Chapter 1. Introduction

1.1 Research Background

Pulse width modulated (PWM) inverters are widely used in uninterruptible power supplies (UPSs), motor drives and utility interfaces. The main advantages of these modern power inverters, such as high efficiency, low weight, small dimensions, fast operation, and high power densities are being achieved through the use of switch mode operation, in which power semiconductor devices are controlled in ON/OFF fashion. The switch mode operation is implemented by different types of PWM schemes, which is a basic energy processing technique applied in power converter systems. In modern converters, PWM is high speed process ranging from a few kilohertz (motor control) upto several megahertz (resonant converters for power supply). The best known triangular carrier based (CB) sinusoidal PWM was proposed by Schonung and Stemmler in 1964. With high speed processor developments, the space vector modulation (SVM) proposed by Pfaff Weschta, and Wick in 1982 and further developed by van der Broeck, Skudenly, and Stanke become the basic processing techniques in these converters [Marian 2002]. Random PWM is suggested by Trzynadlowski, Kirlin, and Legowski [Trzynad 1994]. Random PWM can affect acoustic and electromagnetic noise due to redistribution of spectral power over a wide frequency range. In sinusoidal PWM (SPWM), carrier is a triangular signal. By comparison of carrier signal with reference sinusoidal signal, switching instants of power transistors are generated. Operation with constant carrier signal concentrates voltage harmonics around the switching frequency and multiples of switching frequency. The narrow range of linearity is a limitation for CB-SPWM because the modulation index reaches a maximum value of 1, i.e. the amplitude of reference signal and carrier signal are equal. The over modulation region occurs for modulation index higher than 1, and a PWM converter operates in non-linear region. The space vector modulation strategy is based on space vector representation of the converter ac side voltage. PWM techniques generate a time-periodic switching function, which maps into the frequency domain as a spectrum consisting of discrete frequency components. Apart from the frequency components coming from the reference signal, all other components (harmonics) are generally unwanted as they may cause current and voltage distortion, extra power losses and thermal stress, electromagnetic interference (EMI), torque ripple in rotating machines, mechanical vibrations, and radiation of acoustic noise [Kerkman 1996]. Random PWM technique has been suggested as an alternative to deterministic PWM to reduce the impact of harmonics in systems based on pulse width modulated hard-switched converters. This technique reduces the subjective noise emitted from whistling magnetics in the audible frequency range as investigated in [Habetler 1989]. Compliance with standards defining limits for emission of conducted and radiated EMI may be obtained by less filtering and shielding efforts, if deterministic PWM is replaced by random PWM. In PWM techniques, to achieve high power density and performance, higher switching frequency capability for power devices is desired. It affects the control bandwidth; system ripples, and determines the size of the passive components. MOSFET (metal oxide semiconductor field effect transistor) and IGBT (insulated gate bipolar transistor) are commonly used power devices due to fast switching speed and high voltage ratings. The power MOSFET device was introduced in early 1970s [Baliga 1994] with starting parameters of 3-5 amperes for drain current, up to

400 volts breakdown voltage, and turn off time in the range of 1.2msec. Technology development allowed improvement of the ratings with 9A/600V or 100A/50V and decrease of the turn off time to 600nsec. The most recent technology advancement includes the CoolMOS devices which are able to switch 20A/600V with a turn off time of around 100nsec [Neacsu 2006]. IGBT devices combine the advantages of bipolar and MOSFET transistors and operate under high voltage and high current. The IGBT was introduced in early 1980s with starting parameters 50A/600V and now it has reached up to 1200A/6kV. During the last 20 years the technological advancement has improved the current and voltage handling capacity of these devices four times, turn off time has dropped twenty times and switching frequency has reached up to few MHz. Power MOSFETs exhibit very high switching speed up to few MHz [Rashid 2001]. However, as the voltage rating is increased above 200V, on state resistance increases causing more conduction loss and also the inherent body diode shows inferior reverse recovery characteristics, which leads to higher switching losses. Improved on-state performance at higher ratings is achieved with IGBTs which combines the low turn on resistance property of BJT (bipolar junction transistor) and fast switching speed of MOSFET. As a result, IGBTs have become a popular choice for higher rating applications such as industrial drive applications and UPS systems. The conventional PWM inverters operate in hard-switching mode in which power devices have to cut off the load current within the turn-on and turn-off times under the hard switching condition. The turn-on and turn-off transitions of semiconductor devices require times of tens of nanoseconds to microseconds. During these transitions, very large instantaneous power loss can occur in

the semiconductor devices. Even though the semiconductor switching times are short, the resulting average power loss can be significant. Hard switching refers to the stressful switching behavior of power electronic devices. The device has to withstand high voltage and current simultaneously during turn-on and turn-off process, which leads to high switching loss and stress. Hard switching also gives rise to high electromagnetic interference (EMI) noise level. The high EMI noise level is directly related to high di/dt and dv/dt rates in hard-switching operation, which can be more than 1,000A/µS and 1,000V/µS respectively. High switching frequency PWM inverters are desirable for UPS application in order to achieve fast dynamic response and small filtering components. Consequently, the relatively high switching losses and high EMI noise are major concern in designing hard switched PWM inverters [Mohan 2003].

Soft-switching involves mitigation of switching loss mechanism in a PWM converter. The energy that would otherwise be lost is recovered, and is transferred to the converter source or load. The operation of a semiconductor device, during a given turn-on or turn-off switching transition, can be classified as hard-switched, zero-current, or zero-voltage switched. It is preferable to operate diodes with zero-voltage switching at their turn-off transitions, and to operate MOSFET with zero-voltage switching during their turn-on transitions. However, zero-voltage switching comes at the expense of increased conduction loss.

Resonant switch converters are a broad class of converters in which the PWM switch network is replaced with switch cell containing resonant elements. These resonant elements are positioned such that the semiconductor devices operate with zero-current or zero-voltage switching, and switching loss mechanism is reduced or eliminated. Obtaining zero-voltage or zero-current switching requires that the resonant elements have large ripple and often, these elements are operated in a manner similar to the discontinuous conduction modes of the series or parallel resonant converters. Many resonant switch networks are proposed in literature [Liu 1985, Maksimovic 1993]. In the zero-current-switching quasi-resonant switch, the main devices operate with zero-current switching and in the zero-voltage-switching multi resonant switches, all semiconductor devices operate with zero-voltage switching leading to very low switching loss. In the zero-voltage transition approach, as well as in active clamp snubber approach, transistors are switched under zero-voltage condition and diodes are switched under zero-current condition. These approaches have been successful in substantially improving the efficiencies of transformer-isolated converters. The auxiliary resonant commutated pole induces zero-voltage switching in bridge circuit such as voltage source inverter [Erickson 2001]. The additional advantage of zero-voltage switching is the reduction of EMI associated with device capacitances. In conventional PWM converters and also, to some extent, in zero- current switching converters, significant high frequency ringing and current spikes are generated by the rapid charging and discharging of the semiconductor device capacitances during the turn-on and/or turn-off transitions. Ringing is absent from the waveforms of the converters in which all semiconductor devices switch at zero voltage hence, these converters inherently do not generate this type of EMI.

