ULTRA-CAPACITOR BASED BI-DIRECTIONAL BUCK-BOOST CONVERTER FOR POWER FLOW CONTROL IN HYBRID ELECTRIC VEHICLES

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines & Drives)

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I **Meet Patel**, Roll No. **12MEEP17**, give undertaking that the Major Project entitled **"Ultra-Capacitor Based Bi-Directional Buck-Boost Converter for Power Flow Control in Hybrid Electric Vehicles"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Power Electronics Machines** & **Drives, Electrical Engineering**, under Institute of Technology of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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This is to certify that the Major Project Report entitled "Ultra-Capacitor Based Bi-Directional Buck-Boost Converter for Power Flow Control in Hybrid Electric Vehicles", submitted by Mr.Meet Patel ($12MEEP17$) towards the partial fulfillment of the requirements for for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Electronics, Machines and Drives of Nirma University is the record of work carried out by him 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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It's my pleasure in submitting the report on "Ultra-Capacitor Based Bi-Directional Buck-Boost Converter for Power Flow Control in Hybrid Electric Vehicles".I am grateful to my Project Guide Dr.P.N.Tekwani for allowing me to work on this project and given his constant support and valuable advice when i needed it. I acknowledge with thanks to Mr.M.R.Tilwali for his great encouragement and support. They have been very generous in extending their cooperation and help and this has enabled me to carry out this study properly. I would also like to thank the other faculty members of my group as well as the rest of the faculty for their motivation.At last,I thank my friends and family for their support and encouragement.

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Abstract

Use of various power-buffers in the electrical vehicles have a significant impact on its performance The use of Ultra-Capacitor gives the improvement in power handling capacity of the Electric Vehicles. The system for managing energy flow of hybrid electric vehicles is studied. This system consists of batteries and Ultra-Capacitors. The ultra-capacitor concerns with the rapid rate of energy recovery in the acceleration operation of electric vehicles. By Proper design of converter and with a use of power buffer battery performance can be improved and it's life can be increased. The project utilizes the application of a ultra-capacitor for better energy management in the electric vehicle. This type of system reduces the stress on the main batteries and keeps the stress away from it and increases the efficiency. Such system extracts the power from the batteries at slow rates. The weight of such system is less as compared to non-hybrid systems, hence efficiency is also increased. The active clamped DC-DC converter is used to get controlled and instantaneous power flow. With the help of ATMEGA16 controller, open-loop and closed loop operations of the bidirectional converter are achieved. Pulses are created by using PWM technique. For a high-dynamic energy storage system design and its control, an electrical equivalent circuit modeling of ultra-capacitor using passive elements is performed. This hybrid converter is analyzed. A close resemblance of experimental results with simulated results is achieved by the prototype system of 200 W.

List of Figures

Abbreviations

AC .... Alternating current
CMOS .... Complementary metaloxidesemiconductor
DC .... Direct current
EPROM .... Erasable Programmable Read Only Memory
EMI .... Electromagnetic Interference
GND .... Ground
IGBT .... Insulated Gate Bipolar Transistor
KVA .... Kilo volt ampere
KW .... Kilo watt
MOSFET .... Metal Oxide Semiconductor Field Effect Transistor
MIPS .... Microprocessor without Interlocked Pipeline Stages
PF .... Power factor
PWM .... Pulse Width Modulation
RISC .... Reduced instruction set computer
TOSC .... Timer/Counter Oscillator
ZCS .... Zero Current Switching
ZVS .... Zero Voltage Switching

Nomenclature

C_{cl} .... Clamping capacitor

D .... Duty cycle

D_C .... Converter Dutycycle

f_s .... Switching frequency

I_{lmain} .... Current passing through inductor (L)

L .... Current-fed inductor

N .... Turns ratio

P_o .... Output power

V_p .... Primary winding voltage

V_s .... Secondary winding voltage

V_{gs} .... Gate to source voltage

V_{ds} .... Drain to source voltage

η .... Efficiency

δI .... Ripple in the input inductor current

V_{cc} .... Micro-controller supply

$TOSC_1$ .... Timer/counter control register 1

$TOSC_2$ .... Timer/counter control register 2

Contents

Chapter 1

Introduction

1.1 Scope of Work

In this dissertation, a background description and review of bidirectional dc-dc converters are presented firstly to define this work. Then, the challenges were identified related to the design and control issues in the present non-isolated bidirectional dc-dc power converter. This improvement in the system leads high efficiency, simple circuit and cost effectiveness. The detailed design and operation considerations are analyzed and described. A unified power stage model is investigated and developed. A novel unified controller is proposed and digitally implemented with the AVR ATMEGA 16 controller. By the use of AVR-ATMEGA16 controller the voltages of Capacitor and Batteries are controlled using a PWM technique. This type of system reduces the stress on the main batteries and keeps the stress away from it and increases the efficiency. Such system extracts the power from the batteries at slow rates.The weight of such system is less as compared to non-hybrid systems, hence efficiency is also increased.

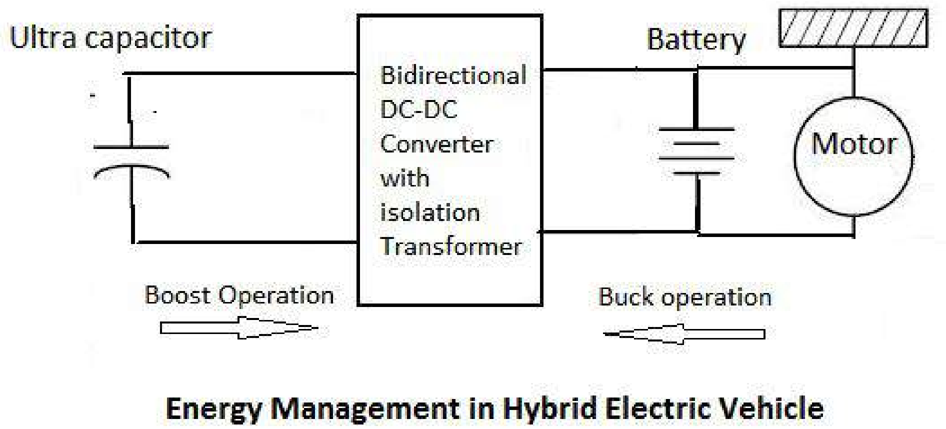

Figure 1.1: Concept of power flow Management in HEV

1.2 Literature survey

Various references have been used for theoretical understandings as well as an aid to the simulation carried out.

1 **L. Zhu, A Novel Soft-Commutating Isolated Boost Full-Bridge ZVS-PWM DCDC Converter for Bidirectional High Power Applications**

This papers introduces the use of RCD snubber circuit in order to reduce the high voltage spikes at the time of switching. At low load condition the switches turn off at zero voltage and the surge voltage of switch is low.[1]

2 **C. Chu and Y. Chen, ZVS-ZCS Bidirectional Full-Bridge DC-DC Converter**

The main focus of this paper is to reduce the ripple in the input current.To improve the overall efficiency, converter uses the leakage inductance L_l of the transformer and a capacitor for achieving resonance condition. The main switches and the output synchronous rectifiers are operated in ZVS(Zero Voltage Switching) and ZCS(Zero Current Switching) in order to improve the overall efficiency.[2]

3 **Jih-Sheng (Jason) Lai, Douglas J. Nelson, Energy Management Power Converters in Hybrid Electric and Fuel Cell Vehicles**

This paper discusses energy management converter system configurations and sizing issues. Various topologies of Basic bidirectional dcdc converter circuit are categorized in voltage source versus current source, isolated versus non-isolated, and buck type versus boost type. Multiplephase interleaved converters and their different operating modes are introduced.[3]

4 **E. Park, S. Choi, J. Moon, and B.H.Cho, A Soft-Switching Active-Clamp Scheme for Isolated Full-Bridge Boost Converter**

This paper introduces the isolated full-bridge boost converter having the active clamp algorithm to improve the efficiency. In the proposed method, to reduce the switching losses resonance condition is created between the clamping capacitor and the leakage inductor.[4]

5 **S. Han, H. Yoon, G. Moon, M. Youn, Y. Kim, and K. Lee, A New Active Clamping Zero-Voltage Switching PWM Current-Fed Half-Bridge Converter**

In this paper a new active clamping zero-voltage switching (ZVS) pulse-width modulation (PWM) current-fed half-bridge converter is proposed in this paper. Its active clamping circuit not only absorbs the surges of voltage across the turned-off switch, but also achieve the ZVS for all power switches.[5]

6 **V. Yakushev and S. Fraidlin, Full-Bridge Isolated Current Fed Converter with Active Clamp**

This paper investigates the application of a ultra-capacitor bank when used as a power buffer to smooth rapid power fluctuations in and out of the battery of an electric or hybrid vehicle. The study considers the simple case where the ultra-capacitor bank is connected directly in shunt with the battery as well as the case where it is connected through a DC/DC converter that is necessary to achieve optimal performance.[6]

7 **T. Mishima, E. Hiraki, T. Tanaka, and M. Nakaoka, A new soft-switched bidirectional dc-dc converter topology for automotive high voltage dc Bus architectures**

This paper deals with dual half-bridge converter linked with a high frequency transformer, which can be applicable as an interface between a high-voltage and low-Voltage bus line power source such as Super-capacitor. To reduce DC Bus switching losses Zero Current Switching (ZCS) is applied to the primary side circuit.[7]

8 **H.J. Chiu and L.W. Lin, A bidirectional dc-dc converter for fuel cell electric vehicle driving system**

This paper introduces a power converter for a fuel cell electric vehicle system. A new bidirectional, isolated topology is proposed in consideration of the differing fuel cell characteristics. Such converter has improved efficiency and low cost.[8]

9 **G. Chen, D. Xu, and Y.S. Lee, A family of soft-switching phase-shift bidirectional dc-dc converters, synthesis, analysis, and experiment**

This paper puts emphasis on study of Soft Switching Phase-Shift Bidirectional DC-DC Converters and to achieve ZVS operation.[9]

10 **F. Caricchi, F. Crescimbini, F.G. Capponi, and L. Solero, Study of bi-directional buck-boost converter topologies for application in electrical vehicle motor drives**

By this paper the motoring and regenerating operations of DC motor are realized. This paper investigates comparison of two bi-directional converter topologies. As per various driving modes, each of them changes the voltage level of the battery up or down.[10]

11 **F.Z. Peng, H. Li, G.-J. Su, and J.S. Lawler, A new ZVS bidirectional dc-dc converter for fuel cell and battery application**

This paper introduces new zero voltage switching(ZVS) technique which makes the new converter promising for medium and high power applications.To get the higher power density, light weight and cost effectiveness such power converters are required.[11]

12 **E. Hiraki, K. Yamamoto, T. Tanaka, T. Mishima, and M. Nakaoka, An isolated bidirectional dc-dc converter based super-capacitor interface for automobile electric power systems**

This paper gives a study of full-bridge and center tapped (push-pull) circuit-based bidirectional DC-DC converter. By this method surges of voltage and currents as wll as the conduction losses are reduced by applying ZVS technique.[12]

13 **R. Li, A. Pottharst, N. Frohleke, and J. Bocker, Analysis and design**

of improved isolated full-bridge bidirectional dc-dc converter

This paper introduces a novel Bi-Directional DC-DC converter which gives the ZVS and ZCS operations by incorporating active clamping circuit.[13]

14 **F. Krismer, J. Biela, and J.W. Kolar, A comparative evaluation of isolated bidirectional dc/dc converters with wide input and output voltage range**

This paper realizes the various DC-DC converter topologies for making 2 kw Bi-Directional battery charger which can be operated in wide range of input-output voltages.[14]

15 **J. Moreno, M.E. Ortuzar, and J.W. Dixon, Energy management system for a hybrid electric vehicle, using ultra-capacitors and neural networks**

Synopsis of hybrid prototype system of 53 kw by realizing different types of power buffers has been done. The system reduces the energy requirement of the EV by recovering the energy from regenerative action.[15]

1.3 Various Topologies of Hybrid Energy Storage System

1 **Basic Passive Parallel**

Passive paralleling is the simplest method of combining battery and UC(Ultra-Capacitor). Here the two energy sources are connected without any isolation or any power electronic converters. As two sources are always in parallel, ultra-capacitor will act as a low pass filter.

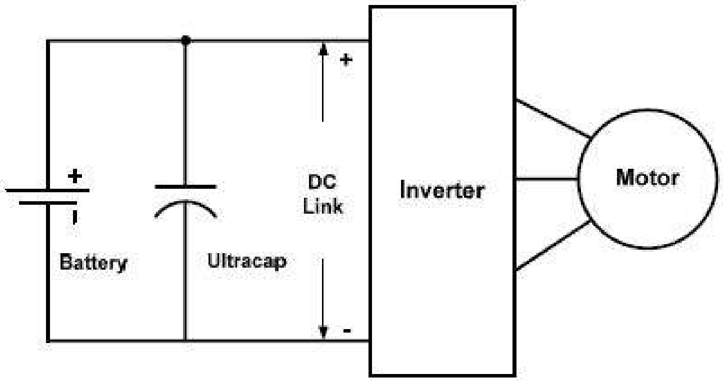

Figure 1.2: Basic Passive Parallel system

2 Ultra-Capacitor/Battery Configuration

The ultra-capacitor/battery configuration is the most used topology. By using a bi-directional DC/DC converter the voltage of UC can be used in a wide range. The bi-directional converter should be made of a larger size in order to handle the bulk amount of power of the UC. The battery is connected directly to the DC link. Hence DC link voltage cannot be varied.

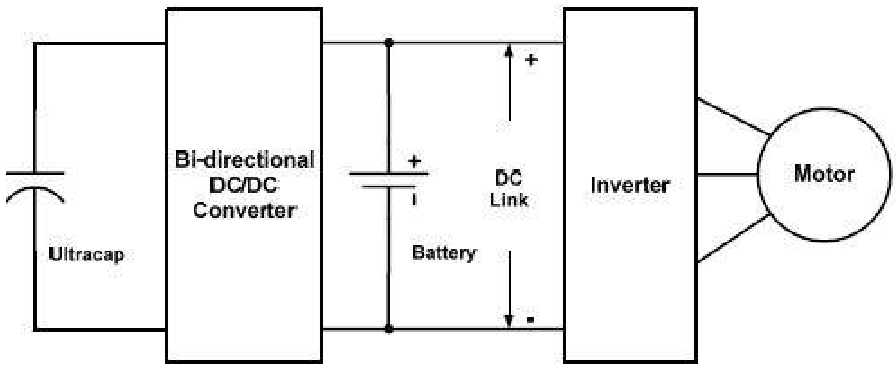

Figure 1.3: Ultra-Capacitor/Battery Configuration

3 **Battery/Ultra-Capacitor Configuration**

By changing the position of the battery and ultra-capacitor in the above topology, we get the battery/UC configuration. In this configuration the voltage of the battery can be maintained low or high than the ultra-capacitor voltage as per the requirement. The direct connection of ultra-capacitor to dc link makes it low pass filter. If proper control is provided to very the ultra-capacitor voltage then, it can be efficiently utilized.

