.=8.2A)[wave forms at D =88%]

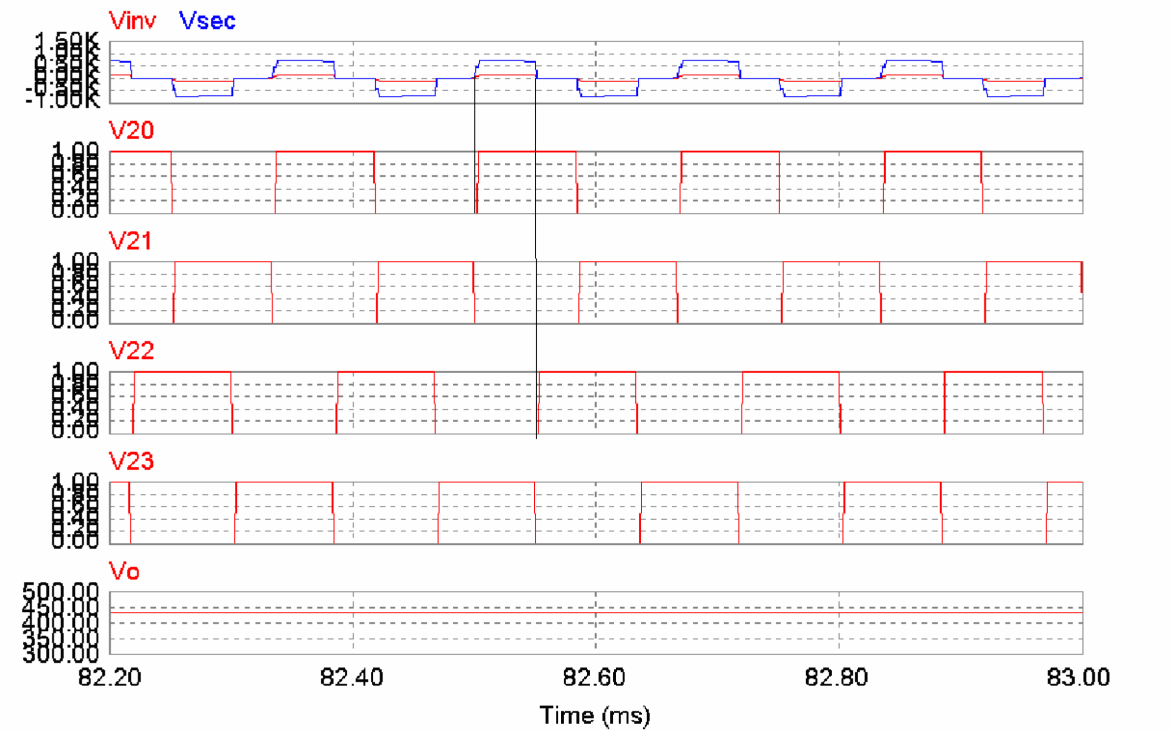

Fig.5.18 Vinv=Transformer primary voltage,Vsec=Transformer secondary voltageV20,V21,V22,V23=Phase shifted Gate pulse,Vo=output voltage(D=60%)

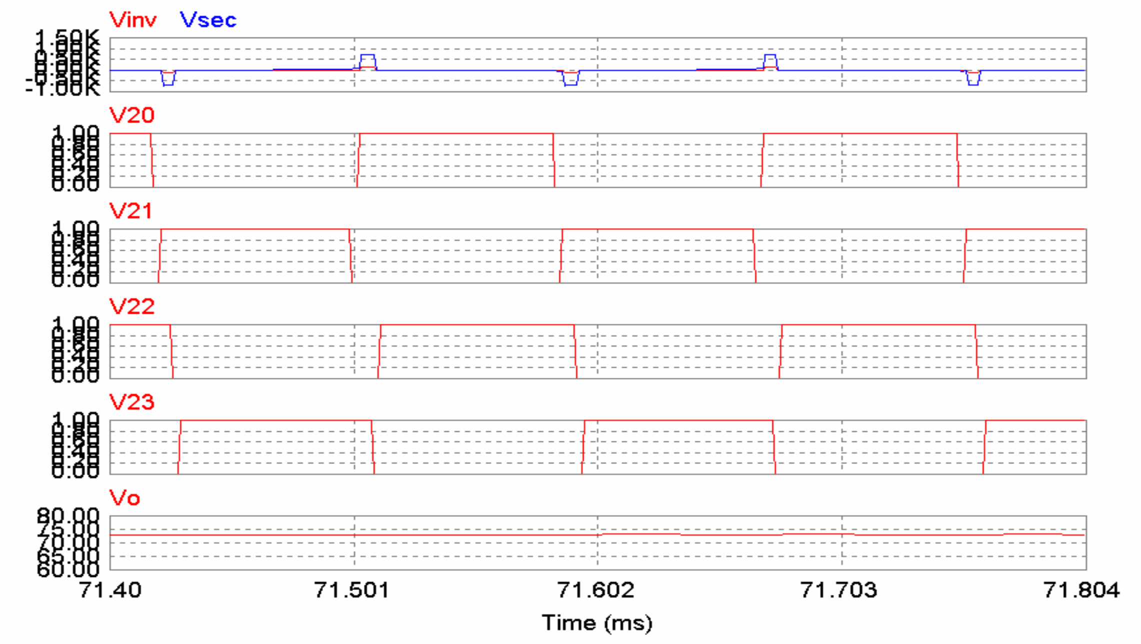

Fig.5.19 Vinv=Transformer primary voltage,Vsec=Transformer secondary voltageV20,V21,V22,V23=Phase shifted Gate pulse,Vo=output voltage(D=10%)

5.2.2.2 Load regulation

5.2.2.2.1 Overload condition

With heavy load variation (two times the normal load) CV mode control gives constant voltage with a permissible limit of fluctuation.

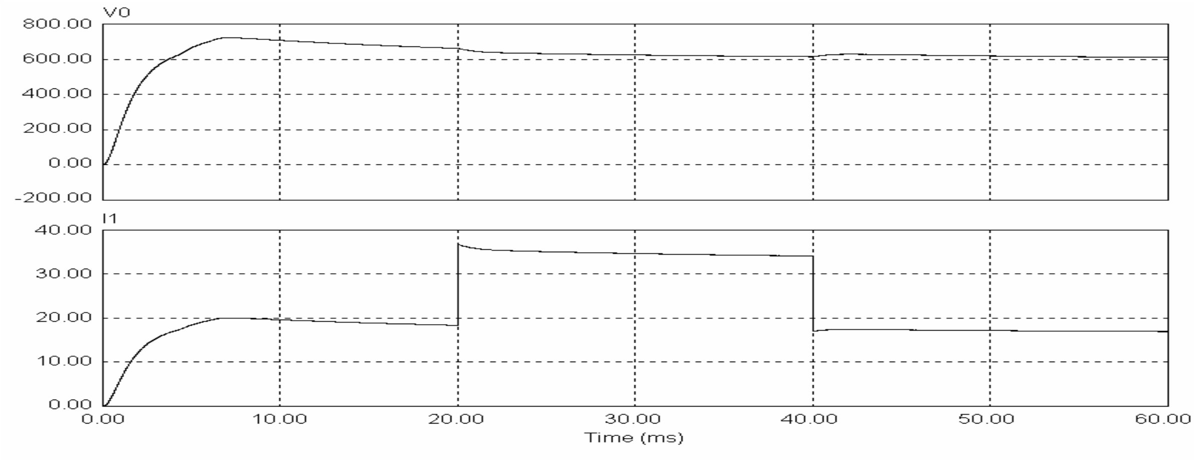

Fig.5.20 Output voltage and current when load is suddenly increase from normal to doubled.

5.2.2.2.2 Under load condition

With half the normal load this method gives constant voltage.

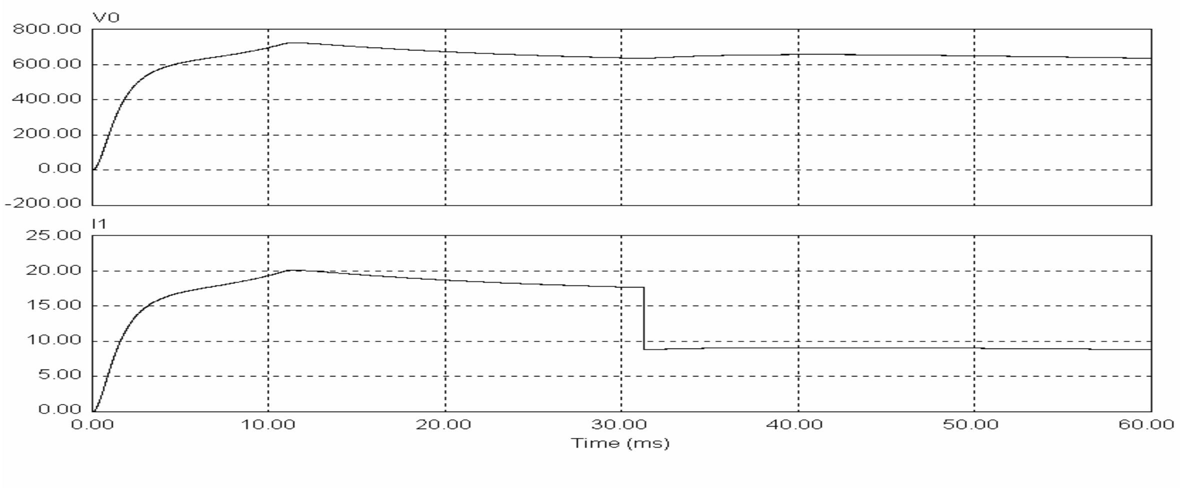

Fig.5.22 Output voltage and current when load is suddenly decrease from Normal to half.

From the above simulation results of different control topologies one can select which topology should be used. Current mode control gives fast transient response against input voltage fluctuation and constant voltage mode control gives fast transient response against output load variation. Current mode control is difficult to use effectively in high-power dc-dc applications due to the dc current-sensing waveform must be scaled down resulting in a very small ramp. .Due to fast response and simplicity Author has decided to use voltage mode control method.

5.3 SIMULATION OF FULL BRIDGE CONVERTER WITH DLL BLOCK

5.3.1 Flowchart of program

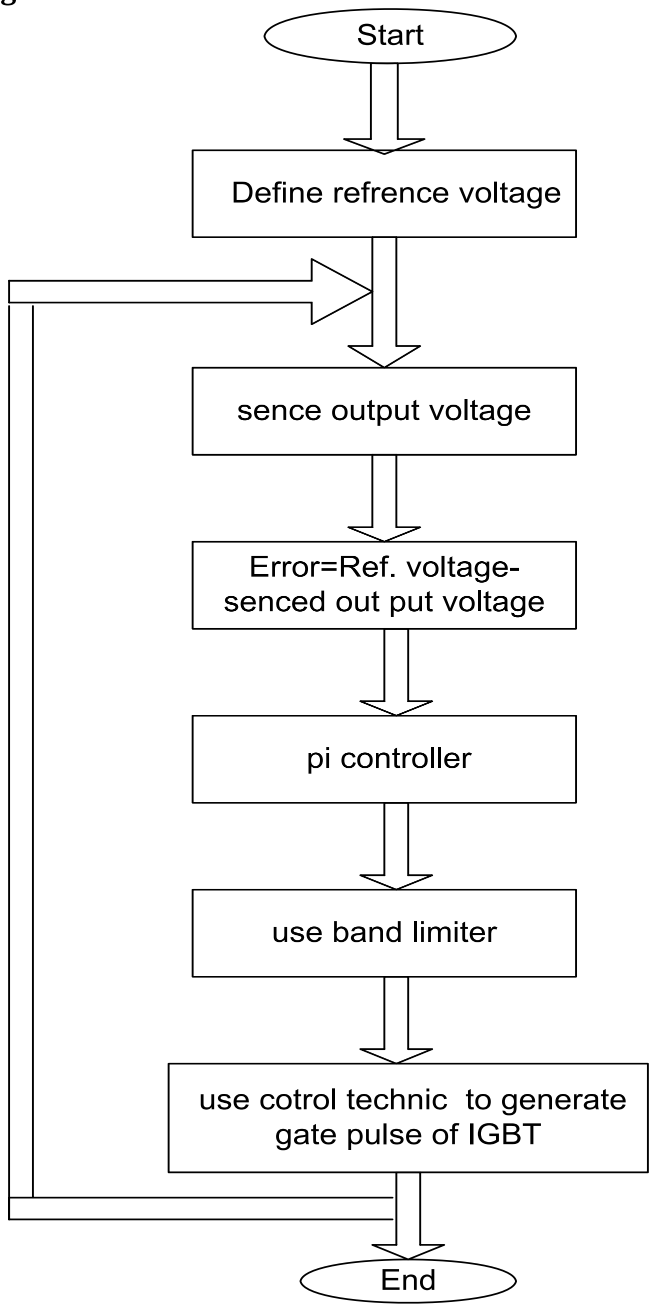

Fig.5.23 Flow chart of CV mode of full bridge converter

The flow chart is showing how the CV mode control is implemented in Dynamic Link Library(DLL).The DLL is one of the tool of PSIM5.0 in which one can program the control algorithm and generate gate pulse for the IGBTs.

