# Soft-Switching Buck-Boost DC/DC Converter Using Partial Resonant Circuit

A Project Report

*Submitted by*

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*in partial fulfillment for the award of the degree*
of

Master of Engineering

in

**Power Electronics and Drives**

**DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING**

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Certified that this project report entitled **"Soft-Switching Buck-Boost DC/DC Converter Using Partial Resonant Circuit"** is the bonafide work of

| | |
|---|---|
| P.Maithili | Register No. 0920105005 |

Who carried out the project work under my Supervision

| | |
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| Signature of the Head of the Department | Signature of the Supervisor |
| Dr.Rani Thottungal | Mr.C.UdhayaShankar |

Certified that the candidate with university Register No. 0920105005 was examined in project viva voce Examination held on 26-04-11

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# CONTENTS

**TITLE** **Page No**

**1. INTRODUCTION**

**2. BUCK-BOOST CONVERTER**

**3. BUCK-BOOST CONVERTER WITH REGENERATIVE SNUBBER CIRCUIT**

**4. BUCK-BOOST CONVERTER WITH PARTIAL RESONANT CIRCUIT**

**5. HARDWARE IMPLEMENTATION OF SOFT SWITCHED BUCK-BOOST CONVERTER WITH PARTIAL RESONANT CIRCUIT**

**6. CONCLUSION AND FUTURE SCOPE**

# ABSTRACT

The snubber circuit had been used in DC-DC converters under hard switching conditions for over current and over voltage protection. But, the snubber is lossy and bulky and is difficult to apply to high frequency switching converters. So, the soft-switching Buck-Boost converter using a passive snubber composed of a pulse current regenerative snubber circuit is proposed. This circuit has the zero voltage soft-switching action (ZVS). But, the Buck-Boost converter with regenerative snubber has able to operate in continuous current mode of operation. So, the zero current switching is not possible in this circuit. The partial resonant circuit is implemented in Buck-Boost converter. The zero voltage and zero current switching is used during turn-off and turn-on conditions. Due to its simple circuit configuration, this proposed converter can able to be controlled by simple (Pulse Width Modulation) PWM signal and the switching losses reduced by soft switching techniques (ZVS&ZCS). The efficiency of this converter is improved than the Buck-Boost converter with regenerative snubber circuit. The simulink model for a Buck-Boost converter with regenerative snubber is developed using MATLAB 7.0.4 and the same is used for simulation studies.

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF FIGURES (Cont.,)

## LIST OF FIGURES (Cont.,)

# ABREVIATIONS

| | |
|---|---|
| DC | Direct Current |
| ZVS | Zero Voltage Switching |
| ZCS | Zero Current Switching |
| PWM | Pulse Width Modulation |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| IGBT | Insulated Gate Bipolar Transistor |
| DCM | Discontinuous Current Mode |

# LIST OF SYMBOLS

$V_d$ - Source Voltage

$V_{cd}$ - Output Capacitor Voltage

$i_{Lr}$ - Resonant Inductor Current

$L_r$ - Resonant Inductor

$C_r$ - Resonant Capacitor

$V_{cr}$ - Resonant Capacitor Voltage

$i_s$ - Supply Current

$n$ - Turns Ratio

$V_{in}$ - Input Voltage

$V_{out}$ - Output Voltage

$\delta$ - Duty Ratio

$f_s$ - Switching Frequency

$T_{ON}$ - Turn ON Time

$T_{OFF}$ - Turn OFF Time

# CHAPTER 1

# CHAPTER 1

# 1. INTRODUCTION

## 1.1 INTRODUCTION OF SOFT SWITCHED CONVERTER

The DC-DC converter converts a fixed voltage DC source into a variable voltage DC source. It can be used to step down or step up a DC voltage source. DC-DC converter circuits are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, fork lift trucks, mine haulers and DC power generation stage of a renewable energy system. To realize high conversion efficiency, a soft switching circuit is useful and effective technologies. In this project work the soft-switching Buck-Boost converter using a passive snubber composed of a pulse current regenerative snubber circuit is proposed. In the 1970's conventional PWM power converters are operated in switched mode. Power switch have to cut off the load current within turn-on and turn-off time under the hard switching conditions. Hard switching refers to stressful behaviour of the power electronic device. During the turn-on and turn-off process, the power device has to withstand high voltage and high current simultaneously, which results in high switching losses and stress. Dissipative passive snubbers are usually added to the power circuit so that the di/dt and dv/dt of the power device can be reduced, and the switching losses and stress can be diverted to the passive snubber circuits. However, switching frequency of the power converter is high. Hard switching has a number of effects such as switching loss, device stress, EMI problems.

Soft switching techniques have been proposed to reduce the switching loss and improve the performance of converters. They can be classified into two basic categories

i) Zero voltage switching

ii) Zero current switching

ZVS reduces the switch turn-off loss by forcing the switch voltage to zero prior to its current flowing, while ZCS reduces the turn-on loss by forcing the switch current to zero before its collector-emitter voltages increases from zero to static value.

Soft switched converters have been researched in recent years for power converters to improve efficiency and reduce switching losses. A nearly proposed passive snubber circuit has only passive power components of inductors and capacitors, but its benefit is offset by high voltage stresses on converter's switching power devices and it has simple circuit configuration. The efficiency has improved than the conventional Buck-Boost converter with snubber circuit. In this project, the partial resonant circuit is implemented in the conventional Buck-Boost converter to improve the efficiency than the converter with regenerative snubber circuit. The zero voltage switching (ZVS) and zero current switching (ZCS) techniques are used to turn-on and turn-off the switches.

## 1.2 OBJECTIVES OF THE PROJECT

Conventional PWM power converters are operated in hard switched mode. Power switch have to cut off the load current within turn-on and turn-off time. The soft switching have been proposed to improve the performance of converter. The main objectives of the project is mentioned below

- Zero voltage switching (ZVS) reduces the switch turn-off loss by forcing the switch voltage to zero prior to its current flowing
- Zero current switching (ZCS) reduces the switch turn-on loss by forcing the switch current to zero
- To reduce switching losses
- To reduce high voltage stresses on converter's switching power devices
- The converter's efficiency is largely improved at high frequency operation
- High switching frequency is achieved for with low switching stress by the effective soft switching action

## 1.3 ORGANIZATION OF THESIS

This gives an overall outline of the project report.

CHAPTER 1

It describes the general introduction, objective, hard switching and soft switching.

CHAPTER 2

It describes the introduction about Buck-Boost converter. It deals with principle of operation and advantages of Buck-Boost converter.

CHAPTER 3

It describes about the introduction, principle of operation and methodology of the Buck-Boost converter with regenerative snubber circuit. It includes the introduction MATLAB (simulink), simulation details of individual block and simulation results of the system.

CHAPTER 4

In this chapter deals with introduction, principle of operation, equivalent circuit and simulation results of the Buck-Boost converter with partial resonant circuit.

CHAPTER 5

It includes the proposed system model and description of all components used in the hardware. It shows the schematic diagram of the hardware and output waveforms and test results.

CHAPTER 6

Gives the conclusion and recommendations for the future work.

# CHAPTER 2

# CHAPTER-II

# 2. BUCK-BOOST CONVERTER

## 2.1. INTRODUCTION

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output voltage is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side. There are two different topologies,

1) Inverting Topology
2) Non-Inverting Topology

The inverting topology of the converter has the output voltage is of the opposite polarity as the input. The non-inverting topology of the converter has the same polarity as the input voltage.

## 2.2. PRINCIPLE OF OPERATION

Fig.2.1 shows the circuit diagram of a Buck-Boost converter. As shown, a Buck-Boost converter is nothing but cascade connection of the two basic converters: the step-down converter and the step-up converter. The main application of such a converter is in regulated d.c power supplies, where a negative polarity output may be desired with respect to the common terminal of the input voltage and the output voltage can be either higher or lower than the input voltage. The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor and the capacitor supplies current to the resistor (output load). When the switch is opened (providing energy is stored into the inductor), the inductor supplies current to the load via the diode D.

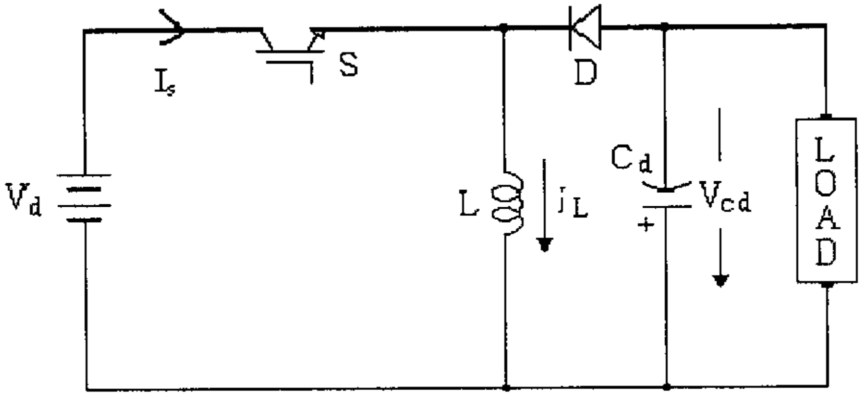


Fig.2.1. Circuit Diagram of Buck-Boost Converter

When the power switch is turned ON, the supply current flows through the path $V_{d+}$ -S-L- $V_{d-}$ . Hence, inductor L stores the energy during the $T_{on}$ period. When the switch is switched OFF, the inductor current tends to decrease and as a result, the polarity of the emf induced in L is reversed as shown in Fig.2.1. Thus, the inductor energy discharges in the load through the path $L_+$-Load-D-$L_-$ .There are two modes of operation,

1) Continuous Mode

2) Discontinuous Mode

### 2.2.1. Continuous Mode of Operation

If the current through the inductor *L* never falls to zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure 2.2. The converter is in On-State, so the switch *S* is closed. At the end of the on-state, the inductor current $I_L$ is increases. Therefore the duty ratio is incrreased to achieve the boost operation.D is the duty cycle. It represents the fraction of the commutation period *T* during which the switch is On. Therefore *D* ranges between 0 (*S* is never on) and 1 (*S* is always on).During the Off-state, the switch *S* is open, so the inductor current flows through the load. If we assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant. Therefore, the variation ofi $I_L$ during the Off-period is calculated. As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle.

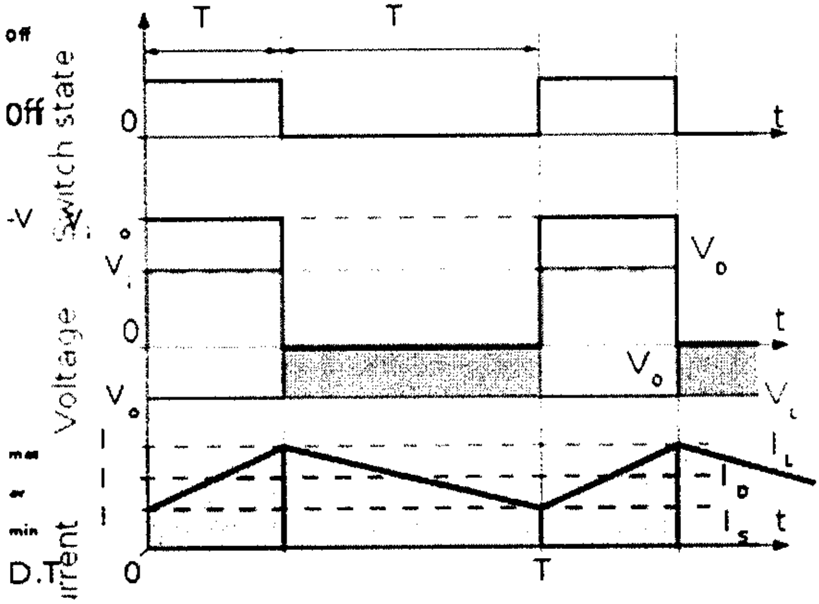


Fig.2.2. Waveforms of Current and Voltage in a Buck–Boost Converter Operating in Continuous Mode

The value of $I_L$ at the end of the Off state must be the same as the value of $I_L$ at the beginning of the On-state, i.e. The sum of the variations of $I_L$ during the on and the off states must be zero. It can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as D approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This converter is referred to as a buck–boost converter.

### 2.2.2. Discontinuous Mode of Operation

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (refer waveforms in Fig. 2.3).

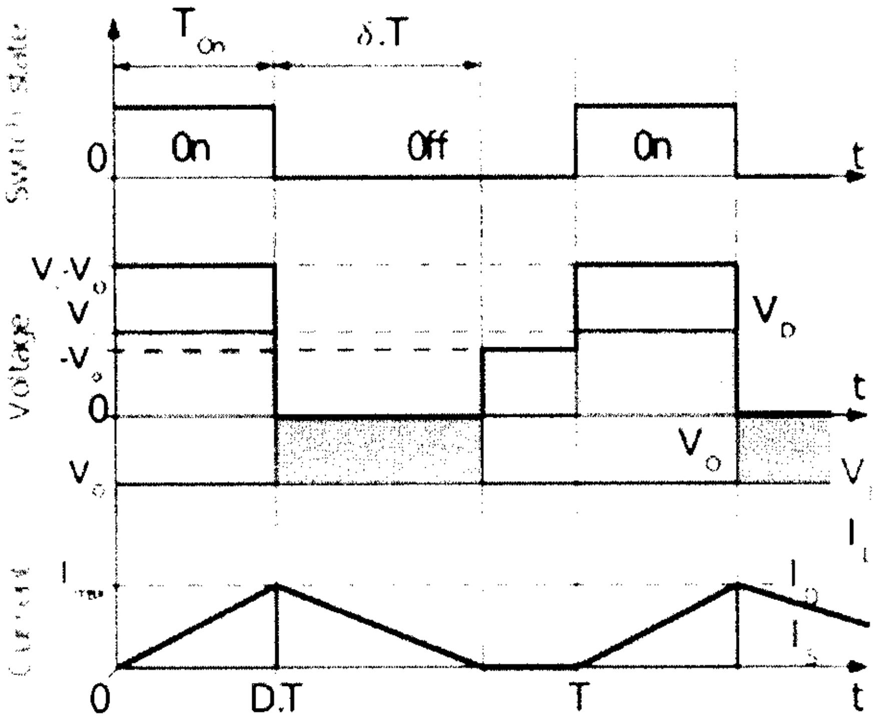


Fig.2.3. Waveforms of Current and Voltage in a Buck–Boost Converter Operating in Discontinuous Mode

The difference has a strong effect on the output voltage equation. As the inductor current at the beginning of the cycle is zero, its maximum value (at ) is During the off-period, $I_L$ falls to zero. In this mode the load current $I_o$ is equal to the average diode current ($I_D$). The diode current is equal to the inductor current during the off-state. Furthermore, in discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

### 2.2.3. Advantages of Buck-Boost Converter

- Designed for converting an unregulated/unstable dc voltage to a regulated dc voltage.
- Suitable for marine and automotive applications
- Isolated with input and output common ground
- Good load and line regulations
- Wide input voltage input range
- Fully electrical protected
- Anodized blue colour aluminium extrusion housing
- Inexpensive high current DC/DC converter stabilizes voltage in automotive and truck applications.
- Also can be used to provide regulated voltage from a sealed lead acid or other battery--excellent for special purpose UPS DC battery backups.

# CHAPTER 3

# CHAPTER-III

# 3. BUCK-BOOST CONVERTER WITH REGENERATIVE SNUBBER CIRCUIT

## 3.1. INTRODUCTION

The conventional Buck-Boost converter with snubber circuit has been used under hard switching conditions for over voltage and over current protection. But, the hard switching has number of effects such as switching losses, device stress, Electro Magnetic Interference (EMI) problems and less efficiency. To overcome these problems, nowadays soft switching techniques are used in the power electronic converter circuits. The regenerative Snubber circuit for a buck- boost converter with soft switching is provided which reduces the switching losses of the Insulated Gate Bipolar Transistor (IGBT) in the converter.

## 3.2. PRINCIPLE OF OPERATION

The soft-switching buck boost converter which uses the passive snubber with energy regenerative function, and which can be operated under the principle of low dv/dt turn-off and simple PWM action. The main power converter circuit consists of one active switch (Q) and the auxiliary passive snubber circuit. The passive snubber circuit with current regeneration for energy recovery is composed of a snubber diode ($D_s$), a snubber capacitor ($C_s$), an auxiliary diode ($D_r$), a secondary winding of a main inductor (L) which has the winding turn ratio (n) and a resonant inductor ($L_r$). The converter switches gets turned ON and OFF at zero voltage of the switch. By the effective soft-switching action the switching turn-on and turn-off losses are reduced. The switching loss of the soft-switching circuit becomes smaller than that of the hard-switching circuit due to the reduction of turn-off dv/dt. The circuit diagram of the Buck-Boost converter with regenerative snubber circuit is shown in Fig.3.1

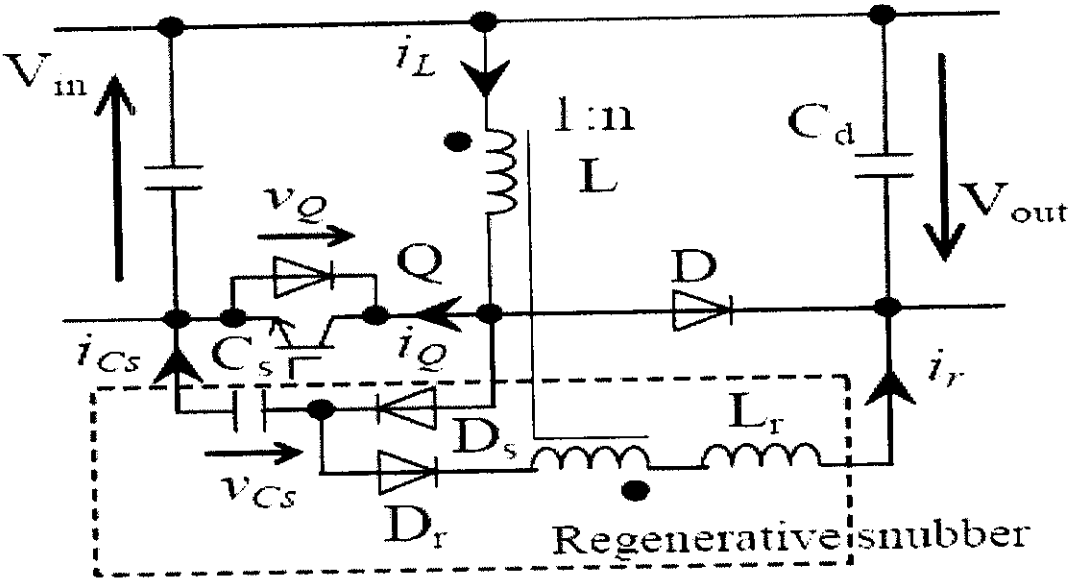


Fig.3.1 Circuit Diagram of Buck-Boost Converter with Regenerative Snubber Circuit.