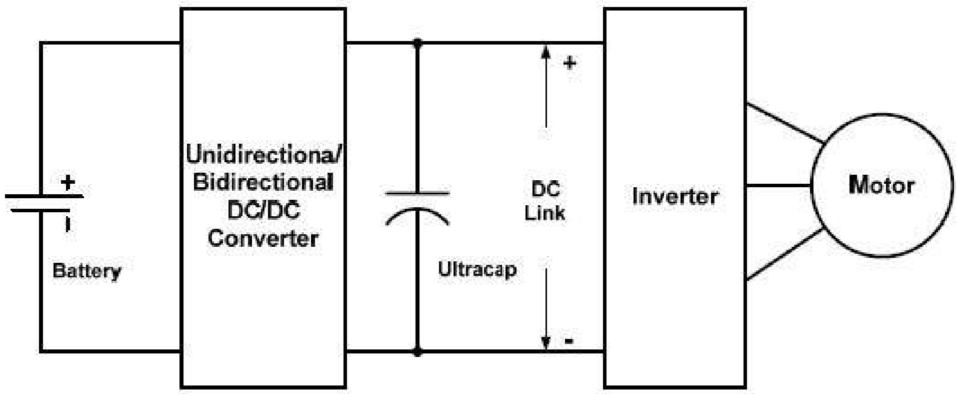

Figure 1.4: Battery/Ultra-Capacitor Configuration

4 **Cascaded Configuration**

For better working range of the ultra-capacitor/battery configuration, additional bi-directional DC/DC converter was added between the ultra-capacitor bank and the DC link.

5 **Multiple Converter Configuration**

Instead of using the cascaded configuration, multiple converter method does paralleling the output of the two converters. The outputs of both converters are same as the DC link voltage. Voltage of both the battery and the ultra-capacitor can be maintained lower than the DC link voltage. Voltage of ultra-

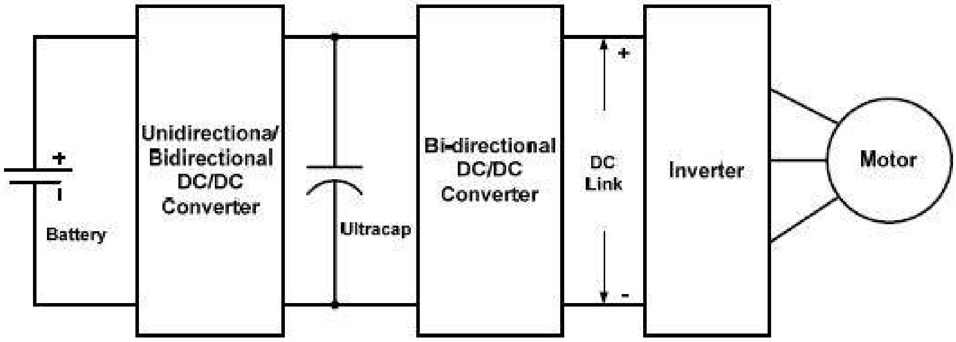

Figure 1.5: Cascaded Configuration

capacitor can varied in a wide range so the capacitor is fully utilized. Here,Two converters are used which can be considered as a disadvantage.

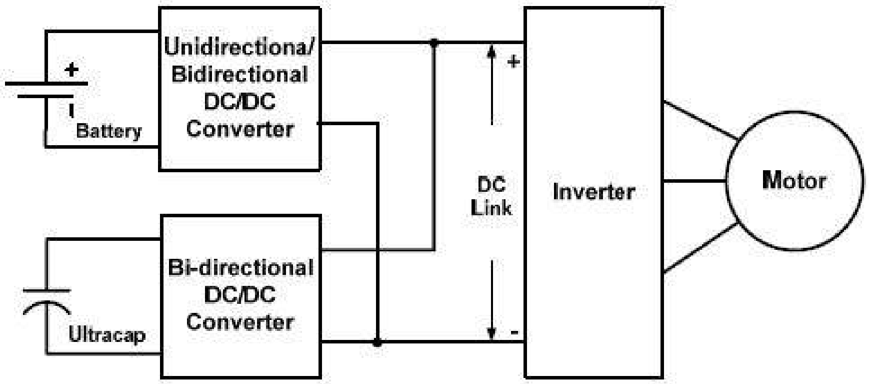

Figure 1.6: Multiple Converter Configuration

1.4 Batteries for HEV

Most of hybrid vehicles have used nickel metal hydride (NMH) type of batteries. Due to developments in lithiumion batteries they are most widely used in hybrid vehicles.

In the hybrid vehicles higher power batteries are given more importance then the higher energy density batteries. In the plug-in vehicles, both high power capability and high energy density batteries are required. Characteristics of plug-in vehicles falls between EV and HEV characteristics. The knowledge of HEV batteries is more recent than EV batteries due to its increasing popularity. Batteries for Hybrid electric

Figure 1.7: Battery modules

vehicles are different from electric-vehicles in several ways mentioned below.

- The cell size of the electric vehicle batteries is larger than Hybrid electric vehicle battery cells. This is necessary because the voltages of the two systems are compared. The energy stored in the Hybrid electric vehicle is much smaller than that in the electric vehicle units.

- Power handling of the batteries designed for hybrid electric vehicles is much higher than those designed for electrical vehicles. This requirement follows the lower weight of the hybrid electric vehicle batteries at high efficiency. For high power handling capability resistance of the battery should be low. Hence knowledge of the resistance is necessary.

- The energy densities of the hybrid electric vehicle batteries are lower than that of the electric vehicle batteries of the same type. For example, energy density of a lithiumion Electric vehicle is 120150 Wh/kg for hybrid electric vehicle battery it will be 5075 Wh/kg. Hence the tradeoff between power density and energy density is done which decides vehicle applications.

The (Ah) of the Plug-in hybrid electric vehicle battery will be smaller than for electric vehicles. The HEV batteries are to be designed as deep discharge for long cycle lifes.

1.4.1 Various Types of Batteries

Batteries are characterized in terms of its energy density but service life, loading characteristics, maintenance, self-discharging and costs.

- **Nickel Cadmium (Ni-cd):** It is having energy density. The Ni-cd battery is mostly used where long life and high rate of discharge are required. In the applications like radios, biomedical equipments and cameras it is used. Disadvantage of such battery is toxicity to the environment.

- **Nickel-Metal Hydride (NiMH):** It has a higher energy density compared to the Nickel-cadmium. It is used at the expense of reduced cycle life. Nickel metal hydride contains no toxic metals. Applications of such batteries are mobile phones and laptops.

- **Lead Acid:** For larger power applications where weight is of the equipment is emphasized the lead acid battery is the preferred. It is used in hospital equipments, UPS, emergency ligts etc.

- **Lithium Ion (Li-ion):** It is most used battery system. Lithium-ion is used in the light weight and high power applications like cellular phones and notebook computers. Though it is more expensive, strict guidelines should be followed for assuring the safety.

- **Lithium Ion Polymer (Li-ion polymer):** It is most economical version of the Lithium-ion. It has the same energy density as lithium-ion batteries has.Its slim geometry makes it use possible in compact applications like mobile phones.

1.5 Ultra-Capacitor

Ultra-capacitors are the energy storage devices. They use electrolytes and to meet the power, energy, and voltage requirements for a wide range of applications. Batteries stores the charges chemically but ultra-capacitors store it electrostatically. Due to charge separation they can withstand thousands of thousands of charge/discharge cycles without having any degradation in its life.

An ultra-capacitor is also known as a double-layer capacitor. It is polarized in the electrolytic solution to store energy. It is an electrochemical device but no chemical reactions are observed in its energy storage mechanism. Such mechanism is highly reversible which allows the ultra-capacitor to charge and discharge for thousands of time.

1.5.1 Working of Ultra-Capacitor

An ultra-capacitor consists of two porous plates. Which are suspended in an electrolyte material with a different voltage potentials applied across its collectors. The individual ultra-capacitors attracts the negative ions in the electrolyte by applying positive potentials at electrodes. A dielectric separator is used between the two electrodes. Which prevents the charges to move between the two electrodes.

Once the ultra-capacitor is charged and energy has been stored in it, a load can use its energy. The total amount of energy stored in it, is very large compared to a normal capacitor due to its enormous surface area. Which is created by the porous carbon electrodes and the separators.

In recent years, total energy density of the devices is increased. For the carbon (double-layer) technology cell voltages are increased to 2.7 V/cell by using acetonitrile

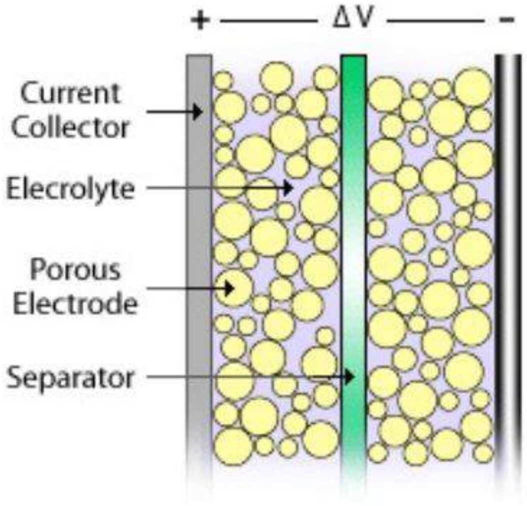

Figure 1.8: Ultra-Capacitor Structure

as the electrolyte material. Recent ultra-capacitors are suitable to use in mild hybrid electric vehicles using either engines or fuel cell. Mild hybrid word means the design of high power rating of the engine.

1.5.2 Characteristics of Ultra-Capacitor

- It has ultra-high Capacity. Its capacity is ranging from several farads to thousands of farads. It is about 5000 times larger than the electrolytic capacitor of same volume.

- It has very high power density. The power density of ultra capacitor is 20 kW/kg. In a short period several hundred to thousand amps of current can be released by ultra-capacitor. This feature proves it ideal for giving short term and high-power outputs.

- It has rapid charging and discharging. Ultra-capacitor can store electrical energy electrostatically without any type of chemical reactions. It has less charging time. It can be easily recharged by current of tens of amperes which can be

Figure 1.9: Stack of Ultra-Capacitor

called as rapid charging. All the batteries need hours of charging.

- It has long cycle life. The ultra capacitors can give required energy and power for thousands of cycles. Which makes it maintenance free. The cyclic behavior leads the poor performance of batteries as compared to ultra-capacitors.

- They have little influence of temperature. Ultra-capacitor has a greater low temperature performance in the range of 35 to 90 degree whereas batteries have the range of 0 to 35 degree.

Ultra-capacitors are not used in plug-in hybrid electric vehicles as the primary energy storage. It gives the best performance when it is combined with batteries in PHEV designs with short ranges.

1.6 Switching Operation

Most important part of the power electronic converter is its switching devices. Diodes and MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) are the Semiconductor devices typically used in switch-mode power converter. Diodes are uncontrolled. When they are forward biased they turns on and reverse bias makes them turn off. In order to divert the current away from the diode, some action should be taken externally. MOSFETs and IGBTs are controlled switches. By feeding a gate driver signal they can be turned on and off at required frequencies.

1.6.1 Power Mosfets

A power MOSFET is designed for different power levels. It has three terminals. A gate, a source and a drain. When current is fed to the gate, the switch turns on and gate to source capacitance of which charges to a threshold voltage V_{th}, because of which a field is created which allows the current to flow from drain to source. It has an isolated gate. Current should not be continuously fed to the gate to keep the device turned on. As long as the device is on, voltage across the gate to source capacitance V_{gs} is larger than V_{th} and field which keeps the drain to source channel open. Even when the switch is off, the MOSFET has an intrinsic parallel body diode which can conduct reverse current in the time of feedback operation. The MOSFET works in three main regions, active, saturation, and cut-off. In all the controllable semiconductor devices and all power electronics applications switches are either fully on or fully off. The MOSFET in a power converters operate either in the cutoff region region (fully off) or in the triode region (fully on). When the MOSFET is in the on-state, it acts as a resistor, $Rds_{(on)}$ (drain to source on-state resistance) between its drain and source terminals. This $Rds_{(on)}$ is responsible for the energy losses when current flows through the device, which are called as conduction losses.

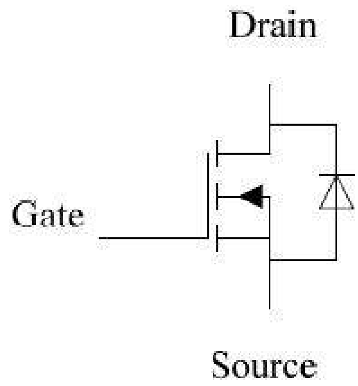

Figure 1.10: A N-Channel power MOSFET symbol

1.6.2 High Switching Frequency Operation

A power electronic converter incorporates energy storage elements like inductors, transformers, capacitors etc. They account for its overall size. Such components transfers the energy as power conversion process. As the converter's switching frequency is increases, values of its energy storage elements decreases. Their physical size and weight also increases. Hence the higher the switching frequency, converter needs small components or the storage elements. However, there are many drawbacks to operate such converters with high switching frequency. The main reason of doing so is increasing the converter's switching losses. The power is dependent on voltage and current hence voltage and current overlaps during switching transitions means that there are power losses during these times. Such losses are referred as switching losses. The more will be the switching frequency, the more losses the converter will have. Main switching loss in a MOSFET is the energy stored in its output capacitance when it is turned on.

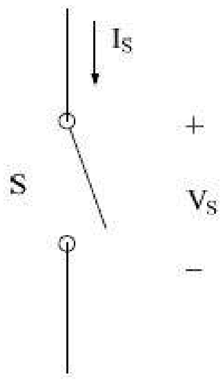

Figure 1.11: A power converter switch symbol

1.6.3 Soft Switching

If the problems related to the switching losses occurs, the higher frequency converters needs some techniques to reduce it. They are called as “soft-switching” techniques. In such techniques the switches are forcefully turned off such thst the voltages and currents spikes at the time of switching instant will be zero. Here all the Switching losses are reduced because there is no overlap of switch voltage and current during the switching transitions. Soft-switching techniques are either zero-voltage switching (ZVS) or zero-current switching (ZCS) techniques.

ZVS Technique

ZVS techniques forces the voltage to be zero at the time of turn-on or turn-off. All MOSFETs have anti-parallel diodes which allows current to flow from source to drain in a MOSFET. Hence the current is forced to pass from the body diode of device at the time of switching. This clamps the voltage across the device so that turn-on switching losses can be reduced. Slowing down the voltage rise rate across the switch (adding a capacitor across the switch) makes such switching possible.It limits the overlapping of voltage and current during the switching state.

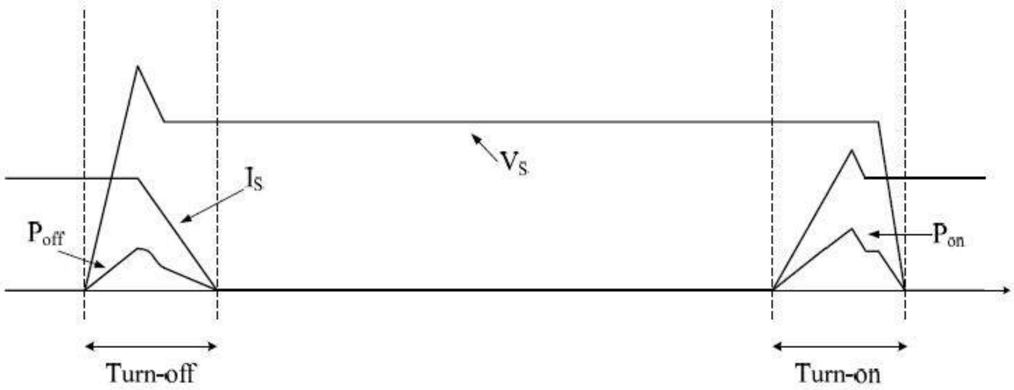

Figure 1.12: Typical switch voltage and current waveforms

ZCS Technique

ZCS techniques forces the current to be zero at the time of turn-on or turn-off. All MOSFETs have anti-parallel diodes which allows current to flow from source to drain in a MOSFET. A negative potential is provided at the switch, hence current path will be affected and at the time of switching, rate of rise of current can be reduced.Hence the current is forced to pass from the body diode of device at the time of switching. This clamps the voltage across the device so that turn-on switching losses can be reduced. Slowing down the voltage rise rate across the switch (adding a capacitor across the switch) makes such switching possible.It limits the overlapping of voltage and current during the switching state. The ZCS turn-on is achieved by adding the inductor in series with the switch which slows down the rate of rise of current.