5.3.2 Simulation results with DLL block

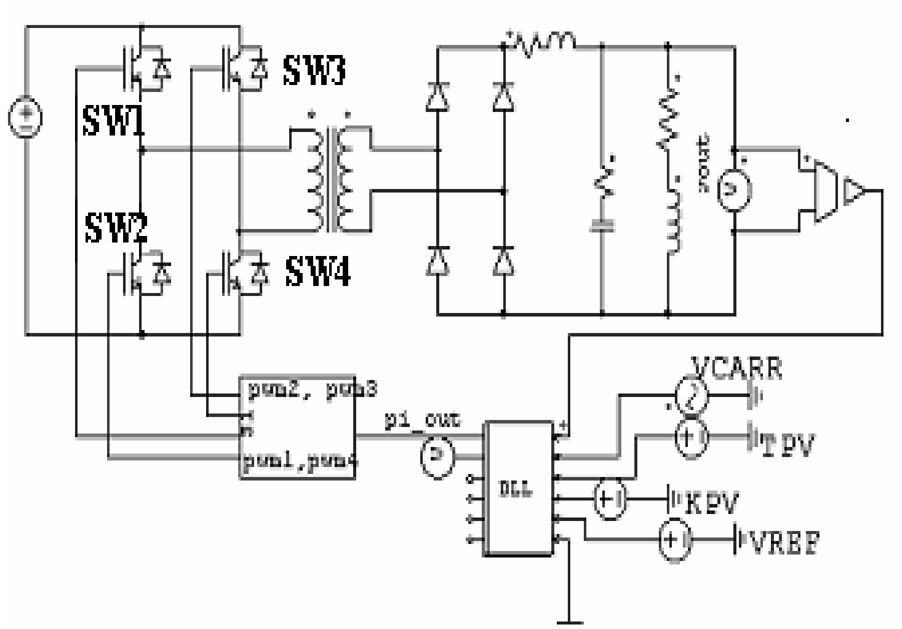

Fig. 5.24 Simulation of full bridge converter using DLL block

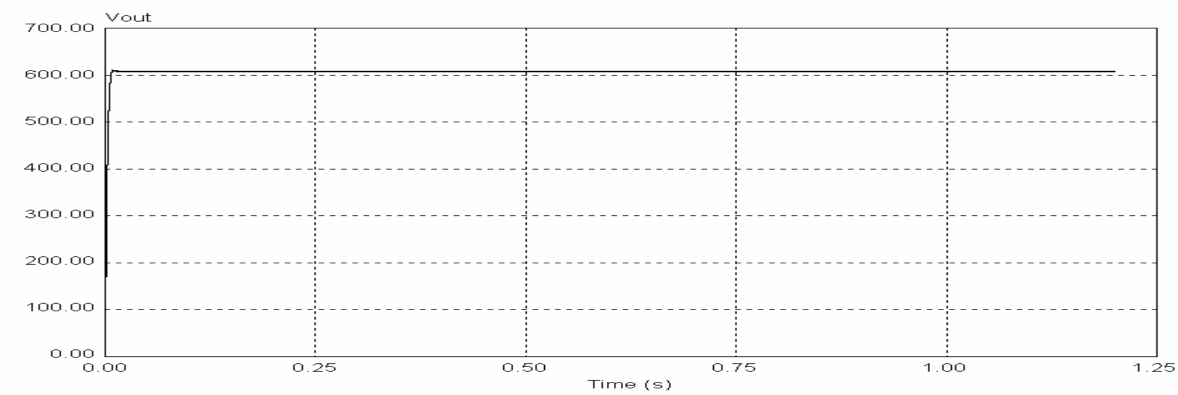

Fig.5.25 Output DC voltage

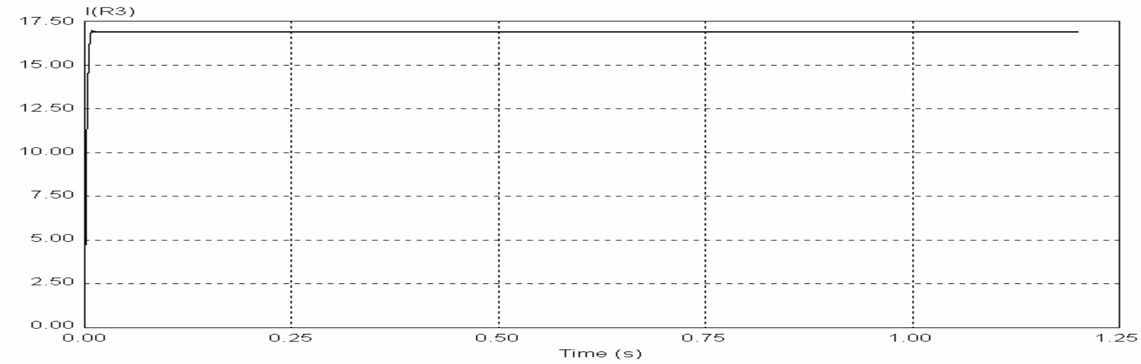

Fig.5.26 Load current

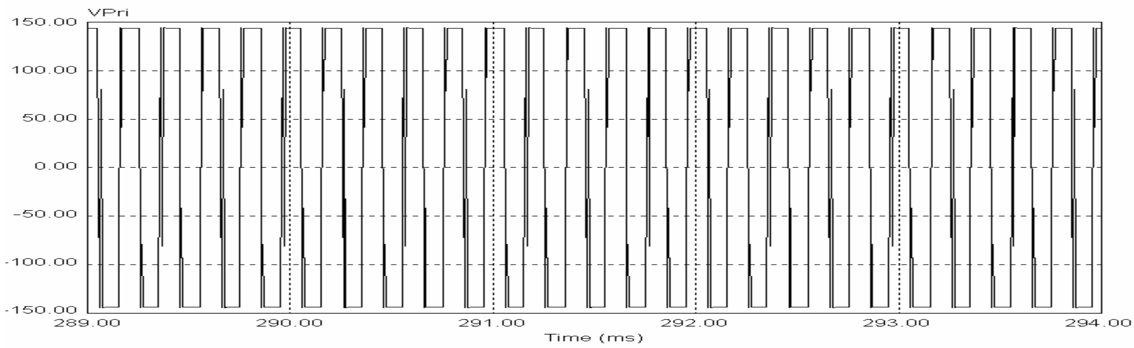

Fig.5.27 Primary voltage of transformer

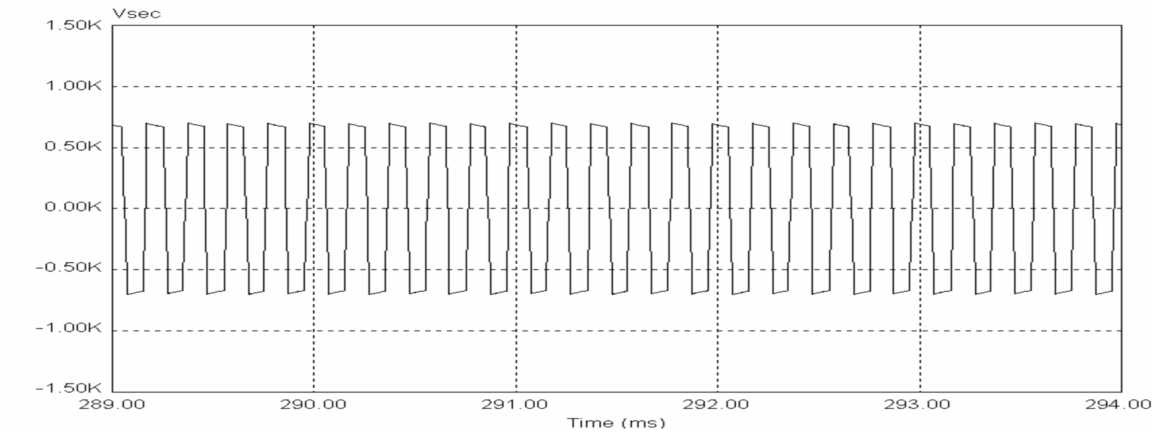

Fig.5.28 Transformer secondary voltage

5.3.3 Simulation for load regulation

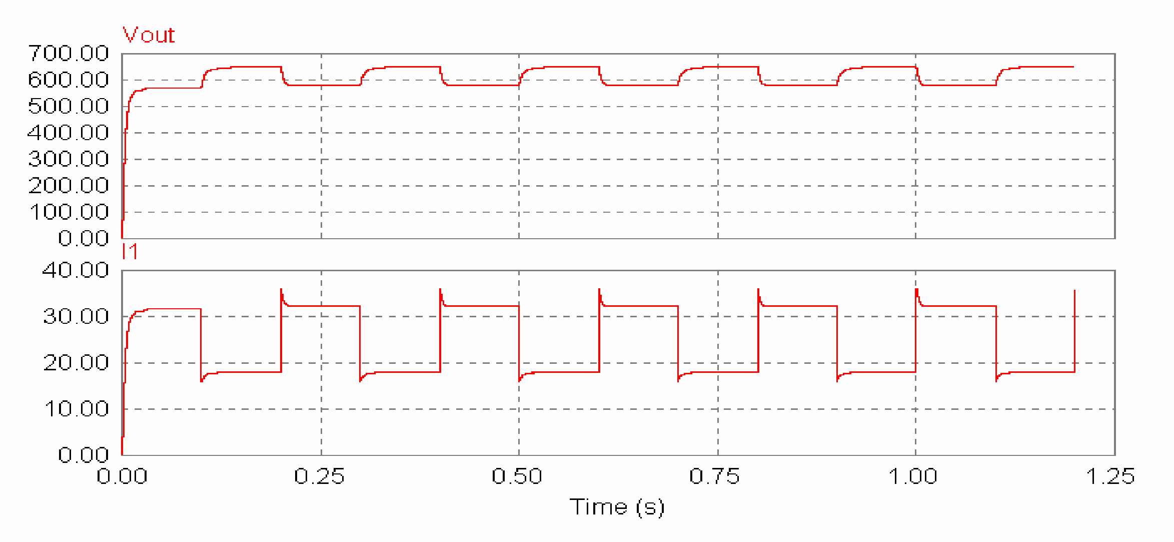

Fig.5.29 Voltage and current wave at output when load is drastically increase

(Output voltage variation is 580-630V which is 5% of 600V)

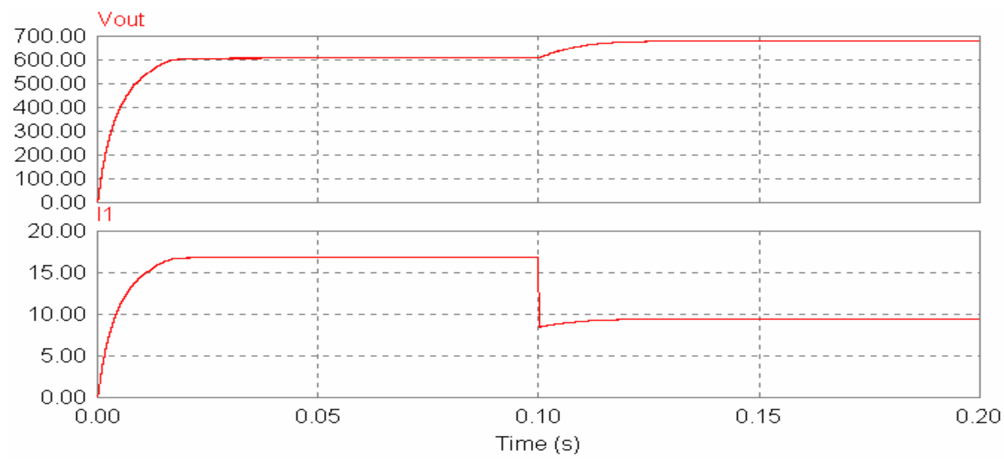

Fig.5.30 Out put voltage and current when load is drastically reduce

(Output voltage variation is 605-670Vwhich is within the limit.)

From the above simulation of the under load and over load condition with DLLblock one can get idea that the voltage across the out put maintain constant and fluctuation of it is within the limit of voltage regulation.

CHAPTER-6

HARDWARE DESCRIPTION AND CONTROL ALGORITHM

6.1 GENERAL

Digital signal processor (DSP) is dominating the field of controlling variable frequency ac drive and its allied equipment. DSPs are providing numerous advantages which are listed in Appendix-B. The IGBT base inverter duty cycle is controlled using DSP. A control algorithm is developed and implemented in DSP.

6.2 HARDWARE DESCRIPTION

The following Fig 6.1 show the hardware software module block diagram of Isolated full bridge converter. Main hardware design is associated with the heat sink for IGBTs and diodes, Transformer, Filter Inductor and capacitor, IGBT gate driver circuit, current sensors.

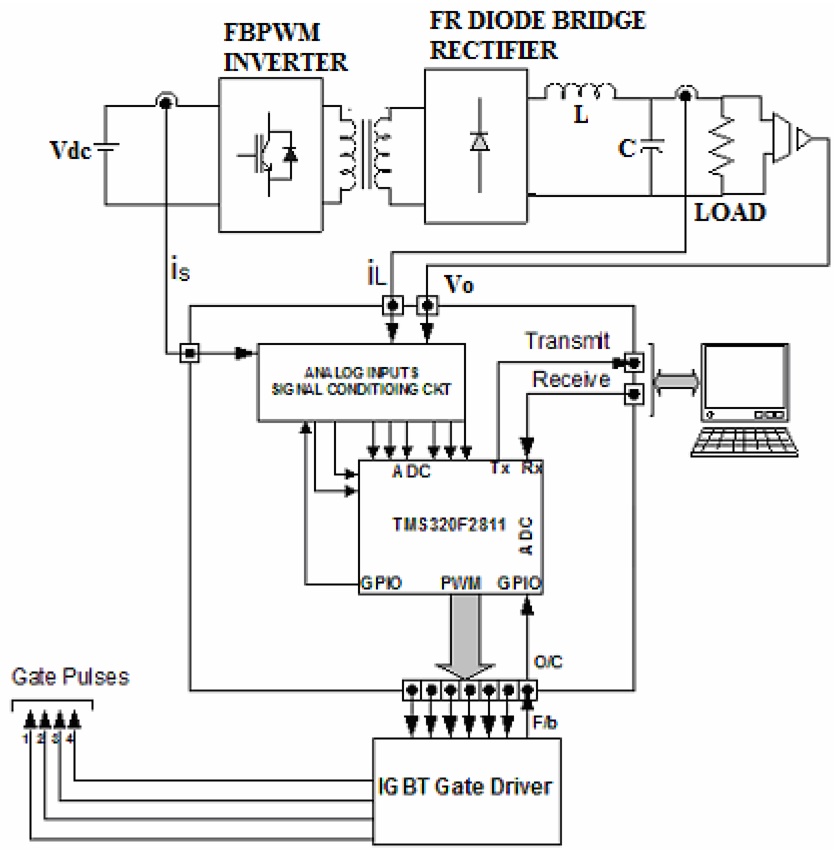

Fig- 6.1: Basic Block Diagram of Isolated Boost converter illustrating the hardware With control circuit.

Fig. 6.1 shows the DSP TMS320F2811 based implementation of Isolated converter. PCA-2004A is the DSP control card, which houses the TMS320F2811 DSP processor along with appropriate interfacing circuitry. The current sensor sense the input current and these current signals are applied to the ADC input pin (ADCINA1) of the DSP processor through proper interfacing circuitry, which reduces the current signal to a maximum of 3.3 V. In addition to this, voltage divider circuit senses the DC bus voltage and through the proper interfacing circuitry the DC bus voltage is fed to the DSP processor.

As per control algorithm generated the pulses to trigger the IGBTs. The task of generating the PWM pulses is accomplished by the DSP with the help of PWM circuit, counters, compare and period resisters. A SMPS provides the DC supply for the gate driver card and DSP control card. The control card has also a facility of serial interfacing. The DSP interrupts are employed for the implementation of over current, over voltage, over temperature.

6.2.1 DSP Control Card

The control card PCA-2004A is shown in Fig. 6.2. This control card provides the interfacing between the DSP controller and other peripherals. The power supply for the control card is provided through the SMPS The output of current and voltage sensors are processed so that under any condition the voltage level at the ADC input does not exceed the maximum voltage level of 3.3 V. The programming for the DSP controller is done in the Code Composer Studio.

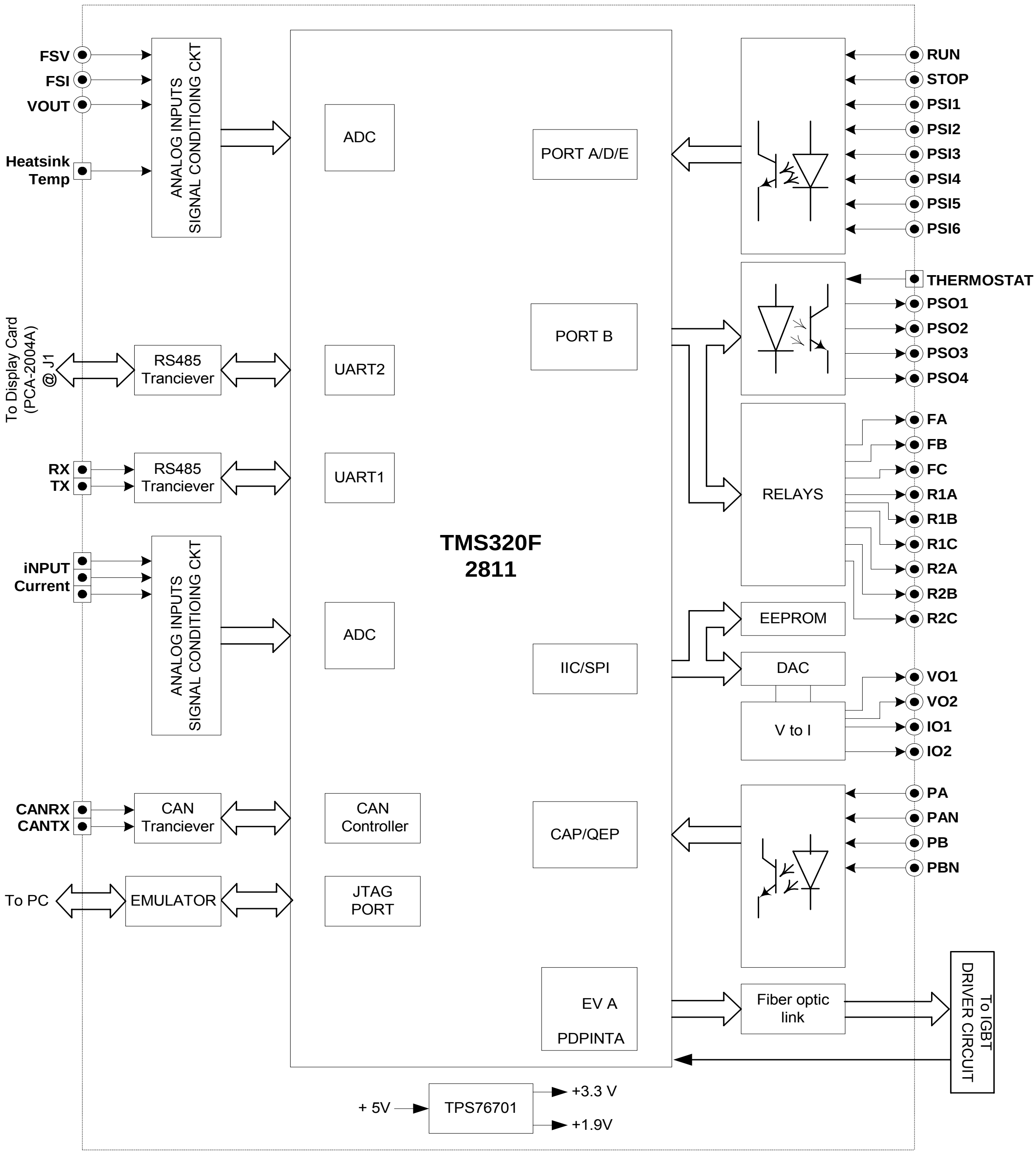

Fig. 6.2 DSP TMS320F2811 based control card PCA-2004A

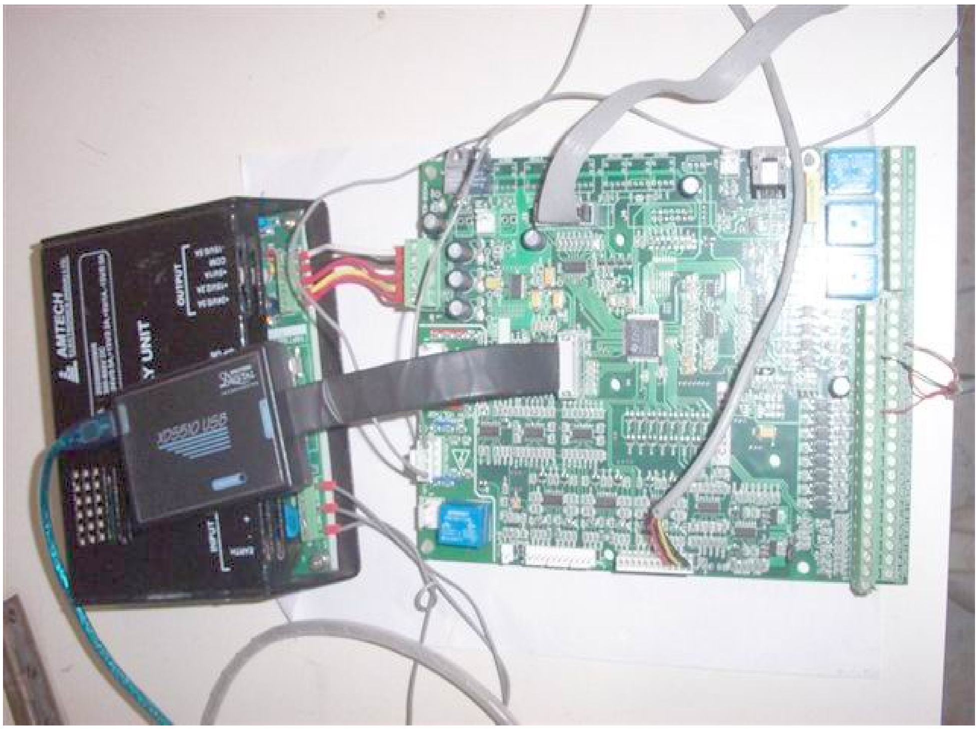

Fig.6.3 DSP control card with smps and JTEG emulator.