To overcome the drawback of hard switching inverters, various soft switching techniques have been proposed in the literature

1.2 Soft Switching Inverter Topologies

Based upon the placement of resonant network (load, inverter bridge and dc bus), characteristics of switching waveforms (ZVS or ZCS), and the type of resonance (series or parallel), the classification is shown in Fig.1.1 [Bellar 1998].

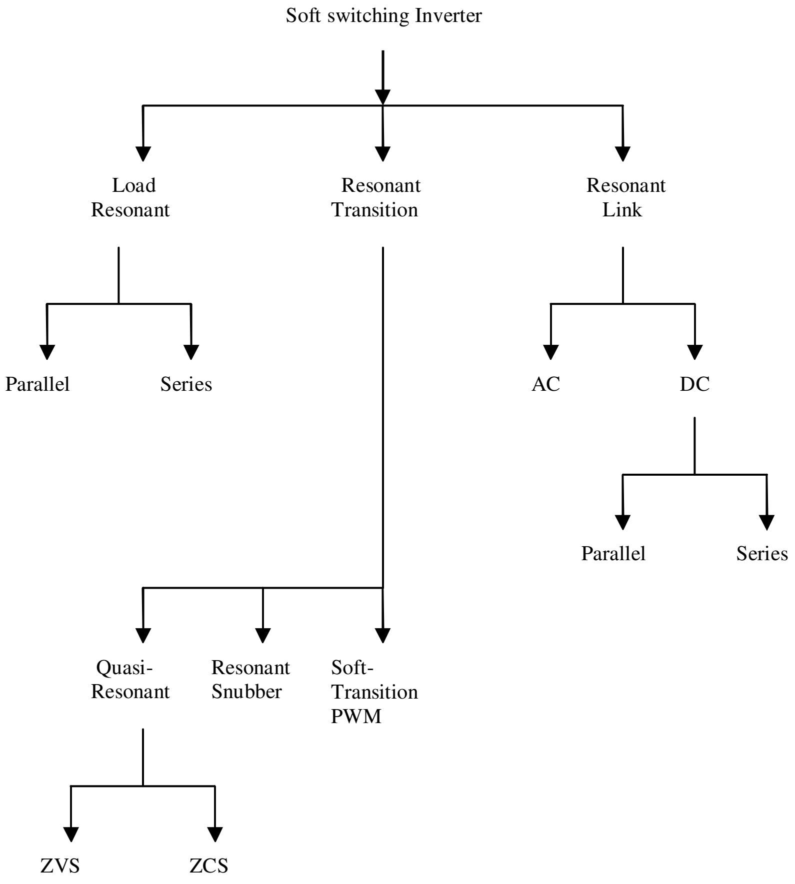

Fig.1.1. Soft Switching Inverter Topologies

1.2.1 Load Resonant Inverters

In these converters an LC resonant link circuit is connected to load. LC resonance causing oscillating voltage and current creates zero voltage and/or zero current instants for converter switches. Power flow in these converters are controlled by switching frequency f_s and resonant frequency f_o of the tank. These converters are sub classified as series loaded resonant converters, parallel load resonant converters, hybrid resonant converters and current source parallel resonant converter [Mohan 2003].

Characteristic impedance and resonant frequency of series resonant circuits decide zero voltage or zero current conditions for switches. The current leads at the switching frequencies below the resonant frequency when the capacitive impedance dominates and zero current condition is met for the switches. At frequencies above resonance zero voltage switching condition can be achieved where the inductive impedance dominates and the current lags the voltage. In parallel resonant circuits, voltage leads the current at frequencies below resonant frequency due to lower inductor impedance and dominating inductor current. At frequencies above resonant frequency voltage lags the current.

Two load resonant inverters, series resonant parallel load inverter (SRPLI) and parallel resonant series load inverter (PRSLC) are shown in Fig1.2 and Fig1.3 respectively [Bellar 1998]. In Fig.1.2 a half bridge SRPLC and its corresponding waveforms for zero current condition for switches is shown. It is achieved when $f_{s<} f_o$ and the output impedance becomes capacitive. The turn-on time of the active switches is decided by the control signal, and their turn-off time is dependent only on the power circuit behavior. The SRPLC can also operate with ZVS during turn-on and turn-off if $f_{s}> f_{o}$. In this case, a capacitor should be connected in parallel with each switch in order to avoid turn-off losses, as a dual of connecting series inductances in the ZCS case.

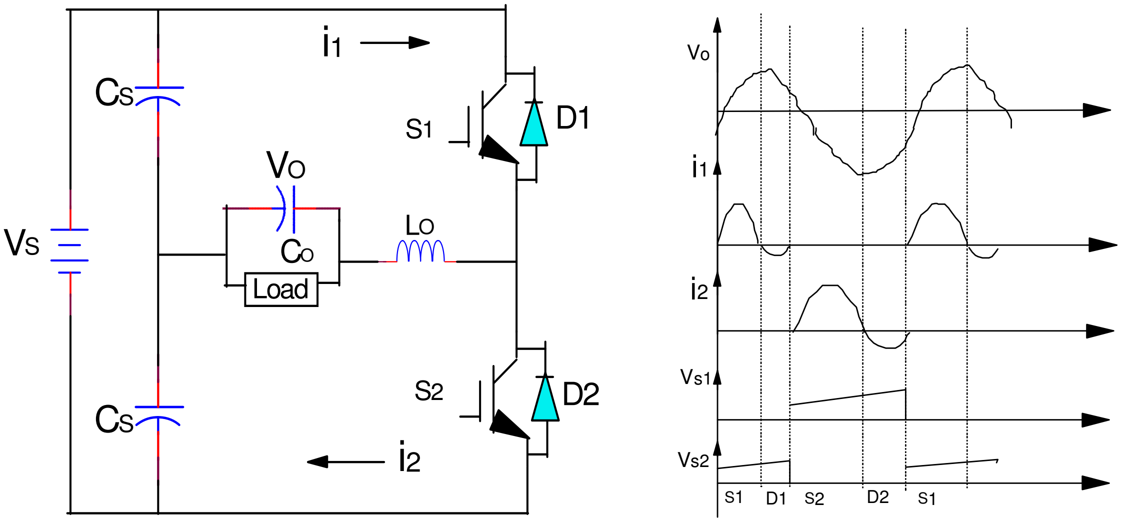

Fig.1.2. Series resonant parallel load inverter and its waveforms

Fig. 1.3 shows PRSLC, where switches are turned on and turned off at zero voltage condition when $f_{s}< f_{o}$. This condition makes impedance inductive and the circuit behavior determines the turn-on time of the switches, and the control signal determines their turn-off time.