Chapter 2

Bidirectional Buck-Boost DC-DC Converter

2.1 Introduction

High efficiency and reliability is the essential requirement for DC-DC converter in the hybrid vehicles. Switching regulators can step-up and step-down the voltage levels. They can invert the voltage too. Such regulators uses inductor, capacitor and transformer as energy storage elements. The feedback circuit maintains the constant voltage and currents within limits.[10]

Various types of DC-DC converters are used for different types of applications. Some converters are used for buck operations whereas some are used only for boost operation. A full isolation is required between input and ouput circuits.[8]

Non-isolated converters are normally used where the voltage needs to be stepped up or down. The different types of converters in non-isolating type are buck, boost, buck-boost and charge-pump type converters. Usually such converters are used in the low voltage applications. Isolating converters are used in the applications where output should not have any type of influence from input fluctuations. Isolating converter operation depends on energy stored in magnetic field. They are used for the low power systems.

For higher power systems, full and half bridge topologies are used. The input is isolated from output. Hence, dual-polarity operation can be achieved. As compared to simple buck-boost topology this topology has several advantages :

- Proper electrical isolation e achieved between input and output.
- Larger boosting ratio can be obtained.
- System can be protected from changes in the output states.

2.2 Non-Isolated Bidirectional DC-DC Converters

Normally in the power systems having simple buck and boost type operations, no isolation is provided. To isolate the load from the source high frequency transformer is implemented. For reducing the losses, weight and cost of the whole system, sometimes such systems are not selected.ctive. Hence in the aero-space systems where the weight is most concerned part, transformer-less converters are preferred.[15]

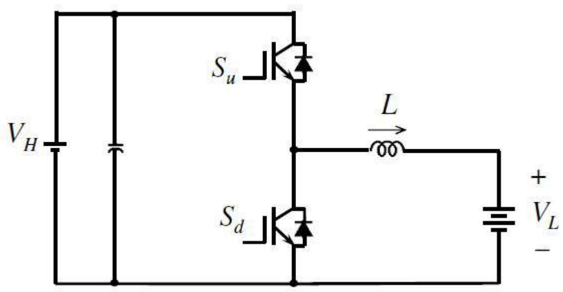

Figure 2.1: Basic bidirectional dc-dc converter with buck and boost structure

2.3 Isolated Bidirectional DC-DC Converters

In the bidirectional dc-dc converters, isolation is provided by high frequency transformers which increases the cost and weight of the system. By proper impedance matching, voltages of both the sources can be maintained to desired values. If converter is used as a current source then transformer inductance should be considered as a part of the main circuit inductance. Such type of converters usually gives the isolation between two DC sources for the better power flow control.[12]

2.4 Dual Active Bridge Converter

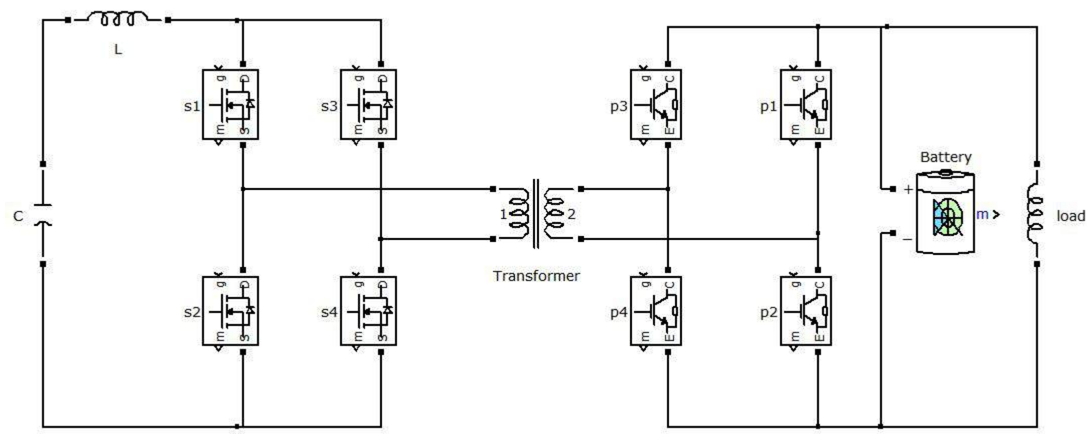

Figure 2.2: The bi-directional DC/DC converter(full-bridge type topology)

The Dual active bridge converter consist of two DC sources on two sides of isolation transformer. In case of the current controlled mode of operation additional inductor is to be placed in series with the transformer winding inductance. Two sides of the dual active bridge are connected with different type of DC sources. It can be a battery, a fuel-cell or ultra-capacitor. Each bridge generates high-frequency square-wave voltage at its terminals.

By adding the proper amount of inductor value two square waves are phase shifted and hence proper power flow control of Converter can be achieved. In the motoring or in the regeneration action Bi-Directional power flow can be achieved.

Basically, in the boost mode of operation the discharging takes place, whereas in the buck mode of operation charging(regenerative action) takes place. One circuit operates as an inverter and other circuit acts as a rectifier at a time. Both the converters simultaneously operates, but in different conversion actions. Hence such converters are called as **Bi-Directional Dual Active Bridge** (DAB) dc-dc converter.

Bidirectional power flow control and energy management is the key feature of dual active converters. Which gives the flexible interfacing of powerbuffers.

2.5 Proposed Clamp Converter

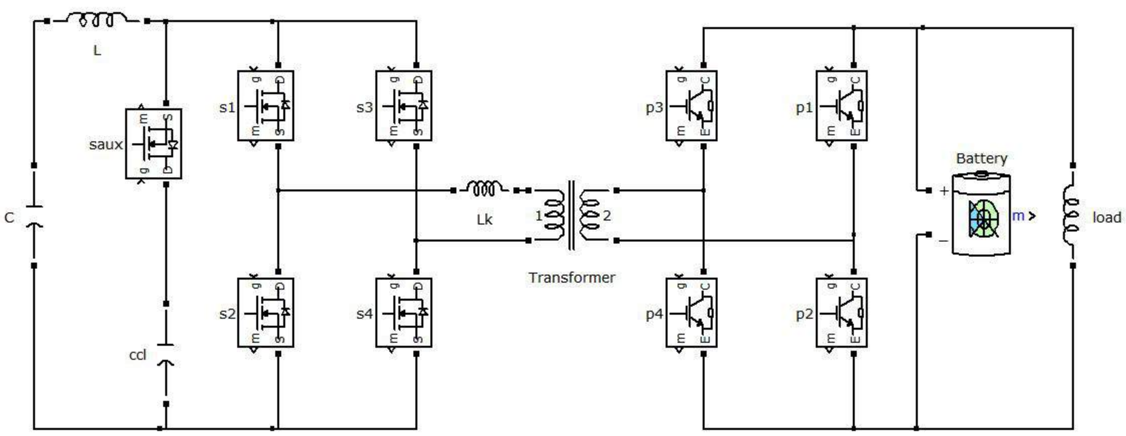

Figure 2.3: The bi-directional active clamp DC/DC converter(full-bridge type topology)

This converter works on the principle of dual active bridge. It incorporates the active clamping circuit to reduce the high voltage and current burdens and protect the switches from high voltage and current spikes. In the functionality it is the same as the conventional dual active bridge but it consists of a additional switch and a clamp capacitor at the input of the full-bridge. When the pair of same leg switches are on, the clamping capacitor gets charged. When diagonal switches turns-on, the clamping capacitor discharges through transformer winding. Hence high voltage surges can be kept away from the switches.[4] [5] [6]

Chapter 3

Converter Operation

3.1 Boost Mode Operation

3.1.1 Mode 1(t_0-t-t_1)

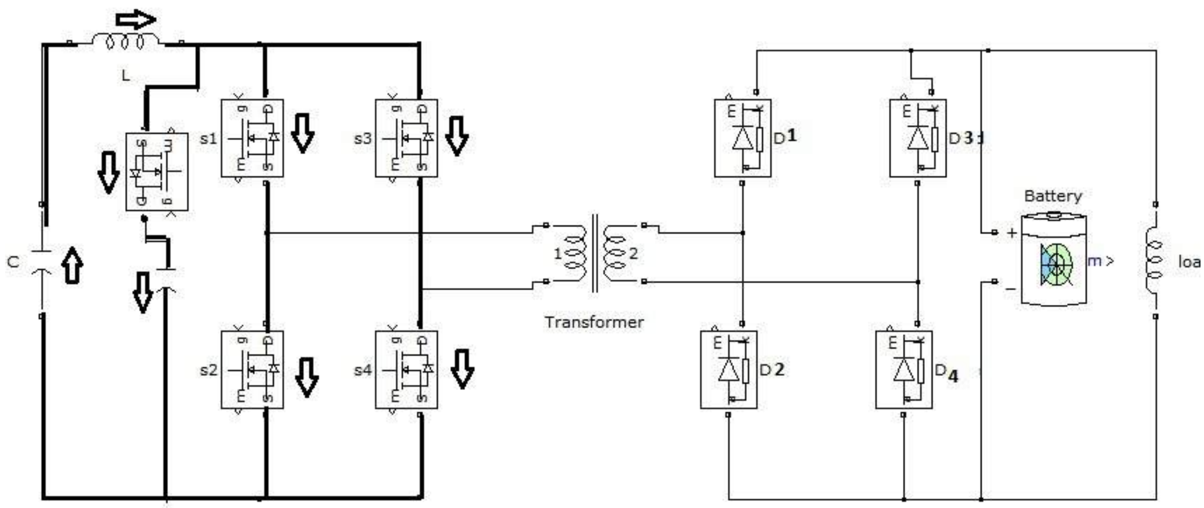

Figure 3.1: Mode 1(t_0-t-t_1)

During this mode all four switches are in on state. Hence inductor will get low resistance charging path through the ultra-capacitor. During this period inductor will increase the current passing through it, exponentially. This time can be called as a overlap time for the current fade converters as the inductor needs to charge in this time duration.

s_1 and s_4 are turned on at t_0 interval whereas s_2 and s_3 were previously on. During this period no current will pass through the transformer winding because the inductor current gets a low resistance path for conduction. The transformer winding primary voltage as well as secondary voltages are zero during this time. Transformer primary winding current(i_p) is also zero during this period. The clamping capacitor also gets a charging path through diode of the Mosfet.

3.1.2 Mode 2(t_1-t-t_2)

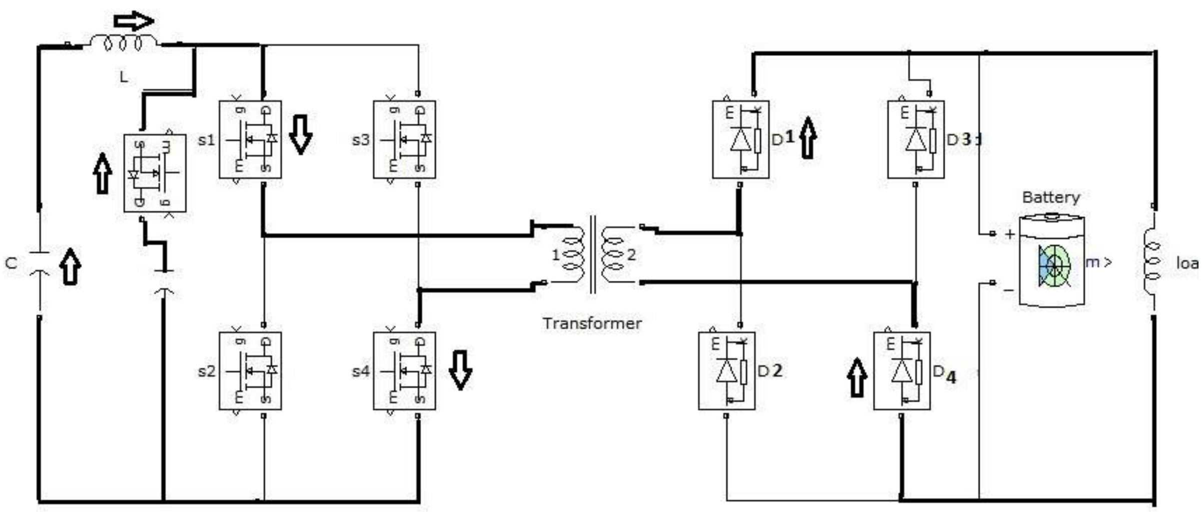

Figure 3.2: Mode 2(t_1-t-t_2)

During this mode switches S_1 and S_4 are previously turned on whereas switches S_2 and S_3 are turned off at t_1 interval. Hence inductor current will be allowed to flow through the transformer and hence to the secondary side. The auxiliary switch S_{aux} is turned on right after the small delay to interval t_1 and turned off right before small time to t_2. The reason to put auxiliary capacitor C_{cl} (known as clamping capacitor) is to have a zero voltage switching and to utilize the transformer leakage inductance.

The inductor is discharged during this period. At the time t_2 auxiliary switch S_{aux} is turned off and switches S_2 and S_3 are turned on. Clamping capacitor will again charge through body diode of Mosfet.

3.1.3 Mode 3(t_2-t-t_3)

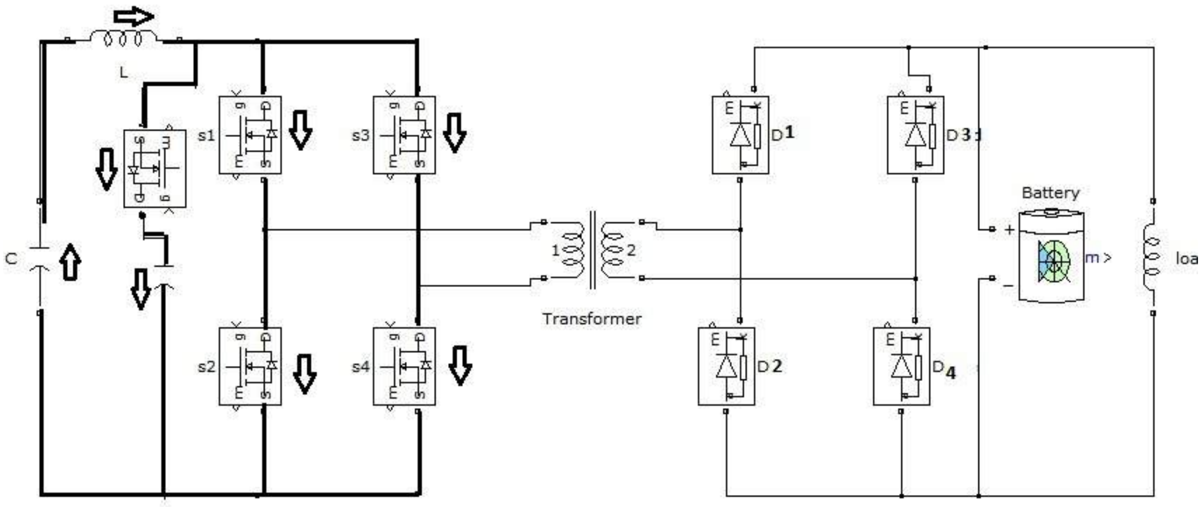

Figure 3.3: Mode 3(t_2-t-t_3)

This mode of operation is same as mode 1. Switches S_2 and S_3 are turned on and S_1-S_4 are previously on. Hence during this period no current will pass through the transformer winding because the inductor current gets a low resistance path for conduction. The transformer winding primary voltage as well as secondary voltages are zero during this time. Transformer primary winding current(i_p) is also zero during this period. The clamping capacitor also gets a charging path through diode of the Mosfet.