6.2.2 IGBT gate driver circuit:

The driver card used to drive the IGBT, the driver IC is made by MITSUBISHI. The driver card is designed to convert the logic level signal into optimal IGBT gate drive. Input signals are isolated through the fiber optic link. It also provides a short circuit protection by monitoring the collector emitter voltage of the IGBT. A collector feedback is taken for this purpose. The driver initiates a controlled slow turn off and generates a fault signal when short circuit is detected. The slow turn off helps to control dangerous transient voltages that can occurs when high short circuit currents are interrupted. This card allows the faster turn off during the normal operation. The output of the driver will remain disabled and the fault signals will remains active for minimum 20μsec after a short circuit has been detected.

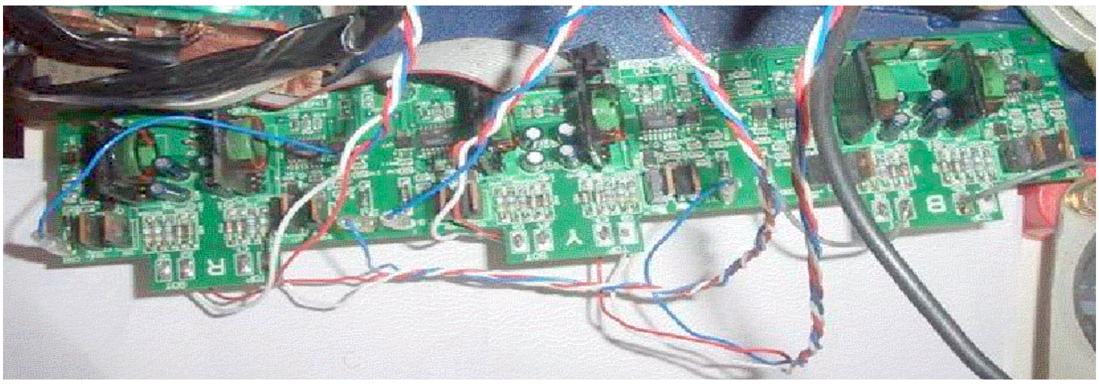

Fig.6.4 IGBT gate driver circuit

6.2.3 SMPS for control and driver card.

The power supply to the control card PCB-2004A is provided through an external SMPS(switched mode power supply) with voltage input of 230V ac and output dc voltage of +24V/0.5A,+15V/2.2A, +5V/1A, 0V/COM,and -15V /0.5A. +24V supply is given to the control terminal, which are programmable with capability to give or take signals to DSP +15 V and -15V supply are used as power supply to driver IC and also as biasing voltage for the DSP TMS320F2811 is regulated from IC with +5V input from SMPS.

6.3 CONTROL ALGORITHM

6.3.1 DSP programming

The main heart of DSP TMS320F2811 is event manager. The event-manager (EV) modules provide a broad range of functions and features that are particularly useful in motion control and motor control applications. The EV modules include general-purpose (GP) timers, full-compare/PWM units, capture units, and quadrature-encoder pulse (QEP) circuits. The two EV modules, EVA and EVB, are identical peripherals, intended for multi-axis/motion-control applications.

Each EV is capable of controlling three Half-H bridges, when each bridge requires a complementary PWM pair for control. Each EV also has two additional PWMs with no complementary outputs.

The GP timers can be operated independently or synchronized with each other. The compare register associated with each GP timer can be used for compare function and PWM-waveform generation. There are three continuous modes of operations for each GP timer in up- or up/down-counting operations. Internal or external input clocks with programmable prescaler are used for each GP timer. GP timers also provide the time base for the other event manager sub modules: GP timer 1 for all the compares and PWM circuits, GP timer 2/1 for the capture units and the quadrature-pulse counting operations. Double-buffering of the period and compare registers allows programmable change of the timer (PWM) period and the compare/PWM pulse width as needed.

There are three full-compare units on each event manager. These compare units use GP timer1 as the time base and generate six outputs for compare and PWM-waveform generation using programmable dead band circuit. The state of each of the six outputs is configured independently. The compare registers of the compare units are double-buffered, allowing programmable change of the compare/PWM pulse widths as needed.[13]

The programming in the DSP is either in Assembly language or in C language. C language is well-known and we can easily do the programming in it. To make the software sections for the isolated dc converter one has to make the following different sections.

1. ADC scanning
2. Timer for ADC scanning
3. Interrupt service routine
4. Discrete PI controller
5. PWM gating pulse generation for IGBTs
6. Over voltage and over current protection.

Unlike analog control circuit, digital control has much outstanding advantages, such as reliability and flexibility. However, its performance is likely weakened by time delays and phase shift in the process of signal sampling, conditioning and computing.[13]

Texas Instruments TMS320F2811 DSP is used to implement phase shift control for Full bridge inverter that maximizes the overall performance of the proposed converter, while allowing the low cost objective to be achieved. The DSP system has a high-speed A/D converter, 16 PWM output channels and serial communication capabilities. In addition, the TMS 320F2811 contains a 12-bit analog-to-digital converter (ADC) having a maximum conversion time of 40 ns that offers up to 16 channels of analog input. The auto sequencing capability of the ADC allows a maximum of 16 conversions to take place in a single conversion session without any CPU overhead. Further, the processor has two modules, which can each accomplish a task such as centered and or edge-aligned PWM generation, programmable dead band to prevent shoot-through faults, and synchronized analog-to-digital conversion.[14] By implementing the control via DSP, the proposed approach offers increased flexibility[15], insensitivity to temperature drifts and minimizes component cost. The proposed DC-DC converter design includes the capability to detect any over-currents, over-temperatures, over voltages or other shut down conditions to prevent damage to the inverter system.

6.3.2 DSP control algorithm for full program

The Fig.6.3 is shows full program algorithm implemented in TMS320F2811.With the starting of DSP, initialize all the variable, peripherals, timers/counters. Once the initialization is complete and the timer 0 interrupt occurs which decided the time of calling the core algorithm. In this case the timer 0 interrupt will call every 166.66 µ second hence ADC scanning is take place in every 1666.66 µsec and accordingly pulse will be generated.

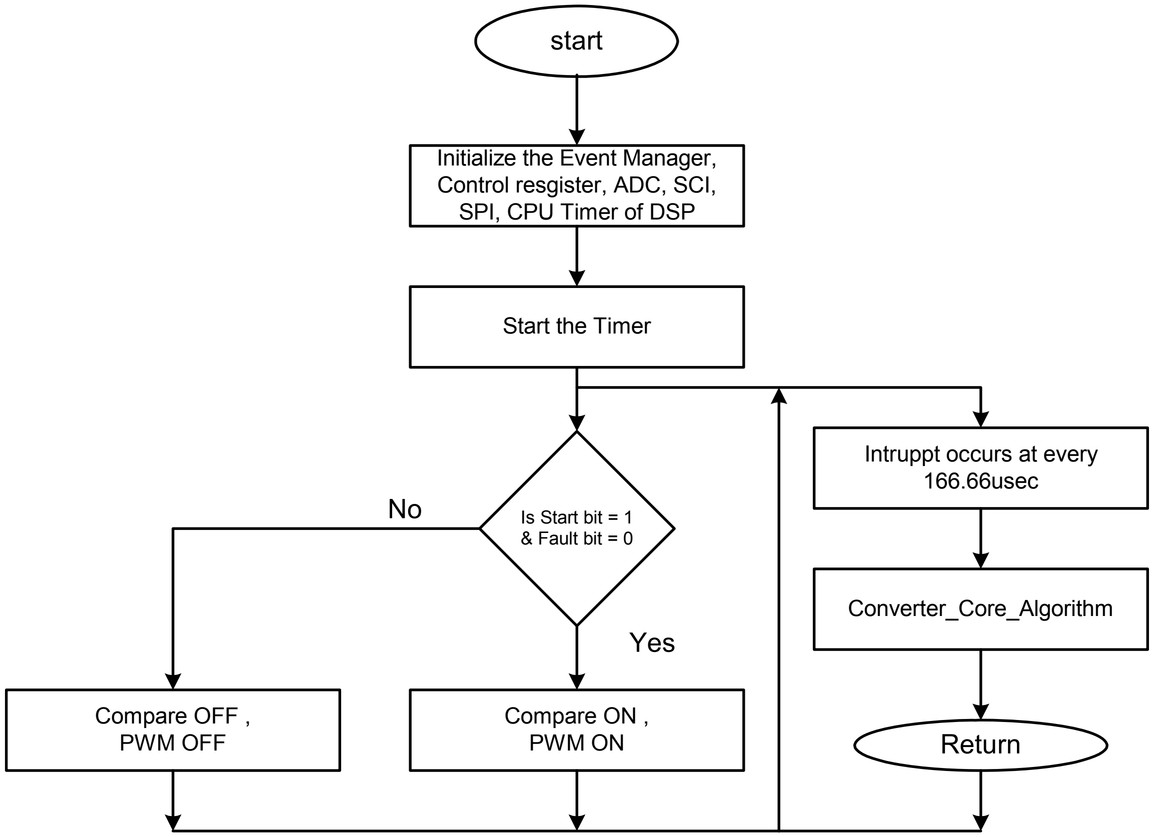

Fig.6.5 DSP control algorithm for full program

6.3.3 Flow chart for core algorithm of program

The core algorithm is implemented in DSP TMS320F2811 for generating the gate pulses for the IGBTs. The implemented control algorithm is shown in Fig.6.4.The over voltage and over load protections are also implemented.

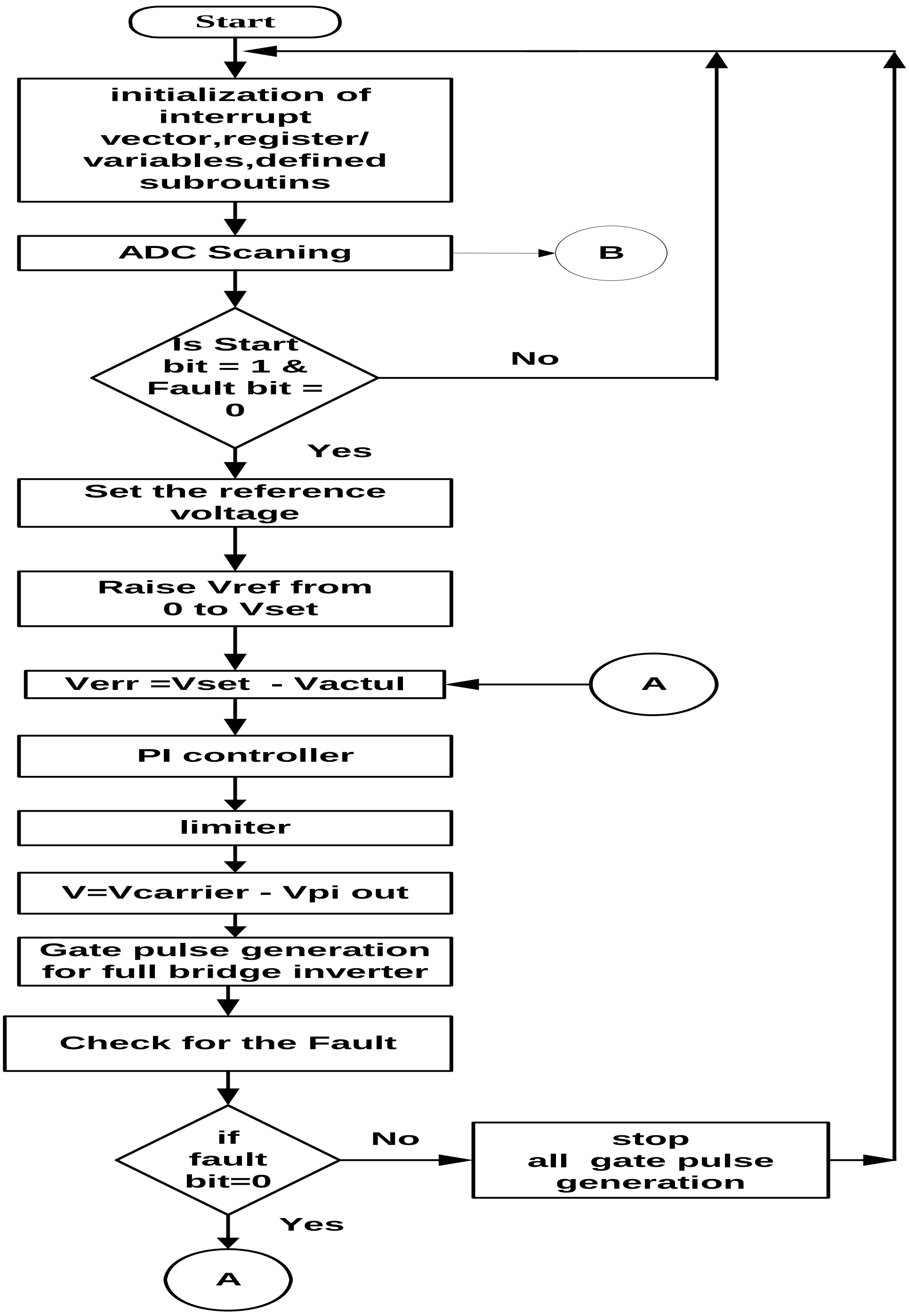

Fig.6.6 Flow chart for core algorithm of program.

6.3.4 Over Voltage protection loop

The Isolated converter should be protected against over voltage at output. The Fig.6.8 shows flowchart of over voltage protection implemented in DSP.

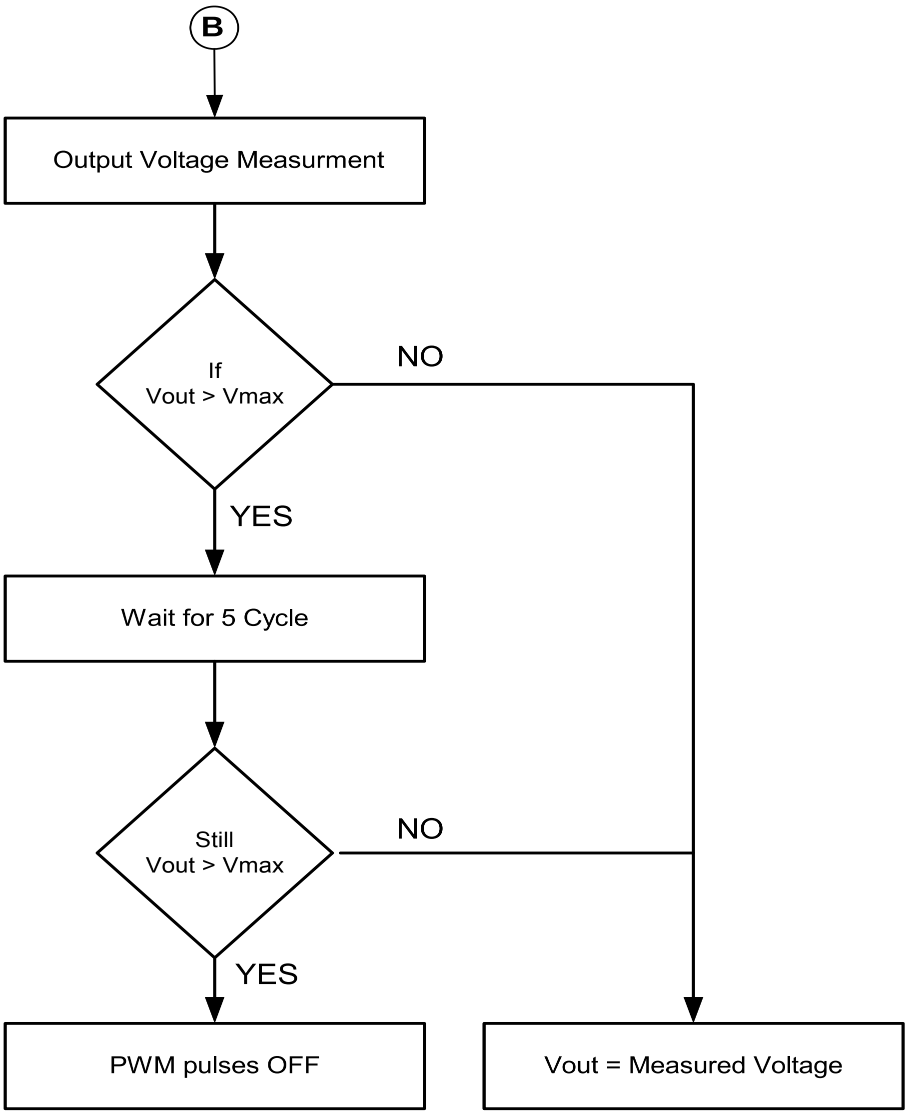

Fig.6.7 Over voltage protection loop

6.3.5 Over current protection loop

The Isolated converter should be protected against over load condition. The Fig.6.8 shows flowchart of over voltage protection implemented in DSP.