The converter circuit is shown in Fig.3.1 consists of passive components which configure CD (capacitor and diode) snubber circuit and regenerative resonant circuit assisted with an auxiliary winding of a main inductor. This circuit has simple configuration and wide operation region of the zero voltage soft-switching action (ZVS). The regenerative snubber circuit for a Buck- Boost converter with soft-switching (ZVS) is provided which reduces the switching losses of the Insulated Gate Bipolar Transistor (IGBT) in the converter. Due to its simple circuit configuration, this proposed converter able to be controlled by simple (Pulse Width Modulation) PWM signal.

To analyze the behaviour of the proposed converter, the following assumptions are made:

(i) The main inductor L is much greater than $L_r$.

(ii) The main inductor L. is large enough to be treated as a current source $I_L$.

(iii) The output capacitor $C_d$ is large enough so that by varying the duty ratio both buck and boost operation achieved.

(iv) The power-semiconductor devices are ideal.

(v) The reactive elements are ideal.

## 3.3 METHODOLOGY

### 3.3.1 Flow Chart

The detailed methodology adopted for the project is given below (Fig 3.1)

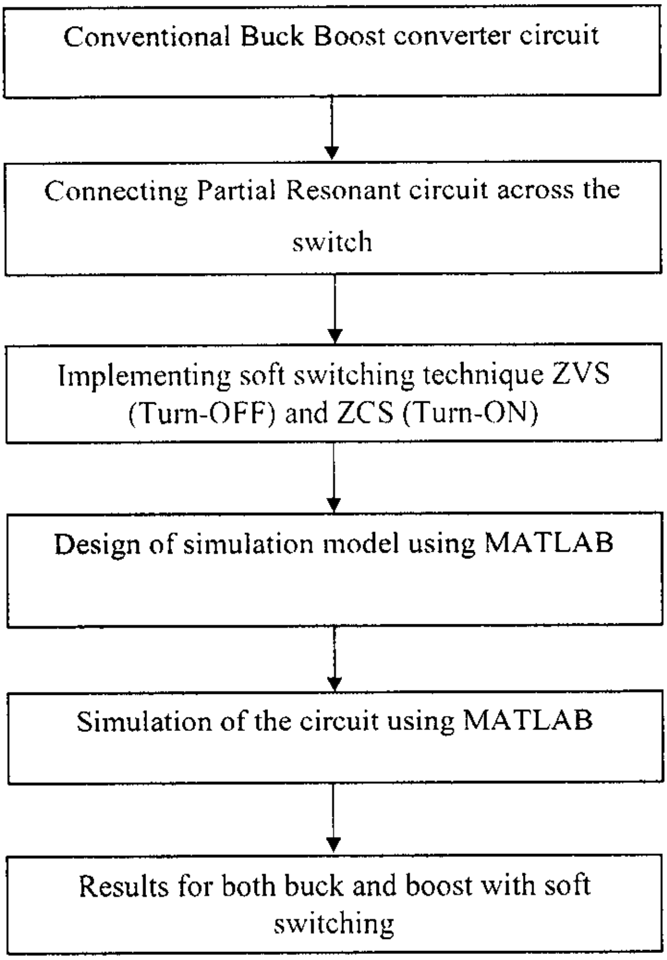


Fig.3.2 Detailed Methodology of the Proposed Converter Circuit

### 3.3.2. Equivalent Circuit of Converter

The operation of the proposed converter over one switching cycle is given below. The equivalent circuits of the proposed converter for each operation mode are shown in Fig.3.3 (a-e). At initial condition the current flowing through the resonant inductor (Lr) is zero, the switch in off state and the snubber capacitor is fully charged. There are typical four modes in one switching period. The switching sequences are shown in table 3.1.

Table 3.1

Switching Sequences

| **Mode/ Device** | **Mode 1 [$t_0 \leq t \leq t_1$]** | **Mode 1-1 [$t_0 \leq t \leq t_1$ ]** | **Mode 2 [$t_1 \leq t \leq t_2$]** | **Mode 3 [$t_2 \leq t \leq t_3$]** | **Mode 4 $t_3 \leq t \leq t_4$** |
|---|---|---|---|---|---|
| **Q** | **On** | **On** | **On** | **Off** | **Off** |
| **D** | **Off** | **Off** | **Off** | **Off** | **On** |
| **$D_s$** | **Off** | **On** | **Off** | **On** | **Off** |
| **$D_r$** | **On** | **On** | **Off** | **Off** | **Off** |

## A. Mode 1: Snubber Energy Regenerative mode

At mode 1, the active switch Q is turned on and a voltage $nV_{in}$ is reflected across the secondary winding of the main inductor. As a result, resonance based on $L_r$ and Cs starts partially. The snubber capacitor voltage is discharged toward to low level. Due to the resonance, the regeneration current start flows through the resonant inductor ($L_r$). The snubber capacitor voltage is discharged towards to low level. The snubber capacitor voltage is fully discharged to zero.

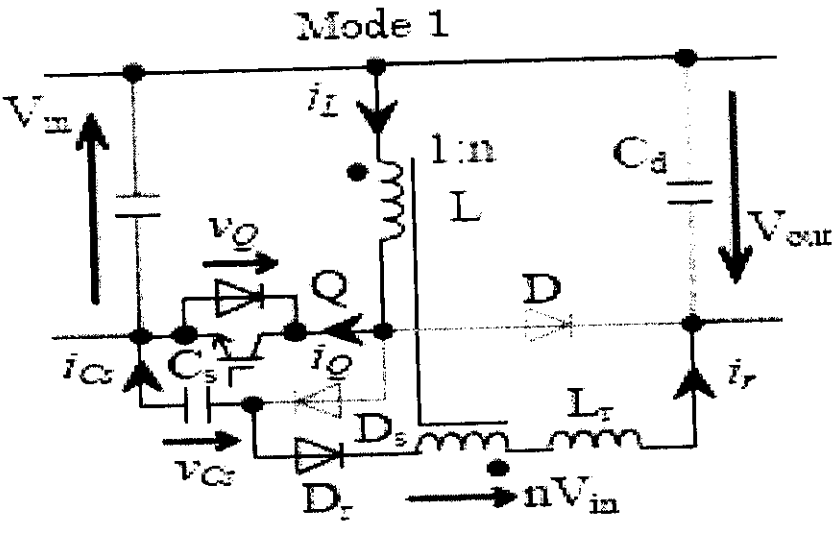


Fig.3.3 Snubber Energy Regenerative mode circuit

$$V_{cs} = V_{in} + V_{out} + nV_{in}[\cos\omega_r(t-t_0)-1] \tag{1}$$

$$i_r = \frac{nV_{in}}{Z_s}\sin\omega_r(t-t_0) \tag{2}$$

Where $Z_s = \sqrt{\frac{L_r}{C_s}}$ is the characteristics impedance and

$\omega_r = \frac{1}{\sqrt{L_r C_s}}$ is the resonance angular frequency

At this time, the additional operation mode of mode 1-1 is started, and the regeneration current decreases linearly to release the resonant inductor energy. The snubber capacitor voltage is fully discharged to zero. When the regeneration current becomes zero, mode 2 starts.

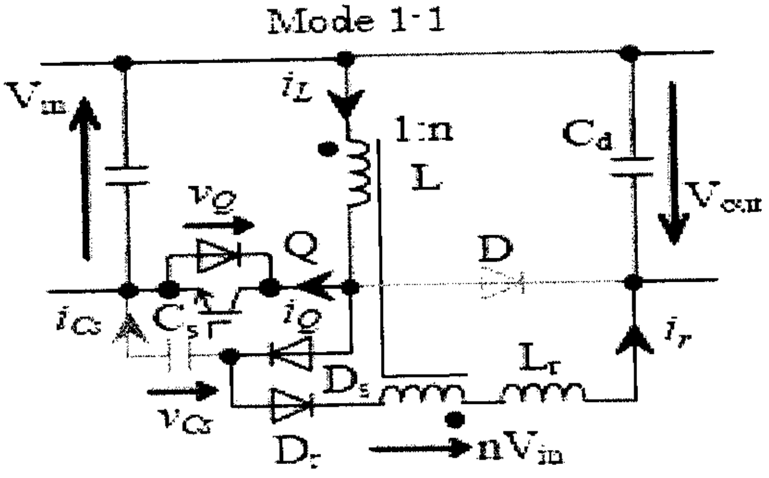


Fig.3.4 Snubber Energy Regenerative Mode Circuit

### B. Mode: 2 Main Inductor Energy Charging Mode

The main inductor energy is stored from the input side in this mode. When the active switch is turned off by the controller gate off signal of duty ratio ($\alpha$), mode 3 starts Since the regeneration current $i_r$ is not to flow continuously at mode 2, the additional condition of $nV_{in} < V_{in} + V_{out}$ should be considered and the conditions to determine the turn ratio of the auxiliary winding is rearranged as $0 < n < 1$ considering worst case output voltage of $V_{out}=0$.

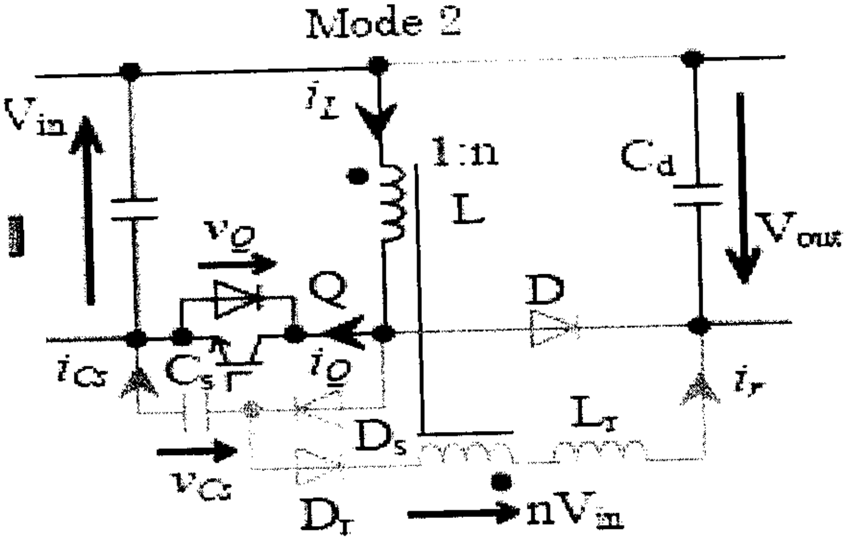


Fig.3.5 Main Inductor Energy Charging Mode circuit

### C. Mode:3 Snubber Capacitor Charging Mode

At this mode, the turn-off voltage applied to the active switch is suppressed by the. snubber capacitor, and then the turn-off loss of the active switch becomes small. When the capacitor voltage reaches to $V_{in}$ +$V_{out}$, mode 4 starts.

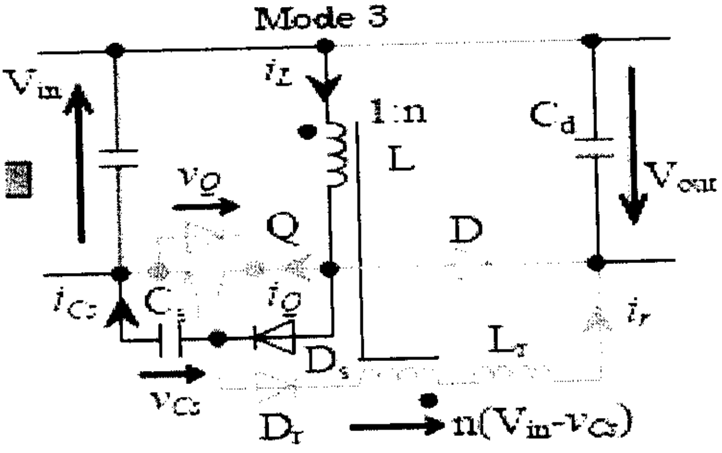


Fig.3.6 Snubber Capacitor Charging Mode

### D.Mode:4 Main Inductor Energy Releasing Mode

The energy stored in the main inductor is released to the output side in this mode.

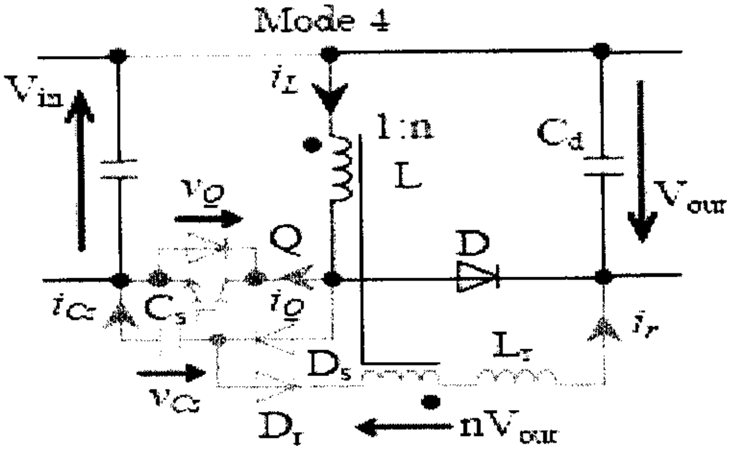


Fig.3.7 Main Inductor Energy Releasing Mode

By the conducting of the diode *D3*, the inductor current $iL_r$ flows through the load side. The current linearly decreases as the next equation. This mode ends when $iL_r = 0$. The time duration *T4* of this mode is obtained by the following. At the turn-on of the switch S another cycle starts.

## 3.4. SIMULATION OF SOFT-SWITCHED CONVERTER

### 3.4.1 MATLAB

The name MATLAB stands for matrix laboratory. MATLAB is a high-performance language for technical computing. It Integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. In this project the modeling and simulation of the proposed system is done using MATLAB (using simulink and power system block set tool boxes).

### 3.4.2 SIMULINK

Simulink is a software package for modeling, simulating, and analyzing non linear dynamical systems. It is a graphical mouse-driven program that allows somebody to model a system by drawing a block diagram on the screen and manipulating it dynamically. Simulink is a platform for multi domain simulation and Model-Based

Design for dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries, and can be extended for specialized applications.

### 3.4.3 POWER SYSTEM BLOCK SET

The Power System Block set allows scientists and engineers to build models that simulate power systems. The block set uses the Simulink environment, allowing a model to be built using click and drag procedures. Not only can the circuit topology be drawn rapidly, but also the analysis of the circuit can include its interactions with mechanical, thermal, control, and other disciplines. SimPowerSystems extends Simulink with tools for modeling and simulating basic electrical circuits and detailed electrical power systems. These tools let you model the generation, transmission, distribution, and consumption of electrical power, as well as its conversion into mechanical power. SimPowerSystems is well suited to the development of complex, self-contained power systems, such as those in automobiles, aircraft, manufacturing plants, and power utility applications

## 3.5 SIMULATION MODELS AND RESULTS

### 3.5.1 BLOCK DIAGRAM OF SOFT-SWITCHED CONVERTER

Simulation work has been done in MATLAB to verify the operation principle of the proposed soft-switching scheme. In our initial simulation, the dc supply voltage is given at 150V. The new Buck-Boost converter circuit was simulated with the following specifications: input voltage $V_{in}$=150V; output voltage $V_0$= $V_{in}$+50%=225V at Boost mode operation and $V_0$=45V at Buck mode operation; switching frequency ($f_s$) =20 KHz. The power stage consisted of the following parameters: Main Inductor L=1.5mH; Leakage inductance referred from aux. winding l=11μH; Snubber capacitor Cs=0.12μF; Resonant inductor $L_r$ =47μH; Active switch (Q) =1200V, 100A. A buck boost converter provides an output voltage that may be less than or greater than input voltage. (i.e.). Both buck and boost operation is achieved using the same circuit by varying the duty ratio of the converter. The duty ratio of the converter is calculated by using the Eq.3.

$$\delta = \frac{T_{ON}}{T_{OFF}} \qquad (3)$$

A block diagram of electronic control circuit for the proposed modular soft-switch circuit is shown in Fig.3.8

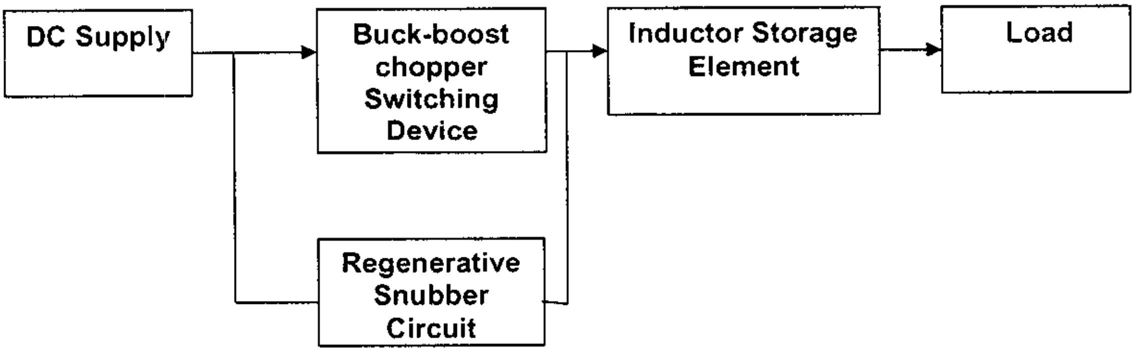


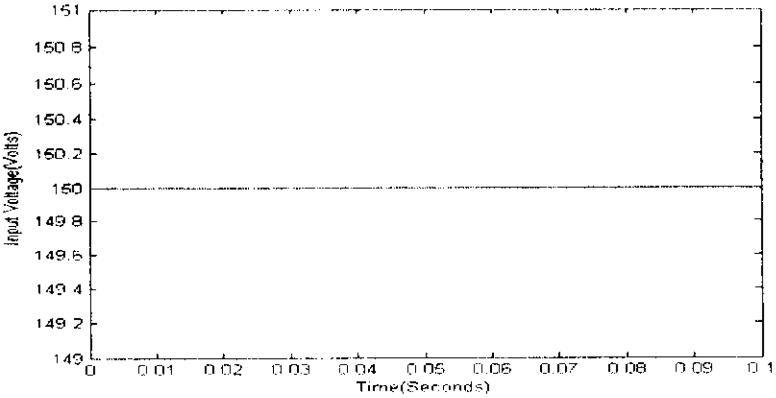
Fig 3.8 Basic Block diagram of Conventional Buck-Boost Converter with Regenerative Snubber Circuit

The DC supply is given into the conventional Buck-Boost DC/DC converter and the regenerative snubber circuit has connected across the converter switching device. The regenerative snubber circuit consists of a Snubber diode ($D_s$), a Snubber capacitor ($C_s$), an auxiliary diode ($D_r$), a secondary winding of a main inductor (L) which has the winding turns ratio (n) and a resonant inductor ($L_r$).