3.1.4 Mode 4(t_3-t-t_4)

During this mode switches S_2 and S_3 are previously turned on whereas switches S_1 and S_4 are turned off at t_3 interval. Hence inductor current will be allowed to flow through the transformer and hence to the secondary side. The auxiliary switch S_{aux} is turned on right after the small delay to interval t_3 and turned off right before small time to t_4. The reason to put auxiliary capacitor C_{cl} (clamping capacitor) is to have a zero voltage switching and to utilize the transformer leakage inductance. The inductor is discharged during this period. At the time t_4 auxiliary switch S_{aux}

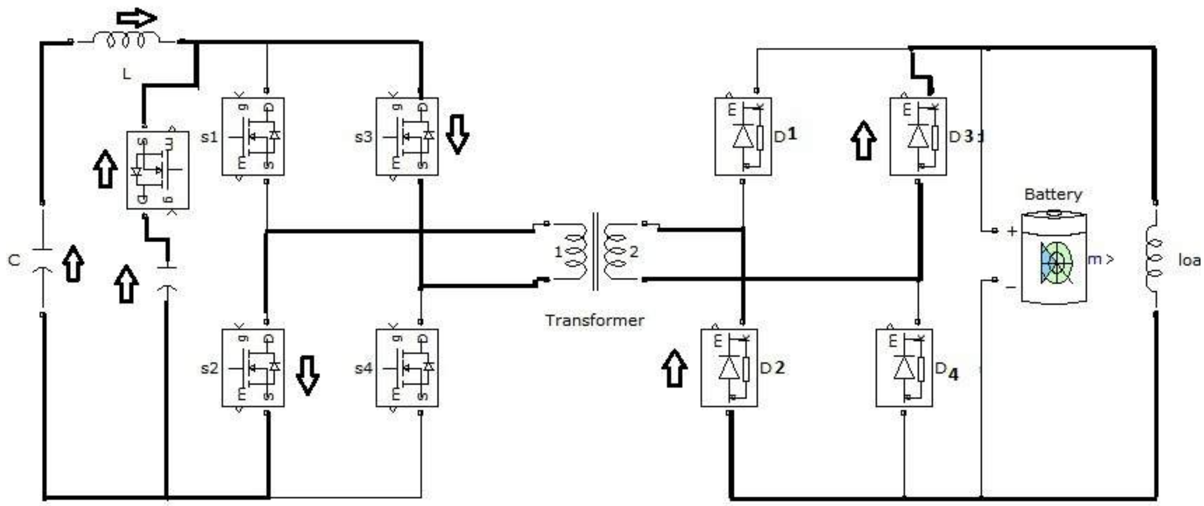

Figure 3.4: Mode 4(t_3-t-t_4)

is turned off and switches S_1 and S_4 are turned on. Clamping capacitor will again charge through body diode of Mosfet. The transformer current will have the negative polarity hence the primary and secondary winding voltage will have it too.

3.2 Buck Mode Operation

3.2.1 Mode 1 (t_0-t-t_1)

During this mode switches P1 and P4 are in on state. And load current (negative polarity) will be transferred to Primary winding via transformer. During this mode diodes D_1 and D_4 gives the path to the current to flow through the input capacitor C and clamping capacitor C_{cl} via body diode of Mosfet. Hence Voltage of capacitor gets increase during this period.

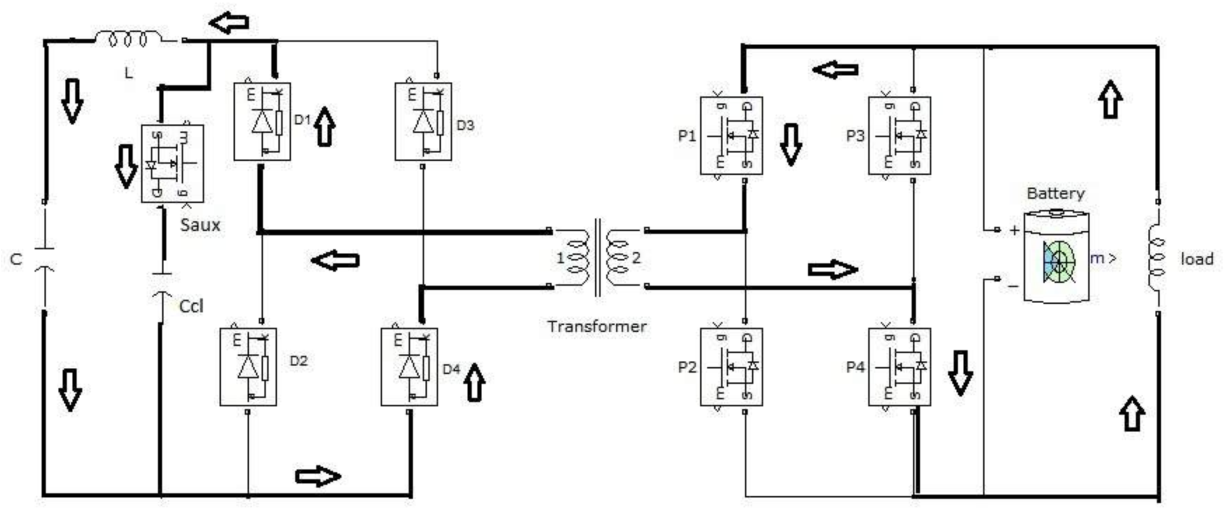

Figure 3.5: Mode 1(t_0-t-t_1)

3.2.2 Mode 2(t1-t-t2)

During this mode all the switches kept off to ensure the zero voltage switching. Transformer primary and secondary winding voltage as well as the current remains zero during this period. Input capacitor voltage remains unaffected.

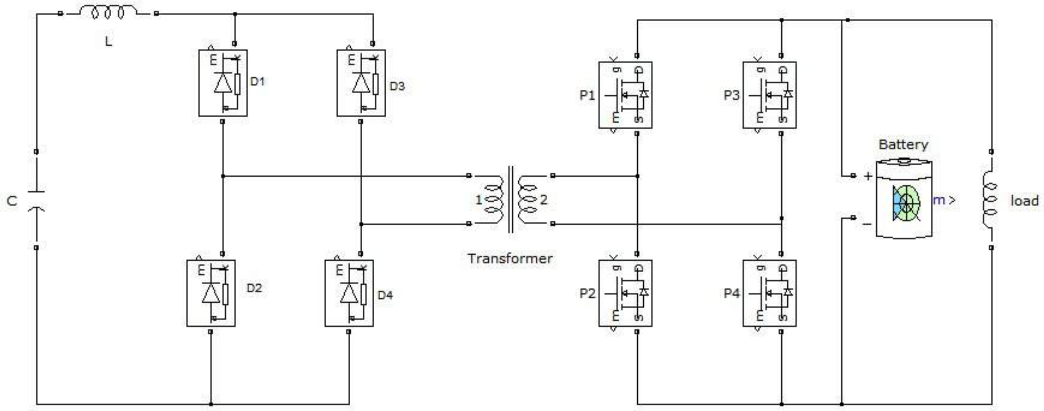

Figure 3.6: Mode 2(t_1-t-t_2)

3.2.3 Mode 3(t_2-t-t_3)

During this mode switches P2 and P3 are in on state and load current (negative polarity) will be transferred to Primary winding via transformer. During this mode diodes D_2 and D_3 gives the path to the current to flow through the input capacitor C and clamping capacitor c_{cl} via body diode of Mosfet. Hence Voltage of capacitor gets increase during this period.

3.2.4 Mode 4(t_3-t-t_4)

This mode is same as mode 2. During this mode all the switches kept off to ensure the zero voltage switching. Transformer primary and secondary winding voltage as well as the current remains zero during this period. Input capacitor voltage remains unaffected.

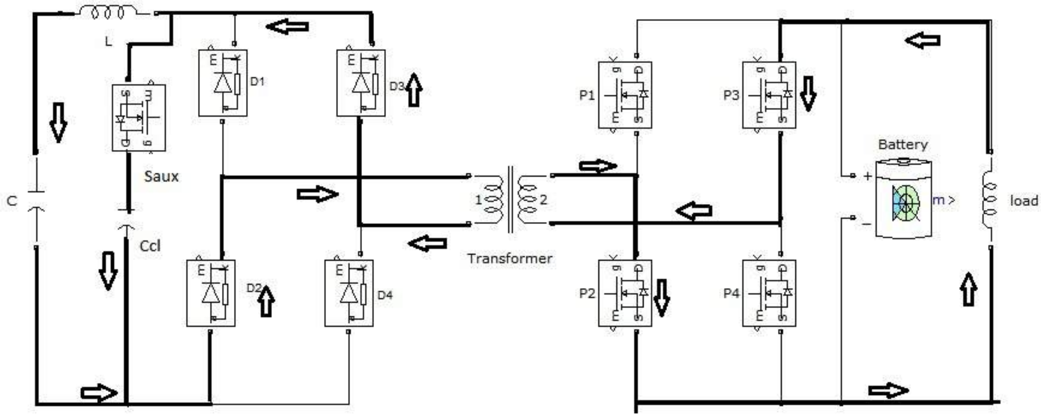

Figure 3.7: Mode 3(t_2-t-t_3)

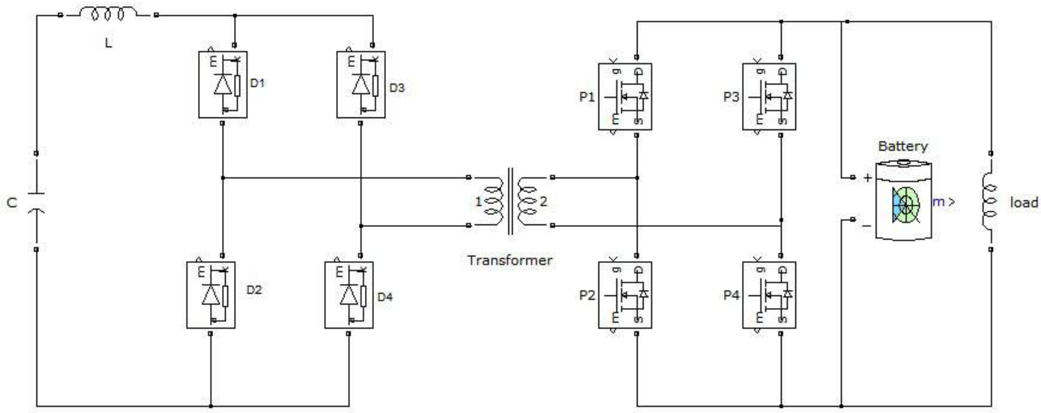

Figure 3.8: Mode 4(t_3-t-t_4)

Chapter 4

Design Procedure

4.1 Design of the Converter

a procedure for the designof the converter parameters is demonstrated with an example. The results of the design work is used in the simulation work and it has been implemened in experimental prototype of the converter.

4.1.1 Procedure

The systematic design of the proposed Bi-Directional full-bridge boost converter is explained. The following specifications are considered for this design :

1 Output Voltage: $V_O = 24$ Volts

2 Input Voltage: $V_{in} = 12$ Volts

3 Expected Efficiency at Full-Load $= 85\%$

4 Switching Frequency: **f** $= 1$ KHz

5 Output Power: $P_O = 50$ Watts

The general approach procedure of design is to design the converter first without clamping circuit.[13] [1]

4.1.2 Transformer Turns Ratio

The turns ratio N and duty cycle are closely related with each other. As per the required voltage at the output the turns of transformer primary and secondary windings are decided. The transformer leakage inductance is also considered while deciding the turns ratio.

The relation between the output voltage V_O and the input voltage V_{in} can be expressed by the following equation, which is based on boost converter principle,

$$V_o = \frac{N}{1 - D_c} V_{in} \tag{4.1}$$

Each switch should be turned on at least for D=T/2 in order to complete the path of charging of the inductor.The converter duty cycle Dc indicates the total amount of overlap of gating pulses of S1 and S4 and those of S2 and S3 so that the relation between D and Dc can be expressed as,

$$DT = D_c \frac{T}{2} + \frac{T}{2} \tag{4.2}$$

where DcT represents the time for which the inductor gets charged.

If (4-2) is substituted into (4-1), then the following equation can be derived:

$$V_o = \frac{N}{2(1 - D)} V_{in} \tag{4.3}$$

and also (4-2) can be rearranged to give,

$$D_c = 2D - 1 \tag{4.4}$$

For this design example, a value of N is taken 1. With this value of N and, assuming that the input inductor current is continuous, a value of D = 0.85 can be taken, based on input voltage V_{in} = 12 V and V_O= 24 V. If D = 0.85, then D_c = 0.70 from (4-4); this value of Dc will be used in next sections to find the input inductor.

4.1.3 Input Inductor

After deciding the values of N and D, the input inductor is designed. The main purpose to design such inductor is to limit peak to peak ripple. There is always a compromise between peak to peak ripple of current and physical size of the inductor. A compromise of 10% peak-to-peak ripple is typically made in this design.

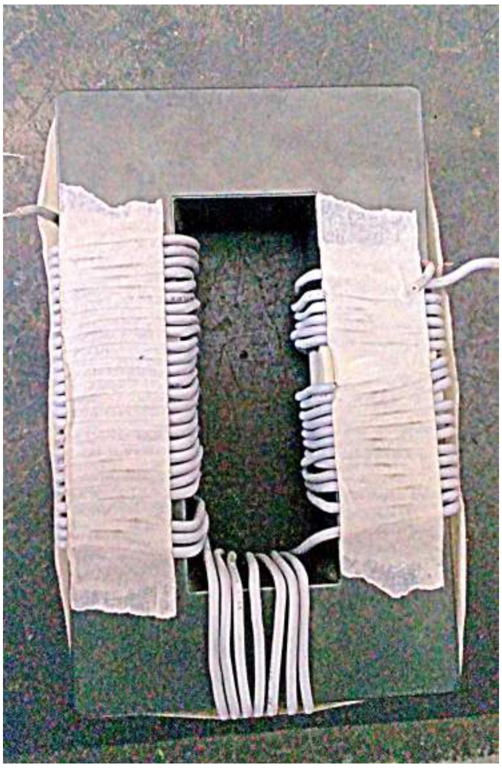

Figure 4.1: Designed Inductor 15mH

The converter operates with continuous input current. The average input current (input current without the ripple) can be found from the converter specifications:

$$I_{in} = \frac{P_o}{V_{in} \times \eta} = \frac{50}{24 \times 0.85} = 2.35\, amp \tag{4.5}$$

Since the average inductor current value has been determined and it has been stated that the input inductor value should be such that the peak-to-peak ripple ΔI of the input inductor current should be 10% of the average input inductor current, then ΔI should be,

$$\Delta I = 0.1 \times I_{in} = 0.235\, amp \tag{4.6}$$

A relation between Lmain and ΔI exists as the voltage across the input inductor when the converter is in a boosting mode and all switches are on can be expressed as,

$$V_{in} = L_{main}\frac{di}{dt} \tag{4.7}$$

where V_{in} is the voltage across L_{main} when switches S1,4 and S2,3 are conducing. DT=D_cT/2 is the duration of the boosting mode in a half switching cycle and dI=ΔI is the change in input current during that time. The value of L_{main} therefore, can be determined by rearranging equ (4-7) to get,

$$L_{main} = V_{in}\frac{D_c T}{2\Delta I} = \frac{24 \times 0.7 \times 1msec}{2 \times 0.235} = 17.319\, mH \tag{4.8}$$

4.1.4 Snubber Capacitor

After design of the parameters N, D and L_{main} done, the active clamping circuit is designed. The first step is to design snubber capacitor C_{cl}.

$$\Delta V_{pk} = I_{in}\sqrt{\frac{i_{lk}}{C_{total}}} \tag{4.9}$$

$$I_{in}\sqrt{\frac{L_{lk}}{C_{Total}}} = 0.2 \times \frac{V_o}{N} \tag{4.10}$$

$$2.35 \times \sqrt{\frac{0.5\mu H}{C_{Total}}} = 0.2 \times \frac{24}{1} \tag{4.11}$$

Hence we get; C_{Total}=0.1μ F. According to the equation C_{total}=c_{cl}+2C_s, where Cs is the output capacitance of a main switch, if it is assumed that mosfet devices which have an output drain-source capacitance of about 600 pF are used as the main power switches, then the required C_{cl} is found to be 0.1μ F, 40V.