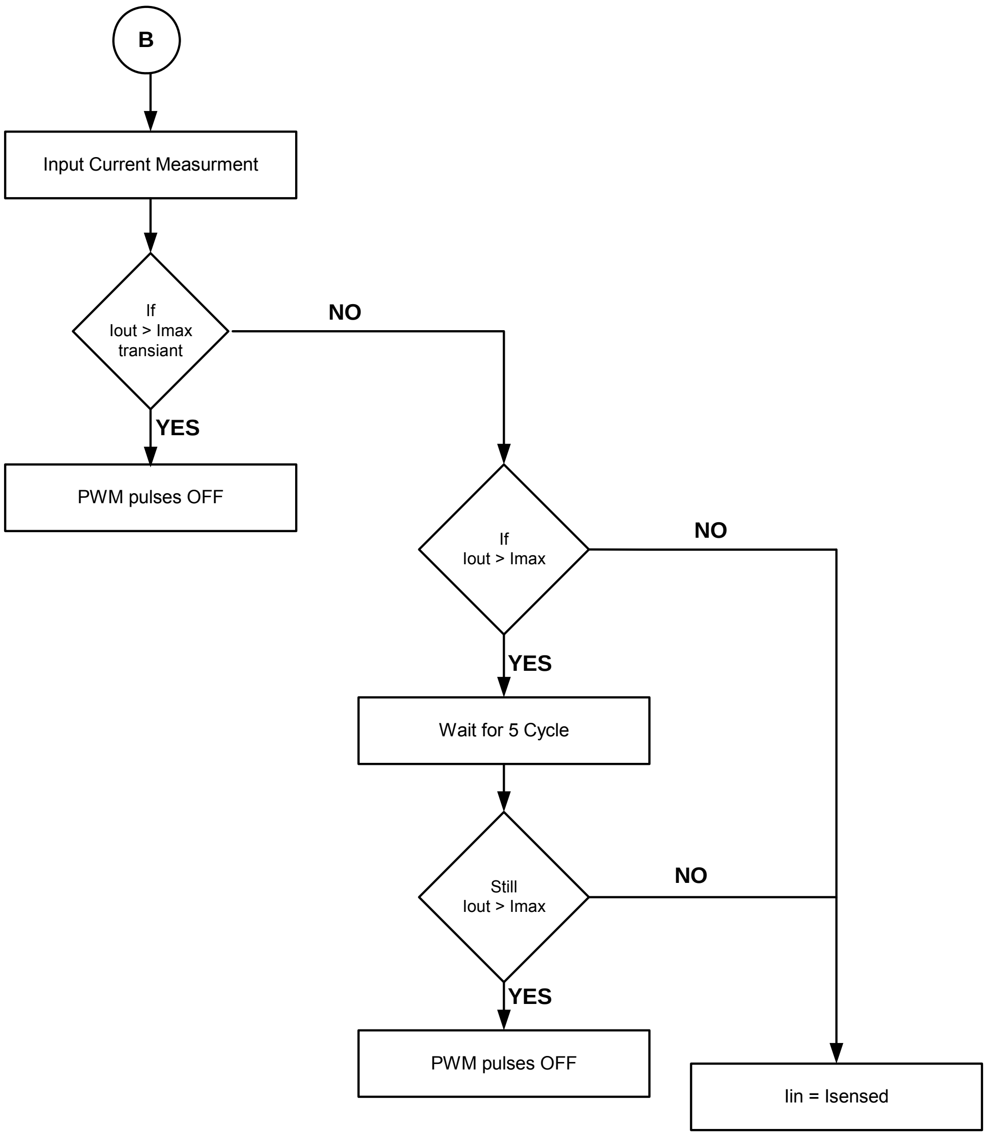

Fig 6.8 Over current protection loop

6.4 DISPLAY

For display of various parameters on computer, the AXPERT COMMUNICATOR is used. This software has been developed on visual basic. This software communicates through RS232 to 485 converter. The quantity like input current, output voltage, PI (pronominal and integration control) gain and time constant, the set output voltage, the error signal and the output of PI, are easy to change through the software.

Fig. 6.5 shows the normal parameters to be displayed on the screen. Some parameters are read only and some parameter value can be modified through the double click on it.

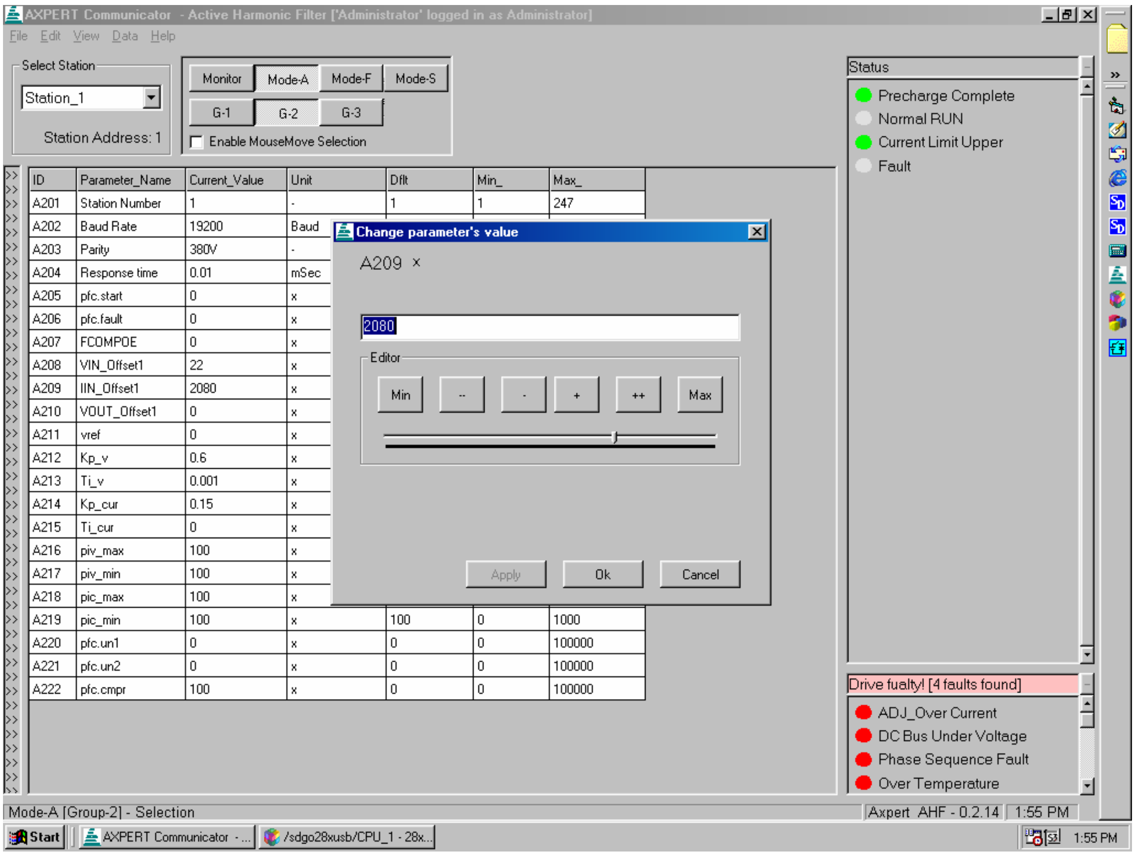

Fig. 6.9 Display of AXPERT COMMUNICATOR used to observing parameter in testing of isolated boost converter

CHAPTER-7

EXPERIMENTAL RESULTS

7.1 GENERAL

The basic control scheme and phase shifted control scheme for full bridge converter is implemented. The experimental results are shown and discussed in this chapter.

7.2 PROTOTYPE TESTING RESULTS

The gate pulse of 6 kHz is generated for h- bridge inverter and tested on the converter module using both the methods like conventional control scheme and phase shift control scheme. The prototype Results includes output dc voltage, input dc voltage, transformer voltage wave. The prototype module will tested on 3.6 Kw load. Firstly, module is tested for lower voltage and then progressively increased it. The step by step testing for higher voltage, higher power is shown. . Due to not availability of batteries, DC input voltage (144V) is developed by rectifier- filter circuit at input side. The following components are use for prototype testing.

Input L-C filter: L=0.5mH, 20A
C=2mF, 500V
HF transformer: Core: AMCC125(C-core),
Transformation ratio: 1:5.3
Output L-C filter: L=1mH, 20A
C=4 mF, 2000V

7.2.1 Gate pulse generation for conventional control scheme

Figure 7.1 shows the gate pulse of two complementary switches of any of two legs of h bridge inverter for conventional control scheme at 6 kHz. The dead band is also created using software.

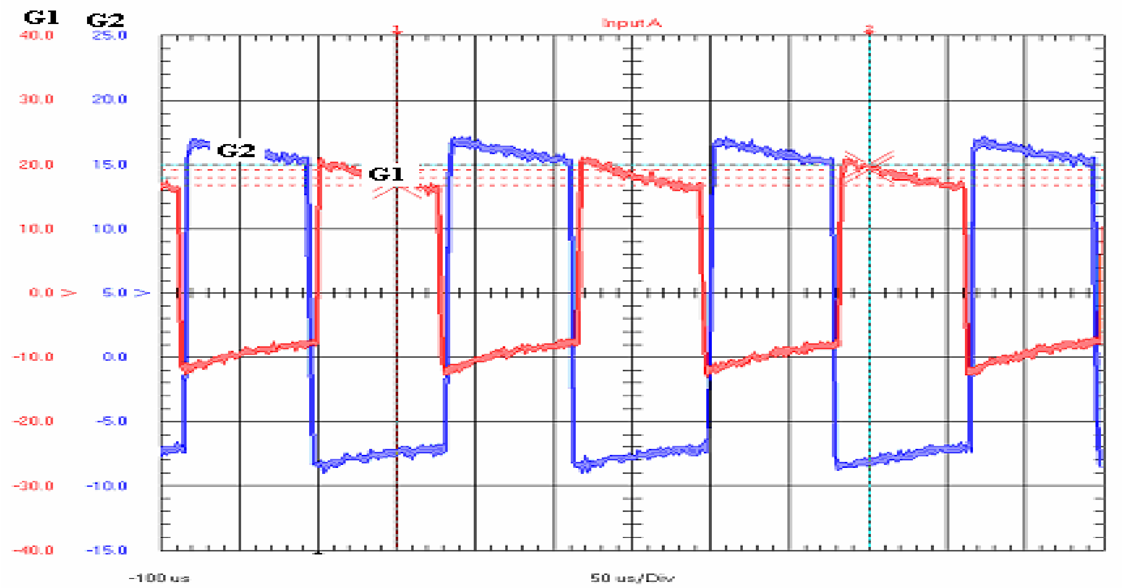

Fig.7.1 gate pulse of two complementary switches of one leg H bridge inverter

(X axis: 1div= 50µs, Trace G1: Y-axis: 1div= 10V, Trace G2: Y axis: 1div= 5V)

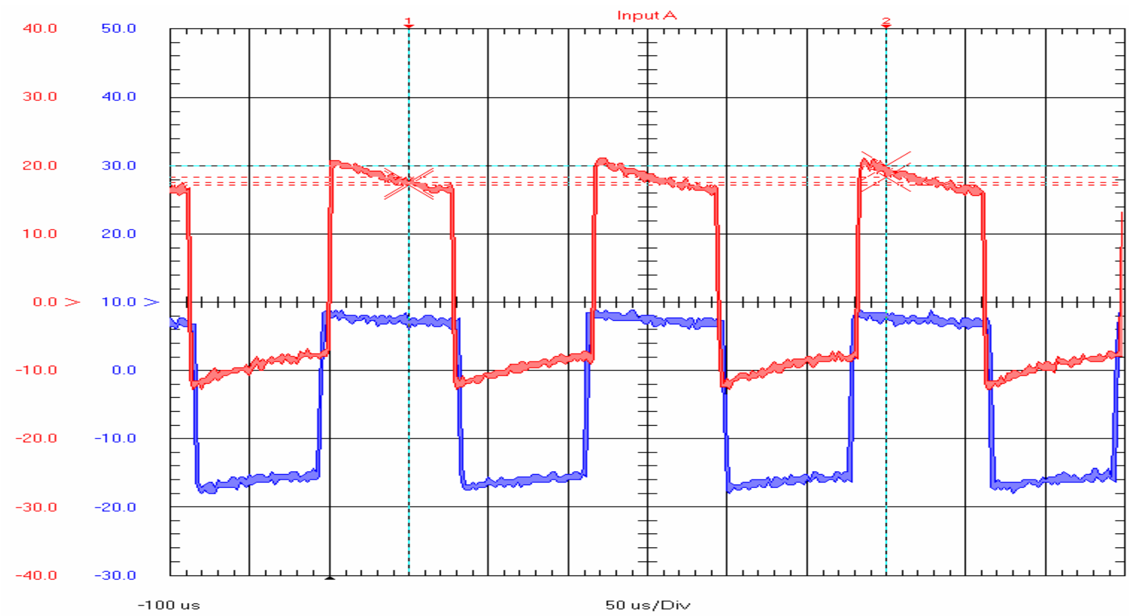

Fig7.2 Gate pulses for top IGBT of one leg and bottom IGBT of Second leg of H-bridge inverter.(X axis: 1div= 50µS,Upper and lower trace: Y-axis: 1div= 10V)

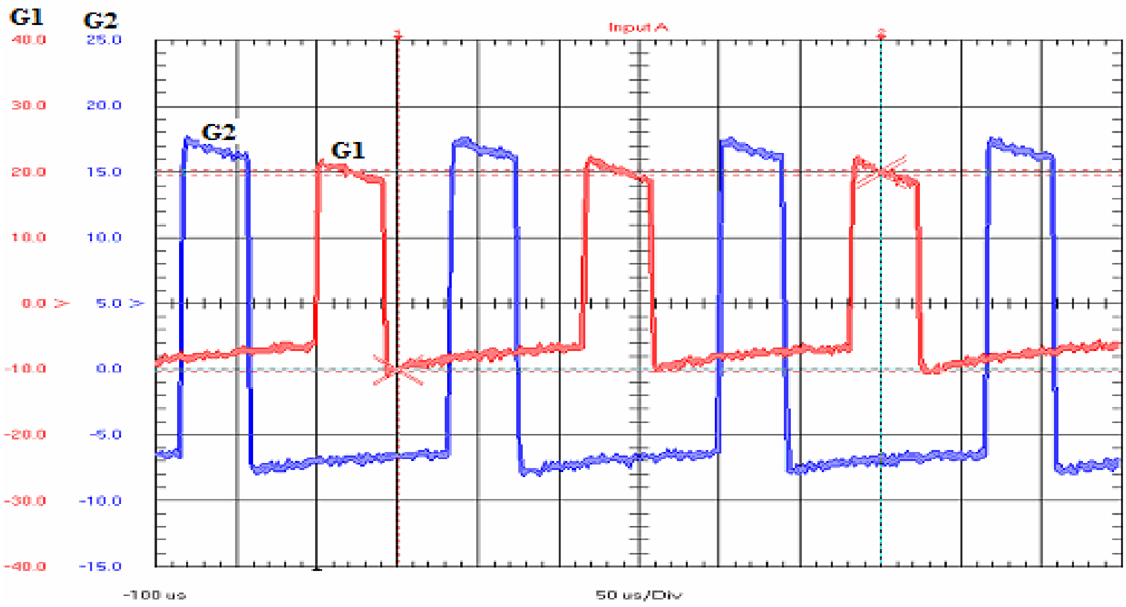

Fig.7.3 Gate pulse for 50%duty cycle for top IGBT of one leg and bottom IGBT of second leg of H-bridge inverter. (X axis: 1div= 50µs, Trace G1: Y-axis: 1div= 10V, Trace G2: Y axis: 1div= 5V)

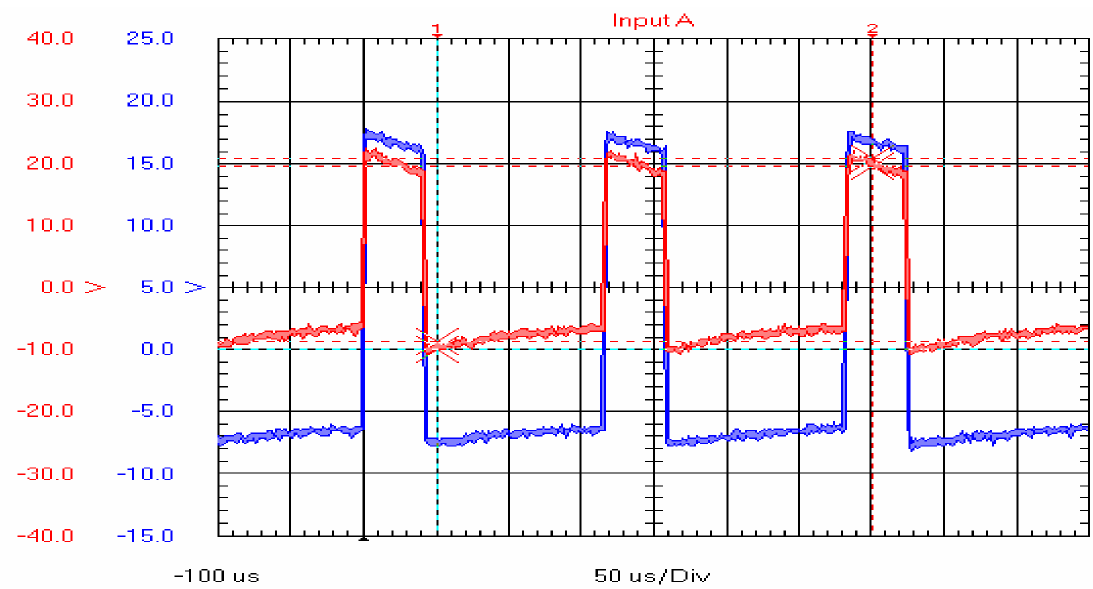

Fig.7.4 Gate pulse for 50%duty cycle for top IGBT of one leg and bottom IGBT of second leg of H-bridge inverter. (X axis: 1div= 50µS, Upper trace: Y-axis: 1div-10V, Lower trace Y-axis: 1div= 5V)

7.2.2 Prototype testing for conventional control scheme

The gate pulse is generated for h bridge inverter and the module is tested on input 15-v dc. That will give controllable 60V output. The figures below represent input and output voltage waveforms, transformer primary voltage, transformer secondary voltage.