### 3.5.2 SIMULATION RESULTS

**BOOST MODE:**

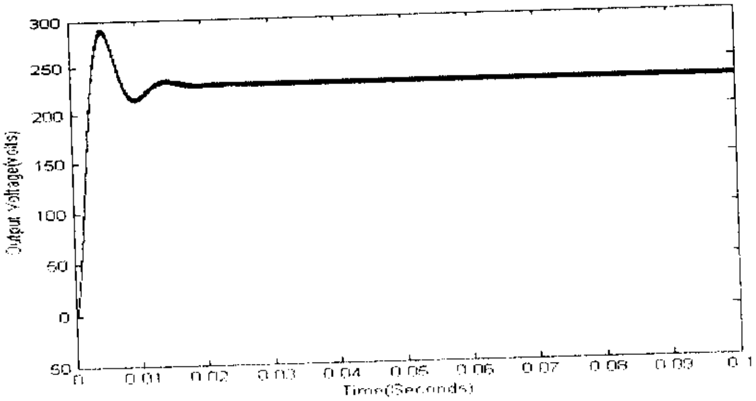
**INPUT VOLTAGE ($V_{dc}$)-150V**



(a) Input Voltage

Fig.3.9 (a) refers the input dc source voltage of the proposed buck boost converter with regenerative snubber circuit. The input voltage range varies from 150V to 450V. High input voltage operation is possible by the effect of snubber circuit.

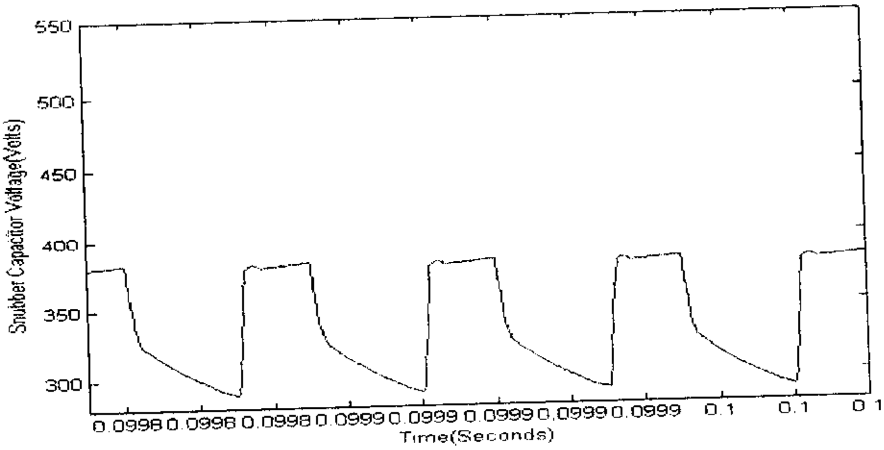
**OUTPUT VOLTAGE (V0)-225V**



(b) Output Voltage

Fig.3.9 (b) shows the output voltage waveform of proposed soft switching converter at boost mode. The 150V input voltage is given to the converter circuit. When the power switch IGBT is turned ON, the input current flowing through the inductor (L) and the switch (Q) start rises. Hence, inductor L stores the energy during turn ON (Ton) period. In boost mode the output voltage ($V_0$)-220V is greater than the input voltage Vin-(150V).

**SNUBBER CAPACITOR VOLTAGE ( Vcs ):**

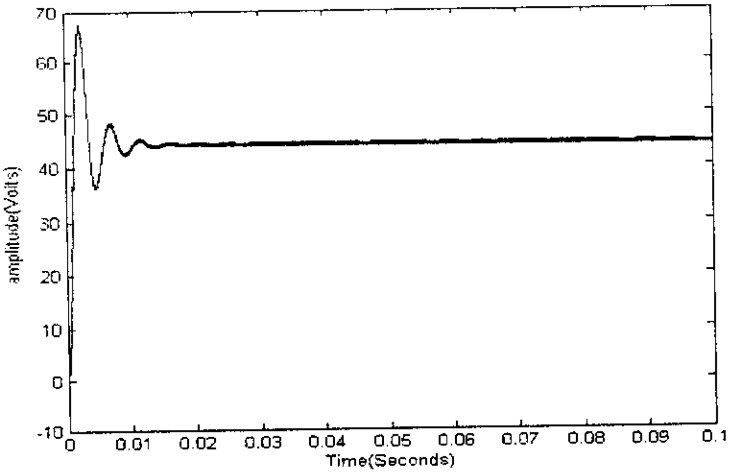


(c) Snubber Capacitor Voltage

Fig.3.9 (c) refers the snubber capacitor voltage waveform. At initial condition, the snubber capacitor Cs is charged to sum of the input voltage ($V_{in}$) and the output dc voltage ($V_0$). When the switches are turned ON, the snubber capacitor voltage is discharged towards to low level.

**BUCK MODE:**

**OUTPUT VOLTAGE ($V_{dc}$)-150V**

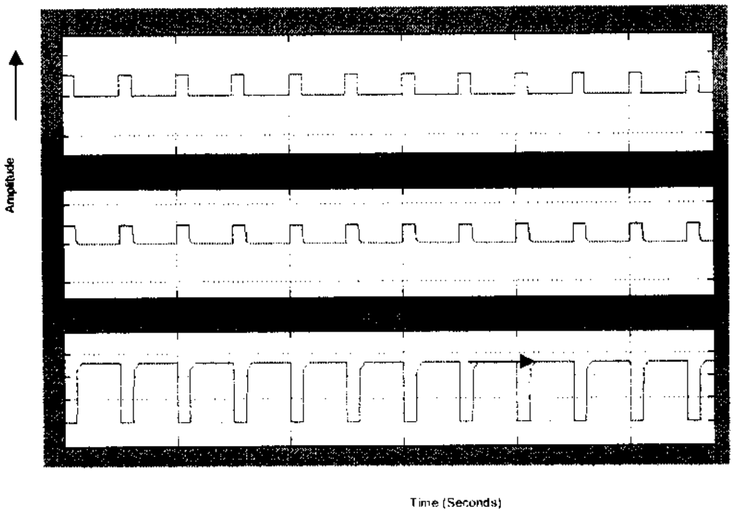


(d) Output Voltage in Buck Mode

Fig.3.9 (d) refers the switch voltage & current of the proposed soft switching converter and the gate pulses for the power switch IGBT at soft switching (ZVS) condition. The active switches are turned OFF by the gate turn off signal of duty ratio (α). At this mode, the turn-off voltage applied to the active switch is suppressed by the regenerative snubber capacitor and then the turn-off loss of the active switch becomes small.

**SWITCH VOLTAGE (Vq) &CURRENT (Iq), GATE PULSES FOR IGBT AT SOFT SWITCHING:**

Fig.3.9 (e) shows the output voltage waveforms. The converter circuit can be able to achieve the buck operation by varying the duty cycle of the converter in pulse generator. The input voltage applied in the buck boost converter circuit is 150V and after the buck operation the output voltage is 45V. If the duty ratio is less than 0.5 then the converter circuit acts as a buck converter and duty ratio is greater than 0.5 the same



(e) Gate Pulses, Switch Voltage and Switch Current

Fig.3.9 (a-e). Simulation wave forms

converter circuit will acts as a boost converter. Then the switches are turned ON & OFF at minimum or Zero Voltage of the switch. So, the switching loss is reduced and efficiency gets improved.

# CHAPTER 4

# CHAPTER-IV

# 4. BUCK-BOOST CONVERTER WITH PARTIAL RESONANT CIRCUIT

## 4.1. INTRODUCTION

The conventional Buck-Boost converter with snubber circuit was used under hard switching conditions for over voltage and over current protection. But, the hard switching has number of effects such as switching losses, device stress, Electro Magnetic Interference (EMI) problems and less efficiency. The regenerative Snubber circuit for a buck- boost converter with soft switching is provided which reduces the switching losses of the Insulated Gate Bipolar Transistor (IGBT) in the converter. But, this circuit can be able to operate in continuous current mode of operation. So, it is not possible to implement the zero current switching (ZCS) in this converter circuit. Finally, the snubber circuit in the conventional converter was replaced by a partial resonant circuit and both ZVS, ZCS techniques are used to turn off & on the switches. Its reduces the switching losses and its improves the efficiency of the converter circuit than the conventional Buck-Boost converter with regenerative snubber circuit.

## 4.2. PRINCIPLE OF OPERATION

The proposed circuit is shown in Fig.4.1 consists of controlling devices, a step up-down inductor $L_r$ , and a snubber capacitor $C_r$ used in the similar way for the conventional converter. It is considered that the snubber circuit in the conventional converter is partly replaced by a partial resonant circuit in the proposed converter. Its consists of a series connected switch-diode pair with a resonant capacitor, which is operated to a loss-less snubber capacitor. The switching devices in the proposed converter are operated with the soft switching by partial resonance and with constant switching frequency. When the switching devices, S1 and *S2*, are turned off, the inductor $L_r$ current charges the capacitor $C_r$ by the partial resonant operation. Therefore, the turn-off of the S1 and S2 is ZVS. Since the current pulses in DCM converter always begin at zero, the turn-on of the S1 and S2 is ZCS. Furthermore, at the turn-on of the S1 and S2, it

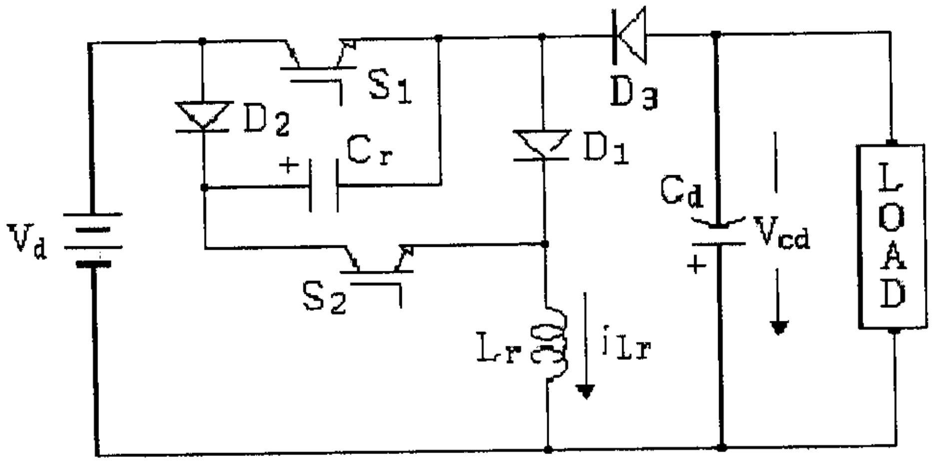


Fig.4.1. Proposed Buck-Boost DC-DC Converter with Partial Resonant Circuit

is for an accumulated energy in the snubber capacitor to regenerate into the input power source by partial resonant operation without the power loss of snubber circuit, which is generally present in the conventional Buck-Boost dc/dc converter. As a result, the proposed converter using a partial resonant circuit achieves the soft switching (the ZCS at turn-on and the ZVS at turn-off). The power losses of the switching devices are drastically decreased, and then the proposed converter is operated with high efficiency.

### 4.2.1 Equivalent Circuit of Converter

The equivalent circuits of the proposed converter for each operation mode are shown in Fig. 4.2 to Fig.4.5. At initial condition the current flowing through the resonant inductor ($L_r$) is zero, the switch in off state and the resonant capacitor is fully charged to sum of the input and output voltages and there is no current flowing through the resonant inductor. The switching sequences of the proposed converter are shown in table 4.1. The operation of the proposed converter over one switching cycle is divided into the following four sequential modes:

Table.4.1 Switching Sequences

| Mode/Device | Mode 1 [$t_0 \le t \le t_1$] | Mode 2 [$t_1 \le t \le t_2$] | Mode 3 [$t_2 \le t \le t_3$] | Mode 4 [$t_3 \le t \le t_4$] |
|---|---|---|---|---|
| **S1** | **On** | **On** | **Off** | **Off** |
| **S2** | **On** | **On** | **Off** | **Off** |
| **D1** | **Off** | **On** | **On** | **Off** |
| **D2** | **Off** | **On** | **On** | **On** |
| **D3** | **Off** | **Off** | **Off** | **On** |

### A. Mode 1[$t_0 \le t \le t_1$ ]:

Mode 1 begins by turning on both *S1* and *S2* at the same time. The input voltage $V_d$ and the capacitor voltage $V_{cr}$ are added and applied to the inductor $L_r$. Then this mode takes the form of a series LC resonance circuit. The capacitor $C_r$ discharges its electric charge through the inductor $L_r$. Hence this is ZCS. The equations about the snubber capacitor voltage ($V_{cs}$) and the regeneration current ($i_r$) for this mode are given in Eq.4&5,

$$Vcr = [2V_{in} + V_{out}]\cos \omega_r t - 1 \qquad (4)$$

$$i_r = \frac{2V_{in} + V_{out}}{X} \sin \omega_r (t) \qquad (5)$$

Where $Xr = \sqrt{\frac{L_r}{Cr}}$ is the characteristics impedance and

$\omega_r = \frac{1}{\sqrt{L_r Cr}}$ is the resonance angular frequency

When the resonant capacitor voltage becomes zero, mode 2 starts. The time duration of $T_1$ is obtained from the following Eq.6

$$T_1 = \sqrt{L_r C_r}\,\cos^{-1}\left(\frac{V_d}{2V_d + V_{cd}}\right) \qquad (6)$$

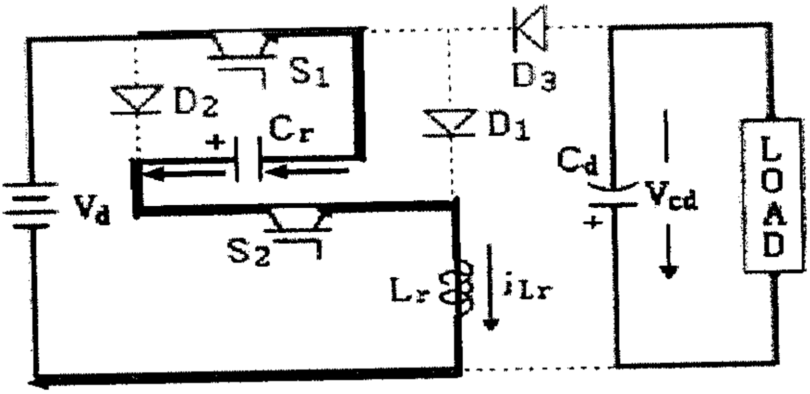


Fig.4.2-Mode-1 operation

**B. Mode 2 [$t_1 \leq t \leq t_2$]:**

The main inductor energy is stored from the input side in this mode. The snubber capacitor voltage is fully discharged to zero. Mode 2 begins when the voltage across $C_r$ becomes zero. Then the diodes D1 and D2 start conducting. The inductor current is divided into two paths of S1-D1 and D2-S2. The inductor current linearly increases as the following until the switches are turned off.

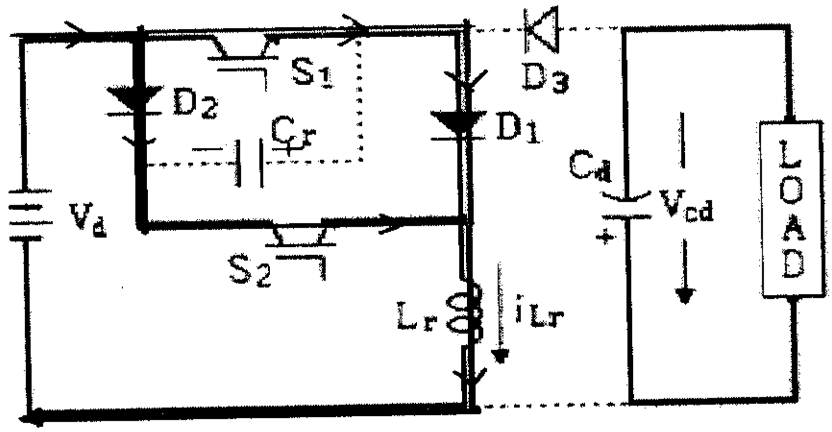


Fig.4.3-Mode-2 operation

This mode ends when both S1 and S2 are turned off simultaneously. Then the time duration T2 of this mode is expressed as

$$T_2 = T_{on} - T_1 \qquad (7)$$

Where, Ton is the turn-on period of the switches *S1* and *S2*, and I2 is the resonant inductor current.

### C. Mode 3 [$t_2 \le t \le t_3$]:

At this mode, the turn-off voltage applied to the active switch is suppressed by the snubber capacitor, and then the turn-off loss of the active switch becomes small. Mode 3 begins by turning off both *S1* and *S2* at the same time. The current flowing through $L_r$ takes a route of D2- $C_r$-D1 and charges $C_r$. Then this mode takes the form of a series LC resonance circuit. The turn-off of *S1* and *S2* occurs at ZVS because the voltage of $C_r$ is zero. In this mode, the voltage of Cr and the current of Lr expressed as follows.