4.2 Design of Gate Driver Circuit for Mosfets

4.2.1 Power Supply

A DC power supply of 15volt is produced with the help of diode bridge rectifier and voltage regulator IC LM7815. AC supply of 13v from the secondary winding of the transformer is given to the diode bridge rectifier, which generates pulsating DC supply. With the help of 100μf capacitor the ripple will get reduced. This supply will then be given too the input of LM7815 IC. It will regulate the output voltage to 15volt. It will not allow the input DC voltage exceed beyond 15V.

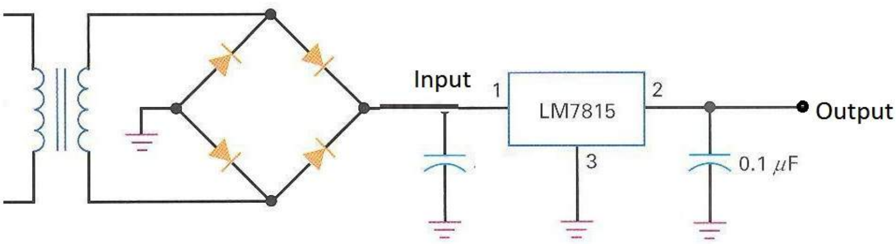

Figure 4.2: Functional Dig of LM7815

4.2.2 TLP 250 IC configuration

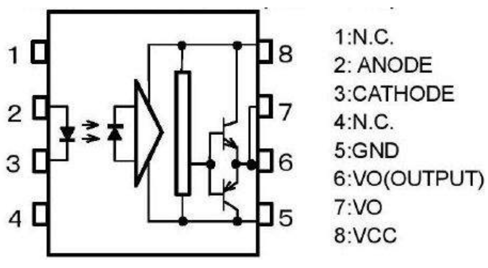

Figure 4.3: Pin Dig of TLP250

The TLP250 has 8 pins out of which pins 2 and 3 are used to give the input signal. Pin 8 is connected to power supply whereas pin pin 5 is connected to output ground.

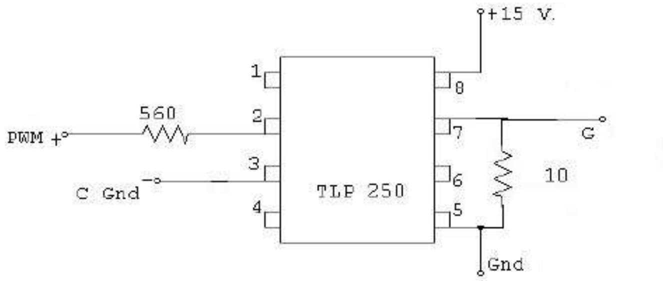

Figure 4.4: IC TLP250 Connections

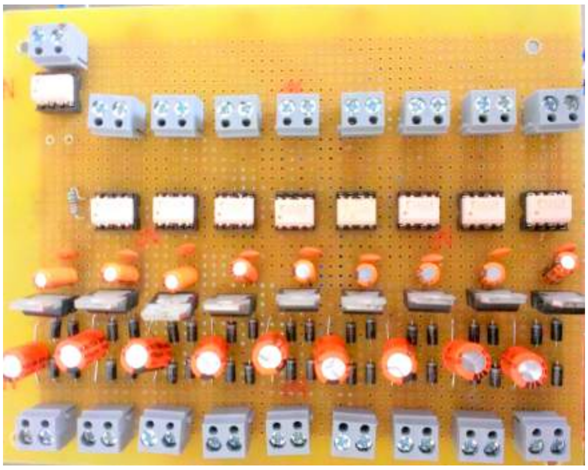

Figure 4.5: Driver circuit Hardware for 9 Mosfets

The pins 6 and 7 are internally shorted. The output pulse can be directly obtained across 6 and GND. TLP250 is optically isolated having the LED at the input stage. input stage, an output stage and a power supply connection It is that the TLP250 is an optically isolated driver, meaning that the input and output are optically isolated. The isolation is optical the input stage is an LED(Light Emitting Diode) and the receiving output stage is light sensitive as photo-detector.

Chapter 5

Micro controller ATMEGA16 and coding

5.1 Overview

The ATmega16 is a low-power CMOS 8-bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega16 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed.

5.2 Features

- High-performance, Low-power Atmel AVR 8-bit Microcontroller
- Advanced RISC Architecture
- 131 Powerful Instructions Most Single-clock Cycle Execution
- 32×8 General Purpose Working Registers
- On-chip 2-cycle Multiplier
- Fully Static Operation

- High Endurance Non-volatile Memory segments
- 16 Kbytes of In-System Self-programmable Flash program memory
- 512 Bytes EEPROM, 1 Kbyte Internal SRAM
- Write/Erase Cycles: 10000 Flash/100000 EEPROM
- Data retention: 20 years
- In-System Programming by On-chip Boot Program
- Up to 16 MIPS Throughput at 16 MHz

5.3 Pin Diagram

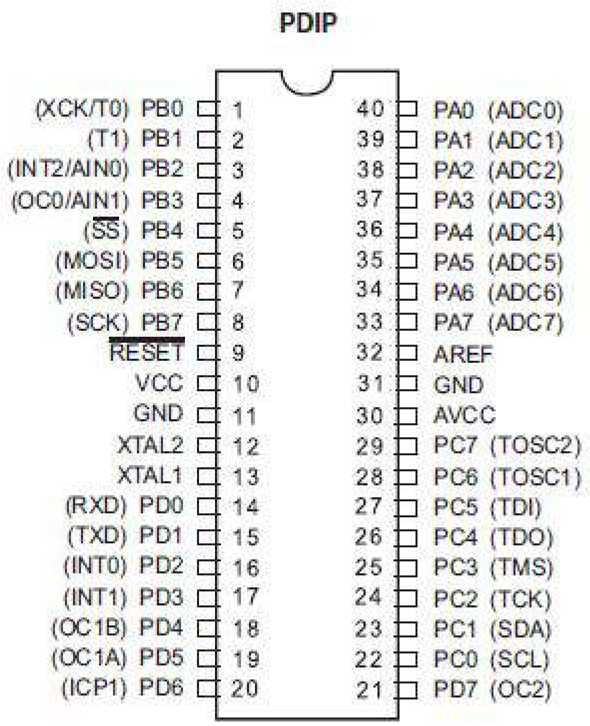

Figure 5.1: Pin Diagram of ATMEGA16 controller

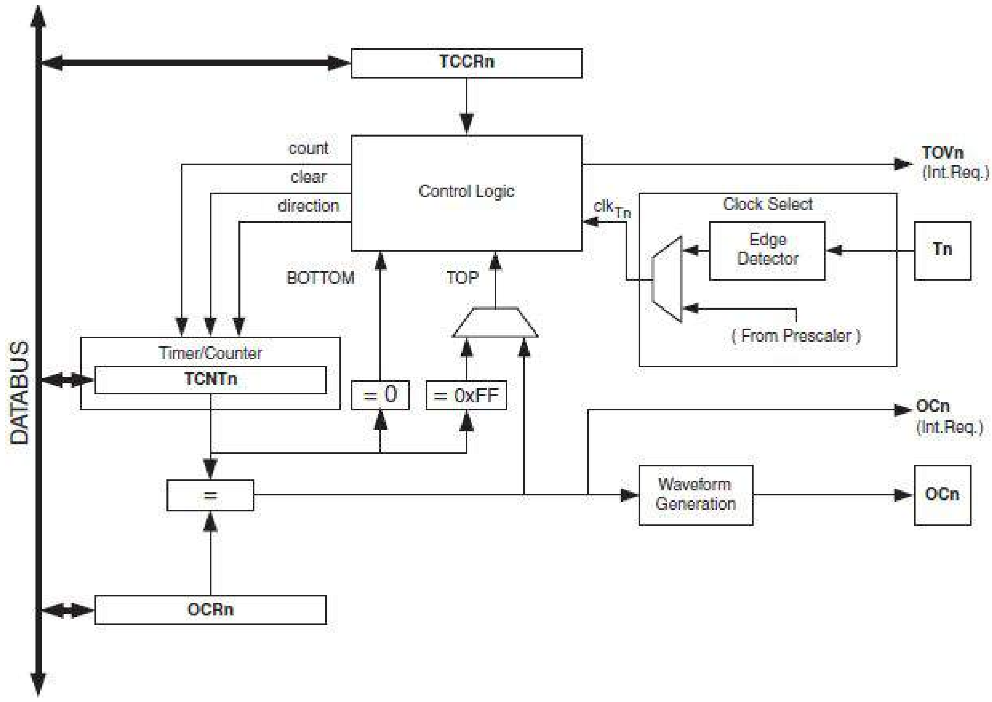

Figure 5.2: Structure of Timer

Timer/Counter0 is a general purpose, single compare unit, 8-bit Timer/Counter module. The main features are:

- Single Compare Unit Counter
- Clear Timer on Compare Match (Auto Reload)
- Glitch-free, Phase Correct Pulse Width Modulator (PWM)
- Frequency Generator
- External Event Counter
- 0-bit Clock Prescaler
- Overflow and Compare Match Interrupt Sources (TOV0 and OCF0)

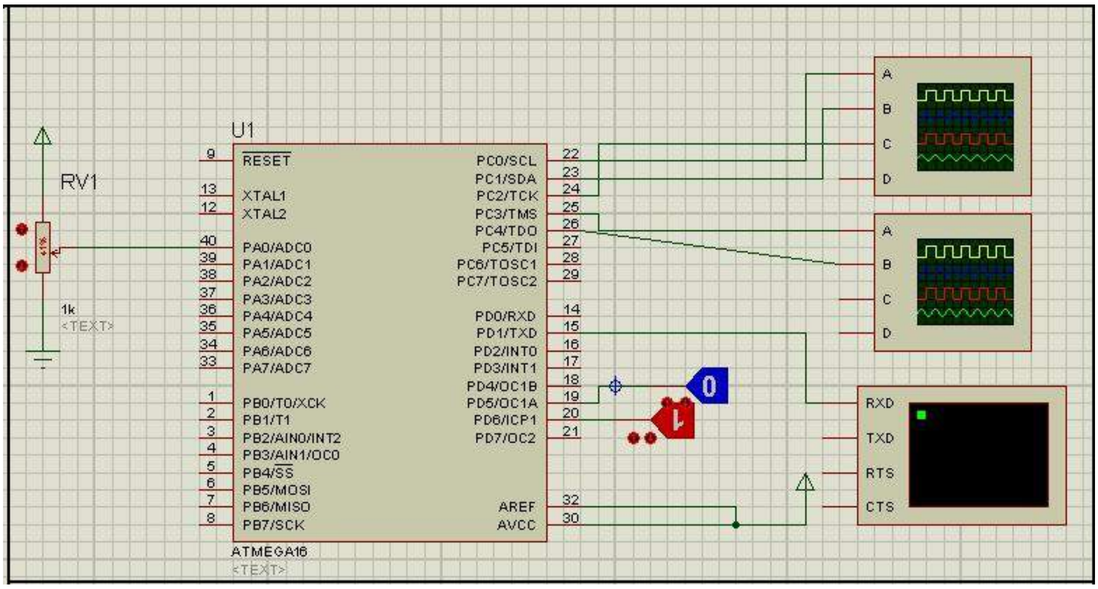

Figure 5.3: Micro-controller Proteus Model

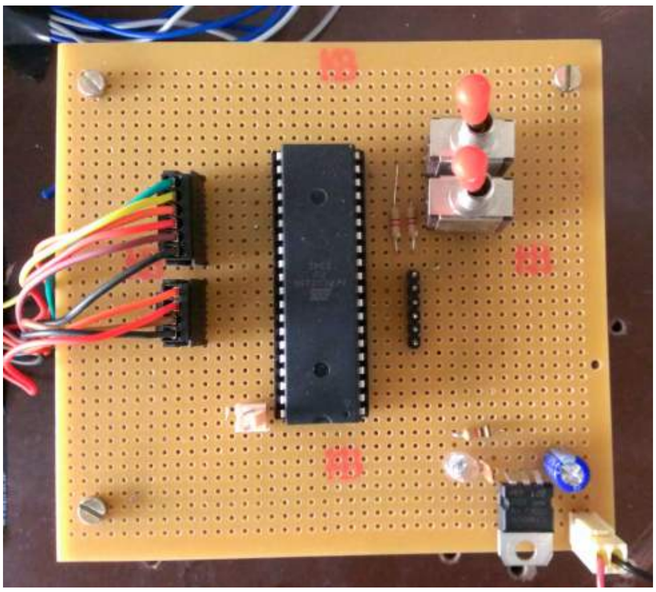

Figure 5.4: Micro-controller Hardware

Fig. 6.2 indicates the structure of timer. Timer control register $TCON_1$ is used to obtain pulses. Fig. 6.3 shows the simulation of the controller in Proteus software. A Coding of the controller is done in the BASCOM language first, then the created HEX file is loaded in virtually in the controller. Fig. 6.4 shows the hardware model of ATMEGA16 micro-controller. As shown in the figure two switches are used. one is used for changeover between open-loop and closed-loop configuration and other switch is used to changeover the control between buck and boost operation.

Chapter 6

Simulation Results

The simulation of bi-directional converter has been done for the boost as well as buck mode. The values of transformer primary-secondary voltages and inductor voltage-currents are estimated for both modes of operation.

6.1 Boost Converter Simulation

Fig. 7.1 indicates the switching pulses for the boost converter, Fig 7.2 and 7.3 indicates the transformer primary and secondary winding voltages in the boost mode of operation respectively. Fig. 7.4 and 7.5 indicates the current passing through L_{lk} and L_{main} respectively. The L_{lk} is the leakage inductance of the transformer having the value of 0.5 mh. I_{lk} and I_L are almost same.