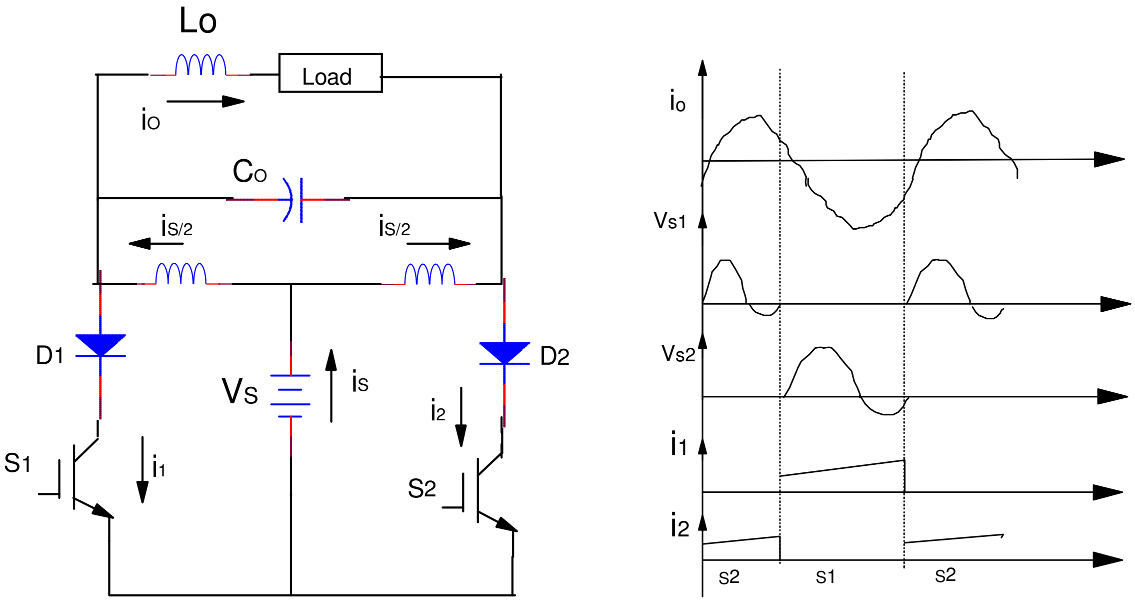

Fig.1.3. Parallel resonant series load inverter and its waveforms

A partial series resonant converter proposed by [Theron 1995] is based on zero voltage switching series resonant converter. Addition of clamping diodes across resonant capacitors reduces voltage stresses on these capacitors. Zero voltage switching is achieved below resonant frequency, reducing the size of all reactive components. Also, higher efficiency is achieved under full load and low load conditions and dynamic output voltage range is two times larger than the conventional series resonant converter. A current source parallel resonant inverter utilizing the magnetizing inductance of the transformer as the inductive part of the resonant circuit is proposed by [Kazimierczuk 1996]. This topology has advantage over voltage source inverter in terms of harmonics injection to the line and absence of isolation transformer or optocoupler needed to drive the switches.

Near resonant frequency inverter does not draw high current but above resonance turn-off and turn-on switching losses increase due to high di/dt across series diodes and non-zero voltage turn-on of transistors.

[Farhangi 1996] proposes a multi resonant series-parallel converter which allows zero current switching suitable for bipolar devices. A closed form solution based on state space analysis using energy concept is derived which gives better physical insight of system variables. A hybrid parallel-series resonant converter is proposed by [Bhat 1997]. Fixed frequency and variable frequency operation of hybrid parallel series converter in continuous conduction mode is discussed. In variable frequency operations, switches operate in zero voltage switching modes for entire range and in fixed frequency operation zero current switching modes is achieved at half load and reduced pulse width.

Low distortion sinusoidal output waveforms and good efficiency, have made the series resonant inverters, either parallel loaded or series loaded, a good choice for high power application (20 kHz/10kVA), such as in induction heating and in space power conversion applications. These inverters are also suitable for high-frequency power supply and utility line applications. Parallel resonant inverters can be used for industrial applications for induction heating and metal melting up to levels of 10 kHz/1000kW [Bellar 1998] .

1.2.2 Resonant Transition Inverters

In these inverters soft-switching condition is implemented by shaping the switch voltage and current with LC resonant circuit. The diode needed for the resonant switch operation is same as the conventional hard switched topology.

Parasitic such as transformer leakage inductance and output capacitance of the semiconductor switch can be utilized as a part of resonant circuit. These converters are further classified as zero current switching (ZCS), zero voltage switching (ZVS) and zero voltage switching clamped voltage (ZVS-CV) topologies. In ZCS topology switches turn-on and turn-off at zero current. The peak resonant current flows through the switch but the switch voltage remain the same as in hard switch converter. Switches turn-on and turn-off at zero voltage and peak resonant voltage appears across the switch but the peak current remains the same as in the hard switch condition for ZVS topology. In ZVS-CV switch turn-on and off at zero voltage but the peak switch voltage remains the same as in the hard switch converter.

A resonant pole inverter for zero voltage switching is shown in Fig.1.4 [Bellar 1998]. The resonant elements C_o can be the output capacitance of active switches or the external capacitor connected in parallel to the power devices. The resonant inductor L_o is at the load side to provide both output filtering and wave-shaping operations. The pole voltage V_P is PWM. The voltage rating on the active switch is V_S, which is the same as that of a conventional PWM converter. The resonant inductor is charged and discharged by this pole voltage and provides alternating current to the load.

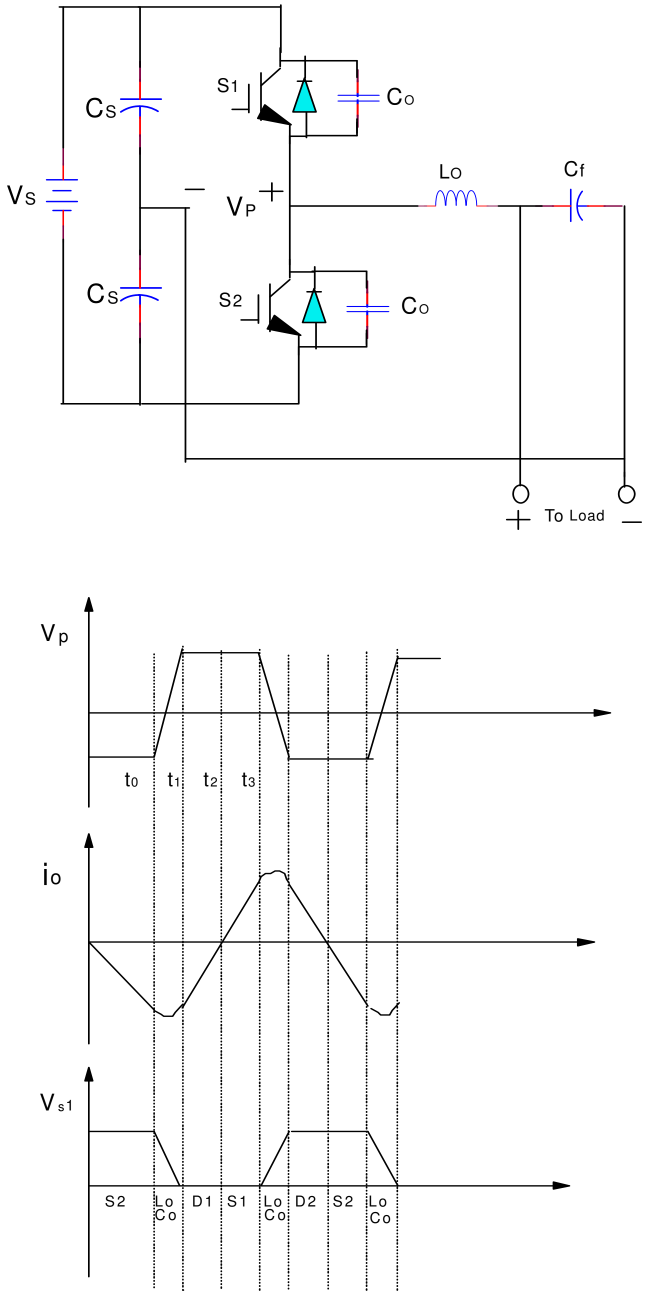

Fig.1.4. Resonant pole inverter or quasi-resonant ZVS inverter and its waveforms

A voltage source inverter with a resonant circuit with auxiliary switches and a nonlinear commutated resonant pole inverter described by [Bellar 1998] are presented in Fig.1.5 and Fig.1.6 respectively.