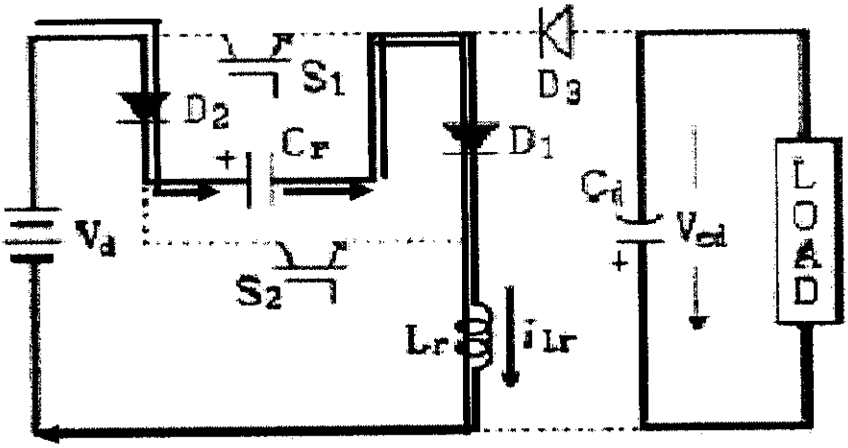


Fig.4.4-Mode-3 operation

The turn-off of S1 and S2 occurs at ZVS because the voltage of $C_r$ is zero. When the capacitor voltage reaches to $V_{in}+V_{out}$, the diode D3 starts conducting and then mode 4 starts.

$$V_{cr} = V_d + \sqrt{\frac{L_r}{C_r}} I_a \sin(\omega_r t + \theta)$$

$$i_{Lr} = I_a \cos(\omega_r t + \theta) \qquad (8)$$

$$I_3 = \sqrt{I_2^2 - \frac{C_r}{L_r}\left(V_{cd}^2 - V_d^2\right)} \qquad (9)$$

### D. Mode 4 [$t_3 \le t \le t_4$]:

The energy stored in the main inductor is released to the output side in this mode. By the conducting of the diode *D3*, the inductor current $iL_r$ flows through the load side. So, the current decreases linearly until the switches gets turned on. Thus, the entire soft

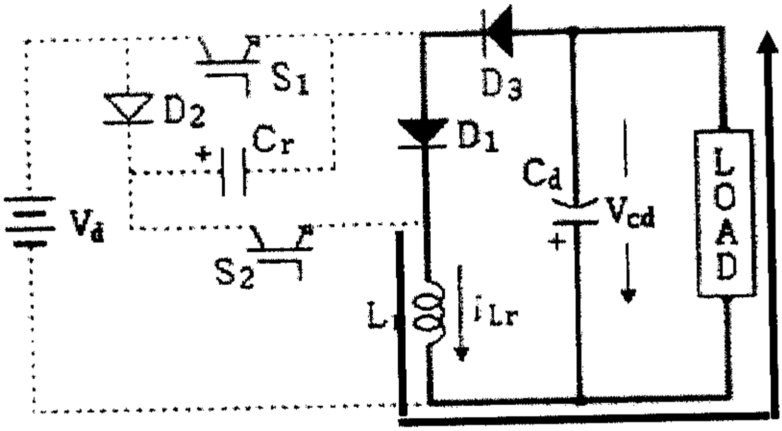


Fig.4.5-Mode-4 operation

switching is completed. This mode ends when the resonant inductor current reaches zero. The circuit returns back to the steady state or initial state as shown in Fig.5.1 and is ready for the next switching period.

## 4.3. DESIGN CONSIDERATIONS

### 4.3.1 Partial resonant Circuit Design

The two main elements to design here are the resonant inductor ($L_r$) and the resonant capacitor or lossless snubber capacitor ($C_r$). This is facilitated by fixing the maximum current in the switch to a certain value $I_{max}$. The value of the capacitor should be chosen to be as large as possible keeping in mind that its charging duration should not be longer than the interval during which switches are off. The dv/dt & di/dt (rate of change in voltage and rate of change in current) is determined by the lossless snubber capacitor ($C_r$), resonant inductor ($L_r$) and partially by the load current. The highest dv/dt happens mode-4 when the dc link forms a resonance circuit through the resonant capacitance ($C_r$) and resonant inductor ($L_r$). Implementation of this partial resonant circuit in conventional Buck-Boost converter the circuit able to operate in discontinuous mode of operation (DCM).

### 4.3.2 Energy Recovery Circuit Design

The energy recovery circuit consists of the auxiliary diode (D1), resonant inductor ($L_r$) and the main resonant inductor ($L_r$). The average power to be recovered through this circuit by the energy stored in resonant capacitor and the energy stored in resonant inductor over a fundamental cycle.

### 4.3.3 Condition for ZVS & ZCS

In order to create a condition for zero voltage switching (ZVS), the resonant or lossless snubber capacitor voltage ($V_{cr}$) should be discharged to zero during the switching period of the converter. To create the condition for zero current switching (ZCS) the resonant inductor current have to reach the zero value. When the resonant capacitor voltage and inductor current reaches zero value the switching devices gets turned off and on due to the LC resonant operation.

## 4 .4 SIMULATION RESULTS AND DISCUSSIONS

The new Buck-Boost converter circuit was simulated with the following specifications: input voltage $V_{in}$=100V; output voltage $V_0$= $2V_{in}$=200V at Boost mode operation and $V_0$=30V at Buck mode operation; switching frequency ($f_s$) =400 kHz. The power stage consisted of the following parameters: Snubber capacitor $C_s$=0.47μF; Resonant inductor $L_r$ =100μH; Active switch (Q) =1200V, 100A. A buck boost converter provides an output voltage that may be less than or greater than input voltage. (i.e.) Both buck and boost operation is achieved using the same circuit by varying the duty ratio of the converter in fixed DC to variable DC.

The Fig.4.6 shows simulation circuit for buck-boost dc/dc converter for variable dc to fixed dc voltage conversion. To investigate the validity of the proposed system, the proposed converter is simulated using MATLAB/SIMULINK. In variable DC to fixed DC the converter output voltage is maintain as constant with variable input voltage. The error signal is given to the PI controller in order to make the error signal within the carrier wave limit for comparing the carrier and reference wave. If the reference wave amplitude is lesser than or equal to carrier wave amplitude then its simulation circuit parameters for variable DC/Fixed DC is shown in table 4.2

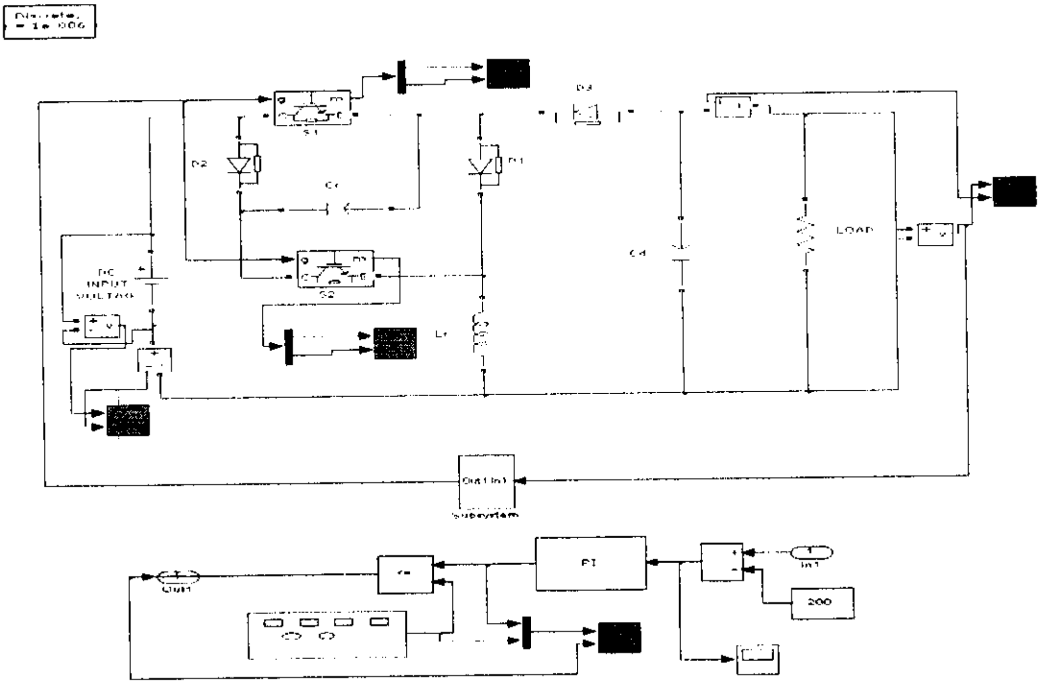


Fig.4.6 Simulation Circuit for Variable DC/ Fixed DC using MATLAB/SIMULINK

Table.4.2 Simulation Circuit Parameters (Variable DC-Fixed DC)

| | |
|---|---|
| Input Voltage($V_{in}$) | 100V – 300V |
| Output Voltage ($V_0$ ) | 200V |
| Smoothing Capacitor($C_d$ ) | 2000μF |
| R Load | 100Ω |

### 4.4.1. Input and Output Voltage

Fig.4.7 infers the input dc source voltage of the proposed buck boost converter with partial resonant circuit. The input voltage range varies from 100V to 450V in variable DC/ Fixed DC and the output voltage is maintained as a constant value of 200V. In Fixed DC/ Variable DC the input voltage is maintained the constant value of 100V.High input voltage operation is possible by the effect of partial resonant circuit.

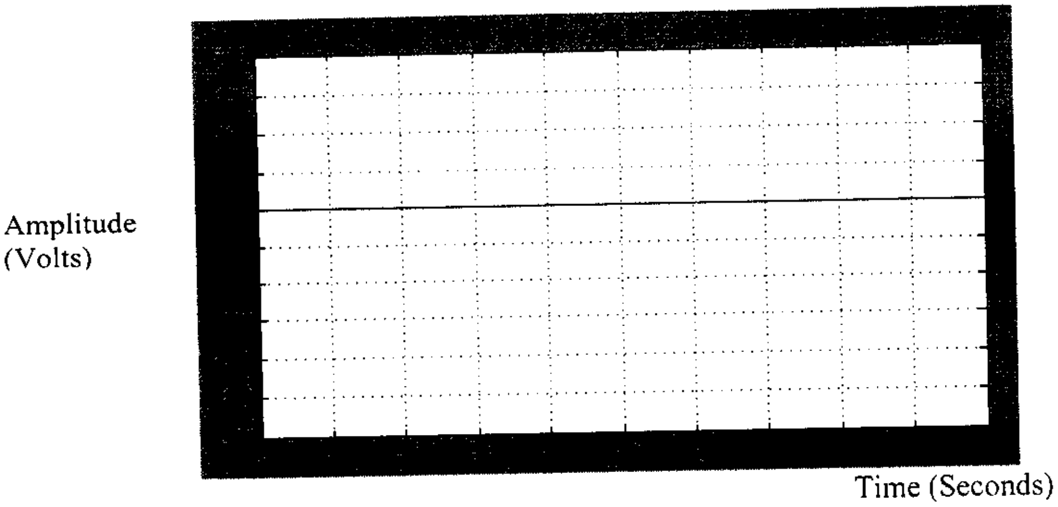


Fig.4.7 Input Voltage-100V

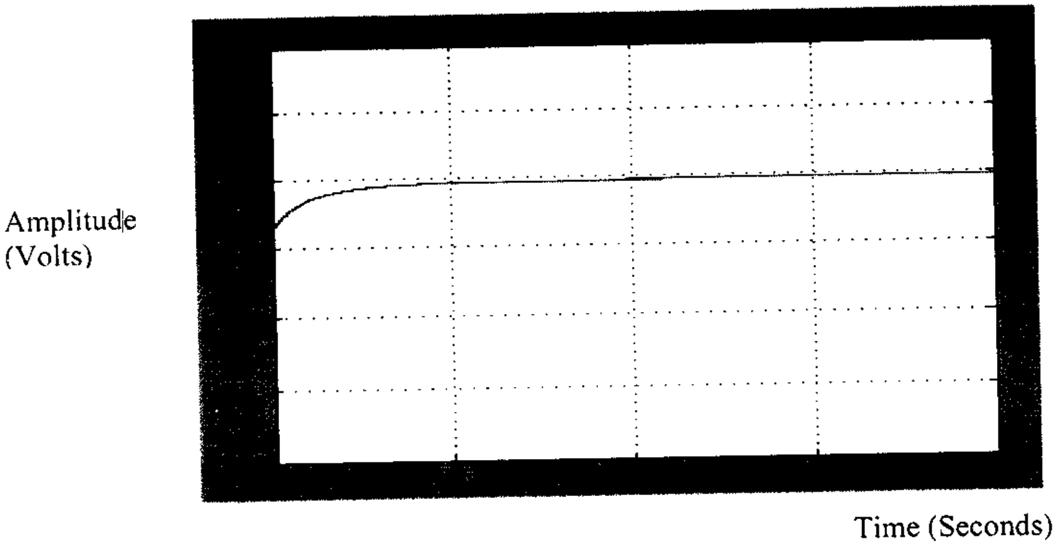


Fig.4.8 Output Voltage-200V

Fig.4.8 & 4.9 shows the output voltage waveforms of proposed soft switching converter at boost and buck mode. The 100V input voltage is given to the converter circuit. When the power switch IGBT is turned ON, the input current flowing through the inductor (L) and the switches start rises. Hence, the inductor L stores energy during turn ON ($T_{on}$) period. In boost mode the output voltage ($V_0$)-200V is greater than the input voltage $V_{in}$-(100V) and in buck mode its step down into 35V.

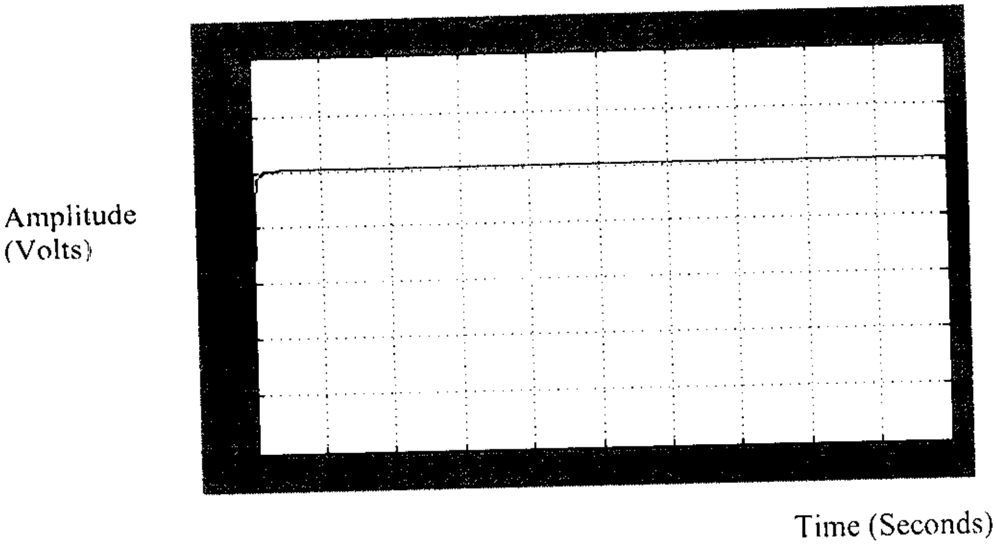


Fig.4.9 Output Voltage-35V

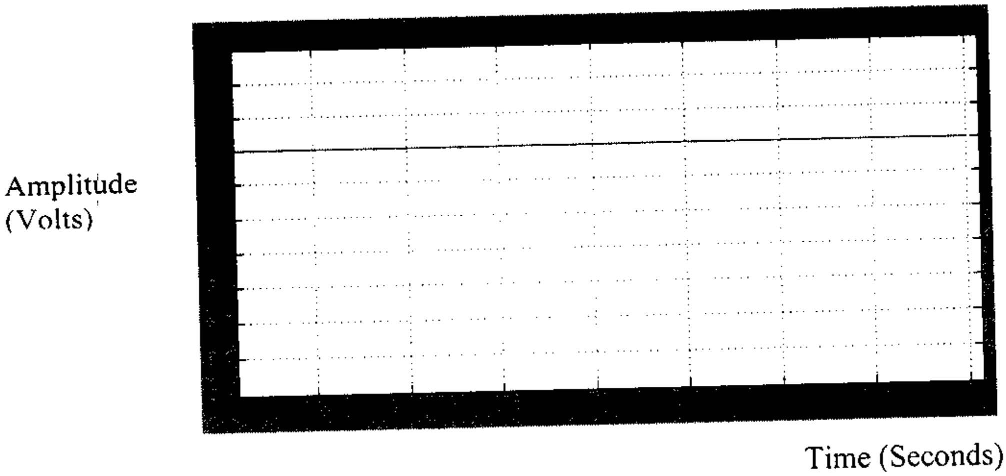


Fig.4.10 Output Voltage-200V

### 4.4.2 Soft Switching Action

Fig.4.11 shows the reduced switching losses by the implementation of soft switching technique. Here the gate pulses for the switches gets turned on at zero current state. Because this converter are operated under the discontinuous mode of operation. Similarly the switches get turned off at zero voltage of resonant capacitor. The voltage $V_{Cr}$ becomes zero at mode1.At mode2, the controlling switches are simultaneously turned off and the capacitor $C_r$ is charged by the inductor current $i_{Lr}$. The voltage of $C_r$ becomes equal to "$V_d + V_{cd}$" at mode3. At mode4, the current $i_{Lr}$ of the inductor reaches zero and the switches are kept off till the next cycle.

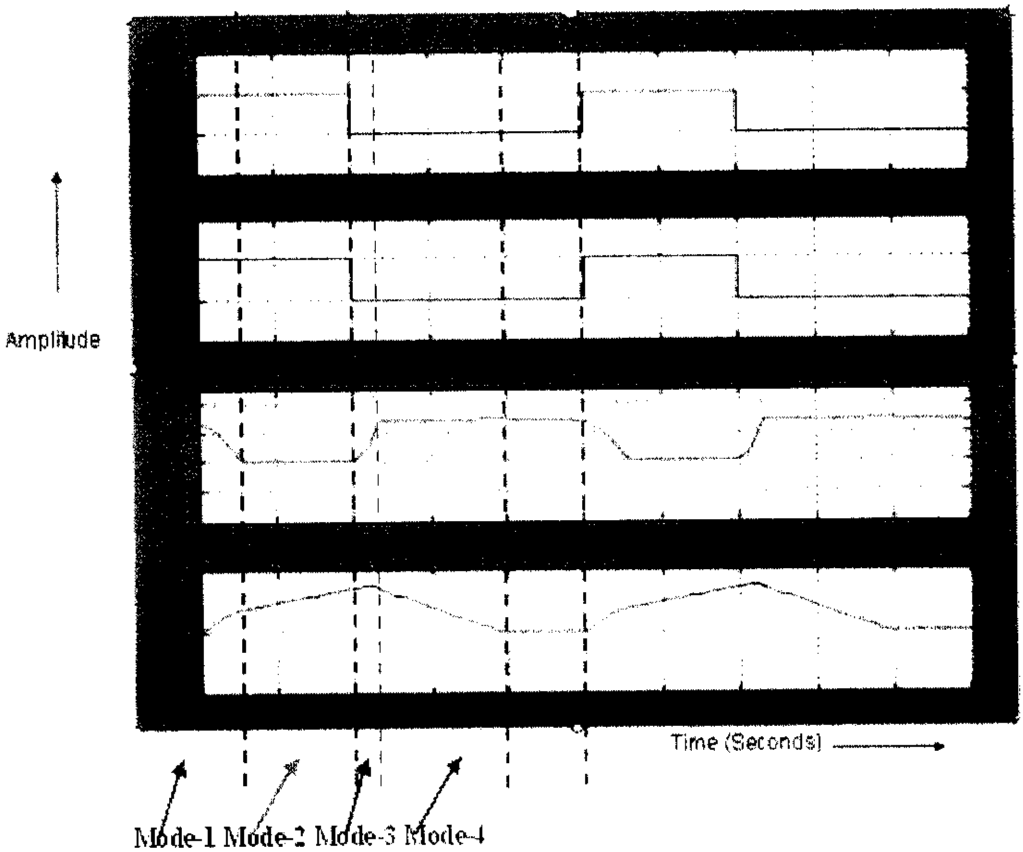


Fig.4.11 Gate Pulses for Switches, Resonant capacitor voltage and Inductor current waveforms

Fig.4.12 shows the current waveforms through the switches and voltage waveforms across the switches. Particularly, the resonant operation of the partial resonant circuit was partially enforced at only switching turn-on time and turn-off time. It reduces the losses and stresses of the resonant devices. The IGBT is used as a switch in simulation. Here the switches gets turned ON at Zero Current of the resonant inductor ($L_r$) and the switches gets turned OFF when the resonant capacitor voltage reaches zero value.