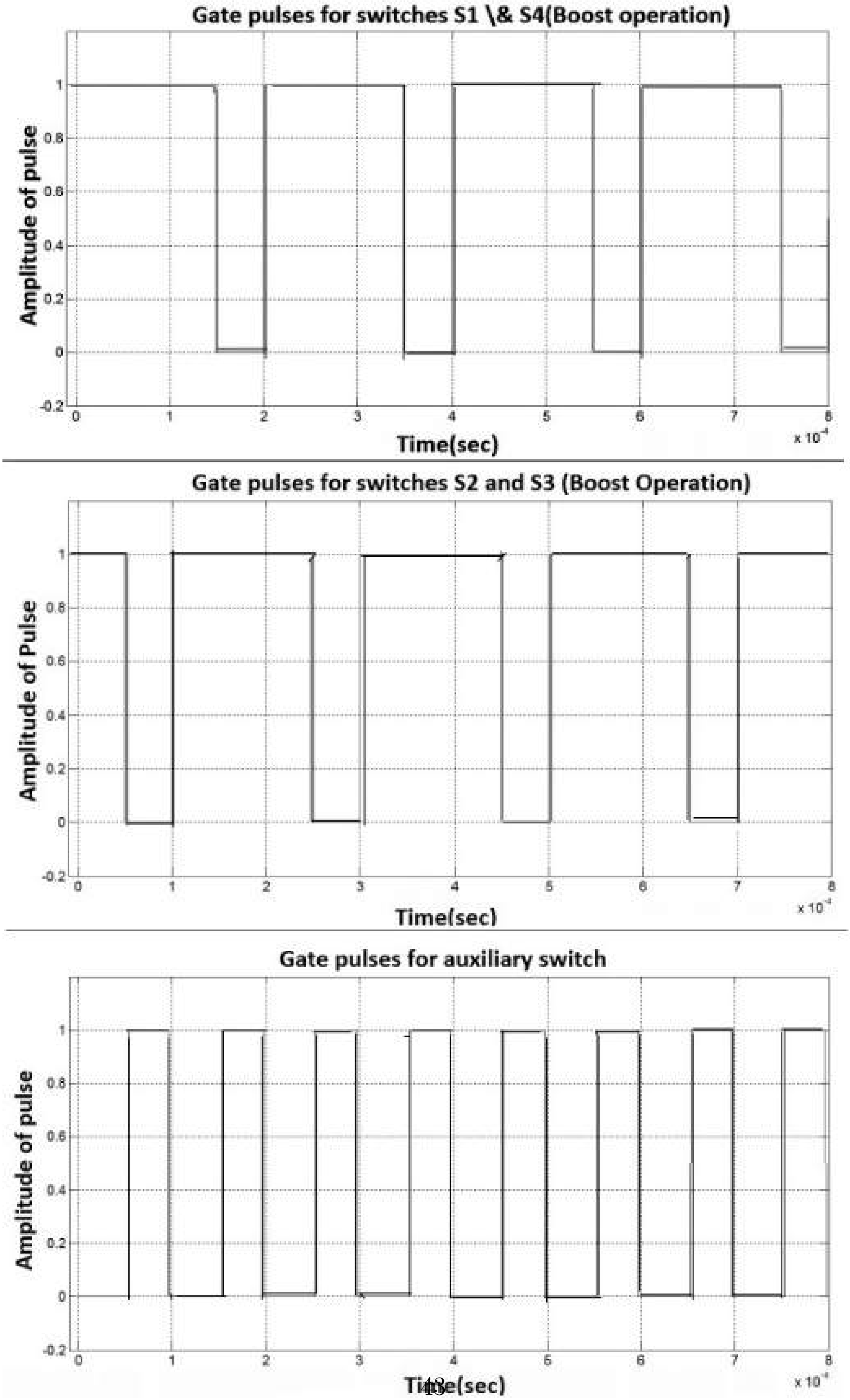

Figure 6.1: Gate pulses for switches(Boost operation) Channel 1: X axis: .10 ms/div Y axis: .2 V/div

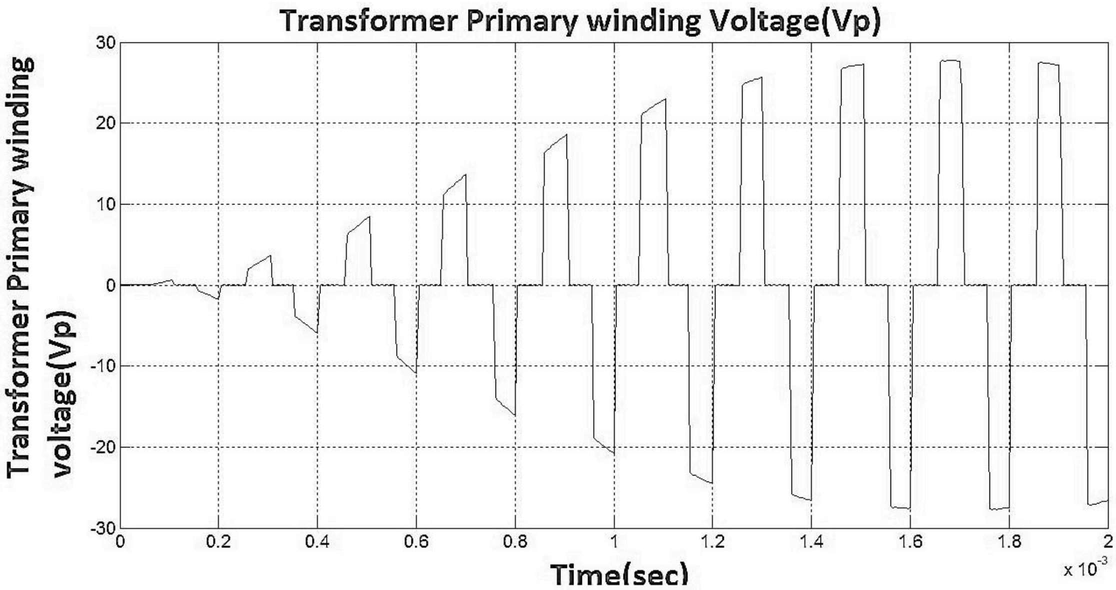

Figure 6.2: Transformer Primary winding Voltage(Boost operation) Channel 1: X axis: .20 ms/div Y axis: 10.0 V/div

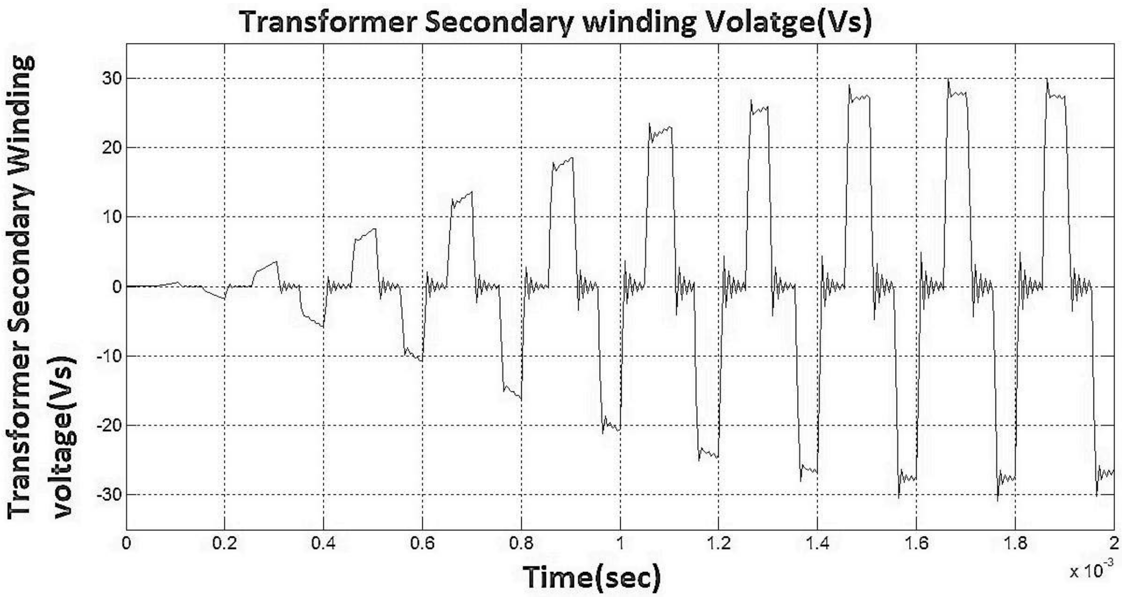

Figure 6.3: Transformer Secondary winding Voltage(Boost operation) Channel 1: X axis: .20 ms/div Y axis: 10.0 V/div

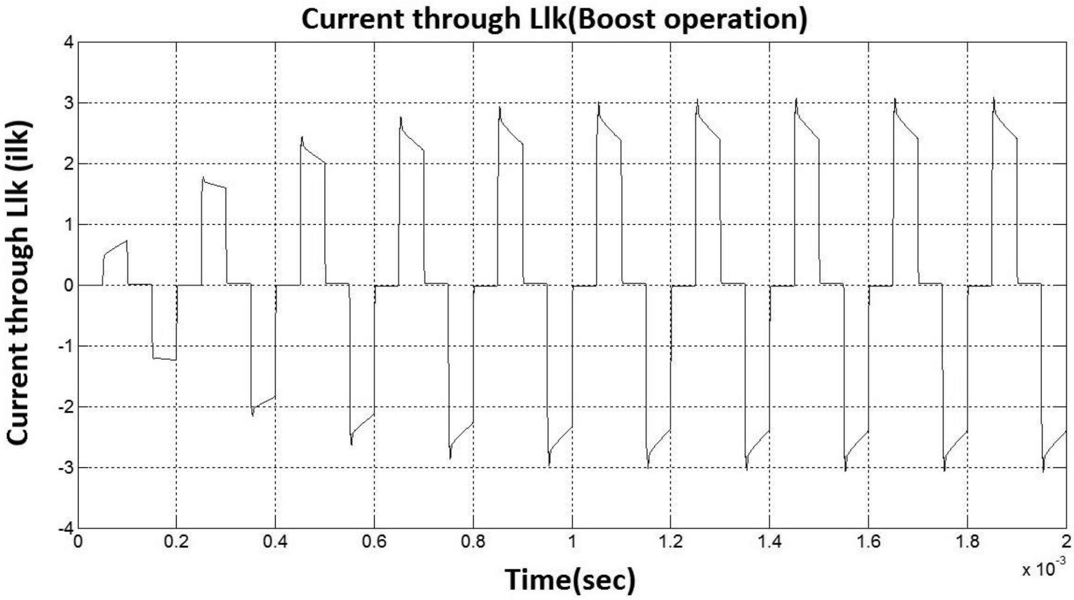

Figure 6.4: Current through Llk(Boost operation) Channel 1: X axis: .20 ms/div Y axis: 1.0 A/div

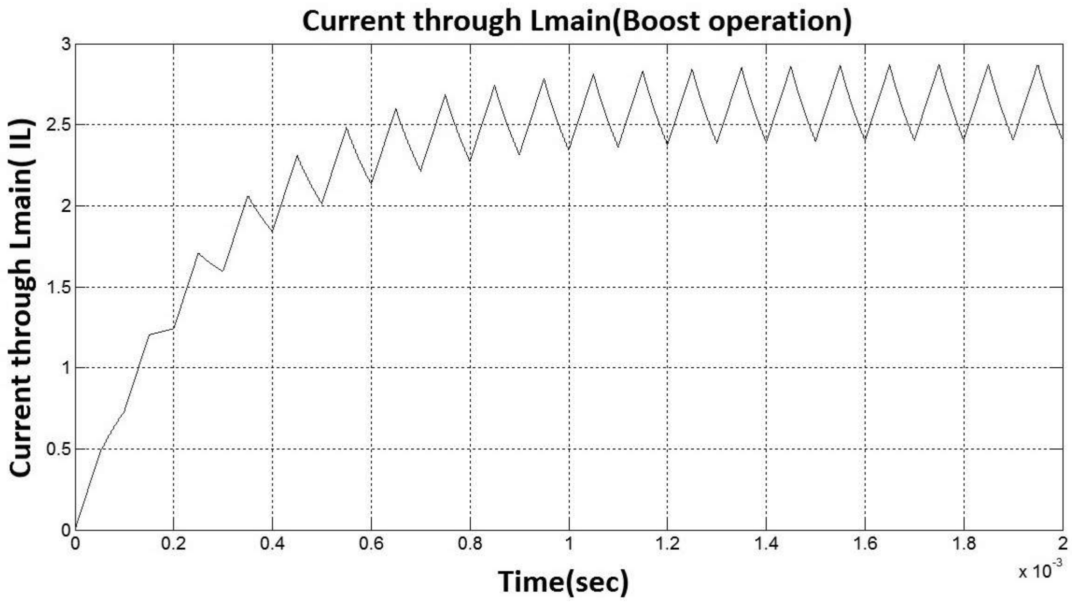

Figure 6.5: Current through Lmain(Boost operation) Channel 1: X axis: .20 ms/div Y axis: .5 A/div

6.2 Buck Converter Simulation

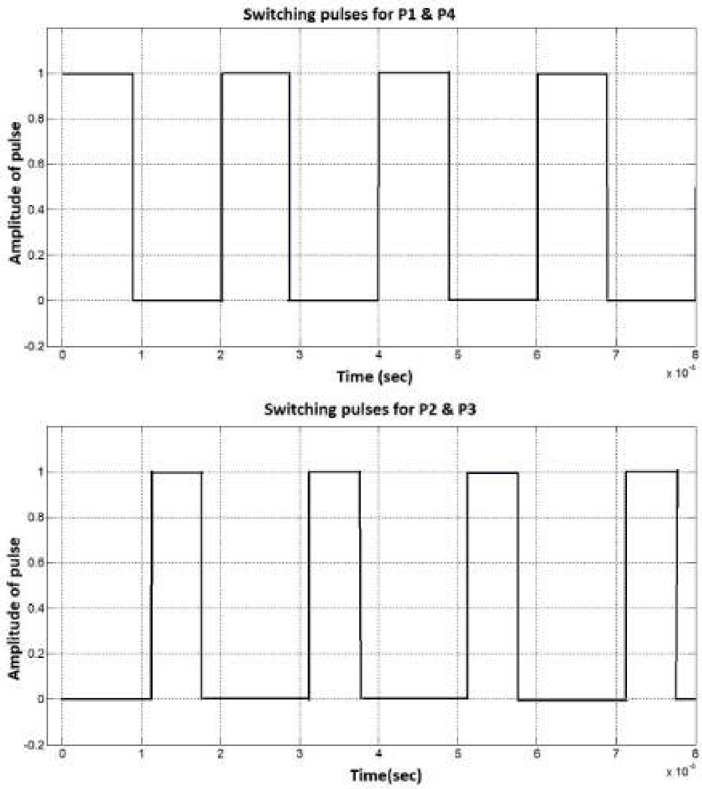

Figure 6.6: Gate pulses for switches(Buck operation) Channel 1: X axis: .10 ms/div Y axis: .2 V/div