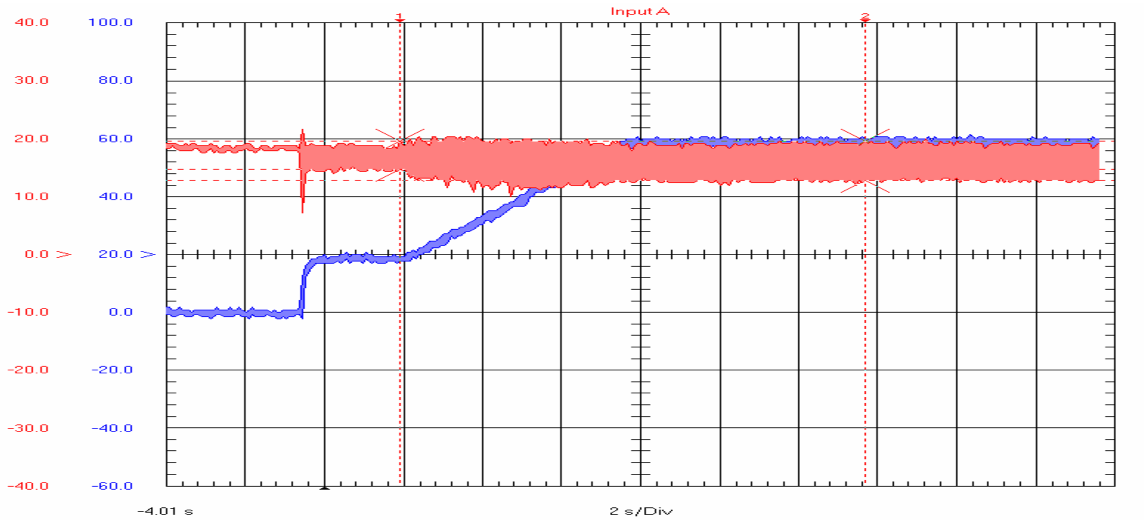

Fig.7.5 Input DC voltage and output dc voltage.

(X axis: 1div= 2s, Upper trace: Y-axis: 1div=10V, Lower trace Y-axis: 1div= 20V)

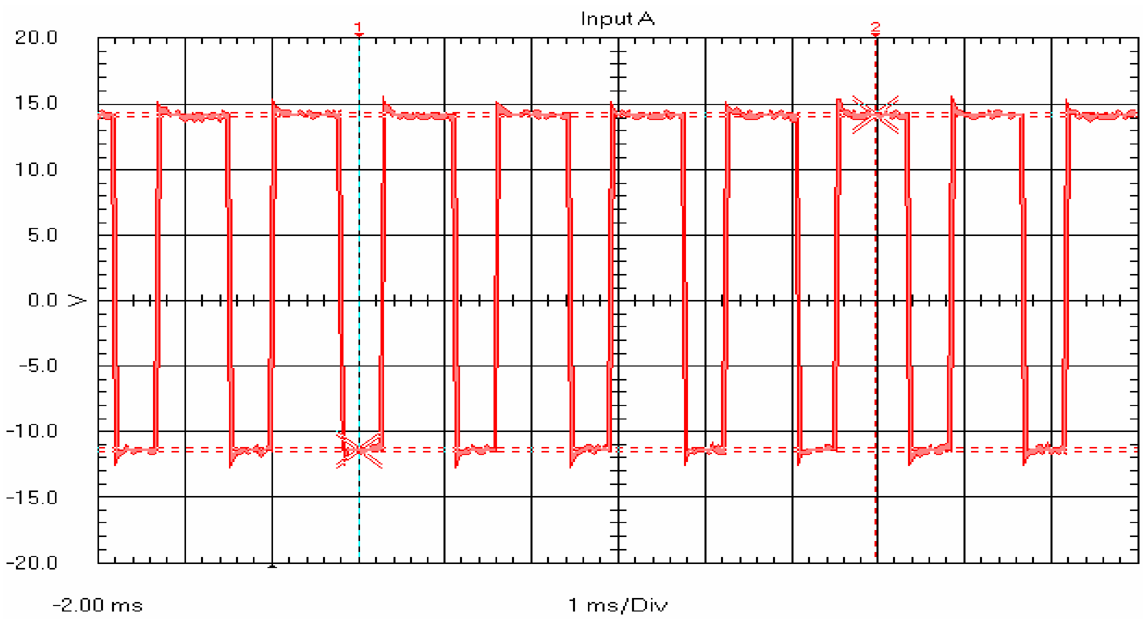

Fig 7.6 Transformer primary voltage at full duty cycle

(X axis: 1div= 1mS,Y-axis: 1div=5V)

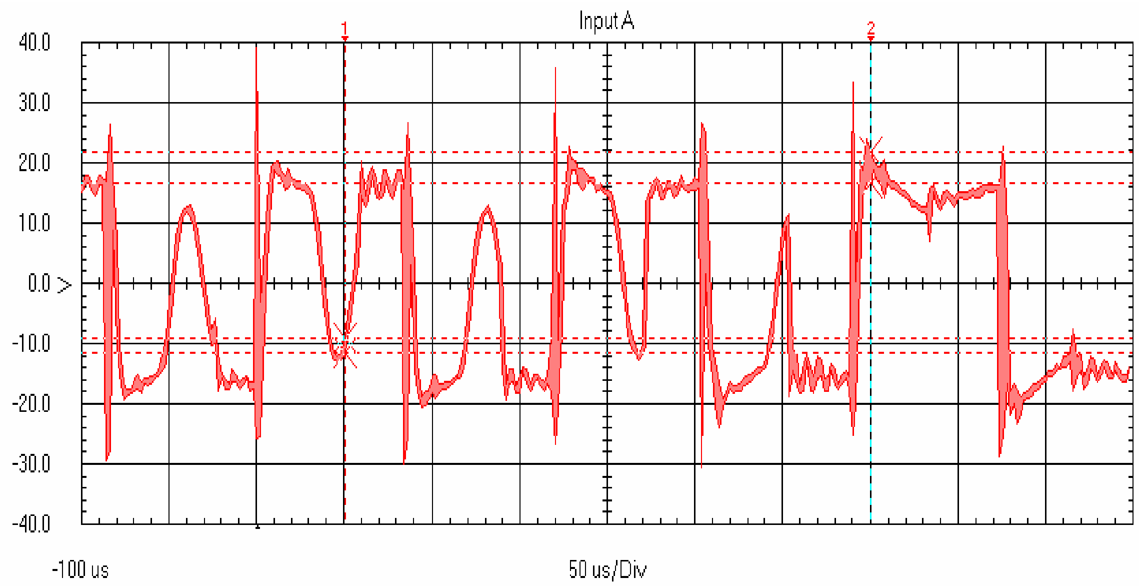

Fig 7.7 Transformer primary voltage at D=50%

(X axis: 1div= 50μS,Y-axis: 1div=10V)

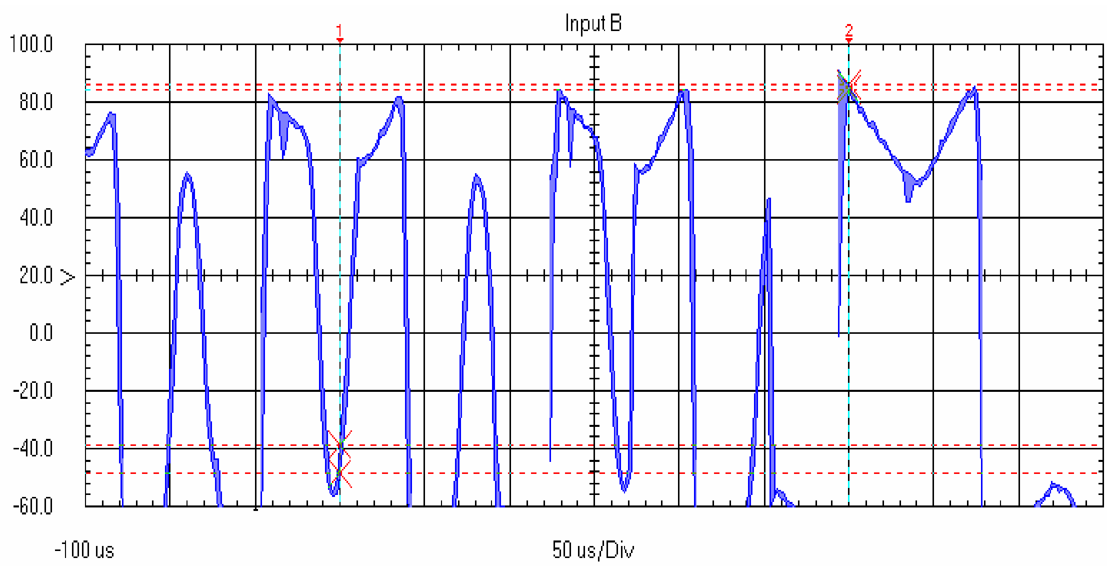

Fig.7.8 Transformer secondary voltage at half duty cycle

(X axis: 1div= 50μS,Y-axis: 1div=20V)

From the above experimental results one can see the same results as the simulation is get for conventional control scheme. In order to minimize the parasitic ringing, the gate signals of SW3 and SW4 are delayed (phase-shifted) with respect to those of SW1 and SW2 as shown in Fig.5.1, so that the primary of the transformer is either connected to the input voltage or shorted. The leakage inductance current is never interrupted, thus solving the problem of parasitic ringing associated with the conventional full-bridge PWM converter. The implementation of phase shift control scheme is shown below.

7.2.3 Gate pulses generation for phase shift control scheme

Figure 7.1 shows the gate pulse of two complementary switches of any of two legs of full bridge inverter.Fig.7.2 shows the phase shifted pulses of upper IGBTS of two different legs of H-bridge inverter.

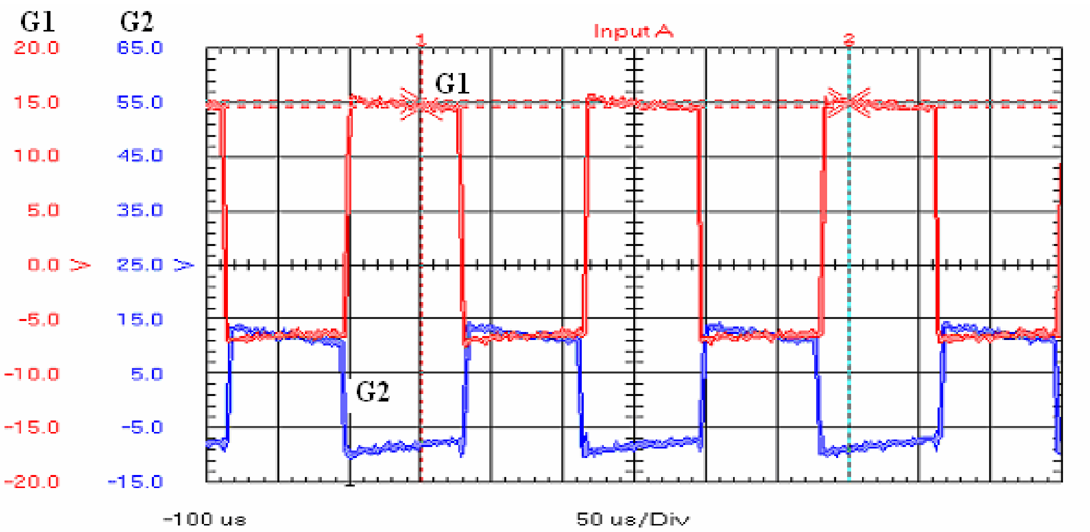

Fig.7.9 Gate pulse of complementary switches (X axis: 1div= 50µS, Upper trace G1: Y-axis: 1div= 10V, Lower trace G2: Y axis: 1div= 5V)

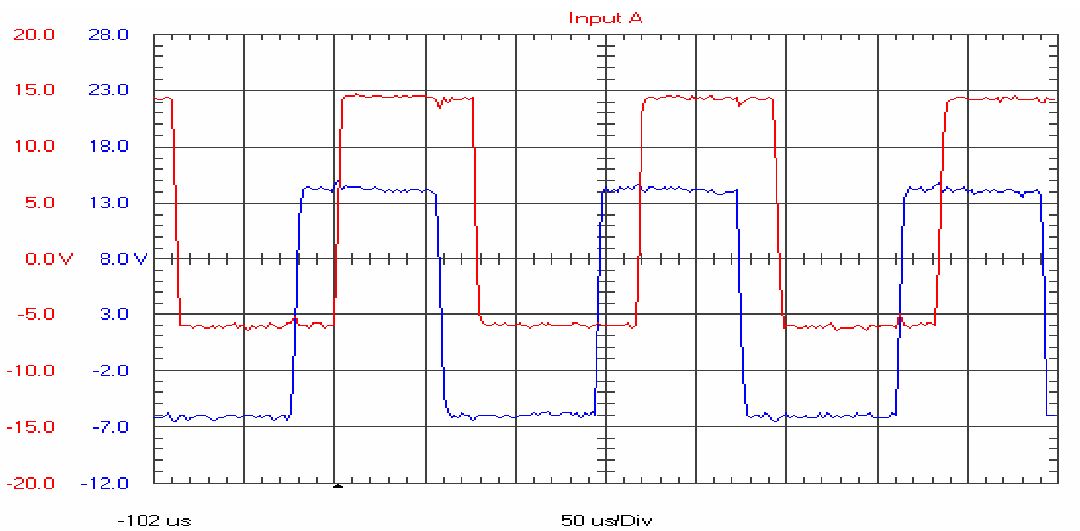

Fig.7.10 Phase shifted gate pulses of IGBTs (X axis: 1div= 50µS, Y-axis: 1div= 5V)

7.2.4 Results for 20V DC input-80V DC output

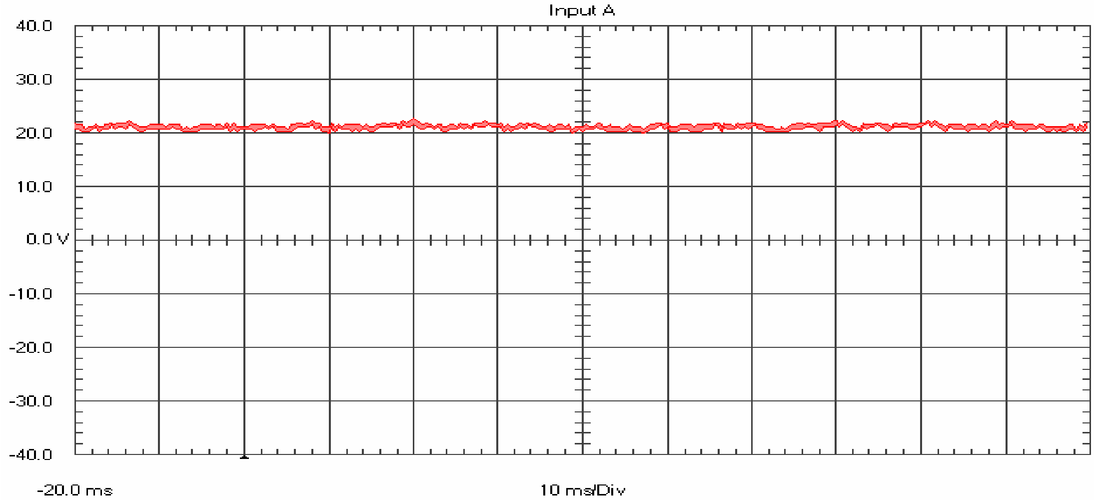

Fig.7.11 Input dc voltage (X axis: 1div= 10mS, Y-axis: 1div= 10V)