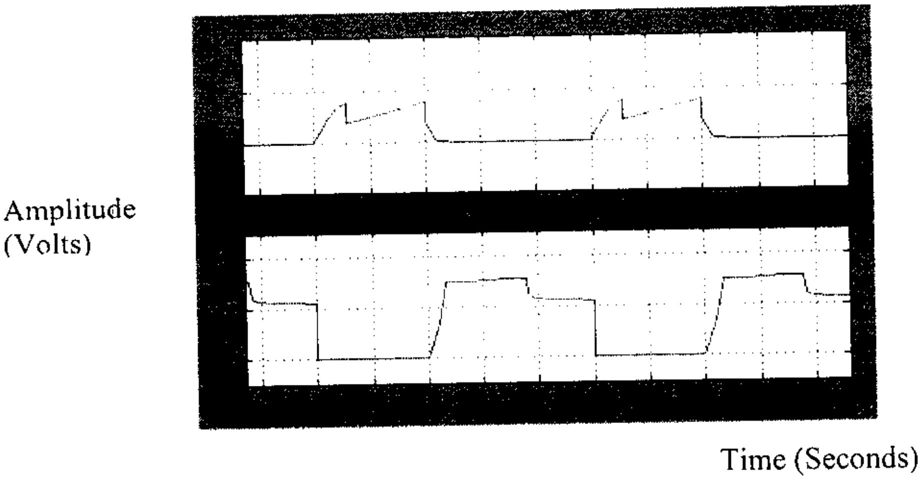


Fig.4.12 Switch currents and Switch voltages

Fig. 4.13 shows the relation between system efficiency and an output power. The output power was measured in the adjusted range of the variable resistor with PWM switching control for a fixed output voltage of dc 200V. The efficiency is compared with the conventional converter. The switching losses in buck-boost converter with partial resonant circuit are less than the regenerative snubber circuit. So, its efficiency was higher than the conventional buck-boost converter.

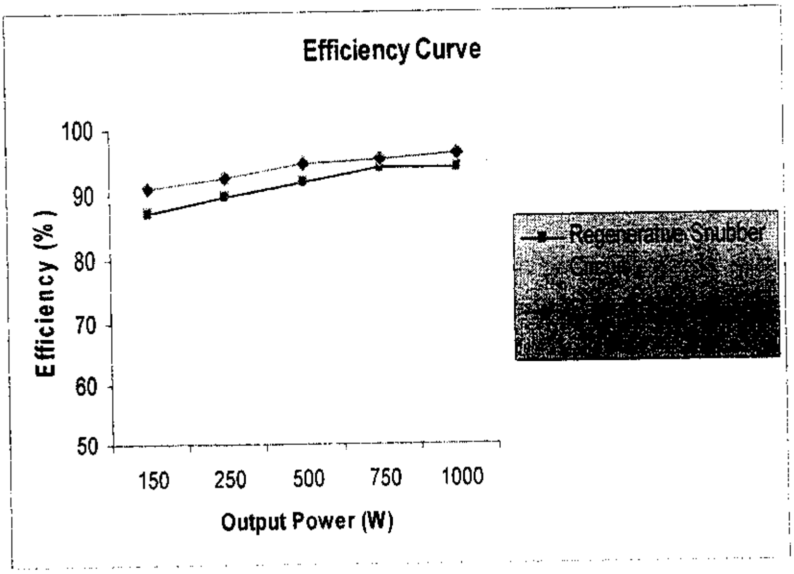


Fig.4.13 Relationship between Efficiency and Output Power

The efficiency is obtained by using the following Equation,

$$Efficiency(\eta) = \frac{P_{out}}{P_{in}}$$

# CHAPTER 5

# CHAPTER 5

# 5. HARDWARE IMPLEMENTATION OF SOFT SWITCHED BUCKBOOST CONVERTER WITH PARTIAL RESONANT CIRCUIT

## 5.1 BLOCK DIAGRAM OF BUCK-BOOST CHOPPER

This chapter explains the block diagram and components used for the hardware prototype of the proposed system. It includes the photographs of the fabricated model and output waveforms. The prototype is done only for Buck-Boost DC/DC converter with partial resonant circuit. The voltage of the system is maintained as a constant value of 12V.

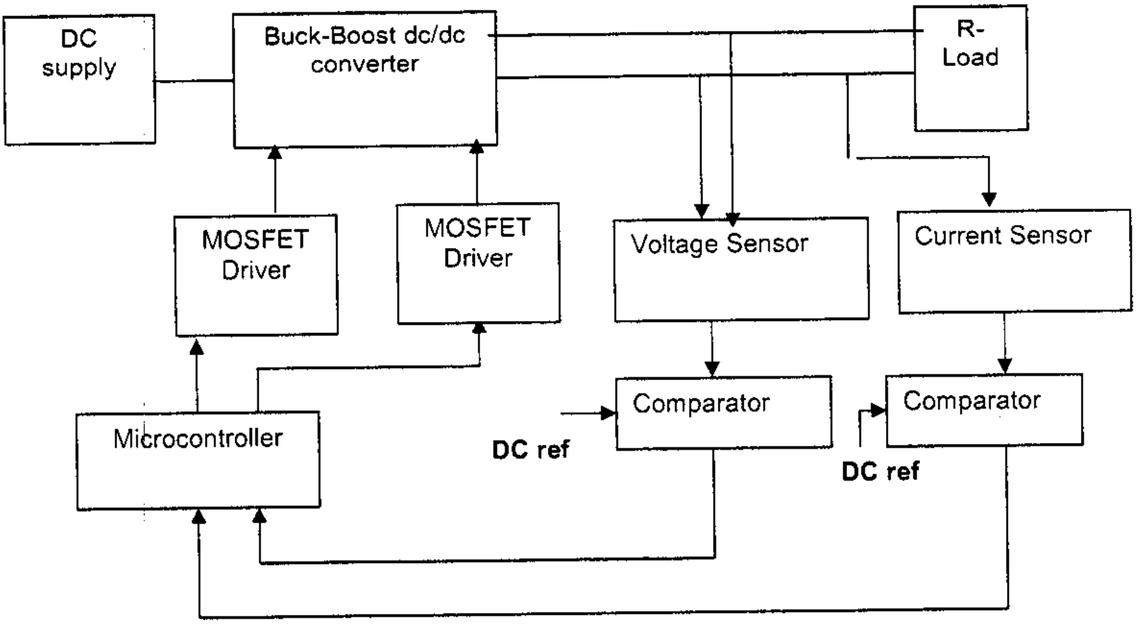


Fig 5.1 Hardware Block diagram

The prototype of the proposed system has Buck-Boost converter, Partial resonant circuit, pulse generation module and micro controller (PIC16F877A) with 5V power supply. These parts are explained with schematic diagram in following sections.

## 5.2 SCHEMATIC DIAGRAM

### 5.2.1. BUCK-BOOST CHOPPER WITH PARTIAL RESONANT CIRCUIT

This circuit consists of active switches S1, S2 and partial resonant circuit which composed of series connected switch diode pair, resonant inductor and capacitor. These power switches are driven by the gate pulse generated by micro controller (PIC16F877A). This circuit bridge is isolated from the gating circuit by the opto-coupler. Then the zener diode is used for protection and R-Load is used.

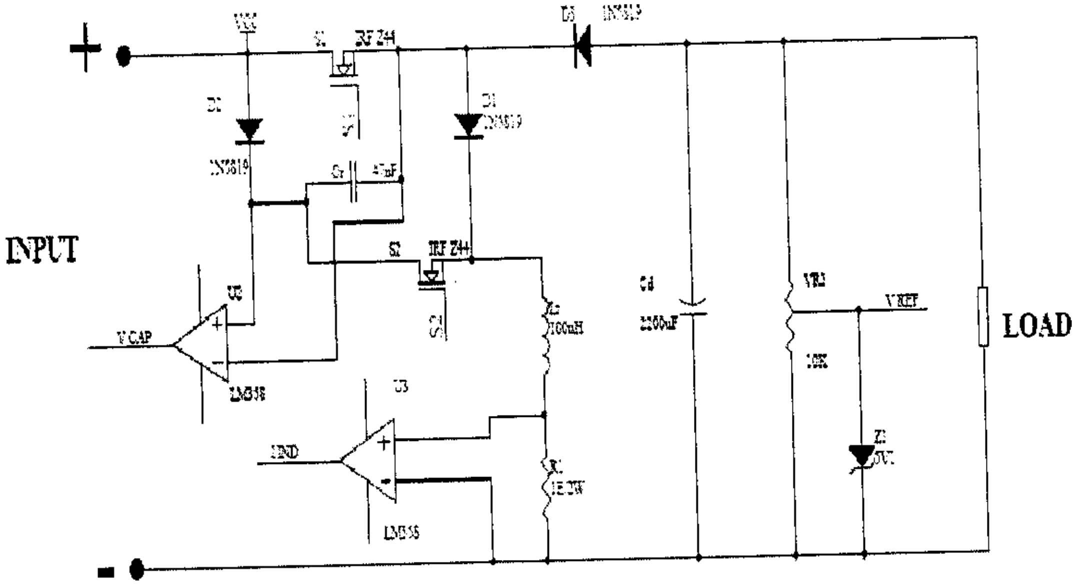


Fig .5.2 Schematic of Buck-Boost Chopper

#### 5.2.1.1 ADVANTAGES OF MOSFET

- MOSFETs provide much better system reliability.
- MOSFET are fast switching devices permit much higher switching frequencies and there by the efficiency is increased.
- MOSFETs have better temperature stability.
- Overload and peak current handling capacity is high.
- MOSFETS have low leakage current.
- MOSFETs are able to operate in hazardous radiation environments.

### 5.2.2 MICROCONTROLLER FOR SOFT SWITCHED BUCK-BOOST CHOPPER

The gate pulse for the inverter switches and the switches in soft-switching module is generated by PIC16F877A controller. This micro controller circuit works in 5V power supply. So separate step down rectifier unit is made for the controller. The details about PIC16F877A are given in APPENDIX II. This controller is isolated from the main circuits by means of opto-coupler. The schematic of micro controller circuit is shown in Fig.5.3.

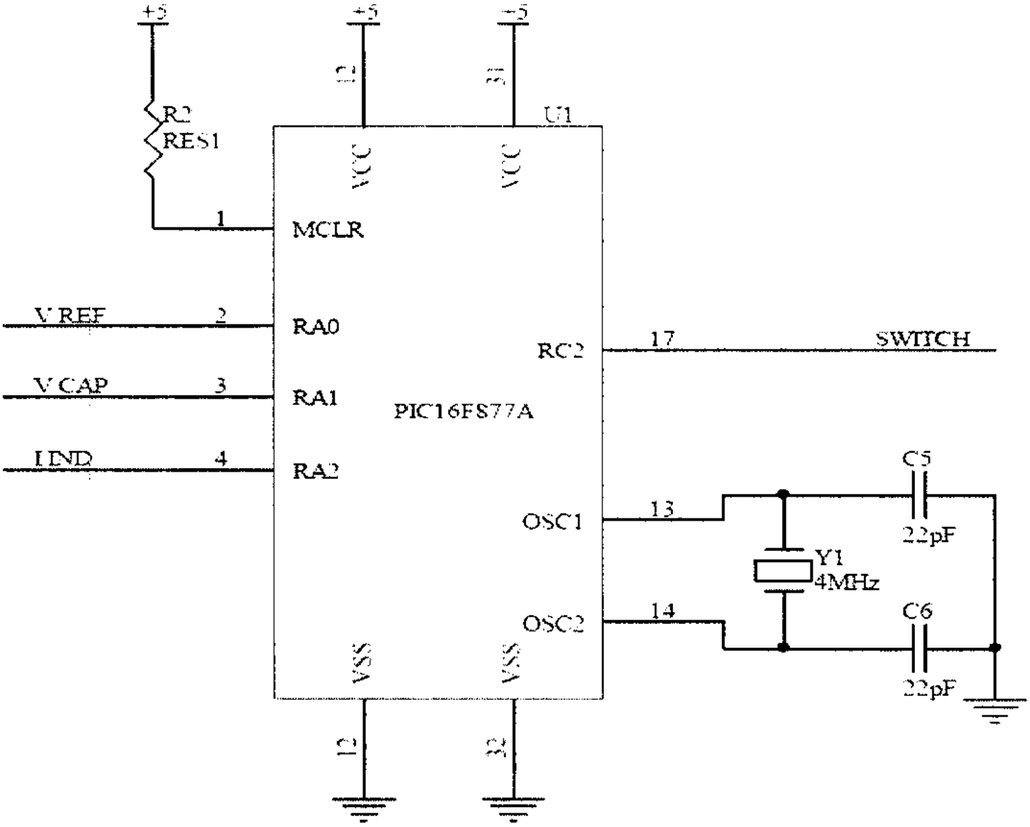


Fig 5.3 Schematic of Microcontroller Circuit

### 5.2.3 RECTIFIER BLOCK

The rectifier block contains a step down transformer, which step downs the input voltage from 220V to 12V. In addition, the step downed voltage is rectified to DC. This is done by uncontrolled single phase diode rectifier. The output of this block is 12V DC. The schematic of rectifier is shown in the Fig.5.4.

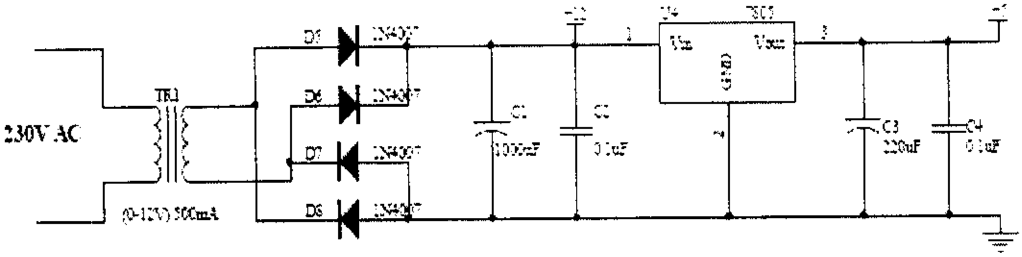


Fig 5.4 Schematic of rectifier

### 5.2.4 MOSFET DRIVER CIRCUIT

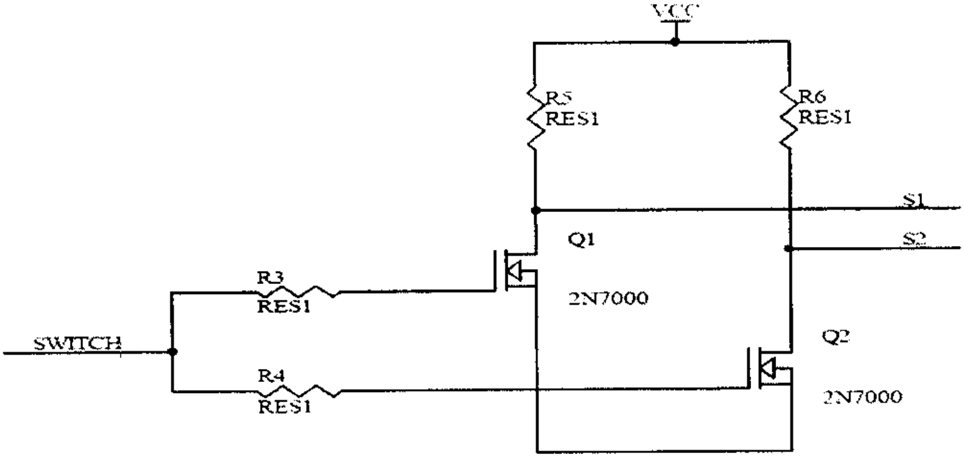


Fig. 5.5 Schematic diagram of MOSFET Driver Circuit

The signal from the controller is not enough to turn ON and OFF the switches in the converter circuit. So, the output signals from the PIC microcontroller is given into the driver circuit. The signal from the driver circuit can be able to witching the devices in the converter circuit. The driver circuit is shown in Fig. 5 5.

### 5.3 HARDWARE PROTOTYPE

The hardware prototype of the Buck-Boost converter with partial resonant circuit is shown in Fig. 5.6. It consists of Buck-Boost converter module, driver circuit fro switching the devices and PIC16F77A microcontroller. The resonant capacitor voltage and inductor current is measured and its converted into digital format by using the ADC in microcontroller. A zener diode is connected parallel to the filter capacitor for protection. The power supply of the controller is drawn from a transformer.

Fig. 5.6 Hardware Photograph

### 5.3.1. HARDWARE RESULTS

The Fig.5.7 shows the input voltage waveform of the proposed Buck-Boost converter with partial resonant circuit. Input is varies from 15V - 26V.

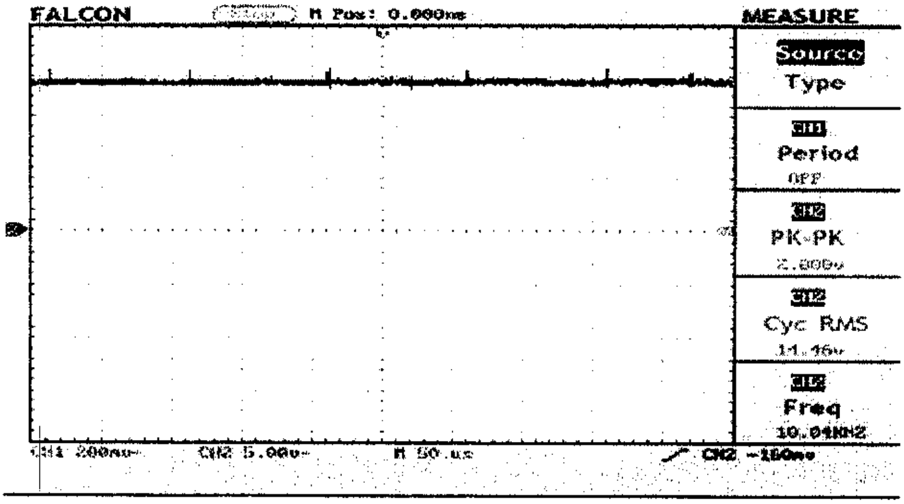


Fig. 5.7 Input Voltage Waveform

Fig. 5.8 refers the output voltage waveform of the converter system. The output voltage is taken across the load.