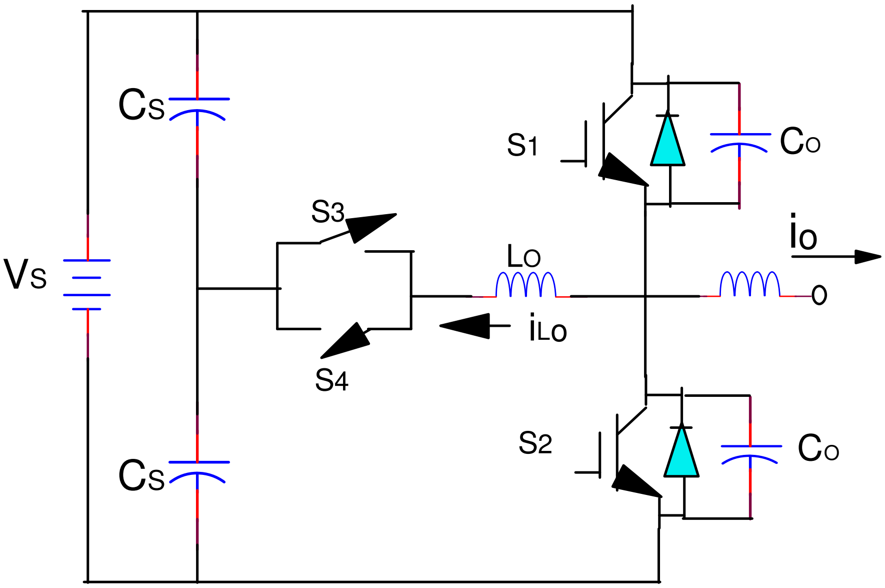

Fig.1.5. The auxiliary resonant commutated pole inverter

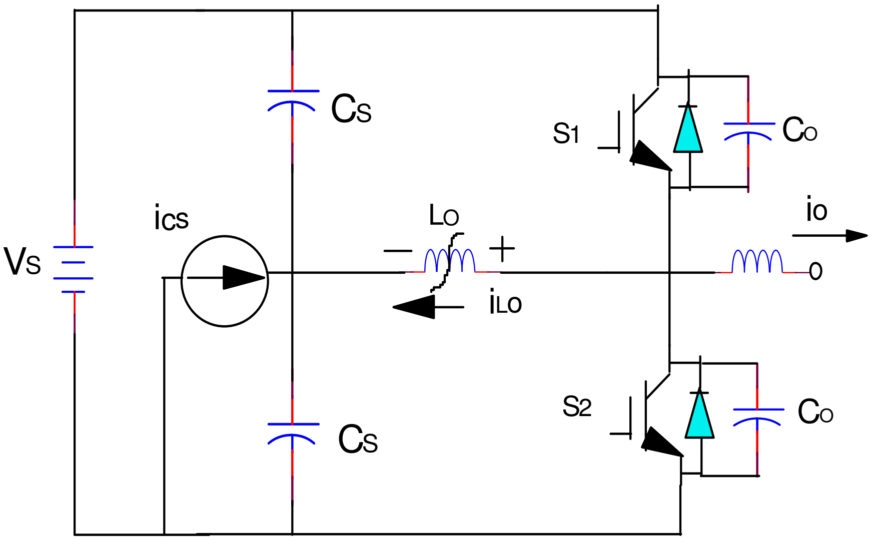

Fig.1.6 Nonlinear commutated resonant pole inverter

The main and auxiliary switches are operating under zero voltage switching and zero current switching respectively. The resonant inductor in series with the auxiliary switch provides the resonant path. Energy is transferred from the resonant inductor to the snubber capacitors during the on time of the auxiliary switches providing the zero voltage condition for the main switches. Power rating of the auxiliary devices is very small since they operate for a very small duration.

In nonlinear commutated resonant pole inverter (NLRPI) the auxiliary commutated circuit is replaced by a saturable inductor which is having the smaller power rating on the resonant inductor and lesser conduction time with the main switches. A controlled current source can be injected into the centre tapped source capacitor to compensate for the residual energy of saturable inductor. This topology is highly efficient and is a good choice for motor drives.

A quasi-resonant zero current switching (QR-ZCS) inverter is shown in Fig.1.7 [Bellar 1998]. Output capacitor C_o is charged by the source inductors L_s in the opposite direction, which is in continuous conduction mode. Capacitive energy of output capacitance is circulated by resonant inductors L_o creating zero current turn-on condition for the main switches S_1 and S_2. The resonant capacitor of the converter provides an alternating voltage waveform to inductive load, making the inverter a good choice for motion control and induction heating applications.

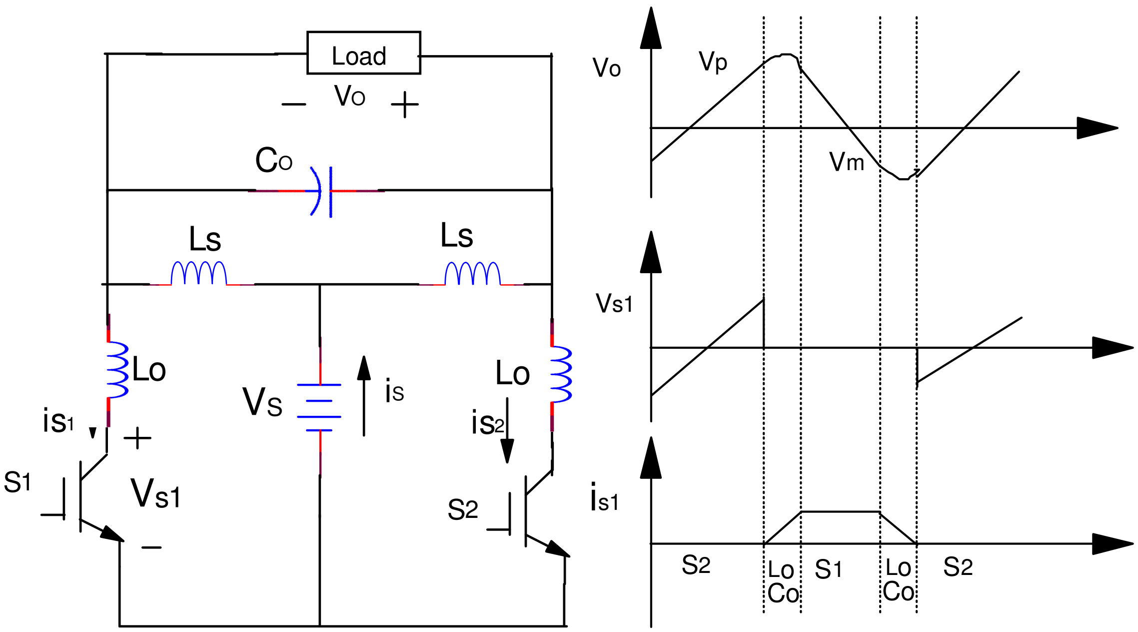

Fig.1.7. Quasi-resonant ZCS inverter and its waveforms

A transfer assisted pulse width modulated zero voltage switching pole inverter is proposed by [Yuan 2000]. This comes under the category of auxiliary resonant commutated pole inverter (ARCPI) which is suitable for high power inverter due to its small rating auxiliary circuit and full pulse width modulation operation capability.