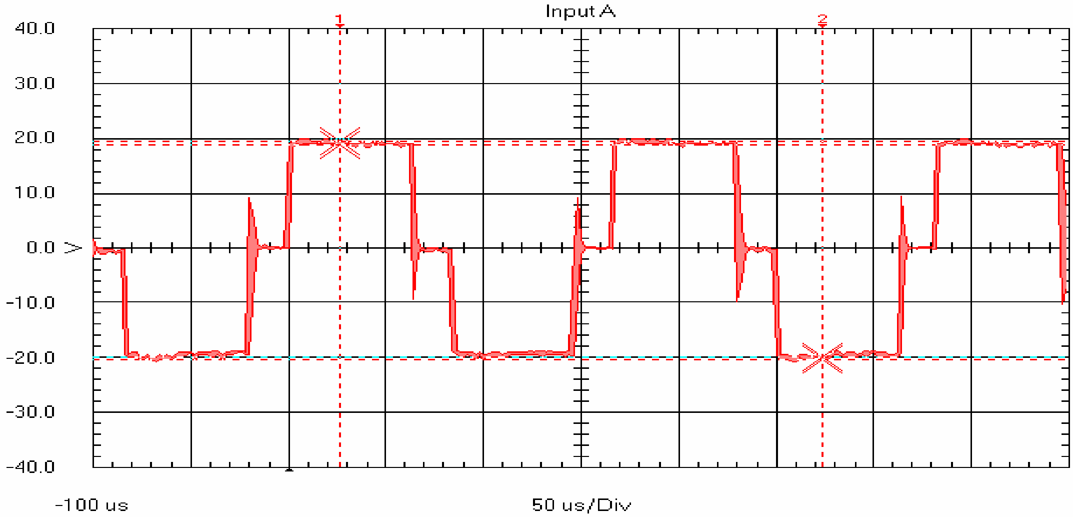

Fig.7.12 Transformer primary voltage with 50% duty cycle

(X axis: 1div= 50µS, Y-axis: 1div= 10V)

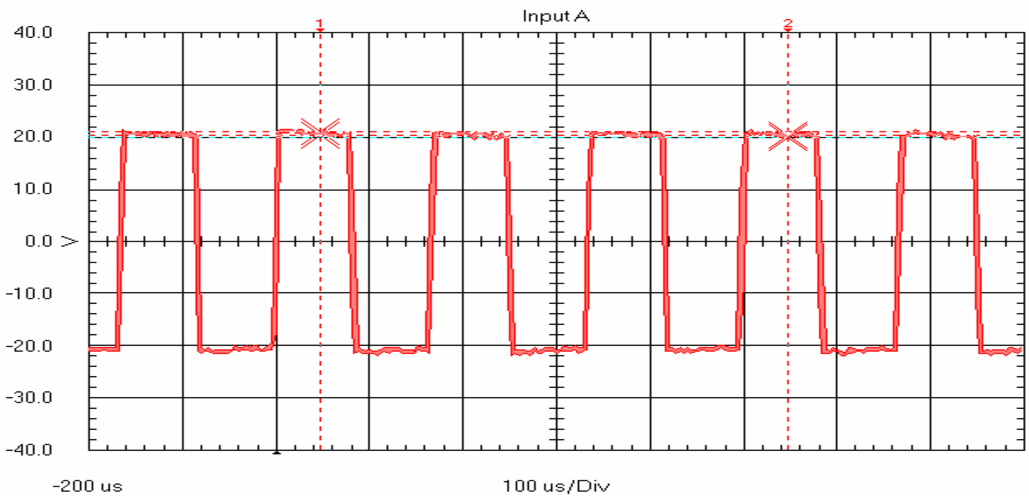

Fig.7.13 Transformer primary voltage with full duty cycle

(X axis: 1div= 100µS, Y-axis: 1div= 10V)

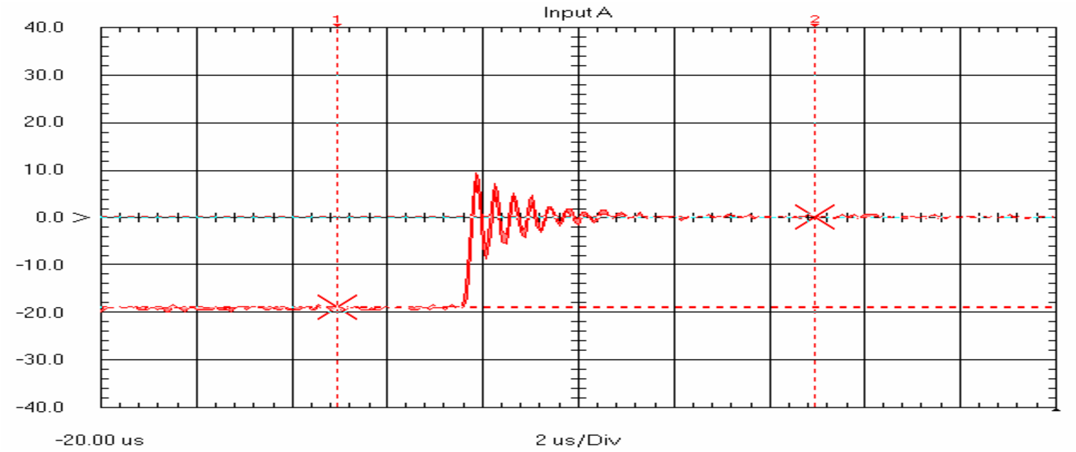

Fig.7.14 Transformer primary voltage with ringing at switches goes off.

(X axis:1div= 2µS, Y-axis: 1div= 10V)

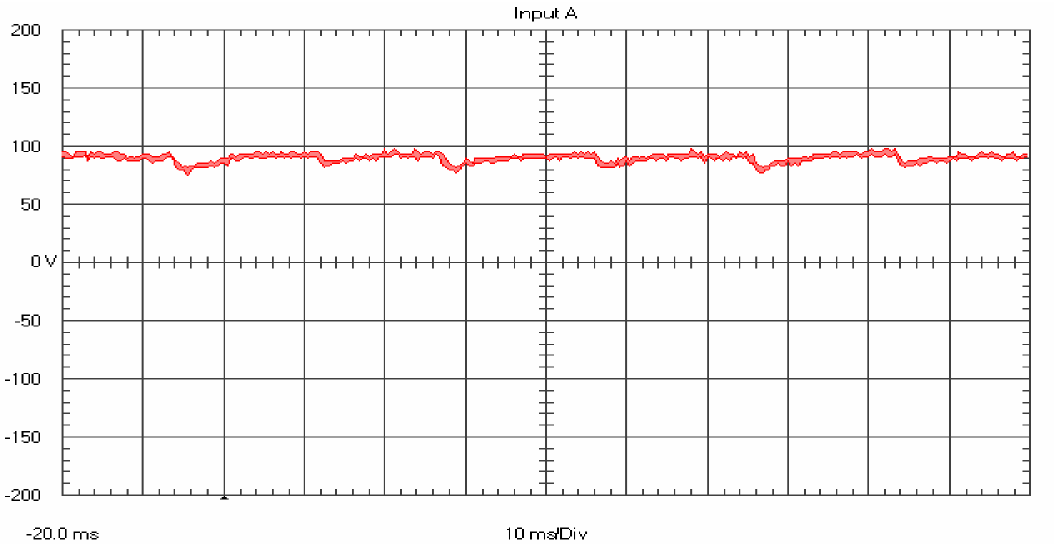

Fig.7.15 Output dc voltage (X axis: 1div= 10mS, Y-axis: 1div= 50V)

7.2.5 Results for 50V input -200V output

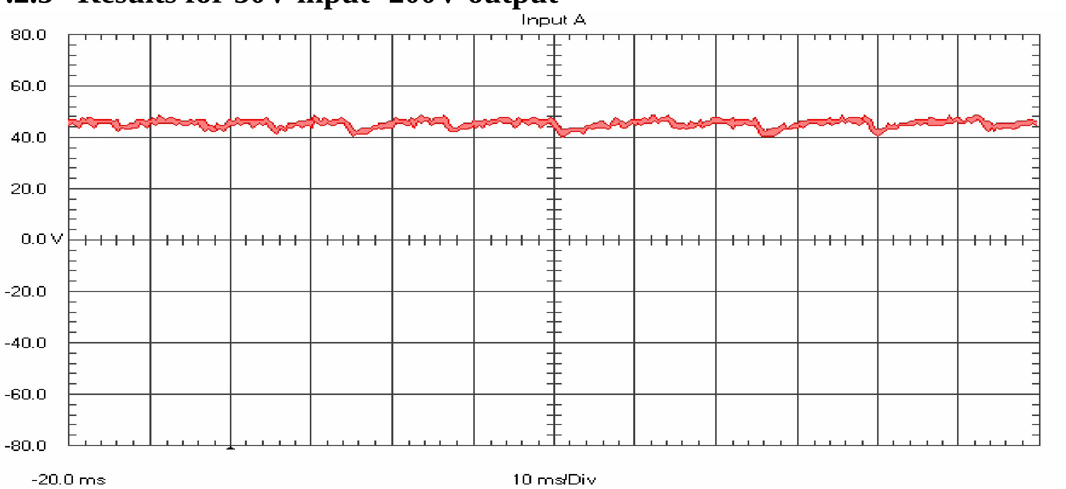

Fig.7.16 Input dc voltage(X axis:1div= 10mS, Y-axis: 1div= 20V)

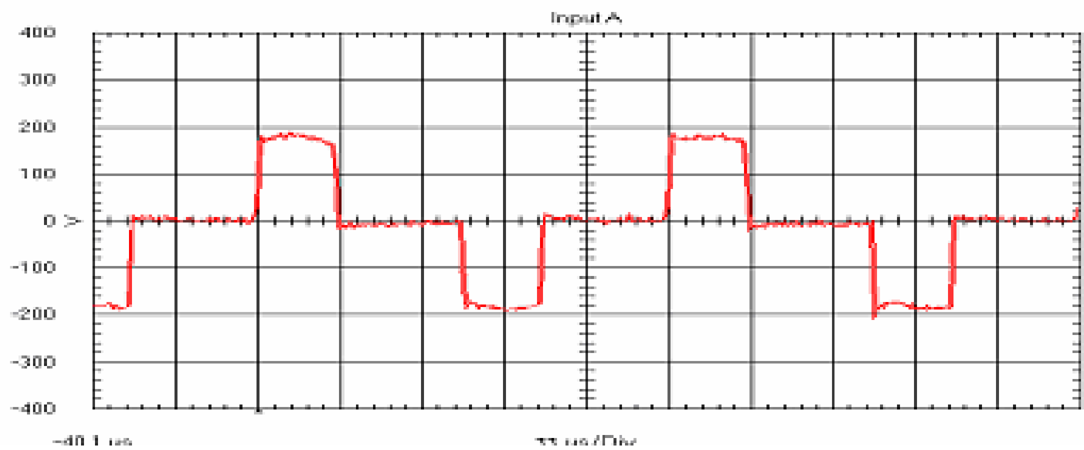

Fig.7.17 Transformer secondary voltage at 67% duty cycle

(X axis: 1div= 33µS, Y-axis: 1div= 100V)

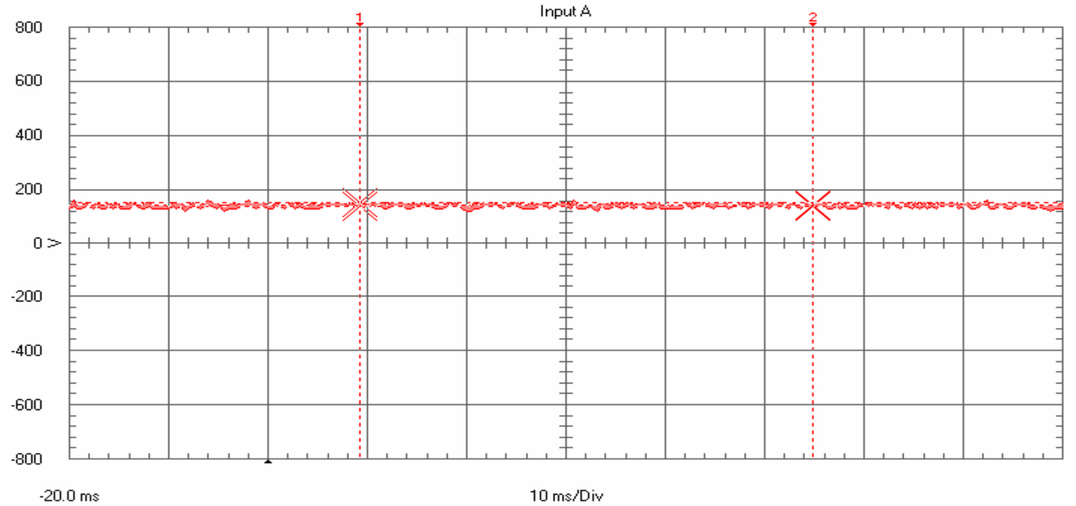

Fig.7.18 Output dc voltage at 67% duty cycle

(Scale: X axis: 1div= 10mS, Y-axis: 1div= 200V)

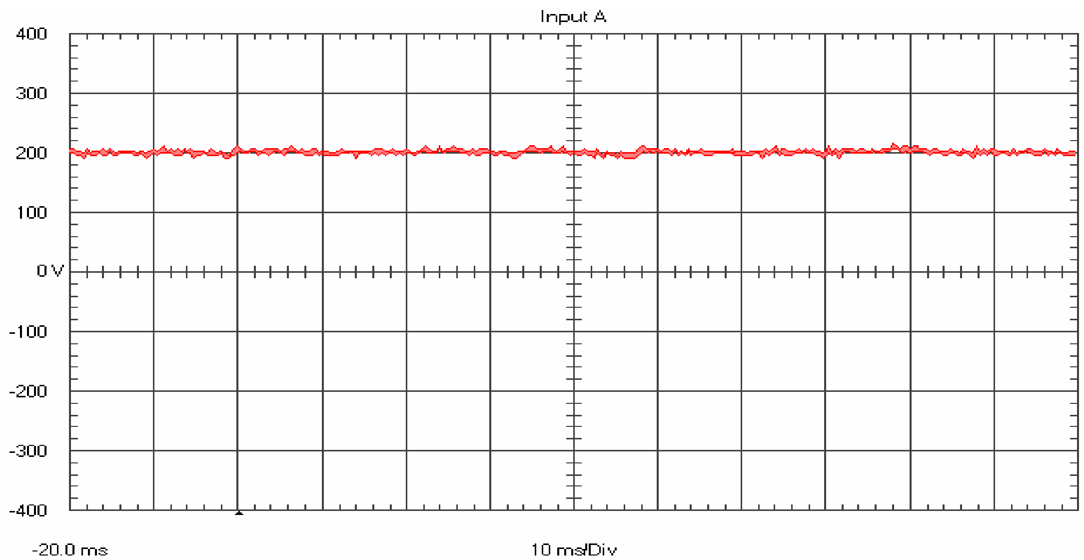

Fig.7.19 Output dc voltage at full duty cycle

(Scale: X axis:1div= 10mS, Y-axis: 1div= 200V)

7.2.6 Results for 100V input-400V out put

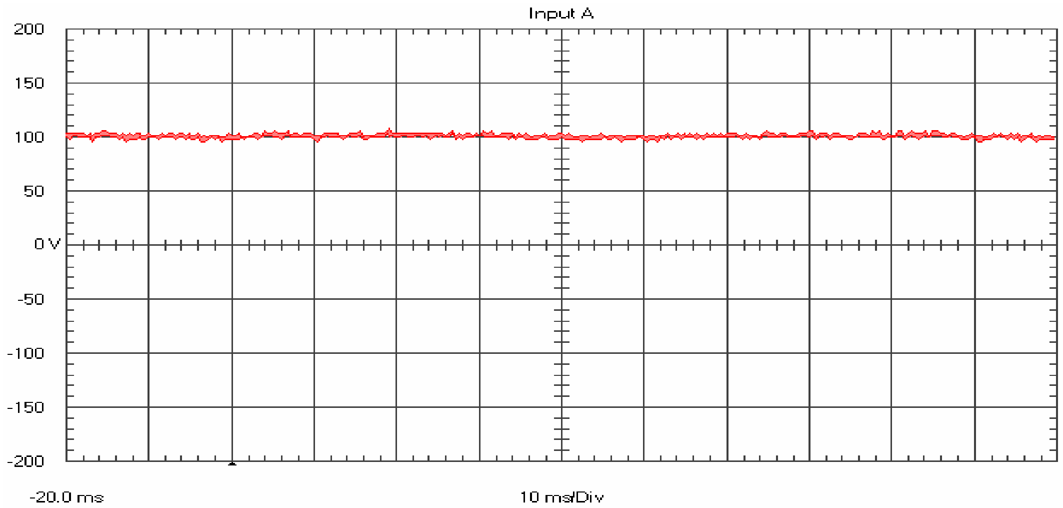

Fig.7.20 Input dc voltage (Scale: X axis:1div= 10mS, Y-axis: 1div= 100V)