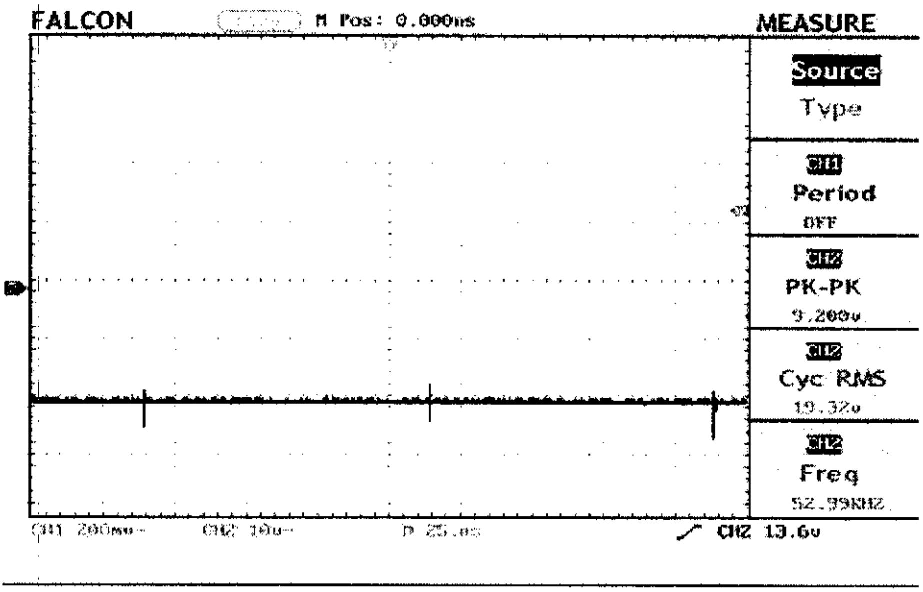


Fig.5.8 Output Voltage Waveform

Fig. 5.9 shows the experimental waveform of Resonant Capacitor Voltage ($V_{cr}$). The Voltage across the resonant capacitor is given into the RB6 pin in PORT B. The resonant capacitor value is 470 nF.

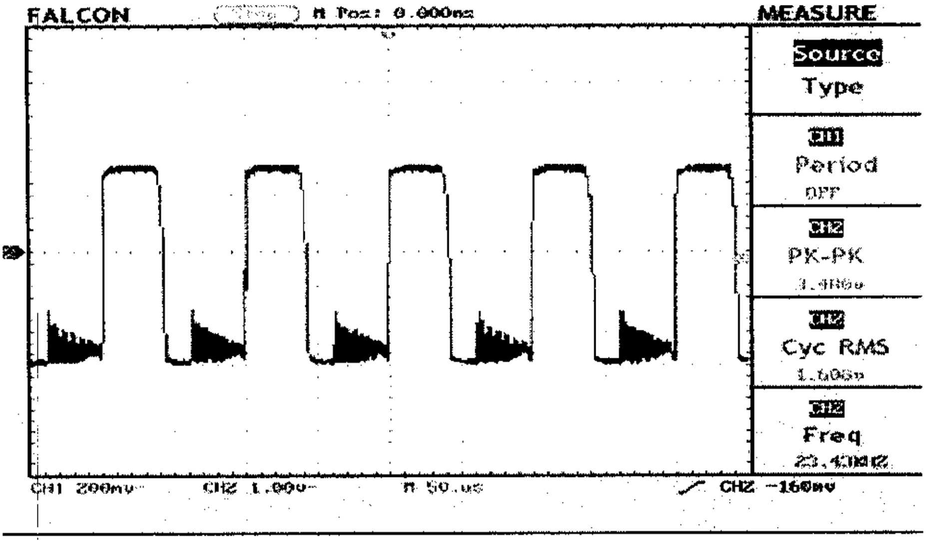


Fig. 5.9 Resonant capacitor voltage Waveform

The current through the resonant inductor ($I_{Lr}$) is shown in Fig. 5.10. This current is given into the RB5 pin PORT B. The resonant inductor is 3mH.

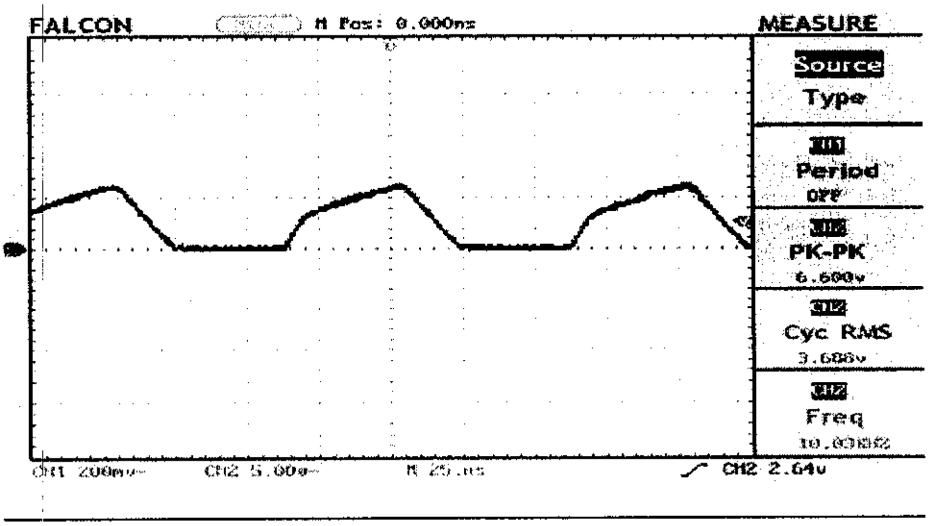


Fig. 5.10 Resonant Inductor Current Waveform

The switching signal was controlled with a programmed PWM data function table and a designed voltage-feedback circuit board through the A/D (analog/digital) converting port of the Microcontroller. The experimental waveforms of switching control signal are taken from the RC3 pin in PORT C of the PIC16F877A microcontroller. The switching pulses of S1 and S2 are shown in Fig. 5.11.

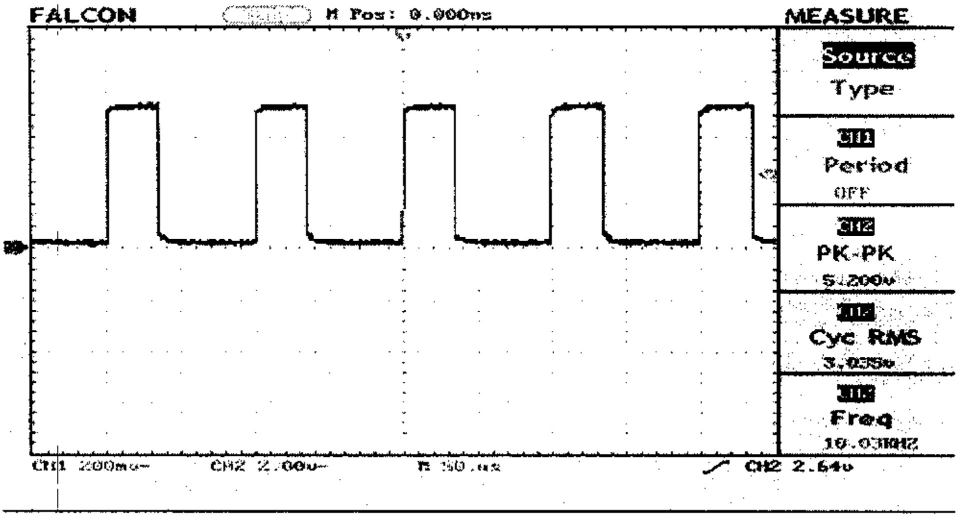


Fig. 5.11 Pulses for S1 and S2

Fig.5.12 shows the feedback voltage waveform. The negative feedback voltage is inverted by using inverting buffer and then its given into the ADC of the microcontroller.

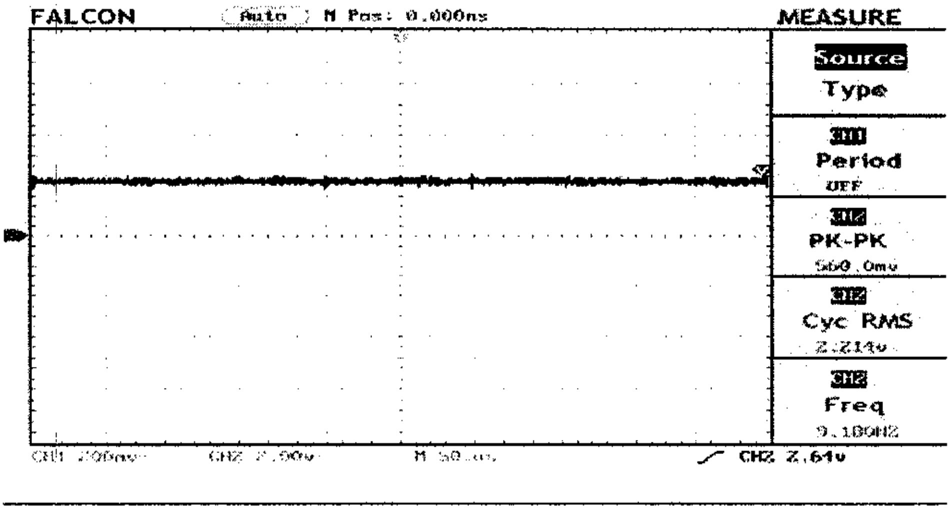


Fig. 5.12 Feedback Voltage Waveform

The voltage across the switches S1 and S2 is shown in Fig. 5.13. In this project the MOSFET IRFZ44 is used as switches.

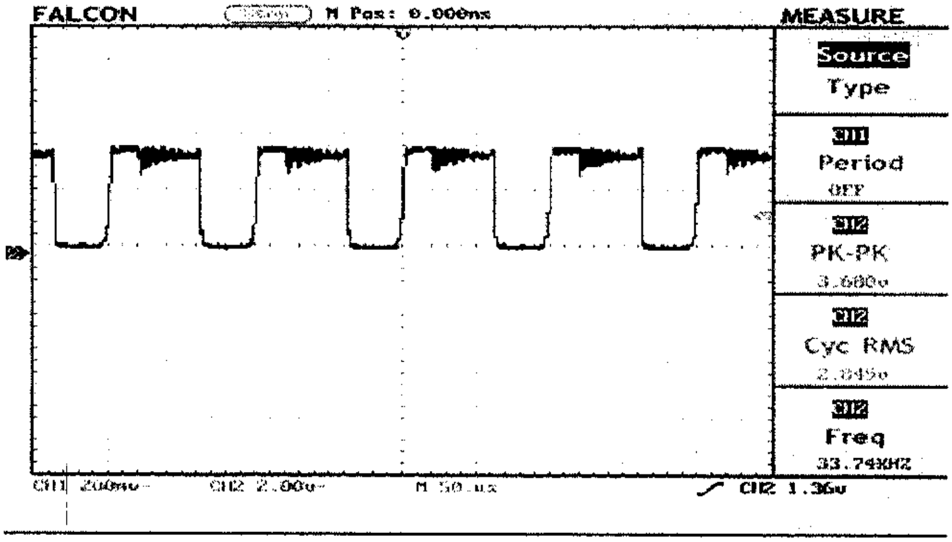


Fig. 5.13 Switch Voltage Waveform

The waveforms of each part in one cycle switching for the proposed converter is shown in Fig. 5.7 to Fig. 5.12, in order to verify the partial resonant and soft switching operation of the control devices. Experimental values are obtained for the case of the load resistor $R_L = 47\Omega$, $L_r = 3mH$ and $C_r = 0.47\ \mu F$. The switches used in the converter were operated with the soft switching, namely turn-on at zero current and turn-off at zero voltage, according to partial resonant operation. Particularly, the resonant operation of the partial resonant circuit was partially enforced at only switching turn-on time and turn-off time. It reduces the losses and stresses of the resonant devices. The above experimental results agree well with theoretical studies and computer simulation results previously stated.

# CHAPTER 6

# CHAPTER 6

# 6. CONCLUSION AND FUTURE SCOPE

## 6.1 CONCLUSION

A zero voltage and zero current switching buck boost converter using partial resonant circuit has been proposed. The advantages of partial resonant circuit are: Implementing the partial resonant circuit, the conventional buck-boost converter able to operate in discontinuous mode of operation, employing only passive components, it has simple circuit configuration. So, it can be able to controlled by simple control scheme ,Low cost and improving the reliability, Losses are less and its improves the efficiency by the effective soft switching operation. The switching devices can turn on and off under zero current and zero voltage condition. Then the operation principle of the proposed circuit, its design consideration is described on the basis of theoretical point of view. The buck boost converter is used to both fixed dc to variable dc and vice versa, it is concluded that the proposed new soft switching converter with partial resonant reduces the switching losses compared to hard switching operation. Its improves the efficiency than the buck boost converter with regenerative snubber circuit.

## 6.2 FUTURE SCOPE

In the future scope of the work, the partial resonant circuit can be implemented for cuk-chopper with soft switching techniques.

# REFERENCES

[1] S. Hishikawa, M. Serguei, M. Nakaoka, I. Hirota, H. Omori, and H. Terai, "New circuit topology of soft switching single-ended high frequency inverter using IGBTs," *IEICE-J Energy Electron. Prof. Meeting*, vol. 100, no. 628, pp. 19–24, Feb. 2000.

[2] S. Inoue and H. Akagi, "A Bidirectional Isolated DC–DC Converter as a Core Circuit of the Next- Generation Medium-Voltage Power Conversion System," *IEEE Transactions on Power Electronics*, vol.22, no.2, pp.535-542, March 2007.

[3] Z. Jiang and R. A. Dougal, "A compact digitally controlled fuel cell/battery hybrid power source," *IEEE Trans. Ind. Electron.*, vol. 53.

[4] X. Xie, J. Zhang, C. Zhao, Z. Zhao, and Z. Qian, "Analysis and optimization of LLC resonant converter with a novel over-current protection circuit," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 435–443, Mar. 2007.

[5] W. McMurray, "Selection of snubbers and clamps to optimize the design of transistor switching converters," in *Con$ Rec. PESC,* 1979, pp. 62-74.

[6] A. Elasser and D.A. Torrey, "Soft switching active snubbers for DC/DC converters," *IEEE Trans. Power Electron.*, vol. 11, No. 5, pp.710-722, Sep. 1996.

[7] W. Abida, D. Sadarnac, and S. D'Almeida, "Comparison between two new soft switching techniques adapted to high frequency converters," in *Proc. Eur. Conf. Power Electron. Applicat.*, 1995, pp. 2807–2812.

[8] K. H. Liu and F. C. Lee, "Zero voltage switching technique in DC/DC converters," *IEEE Trans. Power Electron.*, vol. 5, pp. 293–304, July 1990.

[9] K. M. Smith and K. M. Smedley, "Engineering design of lossless passive soft switching methods for PWM converters – part II. With non-minimum voltage stress circuit cells," *IEEE Trans. Power Electron.*, Vol. 17, No. 6, pp. 864-873, Nov. 2002.

[10] F. C. Lee, "Resonant switches—topologies and characteristics," in *Proc. IEEE Power Electron. Spec. Conf.*, 1985, pp. 106–116.

[11] B. Ivanovic and Z. Stojikovic, "A novel active soft switching snubber designed for boost converter," *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 658–665, May. 2004.

[12] R. J.Wai, L. W. Liu, and R. Y. Duan, "High-efficiency voltage-clamped DC-DC converter with reduced reverse-recovery current and switch voltage stress," *IEEE Trans. Ind. Electron.*, vol. 53, no. 1, pp. 272–280, Feb. 2006.

[13] C.M.C. Duarte and I. Barbi, "An Improved Family of ZVS-PWM Active Clamping DC-DC Converters," IEEE Transactions on Power Electronics, January 2002.

[14] Q. Zhao and F. C. Lee, "High-efficiency, high step-up DC–DC converters," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 65–73, Jan. 2003.

[15] C. J. Tseng and C. L. Chen, "A passive lossless snubber cell for nonisolated PWM DC/DC converters," *IEEE Trans. Ind. Electron.*, vol. 45, no. 4, pp. 593–601, Aug. 1998.

[16] F. H. F. Leung, P. K. S. Tam, and C. K. Li, "An improved LQR-based controller for switching DC–DC converters," *IEEE Trans. Ind. Electron.*, vol. 40, no. 5, pp. 521–28, Oct. 1993.

[17] A. K. S. Bhat and R. Venkatraman, "A soft-switched full-bridge single-stage AC-to-DC converter with low-line-current harmonic distortion," *IEEE Trans*

# APPENDIX I

FAIRCHILD
SEMICONDUCTOR®

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# LM2904,LM358/LM358A,LM258/LM258A

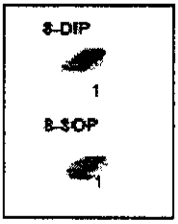
## Dual Operational Amplifier

### Features

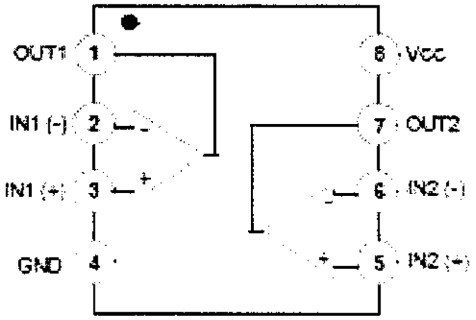
- Internally Frequency Compensated for Unity Gain
- Large DC Voltage Gain: 100dB
- Wide Power Supply Range:
  LM258/LM258A, LM358/LM358A: 3V~32V (or ±1.5V ~ 16V)
  LM2904 : 3V~26V (or ±1.5V ~ 13V)
- Input Common Mode Voltage Range Includes Ground
- Large Output Voltage Swing: 0V DC to Vcc -1.5V DC
- Power Drain Suitable for Battery Operation.