Zero voltage switching of the main switch and zero current switching of the auxiliary switch is achieved without any extra measuring or control. Auxiliary devices are protected against over voltage without extra circuitry since they are tightly clamped to the dc link voltage. It also overcomes the possible potential variation of the dc link capacitor due to heavy low frequency load.

Reduction in additional sensors to achieve soft-switching operation in an auxiliary commutated pole inverter is proposed by [Pickert 1998]. Optimum switching instants for both auxiliary and main devices are determined by a digital signal processor and field programmable gate array based controller. It requires only the load current and dc supply voltage as inputs. A quasi-resonant circuit for soft-switching inverter proposed by [Hui 1996], achieves zero voltage switching without snubber for inverter switches. The major advantage of this topology is that it can create zero voltage switching instants under both loaded and no-load conditions. Any PWM scheme can be used which is the other advantage of this topology.

ZVS PWM full bridge topology is reported by [Ruan2004] which eliminates the voltage oscillation resulted by the reverse recovery of the rectifier diodes. [Ma 2004] proposes a new family of ZVS-PWM converter suitable for low power application. The auxiliary circuit only activated during main switch turn-on. This topology can be used for battery powered system requiring high power density such as low power avionics.

[Stein 2000] describes a zero current and zero voltage transition commutation cell for PWM converter. Zero current switching and zero voltage switching is achieved simultaneously at both turn-off and turn-on of the main switches. Placement of commutation cell outside power path eliminated voltage stresses on the power switches. A novel technique using frequency modulation to improve the efficiency of an inductor commutated soft-switched PWM inverter is proposed by [Nagao 1998]. Frequency modulation based technique suppresses the circulating current without sensing any current or voltage in the inverter, hence improving the efficiency of the system. A zero voltage transition soft-switching inverter for an induction motor drive is proposed by [Chao 2001]. The switches in each leg can be independently controlled by making the

PWM switching control very flexible. Auxiliary switches are turned on during the blanking time of the main switches to achieve soft-switching. [Smith 1998] introduces a magnetic amplifier in addition to the auxiliary switches which automatically determines the necessary amount of redirection current to ensure soft-switching of all switches under any load condition. This topology may be useful for UPS application.

[Lai 1997] describes a resonant snubber based soft-switching inverter suitable for electric propulsion drives. In addition to auxiliary switch a resonant inductor is placed across the load to produce zero voltage across the main switches. Auxiliary switches and resonant inductor operate for a very small time reducing the size and rating of the extra components. A zero current transition inverter suitable for power factor correction rectifier is proposed by [Li 2001]. This topology ensures all the main switches and auxiliary switches to be turned on and turned off under zero current condition. The diode reverse recovery current and switching turn-on losses are drastically reduced and the current and thermal stresses in the auxiliary devices are evenly distributed over every switching cycle. [Yousefzadeh 2004] proposes a combination of zero voltage switching and hybrid pulse width modulation technique to increase the efficiency of a single phase inverter.

1.2.3 Resonant Link Inverters

Resonant link inverters are classified as resonant dc link and resonant ac link inverters. Resonant dc link topology is either series or parallel type. Parallel resonant dc link (PRDCL) topology has oscillating link voltage that oscillates between zero voltage and a peak voltage. To achieve ZVS, switching of devices must be synchronized with zero voltage periods. Series resonant dc link topology uses the principle of zero current switching to reduce switching losses. The dc link current oscillates between zero and peak value. The switching instants of the switches must be synchronized with zero current period of the link. In resonant ac link the link waveform can be either an alternating voltage or current, in order to create ZVS or ZCS conditions for the inverter bridge. Hence, bidirectional switches should be used. In this topology, a high frequency LC resonant tank circuit is inserted into the dc bus.

Two topologies for resonant dc-link inverter are shown in Fig.1.8 and Fig.1.9.

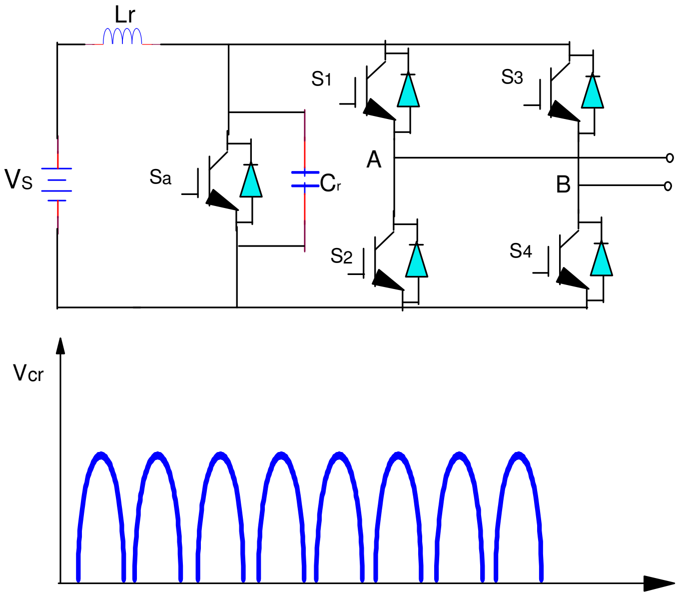

Fig.1.8. Passively clamped resonant dc-link inverter and resonant dc-link voltage