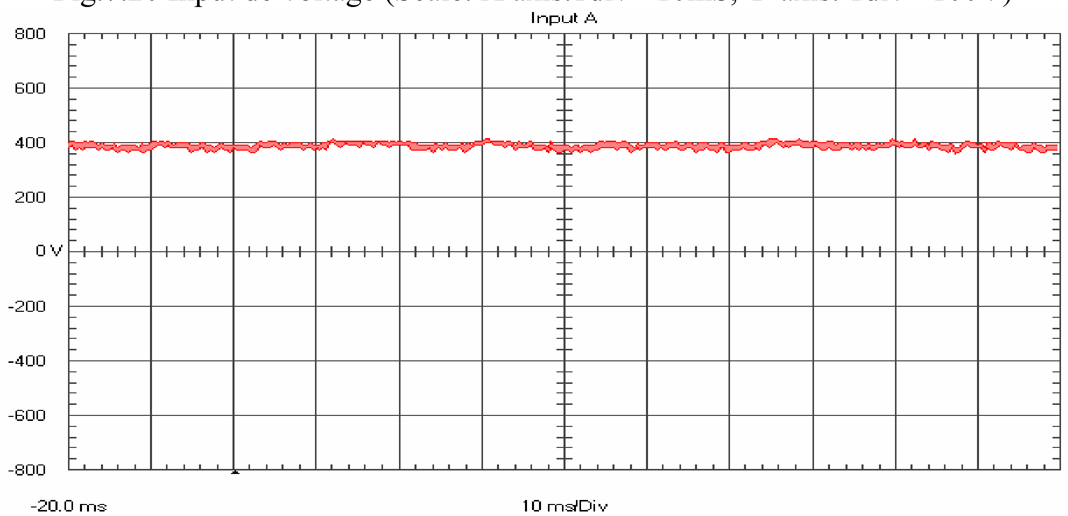

Fig.7.21 Output dc voltage at full duty cycle

(Scale: X axis:1div= 10mS, Y-axis: 1div= 400V)

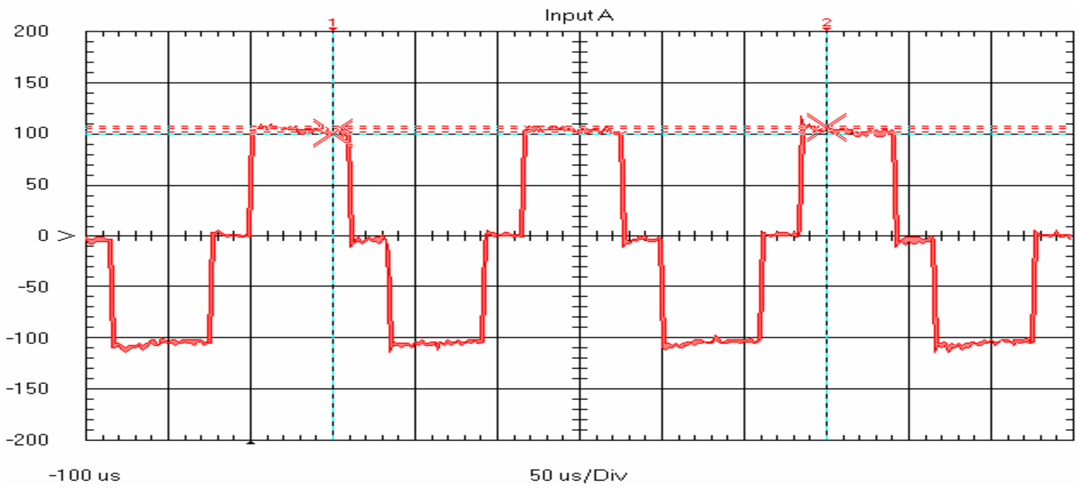

Fig.7.22 Transformer primary voltage at varying duty cycle

(Scale: X axis:1div= 50μS, Y-axis: 1div= 50V)

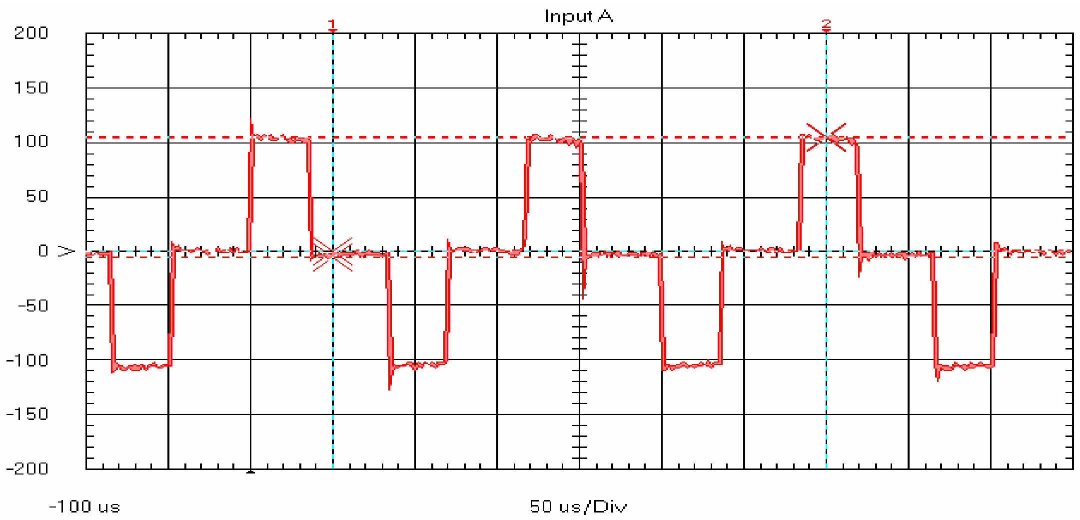

Fig.7.23 Transformer primary voltage at varying duty cycle

(Scale: X axis:1div= 50µS, Y-axis: 1div= 100V)

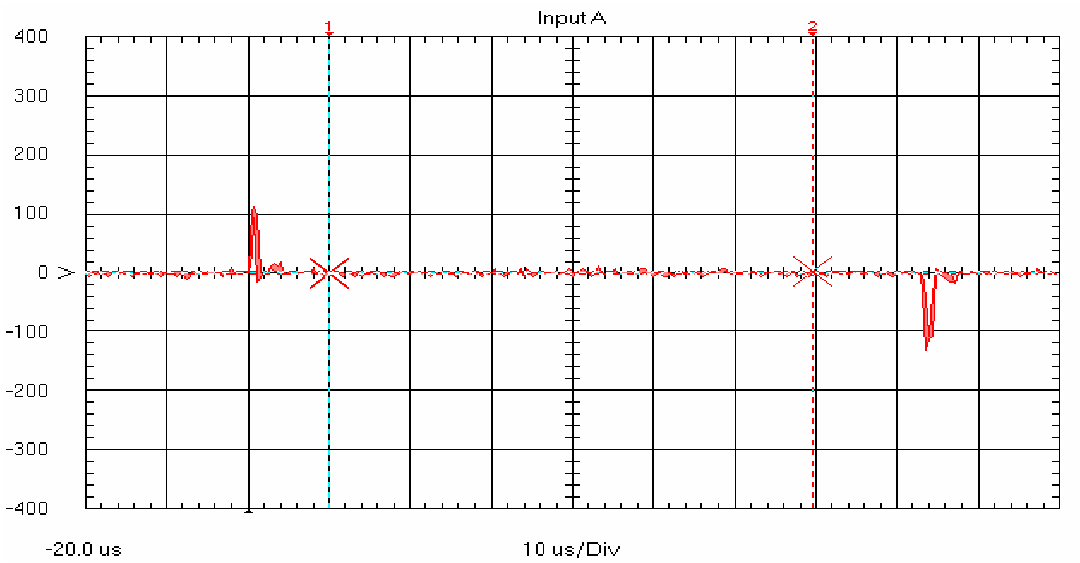

Fig.7.24 Transformer primary voltage at minimum duty cycle
(Scale: X axis:1div= 10µS, Y-axis: 1div= 100V)

7.3 Final experimental results (144V/600V)

The prototype module will operate on 3.6kW (100Ω) load. The results includes controlled output DC Voltage (600V), input DC voltage (144V) and Transformer primary wave.

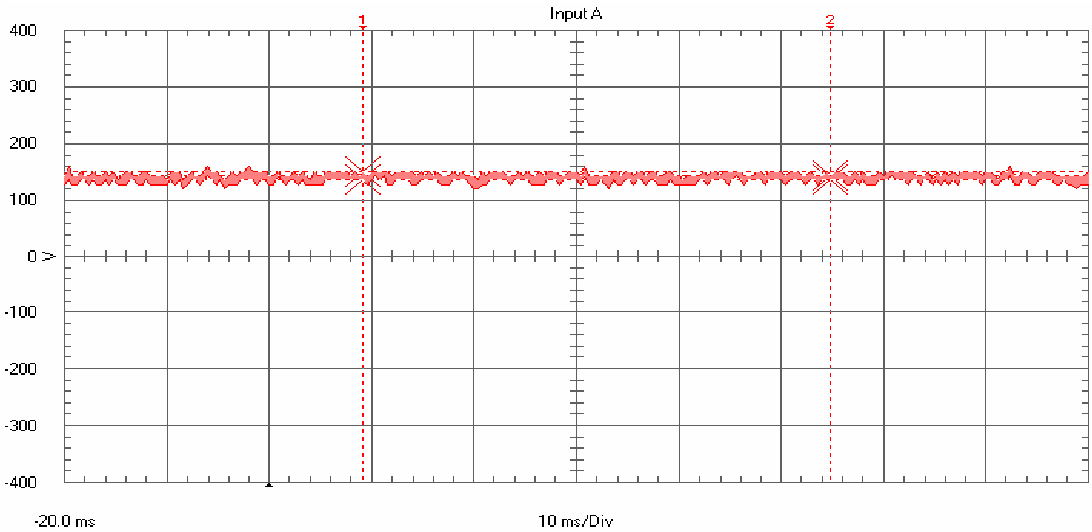

Fig.7.25 Input dc voltage (Scale: X axis: 1div= 10mS, Y-axis: 1div= 100V)

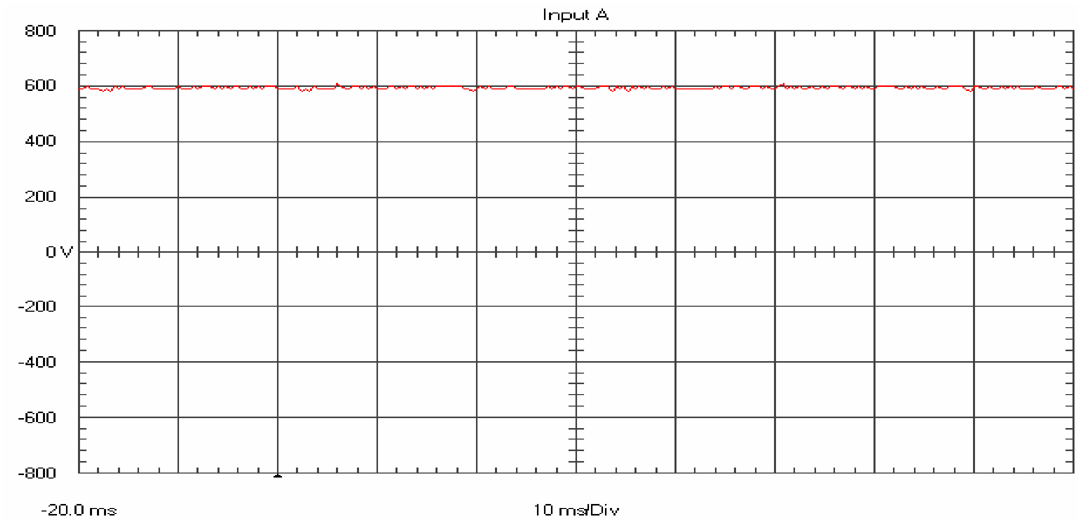

Fig.7.26 Output dc voltage at full duty cycle

(Scale: X axis:1div= 10mS, Y-axis: 1div= 200V)

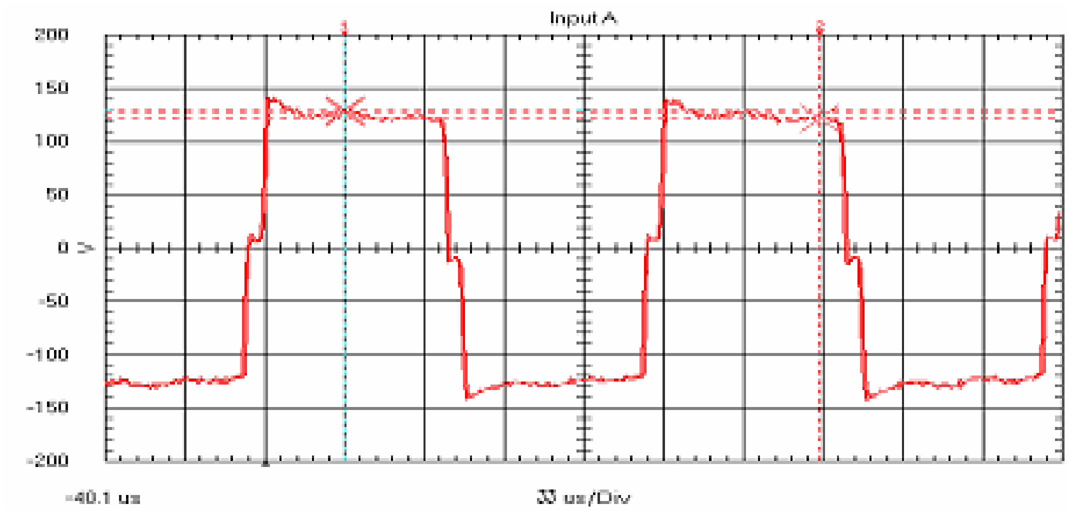

Fig.7.27 Transformer primary voltage

(Scale: X axis: 1div= 33μS, Y-axis: 1div= 50V)

CHAPTER-8
CONCLUSION AND SCOPE FOR FUTURE WORK

8.1 GENERAL

This chapter summarized the major conclusions drawn from the work, compare isolated full bridge converter with non isolated boost converter for the same application and also it proposed the scope of the future work in the field of isolated converters and especially for full bridge converter.

8.2 CONCLUSION

The DC/DC Converter will meet the required specifications. The calculations, design and experimental results illustrate that the full-bridge is the suitable topology. The converter's operation was verified for loads up to 3.6 kW. The constant voltage (CV) mode control is simulated and tested using DSP TMS320F2811with both the methods like conventional control scheme and phase shift control scheme. The CV mode control is failed for conventional control scheme due to not exactly control of duty cycle. The transformer leakage inductance does the severe ringing with the parasitic capacitance of switches. This ringing associated with the conventional full-bridge DC converter solved using phase shift control scheme.The Output voltage regulated with varying duty cycle of full bridge inverter using phase shift control scheme. Overall, the experimental results are satisfactory and matched the prediction from design and simulations.

8.3 COMPARISION OF ISOLATED AND NON ISOLATED CONVERTER

The purpose of this project work is to develop a battery back up supply for the variable frequency AC drive. Here both isolated and non isolated converter topology is studied and compared for this purpose.

Table 8.1 Comparison of isolated and non isolated converter

Sr. No.	Parameter	Isolated converter (Full Bridge Converter)	Nonisolated converter (Boost converter)
1	Voltage across the IGBT	144 V ± 20% (Maximum variation of Input voltage)	(Maximum variation of Output voltage)
2	Average Current through the IGBT	66.51 A (Depends upon the variation of the load current)	68 A (Depends upon the variation of the load current)
3	Total quantity of IGBT	4	1
4	Rating of IGBT	300 V, 100 A	1200 V, 100 A
5	Amorphous Core use in magnetic component	AMCC 50	AMCC 630
6	Total quantity of Fast recovery diode	4	1
7	Rating of Fast recovery diode	1200 V, 50 A	1200 V, 100 A
8	Efficiency (Considering the switching and magnetic component losses)	Achieved by almost 80 to 90 %	Achieved by almost 85 to 90 %
9	Filter requirement	YES	NO
10	Gate driver requirement	4 pulse gate driver circuit required	1 pulse gate driver circuit required
11	Applications	Battery back up AC drive,Ultasound and X-ray equipment, photovoltaic system, High power supplies for plasma application	Wind power generation, Battery back up AC drive, Active Power factor correction

8.4 SCOPE FOR FUTURE WORK

The work carried out during this project work can be improved further with following work.

- This project provides battery back up system to the variable frequency ac drive. CV mode control is most widely used control method of inverter, one can implement other control schemes like current control scheme,CC mode control etc., to improve the performance.
- Implementation of project for very high power may be possible .one can parallel the modules and can get higher power converter module with the same control loop for each module.

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LIST OF PAPER PUBLISHED, SUBMITTED DURING PROJECT WORK

Paper published.

[1] Pravin D. Patel, Mitesh N. Priyadarshi, Vinod P. Patel, Prof.D.B.Dave, “Implementation of High Power Isolated DC/DC Boost Converter Using DSP”, 2nd National conference on computational Intelligence in power apparatus and systems,CIPS-2008,SRM University,Chennai,April 18-19,2008,pp.595-598.

[2] Pravin D. Patel, Mitesh N. Priyadarshi, Vinod P. Patel, “Implementation of Isolated DC/DC Boost Converter with power factor correction Using DSP”, National conference of on recent advancement and technology,Ajmer,26th April 2008.

Papers submitted and under review.

[1] Pravin D. Patel, Mitesh N. Priyadarshi, Vinod P. Patel, “Simulation and Implementation of Isolated DC/DC Boost Converter with power factor correction Using DSP”, International conference on electrical machines and systems, Wuhan, P.R.China, Oct-17-20, 2008.