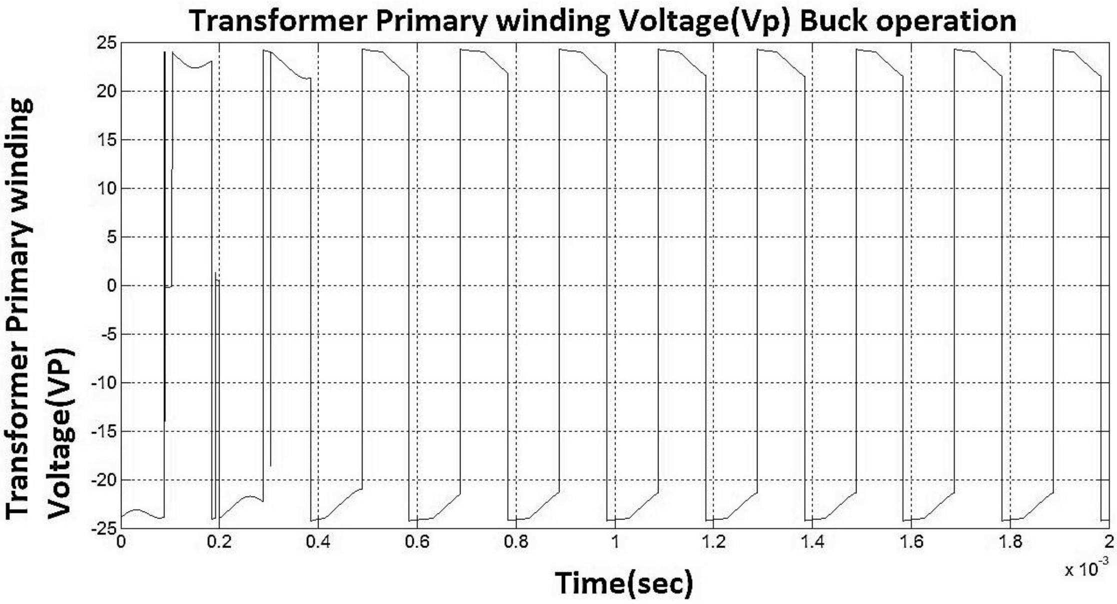

Figure 6.7: Transformer Primary winding Voltage(Buck operation) Channel 1: X axis: .20 ms/div Y axis: 10.0 V/div

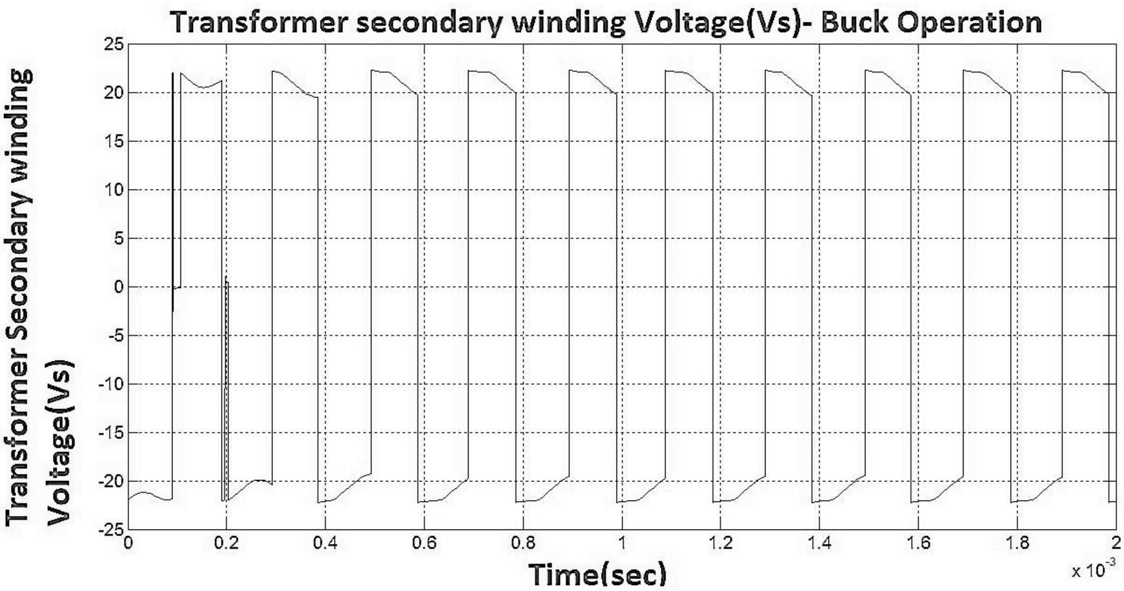

Figure 6.8: Transformer Secondary winding Voltage(Buck operation) Channel 1: X axis: .20 ms/div Y axis: 10.0 V/div

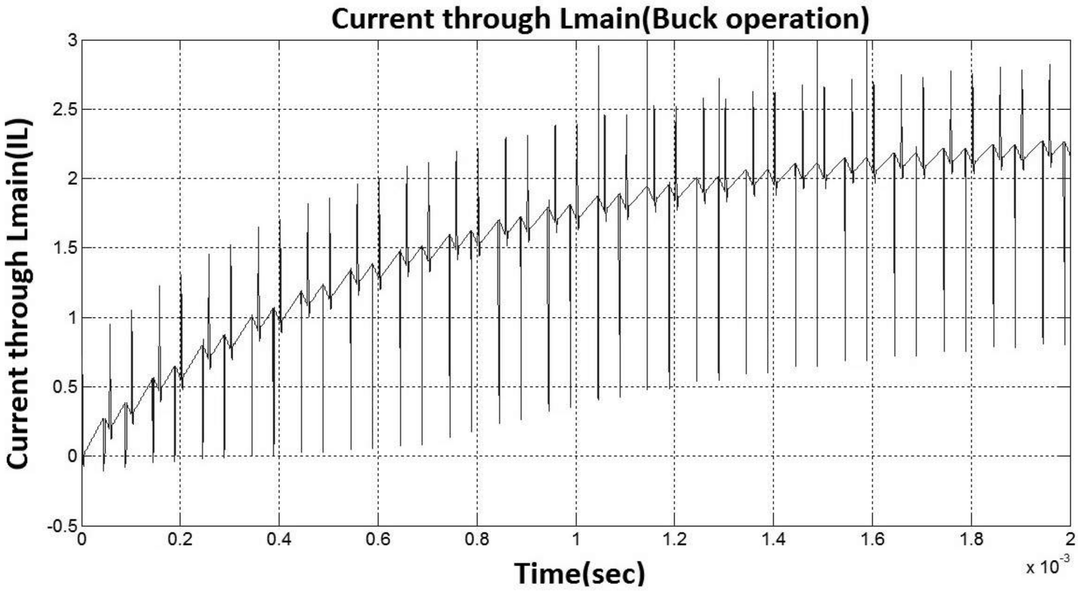

Figure 6.9: Current through Lmain(Buck operation) Channel 1: X axis: .20 ms/div Y axis: .5 A/div

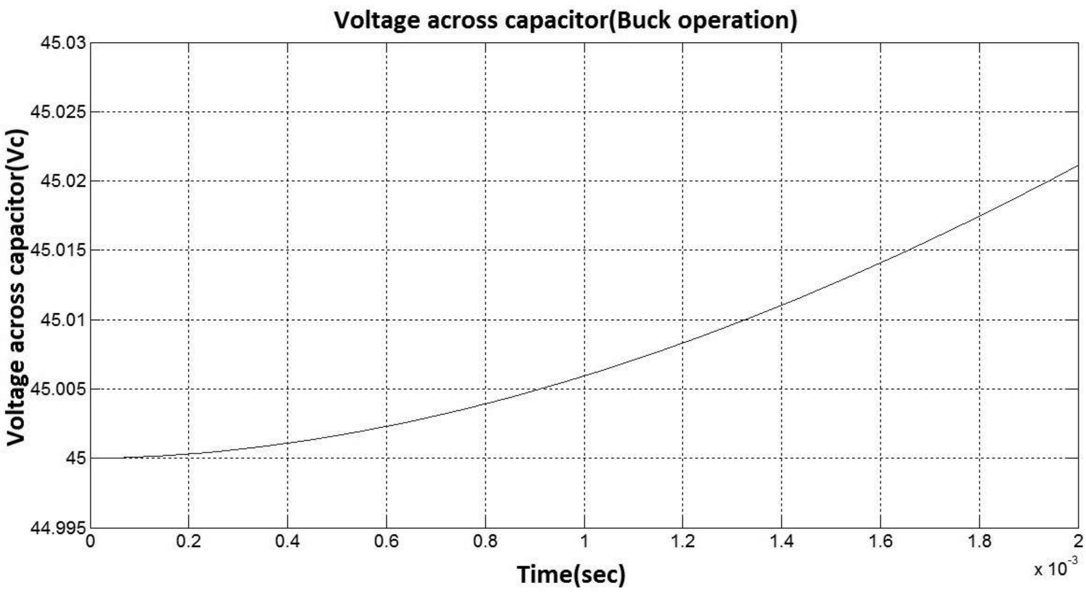

Figure 6.10: Voltage across capacitor(Buck operation) Channel 1: X axis: .20 ms/div Y axis: .005 v/div

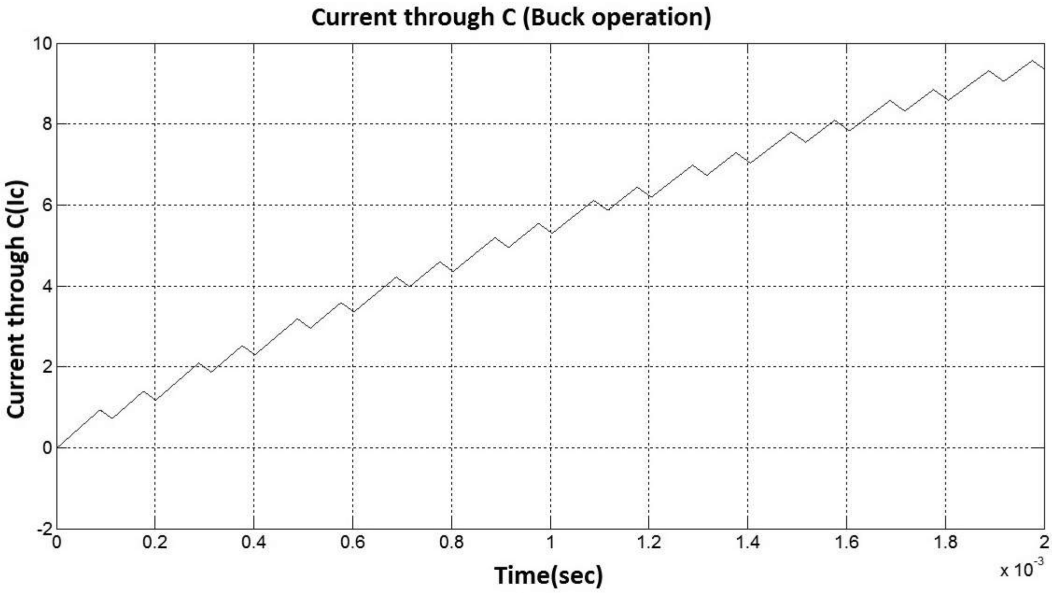

Figure 6.11: Current through C (Buck operation) Channel 1: X axis: .20 ms Y axis: 2 A/div

Fig. 7.6 indicates the gate pulses for the switches in the buck mode of operation. Fig. 7.7 and 7.8 indicates the transformer primary and secondary winding voltages in the buck mode of operation respectively. Fig. 7.9 indicates the current passing through L_{main}. Fig. 7.10 and 7.11 indicates the voltage across the capacitor (V_C) and current passing through it (I_c) respectively.

Chapter 7

Hardware Results

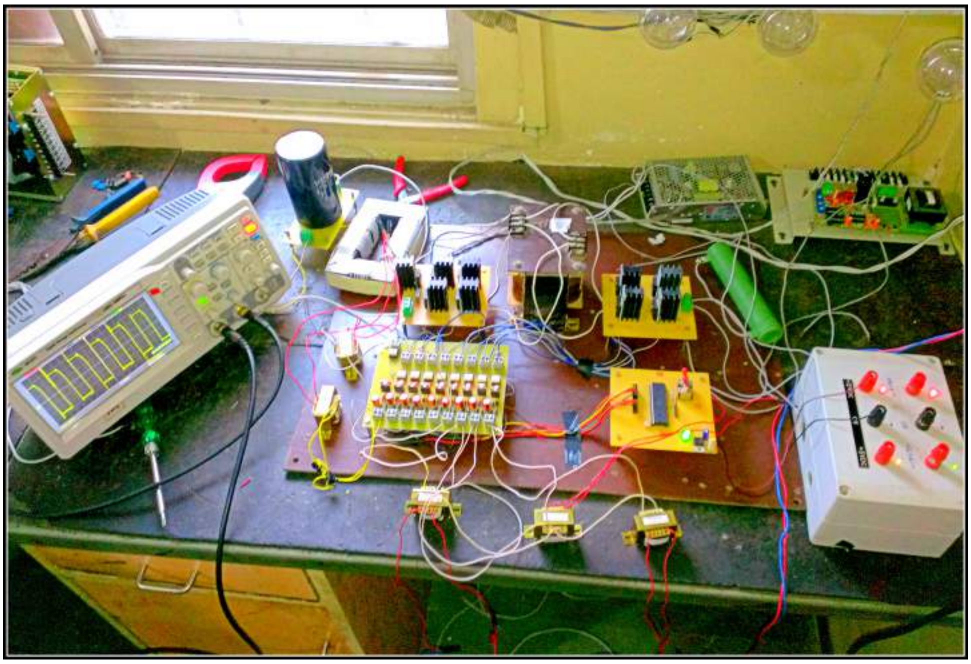

Figure 7.1: Hardware Setup of Bi-Directional Converter

Fig. 8.1 indicates the pictorial view of whole project setup. A bidirectional converter along with the driver-card and mictro-controller assembly is implemented and close resemblance between simulated and experimental results is obtained.

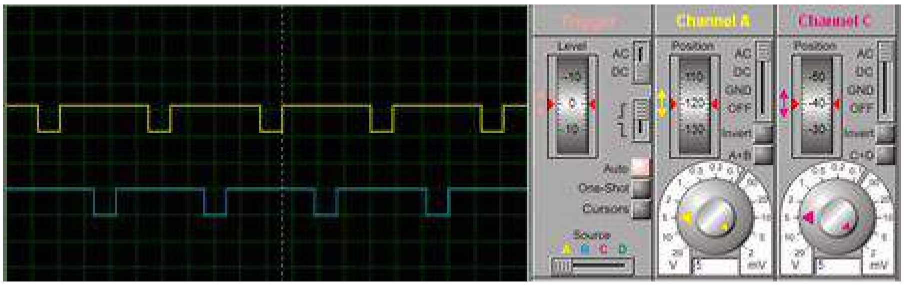

Figure 7.2: Gate pulses for switches(Boost Operation)Proteus software

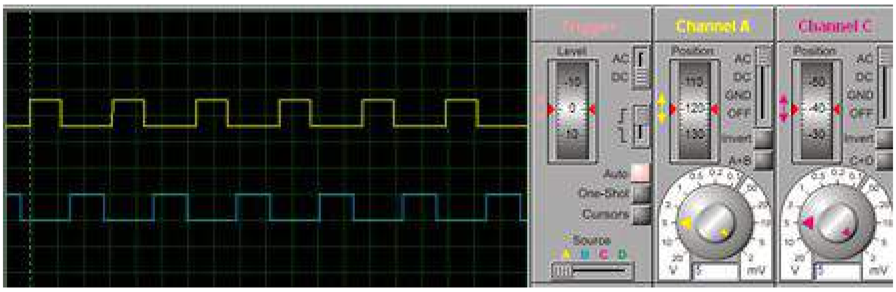

Figure 7.3: Gate pulses for switches(Buck Operation)Proteus software

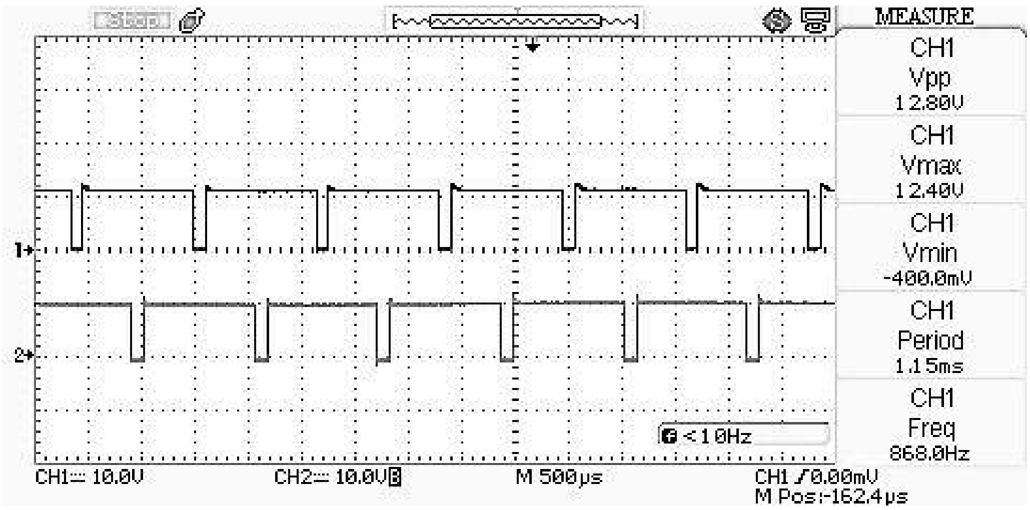

Figure 7.4: Gate pulses for switches(Boost Operation) Channel 1: X axis: 100 us/div Y axis: 10 V/div