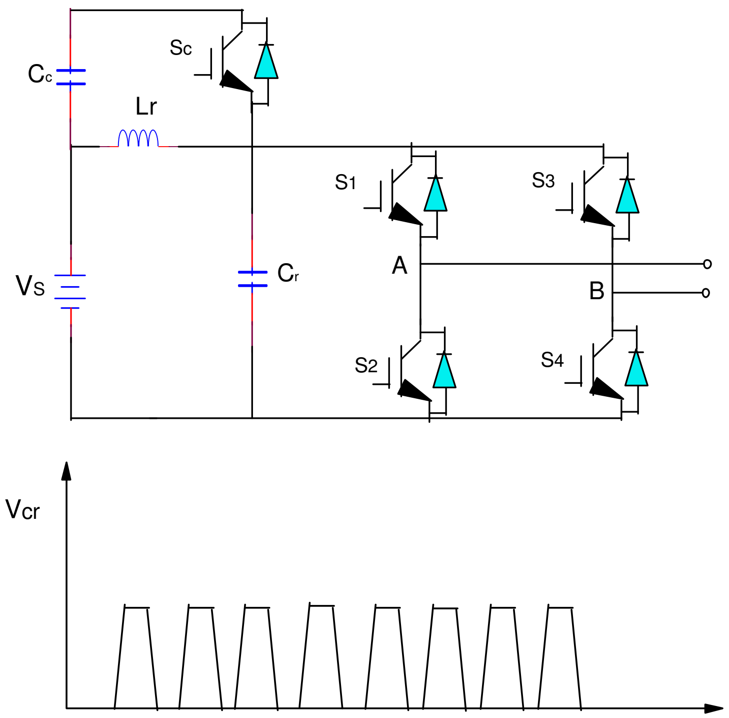

Fig.1.9. Actively clamped resonant dc-link inverter and resonant dc-link voltage

Passively clamped dc-link topology has an auxiliary switch with passive elements and a diode is introduced in the bus. The peak voltage stress on the devices is restricted to $2V_s$. In actively clamped dc-link configuration an auxiliary switch S_c and a stored-voltage clamped capacitor is added in the conventional parallel resonant dc-link.

[Divan 1989,1993] proposes actively clamped resonant dc-link inverter which reduces voltage stress across the device to 1.3-1.5 times the supply voltages compared to 2.5 times the supply voltage in case of resonant dc link inverter topology. A quasi-parallel resonant dc link soft-switching inverter proposed by [Chen 1998] has more flexible PWM capability and easier control with reduced magnetic component and only one diode as compared to previous topologies.

[Cuzner 2001] describes an actively clamped resonant link inverter for low-output harmonic distortion achieving high power density. Optimal design of clamp circuit, resonant components, and output filter is described in detail. Major drawback of synchronized resonant dc link inverter is the voltage stress on the main switches. [Oh 1999] proposes a source voltage clamped resonant link PWM inverter which clamps the dc link resonant voltage to V_{dc} and reduces the current stress on the conventional series resonant dc link inverter. Other advantage of this topology is its single set of auxiliary switches to achieve soft-switching.

A zero voltage switching start up for a current fed resonant inverter is proposed by [Hu 2006]. A dynamic ZVS method using a forced DC current is analyzed and complete dynamic ZVS control is achieved. A passively clamped quasi-resonant link (PCQRL) topology proposed by [Chen 1996] achieves soft-switching condition by introducing magnetic coupling between resonant inductors reducing the auxiliary switches. This topology reduces the voltage stress from more than 2 p.u. to 1.1-1.3 p.u. in comparison to the conventional passively clamped, continuously resonant dc link inverter. [Oh 2004] suggests a parallel resonant dc link circuit to achieve soft-switching with low conduction loss. Power devices are switched on under ZVS condition. The control signals are generated by a dedicated micro controller.

[Jafar 2002] proposes a quasi-resonant dc link PWM inverter using single switch to achieve zero voltage switching instants under all load conditions. It is also claimed in this topology that it can be used for any PWM strategy. A series resonant dc link inverter with a voltage clamped circuit to achieve soft-switching is proposed by [Ishikawa 2000].

The proposed system has advantages of low harmonics, less acoustic noise, smooth regeneration operation with automatic input current regulation.

A parallel resonant dc link circuit for high switching frequency zero-voltage-switching inverter proposed by [He 1993] provides short zero-voltage switching intervals for device switching transition period in the dc link of PWM inverter with less voltage stress on the device. [Wang 2003] explores the possibility of achieving soft-switching in a series resonant inverter without auxiliary switches, employing non-linear control strategy. A constant on-time frequency modulation technique with a variable off-time is used to regulate the system dynamics.

1.3 Recent Trends in Soft-Switching Inverter Topology

A variable turns ratio coupled-magnetic type soft-switching inverter for wide range of source and load adaptability has been proposed for commercial purpose [Lai 2006]. It uses a simple fixed time control to achieve wide range of zero voltage switching. It also helps in reducing the dv/dt problem to a great extent. A generic half-bridge ZCT cell which employs an auxiliary switch and one LC resonant tank to assist switching transition is developed [Li 2006]. This topology reduces the number of auxiliary switches and still achieves soft commutation for all switches and diodes at every switching transition and for all operating modes without any modification in space vector modulation (SVM) scheme. A dc-link series resonant inverter with field programmable gate array (FPGA) based controller is tested and found suitable for UPS applications [Muthu 2006]. This FPGA controlled inverter operates reliably at high resonance frequency around 120 kHz. The high frequency operation and instantaneous control enable the inverter to maintain constant dc link current and sinusoidal output voltage under various loads. Test results show that a sinusoidal inverter output voltage is maintained with THD less than 5% and regulation about 1% from no-load to full-load, including non-linear and transient loads. Brushless DC motor has been widely used in industrial applications because of its low inertia, fast response, high power density, high reliability, and maintenance free reputation. Soft-switching inverter application in brushless DC motor drive system utilizing resonant pole inverter is discussed in [Pan 2005]. All the high switching frequency switches work under soft-switching condition and voltage stress is only up to supply voltage. Freewheeling diodes turn-off under zero-current condition reducing reverse recovery problem of diodes. EMI is reduced due to less dv/dt and di/dt and also switching acoustic noise is eliminated due to high switching frequency operation.

A new generation cost effective soft-switching inverter for induction heating appliances is proposed [Ogura 2004]. It is a high frequency inverter with constant frequency PWM control scheme which uses active auxiliary quasi-resonant lossless inductor snubbers and switched capacitor snubbers to achieve soft-switching. A versatile quasi-resonant inverter which can handle passive and active (induction motor) three phase loads of low as well as high power factor is discussed [Behera 2004]. It uses modified space vector modulation scheme to achieve soft-switching. It may also find application in airborne power supplies.

A ZVS switching Dc-link single phase PWM voltage source inverter with optimized system performance using unipolar, sine-ramp modulation is proposed [Gurunathan 2007]. The soft-switching for all power factor conditions is achieved by modifying the carrier for reactive power flow condition. Only one extra switch is required in the dc-link to achieve ZVS. The voltage stress on all the switches is the dc-link voltage. A negative-bus auxiliary resonant circuit and novel mirror symmetrical pair of resonant-link modules have been reported for ZVS of two-level and three-level inverters [Chang 2006]. This circuit reduces power device counts of resonant circuit, and requires low device voltage ratings. For high voltage and high power inverter applications, power MOSFET has not been used due to its slow body diode reverse recovery and high on-state voltage drop.

The use of low on-state voltage drop CoolMOS allows significant reduction on conduction losses in both forward and reverse conducting periods [Zhang 2006]. Thus adopting CoolMOS in a zero-voltage soft-switching inverter takes the advantages of both conducting and switching loss problem.

1.4 Uninterruptible Power Supply (UPS) Systems [Karve 2000], [Bekiarov 2002].

Uninterruptible power supply systems provide uninterrupted, reliable, and high quality power for vital loads and also protect sensitive loads against power outages as well as over-voltage and under-voltage conditions. Applications of UPS systems include computers, communication systems, medical facilities, life supporting systems, data storage, emergency equipment, telecommunications, industrial processing, and on-line management systems.