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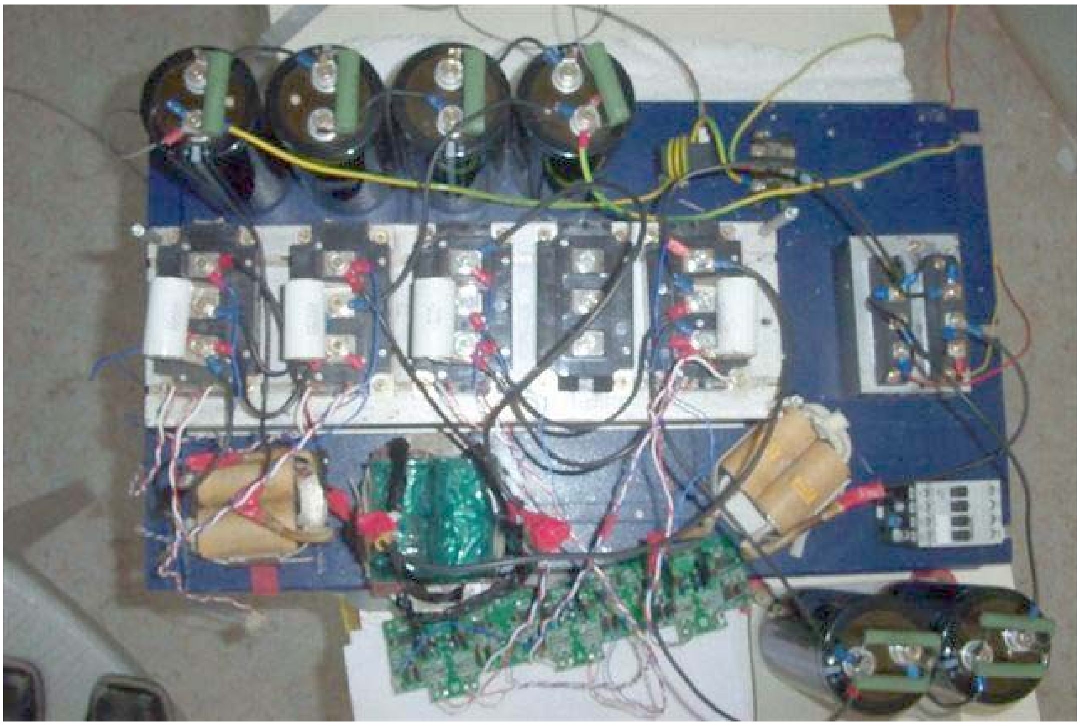
[3] Mitesh N. Priyadarshi, Pravin D. Patel, Vinod P. Patel “Implementation of 10 kW 6 kHz DC/DC Boost Converter Using DSP”, International conference on electrical machines, Khargpur, Dec-2008.

APPENDIX-A

Hardware set up for isolated high power converter module



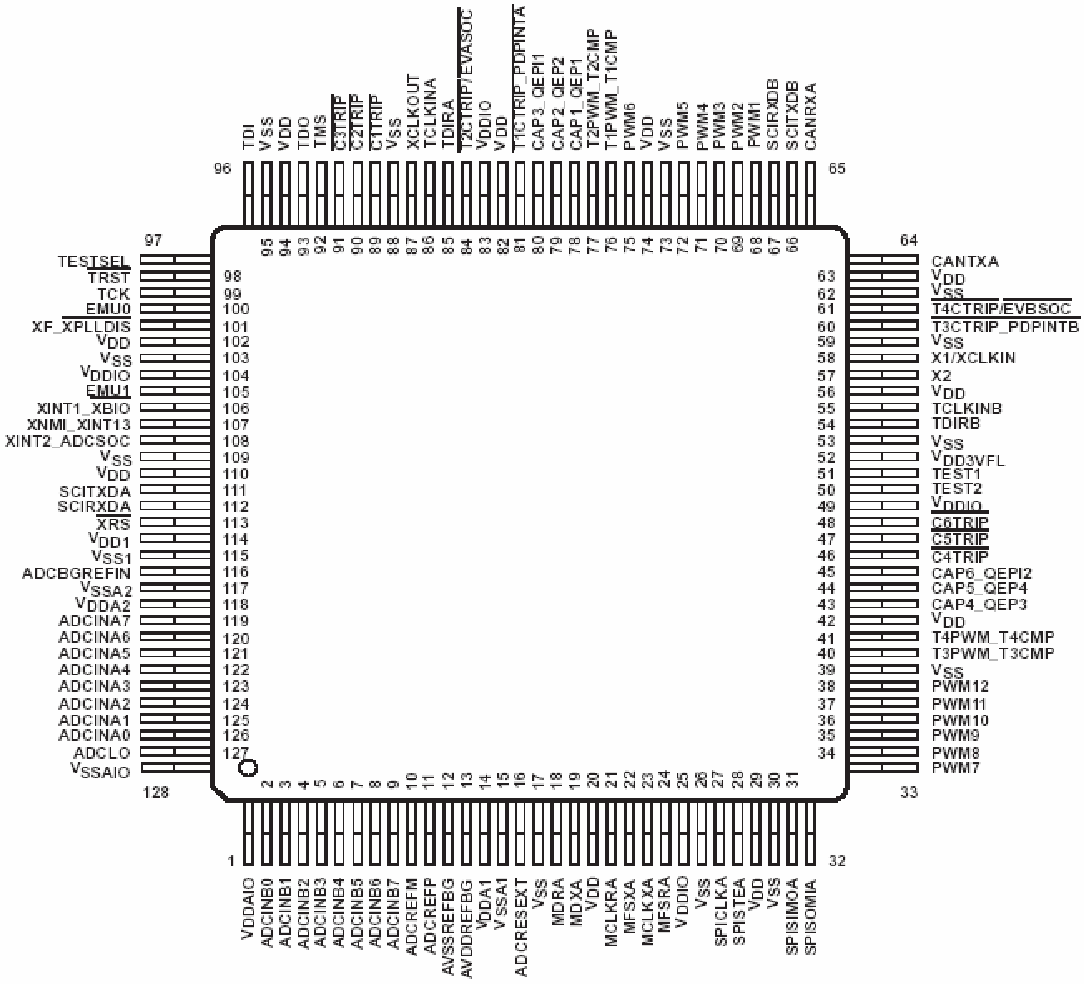
IGBTs module on Heat sink

Load resistance

Control card PCB2004A

APPENDIX-B

PIN DIAGRAM OF DSP TMS320F2811



FEATURES OF TMS320F2811

- High-Performance Static CMOS Technology

  150 MHz (6.67-ns Cycle Time)

  Low-Power (1.8-V Core @135 MHz, 1.9-V Core @150 MHz, 3.3-V I/O) Design

- JTAG Boundary Scan Support

- High-Performance 32-Bit CPU (TMS320C28x)

  - 16 x 16 and 32 x 32 MAC Operations
  - 16 x 16 Dual MAC
  - Harvard Bus Architecture

- Atomic Operations
- Fast Interrupt Response and Processing
- Unified Memory Programming Model
- 4M Linear Program/Data Address Reach
- Code-Efficient (in C/C++ and Assembly)
- TMS320F24x/LF240x Processor Source Code Compatible

- On-Chip Memory
  - Flash Devices: Up to 128K x 16 Flash (Four 8K x 16 and Six 16K x 16 Sectors)
  - ROM Devices: Up to 128K x 16 ROM
  - 1K x 16 OTP ROM
  - L0 and L1: 2 Blocks of 4K x 16 Each Single-Access RAM (SARAM)
  - H0: 1 Block of 8K x 16 SARAM
  - M0 and M1: 2 Blocks of 1K x 16 Each SARAM

- Boot ROM (4K x 16)
  - With Software Boot Modes
  - Standard Math Tables

- Clock and System Control
  - Dynamic PLL Ratio Changes Supported
  - On-Chip Oscillator
  - Watchdog Timer Module

- Three External Interrupts

- Peripheral Interrupt Expansion (PIE) Block That Supports 45 Peripheral Interrupts

- Three 32-Bit CPU-Timers

- 128-Bit Security Key/Lock
  - Protects Flash/ROM/OTP and L0/L1 SARAM
  - Prevents Firmware Reverse Engineering

- Motor Control Peripherals
  - Two Event Managers (EVA, EVB)
  - Compatible to 240xA Devices

- Serial Port Peripherals
  - Serial Peripheral Interface (SPI)
  - Two Serial Communications Interfaces (SCIs), Standard UART
  - Enhanced Controller Area Network (eCAN)
  - Multichannel Buffered Serial Port (McBSP)

- 12-Bit ADC, 16 Channels
  - 2 x 8 Channel Input Multiplexer
  - Two Sample-and-Hold
  - Single/Simultaneous Conversions
  - Fast Conversion Rate: 80 ns/12.5 MSPS

- Up to 56 General Purpose I/O (GPIO) Pins
- Advanced Emulation Features
  - Analysis and Breakpoint Functions
  - Real-Time Debug via Hardware
- Development Tools Include
  - ANSI C/C++ Compiler/Assembler/Linker
  - Code Composer Studio
  - DSP/BIOS
  - JTAG Scan Controllers
- Temperature Options:
  - A: -40°C to 85°C (GHH, ZHH, PGF, PBK)
  - S/Q: -40°C to 125°C (GHH, ZHH, PGF, PBK)

APPENDIX-C

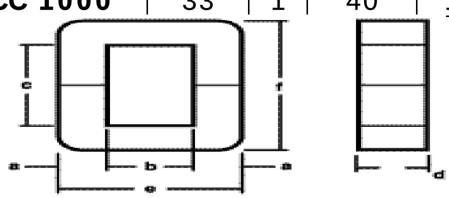
WIRE GAUGE SELECTION TABLE

AWG	Diameter		Turns of wire		Area		Copper resistance	Copper resistance[3]
	(inch)	(mm)	(per inch)	(per cm)	(kcmil)	(mm^2)	(Ω/1 km)	(Ω/1000 ft)
000000(6/0)	0.58	14.73	1.72	0.68	336.5	170		
00000(5/0)	0.5165	13.12	1.94	0.76	266.8	135		
0000(4/0)	0.46	11.68	2.17	0.85	211.6	107	0.16*	0.049*
000(3/0)	0.4096	10.4	2.44	0.96	167.8	85	0.2*	0.062*
00(2/0)	0.3648	9.266	2.74	1.08	133.1	67.4	0.25*	0.077*
0(1/0)	0.3249	8.251	3.08	1.21	105.5	53.5	~0.3281	~0.1
1	0.2893	7.348	3.46	1.36	83.69	42.4	0.4*	0.12*
2	0.2576	6.544	3.88	1.53	66.37	33.6	0.5*	0.15*
3	0.2294	5.827	4.36	1.72	52.63	26.7		
4	0.2043	5.189	4.89	1.93	41.74	21.2	0.8*	0.24*
5	0.1819	4.621	5.5	2.17	33.1	16.8		
6	0.162	4.115	6.17	2.43	26.25	13.3	1.5*	0.47*
7	0.1443	3.665	6.93	2.73	20.72	10.5		
8	0.1285	3.264	7.78	3.06	16.52	8.37	2.2*	0.67*
9	0.1144	2.906	8.74	3.44	13.08	6.63		
10	0.1019	2.588	9.81	3.86	10.38	5.26	3.2772	0.9989
11	0.0907	2.305	11.03	4.34	8.23	4.17	4.1339	1.26
12	0.0808	2.053	12.38	4.87	6.53	3.31	5.21	1.588
13	0.072	1.828	13.89	5.47	5.17	2.62	6.572	2.003
14	0.0641	1.628	15.6	6.14	4.1	2.08	8.284	2.525
15	0.0571	1.45	17.51	6.89	3.26	1.65	10.45	3.184

WIRE GAUGE SELECTION TABLE								
							Copper	Copper
							resistance	**resistance**[3]
AWG	**Diameter**		**Turns of wire**		**Area**			
18	0.0403	1.02362	24.81	9.77	1.62	0.823	20.948	6.385
19	0.0359	0.9116	27.86	10.97	1.29	0.653	26.414	8.051
20	0.032	0.8128	31.25	12.3	1.02	0.518	33.301	10.15
21	0.0285	0.7229	35.09	13.81	0.81	0.41	41.995	12.8
22	0.0253	0.6438	39.53	15.56	0.64	0.326	52.953	16.14
23	0.0226	0.5733	44.25	17.42	0.51	0.258	66.798	20.36
24	0.0201	0.5106	49.75	19.59	0.4	0.205	84.219	25.67
25	0.0179	0.4547	55.87	22	0.32	0.162	106.201	32.37
26	0.0159	0.4049	62.89	24.76	0.255	0.129	133.891	40.81
27	0.0142	0.3606	70.42	27.72	0.201	0.102	168.865	51.47
28	0.0126	0.3211	79.37	31.25	0.16	0.081	212.927	64.9
29	0.0113	0.2859	88.5	34.84	0.127	0.0642	268.471	81.83
30	0.01	0.2546	100	39.37	0.1	0.0509	338.583	103.2
31	0.0089	0.2268	112.36	44.24	0.08	0.0404	426.837	130.1
32	0.008	0.2019	125	49.21	0.063	0.032	538.386	164.1
33	0.0071	0.1798	140.85	55.45	0.05	0.0254	678.806	206.9
34	0.0063	0.1601	158.73	62.49	0.04	0.0201	833	260.9
35	0.0056	0.1426	178.57	70.3	0.032	0.016	1085.958	331
36	0.005	0.127	200	78.74	0.025	0.0127	1360.892	414.8
37	0.0045	0.1131	222.22	87.49	0.02	0.01	1680.118	512.1
38	0.004	0.1007	250	98.43	0.016	0.00797	2127.953	648.6
39	0.0035	0.08969	285.71	112.48	0.012	0.00632	2781.496	847.8
40	0.0031	0.07987	322.58	127	0.01	0.00501	3543.307	1080

AMORPHOUS C-CORE SELECTION TABLE

AMCC CORE TABLE															
	CORE DIMENSION										PERFROMANCE PARAMETERS				
	a (mm)	±	b (mm)	c (mm)	d (mm)	±	e (mm)	±	f (mm)	±	lm (cm)	ac (cm2)	Wa (cm2)	Ap (cm4)	(gms)
AMCC 4	9	0.5	10.5	32.75	15.25	0.3	28.5	0.5	51	1	12.7	1.11	3.44	3.82	102
AMCC 6.3	10	0.5	11	33	20	0.5	31	1	53	2	13.1	1.6	3.6	5.8	150
AMCC 10	11	0.8	13	40	20	0.5	35	1	62	2	15.4	1.8	5.2	9.4	200
AMCC 8	11	0.8	13	30	20	0.5	35	1	52	2	13.2	1.8	3.9	7	170
AMCC 16B	11	0.8	13	50	25	0.5	35	1	72	2	16.9	2.3	6.5	15	280
AMCC 16A	11	0.8	13	40	25	0.5	35	1	62	2	15.1	2.3	5.2	12	250
AMCC 20	11	0.8	13	50	30	0.5	35	1	72	2	17.5	2.7	6.5	17.6	340
AMCC 40	13	0.8	15	56	35	0.5	41	1	82	2	19.9	3.7	8.4	31.1	530
AMCC 25	13	0.8	15	56	25	0.5	41	1	82	2	19.6	2.7	8.4	22.7	380
AMCC 32	13	0.8	15	56	30	0.5	41	1	82	2	20	3.2	8.4	26.9	460
AMCC 50	16	1	20	70	25	0.5	52	1	102	3	24.9	3.3	14	46.2	590
AMCC 63	16	1	20	70	30	0.5	52	1	102	3	25.3	3.9	14	54.6	710
AMCC 80	16	1	20	70	40	1	52	1	102	3	25.4	5.2	14	72.8	950
AMCC 100	16	1	20	70	45	1	52	1	102	3	25	5.9	14	82.6	1,060
AMCC 160	19	1	25	83	40	1	63	1	121	3	28.5	6.5	20.8	135.2	1,330
AMCC 125	19	1	25	83	35	1	63	1	121	3	30.2	5.4	20.8	112.1	1,170
AMCC 250	19	1	25	90	60	1	63	1	128	3	31.4	9.3	22.5	209.3	2,100
AMCC 200	19	1	25	83	50	1	63	1	121	3	29.8	147	20.8	162.2	1,670
AMCC 168S	20.4	0.5	30.2	155.2	20	0.5	71	0.8	196	2	45.4	3.35	45.7	153	1,090
AMCC 320	22	1	35	85	50	1	79	1	129	4	32.5	9	29.8	267.8	2,170
AMCC 400	22	1	35	85	65	1	79	1	129	4	33.6	11.7	29.8	348.1	2,820
AMCC 500	25	1	40	85	55	1	90	1	135	4	35.6	11.3	34	384.2	2,900
AMCC 630	25	1	40	85	70	1	90	1	135	4	35.6	14.3	34	486.2	3,670
AMCC 800A	25	1	40	85	85	1.5	90	1	135	4	35.6	17.4	34	591.6	4,450
AMCC 367S	25.8	1	66	97.8	25	0.7	117.6	1.5	149.4	1.5	43.78	5.29	63.81	338	1,662
AMCC 800B	30	1	40	95	85	1.5	100	1	155	4	39.3	21	38	798	5,930
AMCC 1000	33	1	40	105	85	1.5	106	1	171	5	42.7	23	42	966	7,060



AMORPHOUS C CORES CROSS SECTION

AMORPHOUS C-CORE TABLE

lm = mean magnetic path length

Ac = net cross-sectional area

Wa = core window area