### Description

The LM2904,LM358/LM358A, LM258/LM258A consist of two independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltage. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage. Application areas include transducer amplifier, DC gain blocks and all the conventional OP-AMP circuits which now can be easily implemented in single power supply systems.

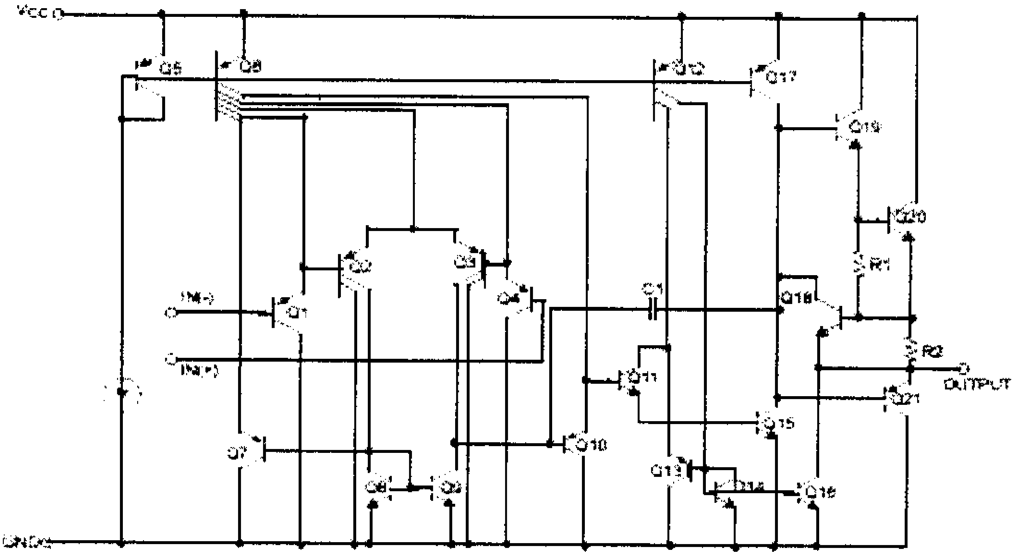


### Internal Block Diagram



## Schematic Diagram

(One section only)



## Absolute Maximum Ratings

| Parameter | Symbol | LM258/LM258A | LM358/LM358A | LM2904 | Unit |
|---|---|---|---|---|---|
| Supply Voltage | $V_{CC}$ | ±16 or 32 | ±16 or 32 | ±13 or 26 | V |
| Differential Input Voltage | $V_{I(DIFF)}$ | 32 | 32 | 26 | V |
| Input Voltage | $V_I$ | -0.3 to +32 | -0.3 to +32 | -0.3 to +26 | V |
| Output Short Circuit to GND<br>$V_{CC} \le 15V$, $T_A$ = 25°C(One Amp) | - | Continuous | Continuous | Continuous | - |
| Operating Temperature Range | $T_{OPR}$ | -25 ~ +85 | 0 ~ +70 | -40 ~ +85 | °C |
| Storage Temperature Range | $T_{STG}$ | -65 ~ +150 | -65 ~ +150 | -65 ~ +150 | °C |

## Electrical Characteristics

($V_{CC}$ = 5.0V, $V_{EE}$ = GND, $T_A$ = 25°C, unless otherwise specified)

| Parameter | Symbol | Conditions | | LM258 | | | LM358 | | | LM2904 | | | Unit |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min. | Typ. | Max. | Min. | Typ. | Max. | Min. | Typ. | Max. | |
| Input Offset Voltage | $V_{IO}$ | $V_{CM}$ = 0V to $V_{CC}$ -1.5V<br>$V_{O(P)}$ = 1.4V, $R_S$ = 0Ω | | - | 2.9 | 5.0 | - | 2.9 | 7.0 | - | 2.9 | 7.0 | mV |
| Input Offset Current | $I_{IO}$ | - | | - | 3 | 30 | - | 5 | 50 | - | 5 | 50 | nA |
| Input Bias Current | $I_{BIAS}$ | - | | - | 45 | 150 | - | 45 | 250 | - | 45 | 250 | nA |
| Input Voltage Range | $V_{I(R)}$ | $V_{CC}$ = 30V<br>(LM2904, $V_{CC}$=26V) | | 0 | - | $V_{CC}$ -1.5 | 0 | - | $V_{CC}$ -1.5 | 0 | - | $V_{CC}$ -1.5 | V |
| Supply Current | $I_{CC}$ | $R_L$ = ∞, $V_{CC}$ = 30V<br>(LM2904, $V_{CC}$=26V) | | - | 0.8 | 2.0 | - | 0.8 | 2.0 | - | 0.8 | 2.0 | mA |
| | | $R_L$ = ∞, $V_{CC}$ = 5V | | - | 0.5 | 1.2 | - | 0.5 | 1.2 | - | 0.5 | 1.2 | mA |
| Large Signal Voltage Gain | $G_V$ | $V_{CC}$ = 15V,<br>$R_L$= 2kΩ<br>$V_{O(P)}$ = 1V to 11V | | 50 | 100 | - | 25 | 100 | - | 25 | 100 | - | V/mV |
| Output Voltage Swing | $V_{O(H)}$ | $V_{CC}$=30V ($V_{CC}$ =26V for LM2904) | $R_L$ = 2kΩ | 26 | - | - | 26 | - | - | 22 | - | - | V |
| | | | $R_L$= 10kΩ | 27 | 28 | - | 27 | 28 | - | 23 | 24 | - | V |
| | $V_{O(L)}$ | $V_{CC}$ = 5V, $R_L$= 10kΩ | | - | 5 | 20 | - | 5 | 20 | - | 5 | 20 | mV |
| Common-Mode Rejection Ratio | CMRR | - | | 70 | 85 | - | 65 | 80 | - | 50 | 80 | - | dB |
| Power Supply Rejection Ratio | PSRR | - | | 65 | 100 | - | 65 | 100 | - | 50 | 100 | - | dB |
| Channel Separation | CS | f = 1kHz to 20kHz (Note1) | | - | 120 | - | - | 120 | - | - | 120 | - | dB |
| Short Circuit to GND | $I_{SC}$ | - | | - | 40 | 60 | - | 40 | 60 | - | 40 | 60 | mA |
| Output Current | $I_{SOURCE}$ | $V_{I(+)}$ = 1V, $V_{I(-)}$ = 0V<br>$V_{CC}$ = 15V,<br>$V_{O(P)}$ = 2V | | 20 | 30 | - | 20 | 30 | - | 20 | 30 | - | mA |
| | $I_{SINK}$ | $V_{I(+)}$ = 0V, $V_{I(-)}$ = 1V,<br>$V_{CC}$ = 15V,<br>$V_{O(P)}$ = 2V | | 10 | 15 | - | 10 | 15 | - | 10 | 15 | - | mA |
| | | $V_{I(+)}$ = 0V, $V_{I(-)}$ =1V ,<br>$V_{CC}$ = 15V,<br>$V_{O(P)}$ = 200mV | | 12 | 100 | - | 12 | 100 | - | - | - | - | µA |
| Differential Input Voltage | $V_{I(DIFF)}$ | - | | - | - | $V_{CC}$ | - | - | $V_{CC}$ | - | - | $V_{CC}$ | V |

**Note:**

1. This parameter, although guaranteed, is not 100% tested in production.

# MC78XX/LM78XX/MC78XXA

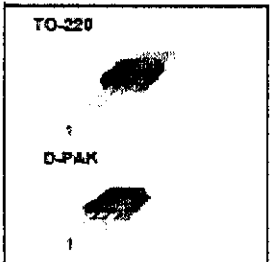
## 3-Terminal 1A Positive Voltage Regulator

### Features

- Output Current up to 1A
- Output Voltages of 5, 6, 8, 9, 10, 12, 15, 18, 24V
- Thermal Overload Protection
- Short Circuit Protection
- Output Transistor Safe Operating Area Protection

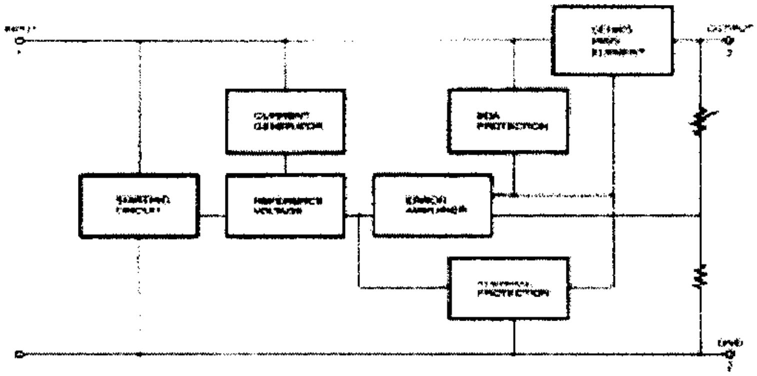
### Description

The MC78XX/LM78XX/MC78XXA series of three terminal positive regulators are available in the TO-220/D-PAK package and with several fixed output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut down and safe operating area protection, making it essentially indestructible. If adequate heat sinking is provided, they can deliver over 1A output current. Although designed primarily as fixed voltage regulators, these devices can be used with external components to obtain adjustable voltages and currents.



1. Input 2. GND 3. Output

### Internal Block Digram



## Absolute Maximum Ratings

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Input Voltage (for $V_O$ = 5V to 18V)<br>(for $V_O$ = 24V) | $V_I$<br>$V_I$ | 35<br>40 | V<br>V |
| Thermal Resistance Junction-Cases (TO-220) | $R_{\theta JC}$ | 5 | °C/W |
| Thermal Resistance Junction-Air (TO-220) | $R_{\theta JA}$ | 65 | °C/W |
| Operating Temperature Range | $T_{OPR}$ | 0 ~ +125 | °C |
| Storage Temperature Range | $T_{STG}$ | -65 ~ +150 | °C |

## Electrical Characteristics (MC7805/LM7805)

(Refer to test circuit ,0°C < $T_J$ < 125°C, $I_O$ = 500mA, $V_I$ = 10V, $C_I$= 0.33µF, $C_O$= 0.1µF, unless otherwise specified)

| Parameter | Symbol | Conditions | | MC7805/LM7805 | | | Unit |
|---|---|---|---|---|---|---|---|
| | | | | Min. | Typ. | Max. | |
| Output Voltage | $V_O$ | $T_J$ =+25 °C | | 4.8 | 5.0 | 5.2 | V |
| | | 5.0mA ≤ $I_O$ ≤ 1.0A, $P_O$ ≤ 15W<br>$V_I$ = 7V to 20V | | 4.75 | 5.0 | 5.25 | |
| Line Regulation (Note1) | Regline | $T_J$=+25 °C | $V_O$ = 7V to 25V | - | 4.0 | 100 | mV |
| | | | $V_I$ = 8V to 12V | - | 1.6 | 50 | |
| Load Regulation (Note1) | Regload | $T_J$=+25 °C | $I_O$ = 5.0mA to1.5A | - | 9 | 100 | mV |
| | | | $I_O$ =250mA to 750mA | - | 4 | 50 | |
| Quiescent Current | $I_Q$ | $T_J$ =+25 °C | | - | 5.0 | 8.0 | mA |
| Quiescent Current Change | $\Delta I_Q$ | $I_O$ = 5mA to 1.0A | | - | 0.03 | 0.5 | mA |
| | | $V_I$= 7V to 25V | | - | 0.3 | 1.3 | |
| Output Voltage Drift | $\Delta V_O/\Delta T$ | $I_O$= 5mA | | - | -0.8 | - | mV/ °C |
| Output Noise Voltage | $V_N$ | f = 10Hz to 100KHz, $T_A$=+25 °C | | - | 42 | - | µV/Vo |
| Ripple Rejection | RR | f = 120Hz<br>$V_O$ = 8V to 18V | | 62 | 73 | - | dB |
| Dropout Voltage | $V_{Drop}$ | $I_O$ = 1A, $T_J$ =+25 °C | | - | 2 | - | V |
| Output Resistance | $r_O$ | f = 1KHz | | - | 15 | - | mΩ |
| Short Circuit Current | $I_{SC}$ | $V_I$ = 35V, $T_A$ =+25 °C | | - | 230 | - | mA |
| Peak Current | $I_{PK}$ | $T_J$ =+25 °C | | - | 2.2 | - | A |

**Note:**

1. Load and line regulation are specified at constant junction temperature. Changes in $V_O$ due to heating effects must be taken into account separately. Pulse testing with low duty is used.

# 1N4001 - 1N4007

**Features**

- Low forward voltage drop.
- High surge current capability.

**DO-41**

COLOR BAND DENOTES CATHODE

## General Purpose Rectifiers (Glass Passivated)

### Absolute Maximum Ratings*

$T_A$ = 25°C unless otherwise noted

| Symbol | Parameter | Value | | | | | | | Units |
|---|---|---|---|---|---|---|---|---|---|
| | | 4001 | 4002 | 4003 | 4004 | 4005 | 4006 | 4007 | |
| $V_{RRM}$ | Peak Repetitive Reverse Voltage | 50 | 100 | 200 | 400 | 600 | 800 | 1000 | V |
| $I_{F(AV)}$ | Average Rectified Forward Current, .375 " lead length @ $T_A$ = 75°C | 1.0 | | | | | | | A |
| $I_{FSM}$ | Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave | 30 | | | | | | | A |
| $T_{stg}$ | Storage Temperature Range | -55 to +175 | | | | | | | °C |
| $T_J$ | Operating Junction Temperature | -55 to +175 | | | | | | | °C |

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

### Thermal Characteristics

| Symbol | Parameter | Value | Units |
|---|---|---|---|
| $P_D$ | Power Dissipation | 3.0 | W |
| $R_{\theta JA}$ | Thermal Resistance, Junction to Ambient | 50 | °C/W |

### Electrical Characteristics

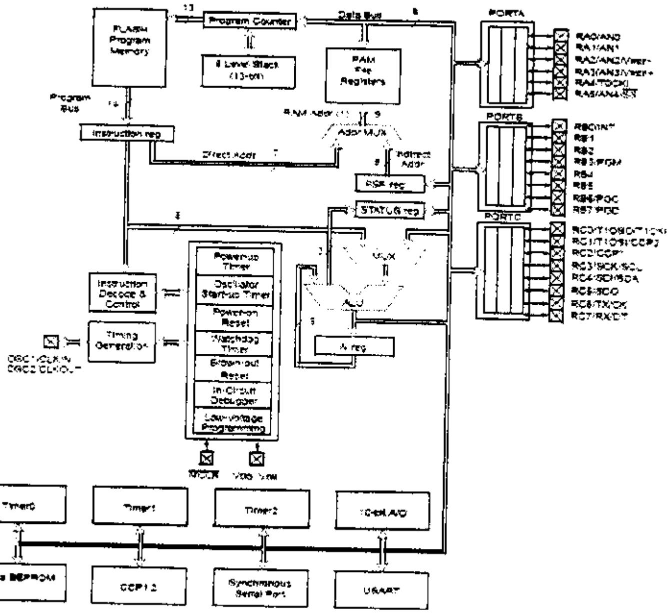
$T_A$ = 25°C unless otherwise noted

| Symbol | Parameter | Device | | | | | | | Units |
|---|---|---|---|---|---|---|---|---|---|
| | | 4001 | 4002 | 4003 | 4004 | 4005 | 4006 | 4007 | |
| $V_F$ | Forward Voltage @ 1.0 A | 1.1 | | | | | | | V |
| $I_{rr}$ | Maximum Full Load Reverse Current, Full Cycle $T_A$ = 75°C | 30 | | | | | | | µA |
| $I_R$ | Reverse Current @ rated $V_R$ $T_A$ = 25°C<br>$T_A$ = 100°C | 5.0<br>500 | | | | | | | µA<br>µA |
| $C_T$ | Total Capacitance $V_R$ = 4.0 V, f = 1.0 MHz | 15 | | | | | | | pF |

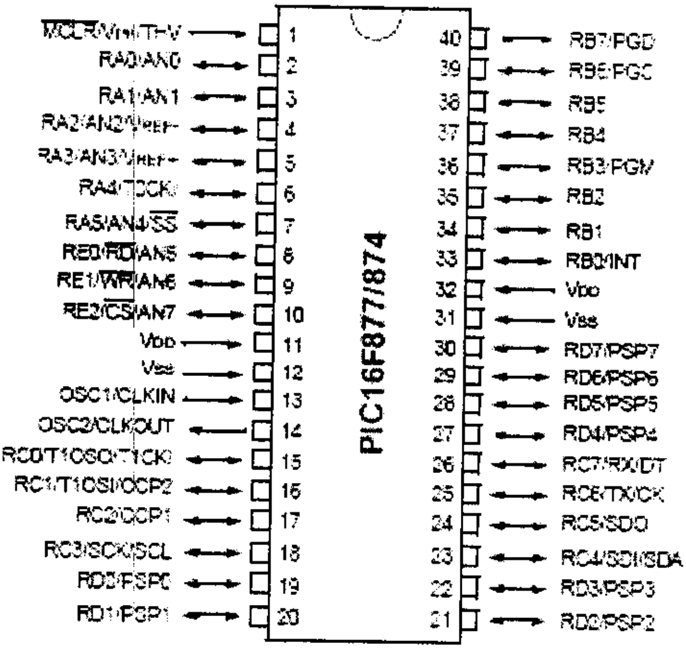
# APPENDIX II

## ARCHITECTURE OF PIC 16F877A

| Device | Program FLASH | Data Memory | Data EEPROM |
|---|---|---|---|
| PIC16F873 | 4K | 192 Bytes | 128 Bytes |
| PIC16F876 | 8K | 368 Bytes | 256 Bytes |