The necessary features of any UPS system are: regulated sinusoidal output voltage with low total harmonic distortion (THD) independent of the changes in input voltage or in the load, on-line operation, low THD sinusoidal input current and unity power factor, high reliability, high efficiency, low EMI and acoustic noise, electric isolation, and low cost, weight and size. UPS systems are classified into three general types, static, rotary and hybrid static/rotary systems. Static UPS systems are most commonly used in broad variety of applications from low power to high power applications. Classification of static UPS system is as follows:

a) On-line UPS: On-line UPS systems consists of a rectifier/charger, a battery set, an inverter, and a static switch (bypass) as shown in Fig.1.10. The load gets continuous power supply from the inverter both during normal mode of operation and during back-up time. Tolerance to wide range of input voltage and good regulation of output voltage are the advantages of this topology. Low power factor and high THD makes it less efficient.

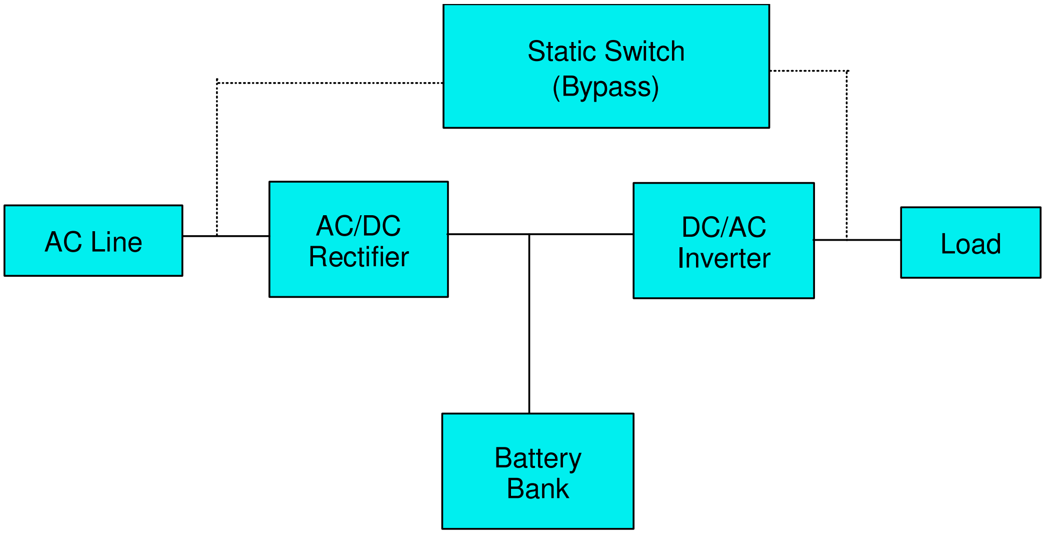

Fig. 1.10 Block diagram of on-line UPS

b) Off-line UPS: It consists of an AC/DC converter, a battery bank, a DC/AC inverter, and a static switch as shown in Fig.1.11. The inverter is not directly connected to the load in series with the power supply but in parallel in a standby mode. The static switch is on during the normal mode of operation. It is turned-on only when the primary power is out of a given preset tolerance or is not available at all. During this mode of operation the power to the load is supplied by the battery set via the inverter for the duration of preset back-up time or till the AC line is back again. It has advantage of simple design, low cost and small size but it suffers from long switching time and poor performance with non-linear loads.

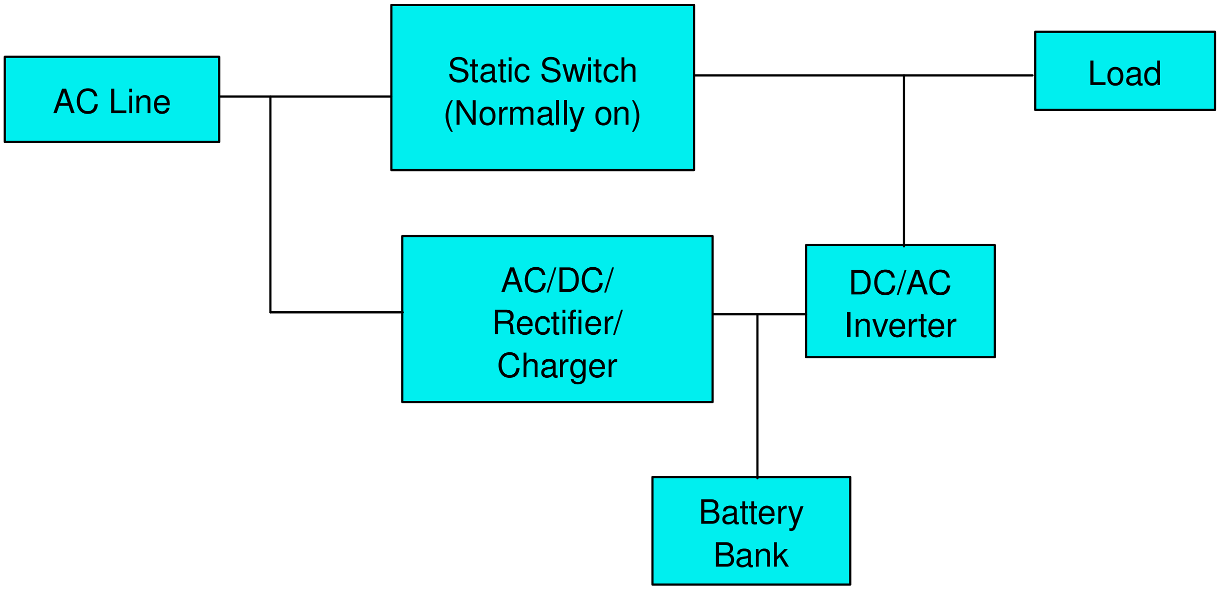

Fig. 1.11 Block diagram of an off-line UPS

c) Line interactive UPS: Line interactive UPS systems, as shown in Fig.1.12, consists of a static switch, a series inductor, a bidirectional converter, and a battery bank. It can operate either as an on-line UPS or as an off-line UPS. The inverter is connected in parallel, acting as a back-up to utility power through its reversible operation. This UPS can operate in three modes of operations namely, normal mode, stored-energy mode and bypass mode. In normal mode, load is connected through a parallel connection of inverter with main power supply providing voltage conditioning and battery charging. In stored-energy mode, the inverter and battery supplies power to the load when the main power supply is off or it goes out of preset value. When the UPS malfunctions internally, the load is allowed the bypass input in the bypass mode. It suffers from poor protection against spikes and over-voltages, poor efficiency when operating on non-linear load.