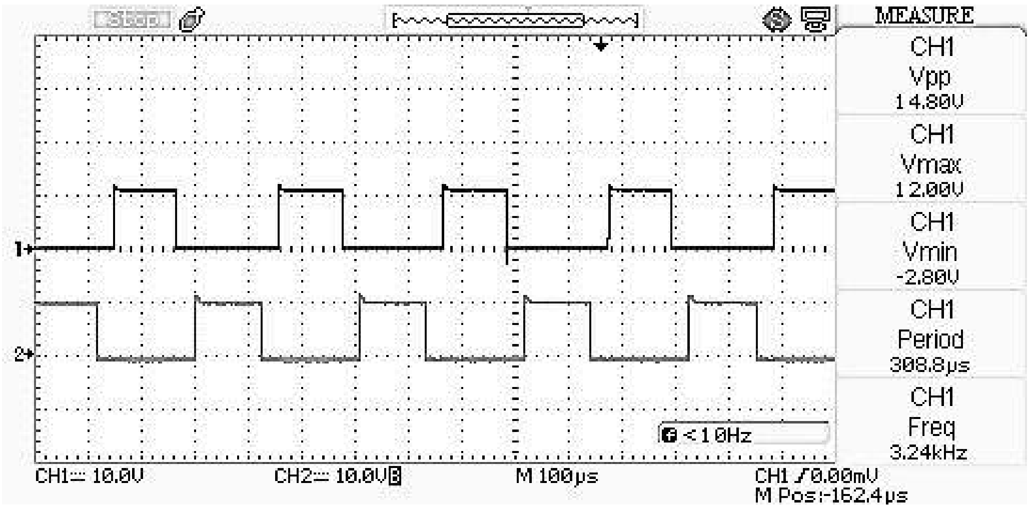

Figure 7.5: Gate pulses for switches(Buck Operation) Channel 1: X axis: 100 us/div Y axis: 10 V/div

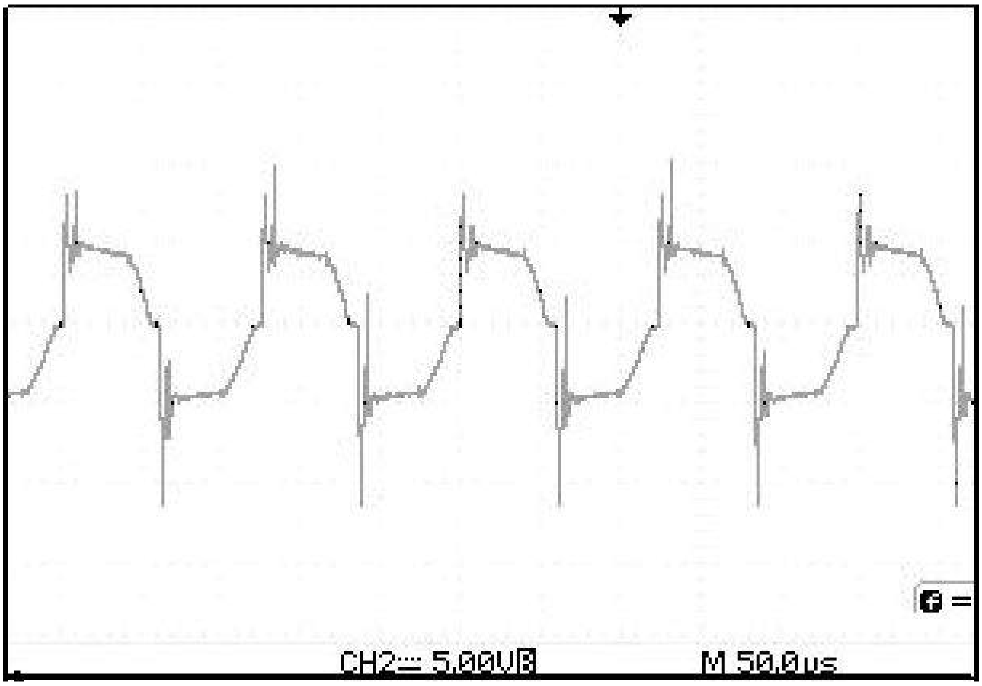

Figure 7.6: Clamping Capacitor Voltage(Boost Operation) Channel 1: X axis: 50 us/div Y axis: 5 V/div

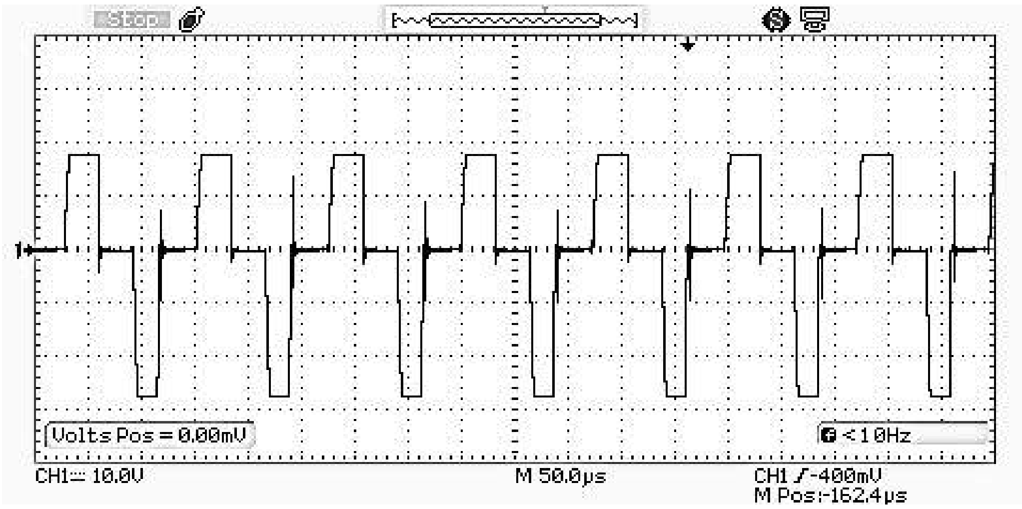

Figure 7.7: Primary winding voltage(Boost Operation) Channel 1: X axis: 50 us/div Y axis: 10 V/div

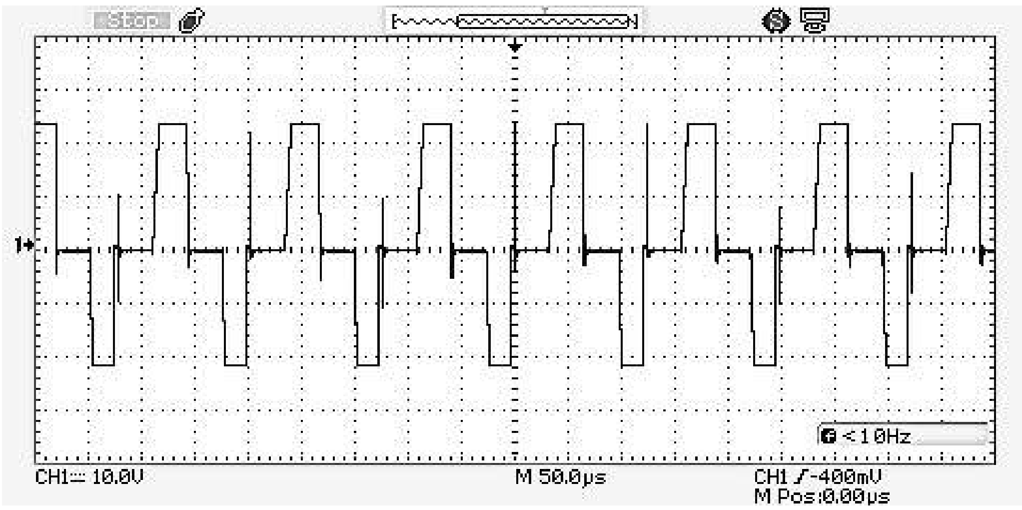

Figure 7.8: Secondary winding voltage(Boost Operation) Channel 1: X axis: 50 us/div Y axis: 10 V/div

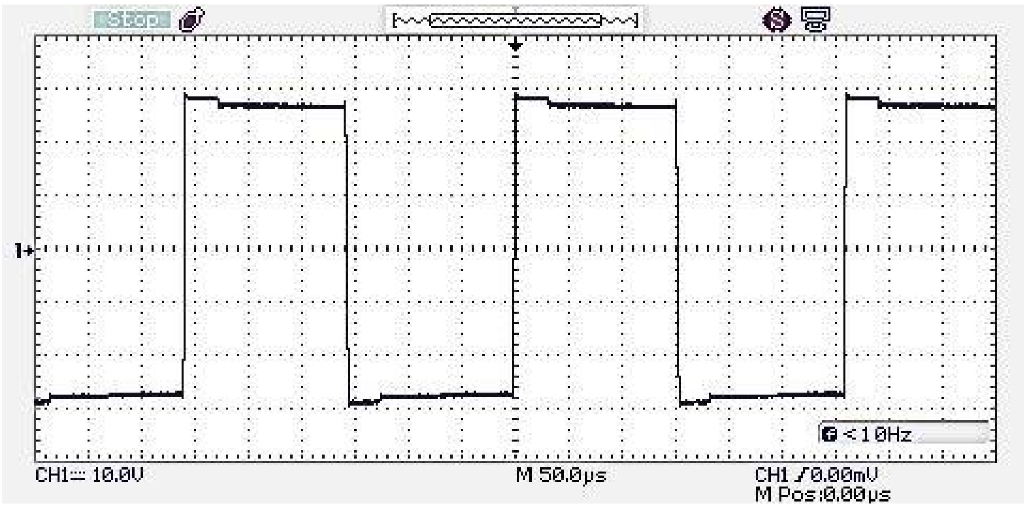

Figure 7.9: Primary and Secondary winding voltage(Buck Operation) Channel 1: X axis: 50 us/div Y axis: 10 V/div

Fig. 8.2 and 8.3 indicates the gate pulses obtained from the controller in proteus software virtually for both boost and buck modes of operation respectively. Fig 8.4 and 8.5 indicates the output of the driver-card circuit which is directly given to the MOSFETs for the switching having the value of 12.1 to 12.5 V for boost and buck modes of operation respectively.

Fig. 8.6 shows the clamping capacitor voltage for boost mode of operation.

Fig 8.7 and 8.8 indicates the transformer primary and secondary winding voltages for the boost mode of operation respectively. This results shows less voltage spikes at the the time of switching (By obtaining the ZVS operation) and hence implies the use of clamping circuit is advantageous. Fig 8.9 indicates the primary and secondary winding voltages of transformer in the buck mode of operation respectively.

A close resemblance is observed between the simulated and experimental results.

Chapter 8

Conclusion and Futurework

- Optimized design of Bi-Directional converter using the active clamping circuit is studied. A efficient model of the Bi-Directional model is simulated and a close resemblance is obtained between simulated results and experimental results. For a high-dynamic energy storage system design and its control, an electrical equivalent circuit modeling of ultra-capacitor using passive elements is performed. This hybrid converter is analyzed.

- The converter is assumed to have a good efficiency due to regenerative action.

- The maximum voltage stress the switches exposes, can be controlled by properly deciding the values of that the main power switches are exposed to is dependent on transformer leakage inductance L_{lk} and the clamping capacitor C_{cl}. As the value of the clamping capacitor increases, voltage stress or the peak voltage across the bridge switches can be reduced.

8.1 Proposal for Futurework

- The proposed prototype of the converter uses MOSFETs as its switches. Converter behavior with the other switches like IGBT can be studied.

- The proposed converter is best suited for maximum output loads of 500 W. Research can be done to extend the load range by proper paralleling of converters.

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Appendix A

Coding of ATMEGA16 Controller in BASCOM

regfile "M16DEF.DAT"

Dim A As Integer Dim Feedback As Integer

Config Portc = Output

Config Portd. 6 = Input

Config Portd. 5 = Input

Config Portd. 7 = Output

P1 Alias Portd. 7 P2 Alias Portc. 1 Pb Alias Portc. 2 I1 Alias Portc. 3 I2 Alias Portc. 4 Opncls Alias Pind. 5

Config Timer 0=Timer, Prescale=1

Config Adc=Single, Prescaler=Auto

Do Feedback=Getadc(0)

Loop Tim0isr: A=A+1

If Pind. 6=0 Then If Opncls=0 Then If Feedback¡1024 And Feedback¿800 Then If A=2 Then

P1=1 P2=1 Pb=1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If If A = 12 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then

P1 = 0 P2 = 1 Pb = 0 A = 0 End If

End If

If Feedback ¡ 800 And Feedback ¿ 700 Then

If A = 3 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If

If A = 13 Then P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then P1 = 0 P2 = 1 Pb = 0 A = 0 End If

End If If Feedback ¡ 700 And Feedback ¿ 600 Then If A = 4 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then P1 = 1 P2 = 0 Pb = 0 End If

If A = 14 Then P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then P1 = 0 P2 = 1 Pb = 0 A = 0 End If

End If If Feedback ¡ 600 And Feedback ¿ 500 Then If A = 5 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If

If A = 15 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then

P1 = 0 P2 = 1 Pb = 0 A = 0 End If

End If If Feedback ¡ 500 And Feedback ¿ 400 Then If A = 6 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If

If A = 16 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then

P1 = 0 P2 = 1 Pb = 0

A = 0 End If End If

If Feedback ¡ 400 And Feedback ¿ 300 Then If A = 7 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If

If A = 17 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then P1 = 0 P2 = 1 Pb = 0 A = 0

End If End If If Feedback ¡ 300 And Feedback ¿ 200 Then

If A = 8 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then

P1 = 1 P2 = 0 Pb = 0 End If

If A = 18 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then

P1 = 0 P2 = 1 Pb = 0 A = 0 End If End If If Feedback ¡ 200 And Feedback ¿ 0 Then

If A = 9 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 10 Then P1 = 1 P2 = 0 Pb = 0 End If

If A = 19 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 20 Then

P1 = 0 P2 = 1 Pb = 0 A = 0 End If End If Else If A = 1 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 2 Then P1 = 1 P2 = 0 Pb = 0 End If If A = 3 Then

P1 = 1 P2 = 1 Pb = 1 End If

If A = 4 Then

P1 = 0 P2 = 1 Pb = 0 A = 0 End If

End If

Else

If A = 4 Then I1 = 0 End If

If A = 5 Then I2 = 1 End If

If A = 9 Then I2 = 0 End If

If A = 10 Then I1 = 1 A = 0

End If

End If

Return