## PIN CINFIGURATION OF PIC16F877A

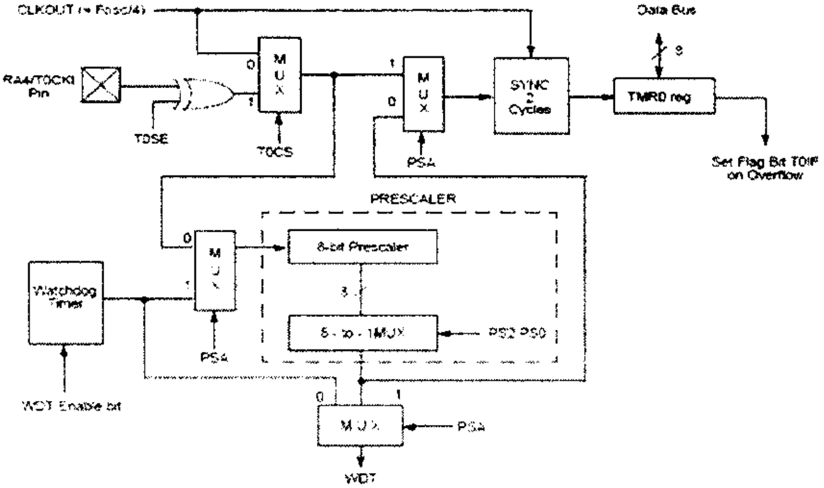


## TIMER 0 CONTROL REGISTER:

| R/W-1 | R/W-1 | R/W-1 | R/W-1 | R/W-1 | R/W-1 | R/W-1 | R/W-1 |
|---|---|---|---|---|---|---|---|
| $\overline{\text{RBPU}}$ | INTEDG | T0CS | T0SE | PSA | PS2 | PS1 | PS0 |
| bit 7 | | | | | | | bit 0 |

bit 7: **RBPU**
bit 6: **INTEDG**
bit 5: **T0CS**: TMR0 Clock Source Select bit
1 = Transition on T0CKI pin
0 = Internal instruction cycle clock (CLKOUT)
bit 4: **T0SE**: TMR0 Source Edge Select bit
1 = Increment on high-to-low transition on T0CKI pin
0 = Increment on low-to-high transition on T0CKI pin
bit 3: **PSA**: Prescaler Assignment bit
1 = Prescaler is assigned to the WDT
0 = Prescaler is assigned to the Timer0 module
bit 2-0: **PS2 PS1 PS0**: Prescaler Rate Select bits

## TIMER 0 BLOCK DIAGRAM:



## TIMER 1 CONTROL REGISTER:

| U-0 | U-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 |
|---|---|---|---|---|---|---|---|
| — | — | T1CKPS1 | T1CKPS0 | T1OSCEN | $\overline{\text{T1SYNC}}$ | TMR1CS | TMR1ON |
| bit7 | | | | | | | bit0 |

bit 7-6: **Unimplemented:** Read as '0'

bit 5-4: **T1CKPS1:T1CKPS0**: Timer1 Input Clock Prescale Select bits

11 = 1:8 Prescale value

10 = 1:4 Prescale value

01 = 1:2 Prescale value

00 = 1:1 Prescale value

bit 3: **T1OSCEN**: Timer1 Oscillator Enable Control bit

1 = Oscillator is enabled

0 = Oscillator is shut off (The oscillator inverter is turned off to eliminate power drain)

bit 2: **T1SYNC**: Timer1 External Clock Input Synchronization Control bit

TMR1CS = 1

1 = Do not synchronize external clock input

0 = Synchronize external clock input

TMR1CS = 0

This bit is ignored. Timer1 uses the internal clock when TMR1CS = 0.

bit 1: **TMR1CS**: Timer1 Clock Source Select bit

1 = External clock from pin RC0/T1OSO/T1CKI (on the rising edge)

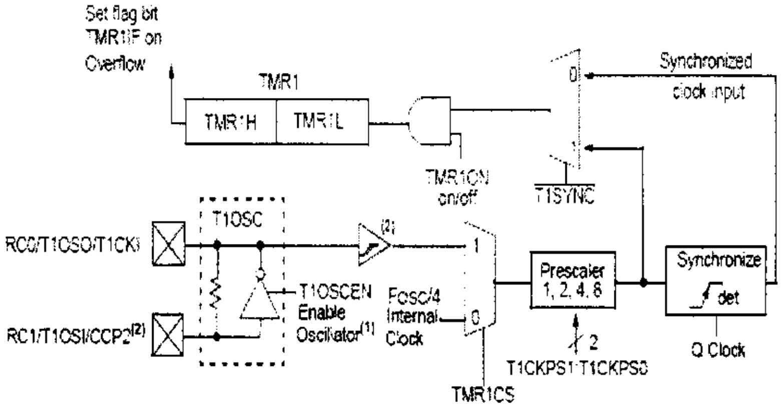
0 = Internal clock (FOSC/4)

bit 0: **TMR1ON**: Timer1 On bit

1 = Enables Timer1

0 = Stops Timer1

## TIMER 1 BLOCK DIAGRAM:



## TIMER 2 CONTROL REGISTER:

| U-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 |
|---|---|---|---|---|---|---|---|
| — | TOUTPS3 | TOUTPS2 | TOUTPS1 | TOUTPS0 | TMR2ON | T2CKPS1 | T2CKPS0 |
| bit7 |  |  |  |  |  |  | bit0 |

bit 7: **Unimplemented:** Read as '0'

bit 6-3: **TOUTPS3:TOUTPS0**: Timer2 Output Postscale Select bits

0000 = 1:1 Postscale
0001 = 1:2 Postscale
0010 = 1:3 Postscale
1111 = 1:16 Postscale

bit 2: **TMR2ON**: Timer2 On bit

1 = Timer2 is on
0 = Timer2 is off

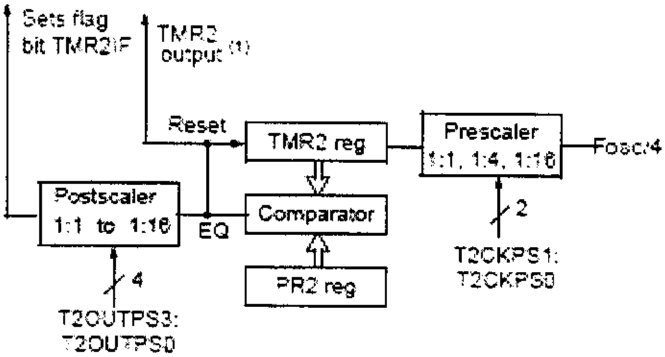
bit 1-0: **T2CKPS1:T2CKPS0**: Timer2 Clock Prescale Select bits

00 = Prescaler is 1

01 = Prescaler is 4

1x = Prescaler is 16

## TIMER2 BLOCK DIAGRAM:



## CCP1CON REGISTER/CCP2CON REGISTER:

| U-0 | U-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 | R/W-0 |
|---|---|---|---|---|---|---|---|
| — | — | CCPxX | CCPxY | CCPxM3 | CCPxM2 | CCPxM1 | CCPxM0 |
| bit7 | | | | | | | bit0 |

bit 7-6: **Unimplemented:** Read as '0'

bit 5-4: **CCPxX :CCPxY**: PWM Least Significant bits

Capture Mode: Unused

Compare Mode: Unused

PWM Mode: These bits are the two LSB s of the PWM duty cycle. The eight MSB s are found in CCPRxL.

bit 3-0: **CCPxM3:CCPxM0**: CCPx Mode Select bits

0000 = Capture/Compare/PWM off (resets CCPx module)

0100 = Capture mode, every falling edge

0101 = Capture mode, every rising edge

0110 = Capture mode, every 4th rising edge

0111 = Capture mode, every 16th rising edge

1000 = Compare mode, set output on match (CCPxIF bit is set)

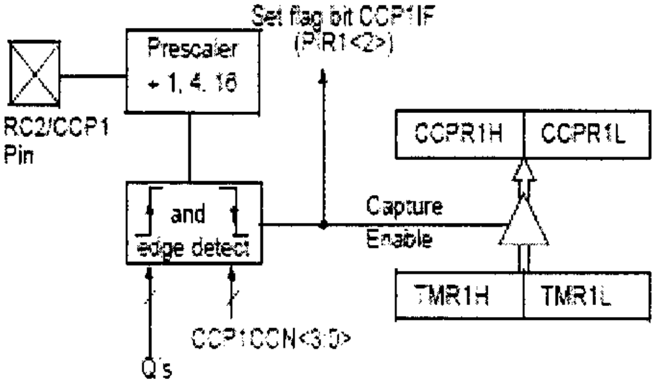
1001 = Compare mode, clear output on match (CCPxIF bit is set)

1010 = Compare mode, generate software interrupt on match (CCPxIF bit is set, CCPx pin is unaffected)

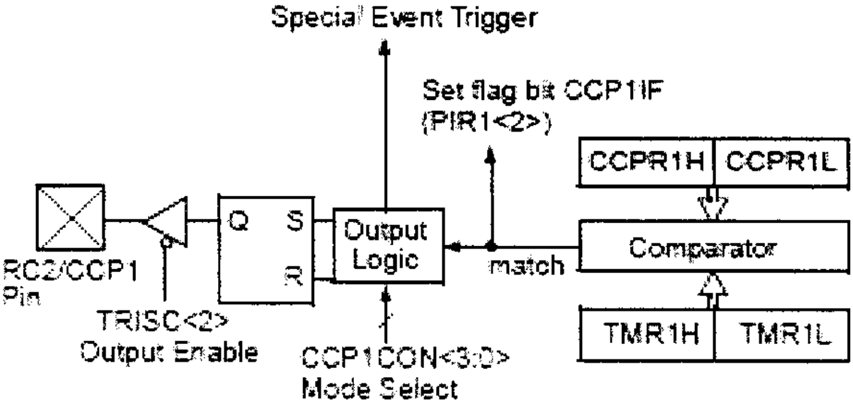
1011 = Compare mode, trigger special event (CCPxIF bit is set, CCPx pin is unaffected); CCP1 resets TMR1; CCP2 resets TMR1 and starts an A/D conversion (if A/D module is enabled)

11xx = PWM mode

## CAPTURE MODE OPERATION BLOCK DIAGRAM:



## COMPARE MODE OPERATION BLOCK DIAGRAM:



# N-channel enhancement mode TrenchMOS™ transistor

**IRFZ44N**

## GENERAL DESCRIPTION

N-channel enhancement mode standard level field-effect power transistor in a plastic envelope using 'trench' technology. The device features very low on-state resistance and has integral zener diodes giving ESD protection up to 2kV. It is intended for use in switched mode power supplies and general purpose switching applications.

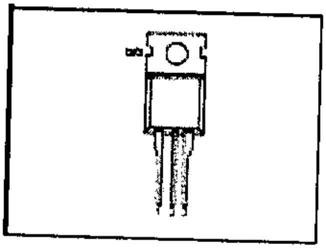
## QUICK REFERENCE DATA

| SYMBOL | PARAMETER | MAX. | UNIT |
|---|---|---|---|
| $V_{DS}$ | Drain-source voltage | 55 | V |
| $I_D$ | Drain current (DC) | 49 | A |
| $P_{tot}$ | Total power dissipation | 110 | W |
| $T_j$ | Junction temperature | 175 | °C |
| $R_{DS(ON)}$ | Drain-source on-state resistance $V_{GS}$ = 10 V | 22 | mΩ |

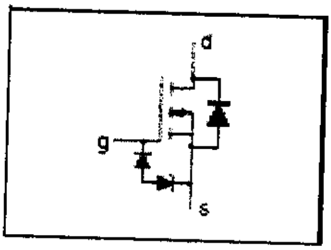
## PINNING - TO220AB

| PIN | DESCRIPTION |
|---|---|
| 1 | gate |
| 2 | drain |
| 3 | source |
| tab | drain |

## PIN CONFIGURATION



## SYMBOL



## LIMITING VALUES

Limiting values in accordance with the Absolute Maximum System (IEC 134)

| SYMBOL | PARAMETER | CONDITIONS | MIN. | MAX. | UNIT |
|---|---|---|---|---|---|
| $V_{DS}$ | Drain-source voltage | - | - | 55 | V |
| $V_{DGR}$ | Drain-gate voltage | $R_{GS}$ = 20 kΩ | - | 55 | V |
| $\pm V_{GS}$ | Gate-source voltage | - | - | 20 | V |
| $I_D$ | Drain current (DC) | $T_{mb}$ = 25 °C | - | 49 | A |
| $I_D$ | Drain current (DC) | $T_{mb}$ = 100 °C | - | 35 | A |
| $I_{DM}$ | Drain current (pulse peak value) | $T_{mb}$ = 25 °C | - | 160 | A |
| $P_{tot}$ | Total power dissipation | $T_{mb}$ = 25 °C | - | 110 | W |
| $T_{stg}$, $T_j$ | Storage & operating temperature | - | - 55 | 175 | °C |

## ESD LIMITING VALUE

| SYMBOL | PARAMETER | CONDITIONS | MIN. | MAX. | UNIT |
|---|---|---|---|---|---|
| $V_C$ | Electrostatic discharge capacitor voltage, all pins | Human body model (100 pF, 1.5 kΩ) | - | 2 | kV |

## THERMAL RESISTANCES

| SYMBOL | PARAMETER | CONDITIONS | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|
| $R_{th\ j-mb}$ | Thermal resistance junction to mounting base | - | - | 1.4 | K/W |
| $R_{th\ j-a}$ | Thermal resistance junction to ambient | in free air | 60 | - | K/W |

## STATIC CHARACTERISTICS

$T_j$ = 25°C unless otherwise specified

| SYMBOL | PARAMETER | CONDITIONS | MIN. | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|
| $V_{(BR)DSS}$ | Drain-source breakdown voltage | $V_{GS}$ = 0 V; $I_D$ = 0.25 mA; | 55 | - | - | V |
| | | $T_j$ = -55°C | 50 | - | - | V |
| $V_{GS(TO)}$ | Gate threshold voltage | $V_{DS}$ = $V_{GS}$; $I_D$ = 1 mA | 2.0 | 3.0 | 4.0 | V |
| | | $T_j$ = 175°C | 1.0 | - | - | V |
| | | $T_j$ = -55°C | - | - | 4.4 | |
| $I_{DSS}$ | Zero gate voltage drain current | $V_{DS}$ = 55 V; $V_{GS}$ = 0 V; | - | 0.05 | 10 | µA |
| | | $T_j$ = 175°C | - | - | 500 | µA |
| $I_{GSS}$ | Gate source leakage current | $V_{GS}$ = ±10 V; $V_{DS}$ = 0 V | - | 0.04 | 1 | µA |
| | | $T_j$ = 175°C | - | - | 20 | µA |
| $\pm V_{(BR)GSS}$ | Gate source breakdown voltage | $I_G$ = ±1 mA; | 16 | - | - | V |
| $R_{DS(ON)}$ | Drain-source on-state resistance | $V_{GS}$ = 10 V; $I_D$ = 25 A | - | 15 | 22 | mΩ |
| | | $T_j$ = 175°C | - | - | 42 | mΩ |

## DYNAMIC CHARACTERISTICS

$T_{mb}$ = 25°C unless otherwise specified

| SYMBOL | PARAMETER | CONDITIONS | MIN. | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|
| $g_{fs}$ | Forward transconductance | $V_{DS}$ = 25 V; $I_D$ = 25 A | 6 | - | - | S |
| $C_{iss}$ | Input capacitance | $V_{GS}$ = 0 V; $V_{DS}$ = 25 V; f = 1 MHz | - | 1350 | 1800 | pF |
| $C_{oss}$ | Output capacitance | | - | 330 | 400 | pF |
| $C_{rss}$ | Feedback capacitance | | - | 155 | 215 | pF |
| $Q_{g(tot)}$ | Total gate charge | $V_{DD}$ = 44 V; $I_D$ = 50 A; $V_{GS}$ = 10 V | - | - | 62 | nC |
| $Q_{gs}$ | Gate-source charge | | - | - | 15 | nC |
| $Q_{gd}$ | Gate-drain (miller) charge | | - | - | 26 | nC |
| $t_{d\,on}$ | Turn-on delay time | $V_{DD}$ = 30 V; $I_D$ = 25 A;<br>$V_{GS}$ = 10 V; $R_G$ = 10 Ω<br>Resistive load | - | 18 | 26 | ns |
| $t_r$ | Turn-on rise time | | - | 50 | 75 | ns |
| $t_{d\,off}$ | Turn-off delay time | | - | 40 | 50 | ns |
| $t_f$ | Turn-off fall time | | - | 30 | 40 | ns |
| $L_d$ | Internal drain inductance | Measured from contact screw on tab to centre of die | - | 3.5 | - | nH |
| $L_d$ | Internal drain inductance | Measured from drain lead 6 mm from package to centre of die | - | 4.5 | - | nH |
| $L_s$ | Internal source inductance | Measured from source lead 6 mm from package to source bond pad | - | 7.5 | - | nH |

## REVERSE DIODE LIMITING VALUES AND CHARACTERISTICS

$T_j$ = 25°C unless otherwise specified

| SYMBOL | PARAMETER | CONDITIONS | MIN. | TYP. | MAX. | UNIT |
|---|---|---|---|---|---|---|
| $I_{DR}$ | Continuous reverse drain current | | - | - | 49 | A |
| $I_{DRM}$ | Pulsed reverse drain current | | - | - | 160 | A |
| $V_{SD}$ | Diode forward voltage | $I_F$ = 25 A; $V_{GS}$ = 0 V | - | 0.95 | 1.2 | V |
| | | $I_F$ = 40 A; $V_{GS}$ = 0 V | - | 1.0 | - | |
| $t_{rr}$ | Reverse recovery time | $I_F$ = 40 A; $-dI_F/dt$ = 100 A/µs;<br>$V_{GS}$ = -10 V; $V_R$ = 30 V | - | 47 | - | ns |
| $Q_{rr}$ | Reverse recovery charge | | - | 0.15 | - | µC |

## APPENDIX III

### PROGRAM for PIC MICROCONTROLLER

```
#include<pic.h>
__CONFIG(0X20A4);
__CONFIG(0X3FFF);
unsigned int REFF1;
void main()
{
        TRISC=0;                //      PORTC AS OUTPUT
        PORTC=0;
        TRISA=0XFF;             //      PORTA [ADC] INPUT
        ANSEL=0X0F;                     //      ADC CHANNEL SELECTION
        ANSELH=0;
        ADCON1=0X80;
        PR2=99;                         //      PWM FREQUENCY SELECTION
        CCP1CON=0X0C;
        T2CON=0X04;
        CCPR1L=35;
        while(1)
        {
                ADCON0=0X81;    //      ADC CHANNEL [AN0]
                delay();
                GODONE=1;
                while(GODONE);
                REFF1=(ADRESH*256)+ADRESL;
                if(CCPR1L<15)                   //      DUTY CYCLE LOWER
LIMIT
                        CCPR1L=15;
                if(CCPR1L>75)                   //      DUTY CYCLE UPPER
LIMIT
                        CCPR1L=75;
```

```
/**************************** OUTPUT REGULATION
***********************/
        delay1();
        if(REFF1>400)
            CCPR1L--;
        delay();
        if(REFF1<405)
            CCPR1L++;
        delay1();
    }
    if(RB6==0)
        CCPR1L=0;
    else if(RB5==1)
        CCP1CON=0X0C;
}
delay()
{
    unsigned int i;
    for(i=0;i<100;i++);
}
delay1()
{
    unsigned int j;
    for(j=0;j<10000;j++);
}
```