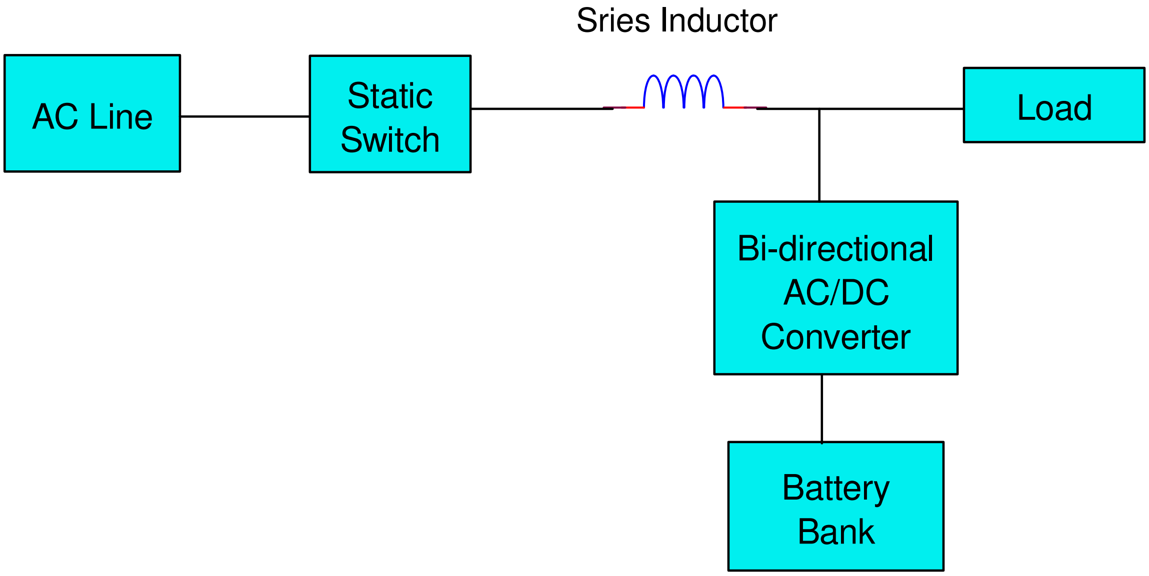

Fig.1.12 Block diagram of a line-interactive UPS

As it is seen from the topology of UPS systems, inverter is the main component of this system and its performance depends on the quality of the output of inverter. Replacing conventional hard switched inverter with soft-switched inverter improves the efficiency and reduces the EMI of UPS system.

1.5 Power Loss in Inverter

1.5.1 Switching Losses

The actual voltage and current wave shapes during switching intervals either turn-on and turn-off determines the losses. If the switch voltage and current makes linear transition between turn-on and turn-off, the energy loss is given by

$$E_{switch} = \frac{V_{off} I_{on} t_{turn-on}}{6} + \frac{V_{off} I_{on} t_{turn-off}}{6} \qquad (1)$$

For clamped inductive rectangular commutation the energy loss is given by

$$E_{switch} \ \frac{V_{off} I_{on} t_{switch}}{2} \qquad (2)$$

Where,

$$t_{switch} = t_{turn-on} + t_{turn-off} \qquad (3)$$

Losses in terms of voltage gradients (dv/dt), current gradient (di/dt), reverse recovery peak current in diode ($I_{RM)}$ and stray inductance (L_{st}) , for IGBT switch are given below [Blaaberg 1997].

Energy loss at IGBT turn-on

$$E_{Ton} = 0.5[V_{DC} - L_{st}(di/dt)_{on}]\frac{(I_L + I_{RM})^2}{(di/dt)} + 0.5 I_L \frac{V^2{}_{DC}}{(dv/dt)_{on}} \qquad (4)$$

Energy loss at IGBT turn-off

$$E_{Toff} = 0.5\frac{V^2{}_{DC}}{(dv/dt)_{off}} I_L - 0.5[V_{DC} - 2L_{st}(di/dt)_{off}]\left[\frac{(I_L)^2}{(di/dt)_{off}} + 0.5 k_t V_{DC} I_L t_{tail}\right]$$

Where, (5)

K_t is current tail factor and t_{tail} is tail current for IGBT.

Diode turn-off loss is given by

$$E_{Doff} = 0.5[V_{DC} + 2L_{st}(di/dt)_{diode}]\frac{(I_L)^2}{(di/dt)_{diode}} \qquad (6)$$

1.5.2 Conduction loss

Conduction loss is given by,

$$P_{cond} = 1/T\int_0^T V_{on}(t) i_L(t) dt \qquad (7)$$

Conduction loss also depends upon the modulation function given by

$$\delta = \frac{1}{2} + \frac{1}{\sqrt{3}} m\left(\sin(\omega t) + \frac{1}{6}\sin 3(\omega t)\right) \tag{8}$$

Where, m is the modulation index,

ω is the angular frequency of the fundamental,

δ is the modulation function

1.6 Motivation of Research

The hard switched SPWM inverters are replaced by soft switched SPWM inverters in many applications. Suitable topology is selected depending on the application. One of the main applications of soft switching inverters is in UPS systems. Keeping in view of growing demand of UPS systems, a suitable topology is needed to limit the total harmonic distortion less than 3% with reduced switching losses. This topology will also be helpful in increasing the efficiency of photovoltaic systems [Aiello 2006] and the efficiency of inverters used for active power filtering applications [Akagi 2005].

The other motive is to introduce some wavelet based idea in calculating switching power loss. The instantaneous power loss method calculates the switching loss accurately but the information regarding the frequency content of switching transients is missing. Wavelet based method identifies the frequencies in switching transients and calculates power loss for corresponding frequencies. This will be helpful in designing the snubber for solid state switches and also in analyzing the EMI analysis. Recently the power definitions based on discrete wavelet transform have been proposed for balanced and sinusoidal as well as unbalanced and non-sinusoidal polyphase systems [Morsi 2007(1), (2)]. Active and reactive powers using these definitions have been calculated with acceptable accuracy but with fast processors and dedicated application specific chips available, in addition to power loss calculation, the wavelet based idea will be helpful in the analysis of EMI and better closed loop control of soft switching inverters.

1.7 Thesis Outline

This thesis presents a systematic analysis of hard switching SPWM inverter and soft switching SPWM inverter suitable for UPS application. A wavelet based approach to find the switching loss and, analysis of switching waveforms is introduced.

Chapter 2 presents detailed analysis of hard switching inverter with total harmonic distortion (THD) of output voltage less than 3%. A simple control strategy based on modulation index (MI) is presented to control the change in output voltage.

In chapter 3 design and analysis of soft switching inverter based on ZVT principle is discussed. Design criteria for suitable resonant components are discussed in detail. Also analysis under various loading condition is done to verify the design. Theoretical results are compared with the simulated result with MATLAB SIMULINK software package.

Chapter 4 presents the idea of wavelet based switching loss analysis. Some basic concepts of wavelets and its application in power loss calculation are discussed with example and case study.

In chapter 5, Experimental results are presented for a single phase SPWM inverter to verify the design to meet a THD of less than 3% for load voltage. Frequency spectrum of load voltage is observed for both lower order and higher order harmonics.

Also, Simulation results of a ZVT converter topology are verified from laboratory prototype with reduced voltage and current ratings. It achieves soft-switching for one pair of switches. Snubber capacitor and resonant inductor values are selected with design equations and corresponding pre turn-on time for auxiliary switch and delay time for main switch is calculated. Waveforms from both hard and soft switched converters are presented. It is seen that near ZVT condition is met.

Detailed wavelet based analysis of switching power loss is presented and verified with the experimentally calculated power loss. Frequency content of switching waveforms is also presented.

Chapter 6 presents the conclusion part discusses the future scope with some suggestions.