CHAPTER 1

INTRODUCTION

1.1 GENERAL

DC-DC power converters are employed in a variety of applications, including power supplies for personal computers, office equipments, spacecraft power systems, laptop computers, and telecommunication equipments, as well as DC motor drives. Significant progress in the fields of circuit topologies, semiconductor power devices, control theory, advances in integrated electronics have greatly reduced the size of many electronic systems. In order to utilize the advantages of compact denser electronics, power densities (output power per unit volume) that are much higher than what is possible with present DC-DC power converters are demanded.

Based on the system requirements such as output to input voltage relationship, power rating, and the need of galvanic isolation, there are various types of DC to DC converter topologies.

Based on the electrical isolation requirement DC-DC converters can be classified as isolated and non isolated converters. Step-down (Buck) converters and step-up (Boost) converters are the basic topologies. The other topologies can be derived from these two converters.
1.2 RESONANT SWITCHING

In hard switching during the turn-on and turn-off processes, the power device has to withstand high voltage and current, resulting in high switching losses and stress. By adding dissipative passive snubbers to the power circuits the dv/dt and di/dt of the power devices can be reduced. The maximum switching frequency of the power converters are limited (typically 20 kHz to 50 kHz), since the switching loss is proportional to the switching frequency. The electro magnetic interference (EMI) is due to transient ringing effect.

Semiconductor switching devices can operate in hard switch mode in pulse width modulation (PWM) converters and inverters. In hard switching mode whenever switching occurs, a specific current is turned on or off at a specific level of voltage. This results in switching losses. The more the increase of switching frequency, the higher the increase of switching loss. Hence the switching frequency cannot be increased. A large amount of di/dt and dv/dt is generated which causes EMI problem.

\[ P_{SW} = \frac{1}{2} V_{SW} I_{SW} f_s (t_{on} + t_{off}) \]  
(1.1)

Total power dissipation = \( P_{d1} + P_{d2} + P_{d3} + P_{d4} \)  
(1.2)

\[ V_{ds} = r_{ds \ (on)} . I_0 \]  
(1.3)

\( V_{ds} \) is the drain - source voltage of the switch

\( r_{ds \ (on)} \) be the drain - source on state resistance

Average \( I_d = I_0 \)

\( I_0 \) be the DC output current

Power dissipation across the switch
\[ P_d = D \cdot r_{ds\,(on)} \cdot I_0 \]  
\[ \text{D}= \text{Duty cycle of switch} \]
\[ t_{rr} = \text{reverse recovery time of body diode of MOSFET} \]
\[ I_{rm} = \text{Peak of sum of displacement current and diode reverse recovery current} \]

\[
P_d = (0.5 - D) \cdot r_{ds\,(on)} \left[ I_o + T_{on} \left( \frac{V_o}{4L} \left( \frac{DV_o}{2L} \right) \right)^2 \right] \]
\[ (1.5) \]

\[
P_d = (0.5 - D) \cdot r_{ds\,(on)} \left[ T_{off} \left( \frac{V_o}{4L} \left( \frac{DV_o}{2L} \right) \right)^2 \right] \]
\[ (1.6) \]

Turn off power loss of diode across the switch

\[
P_d = t_{rr} \cdot V_{ds\,(off)} \cdot \frac{I_{rm}}{2T} \]
\[ (1.7) \]

Increasing the switching frequency reduces the size of the transformer and filters, which results in smaller and lighter converter with high power density. As more losses are generated at high frequencies the efficiency of the system is reduced.

In order to protect the devices from the switching stresses snubber circuits are used. There are two types of snubber circuits one is turn–on snubber and the other is turn –off snubber. The snubber circuits reduce the loss during one switching transition, in the other switching transition, the energy stored in snubber L and C will be dissipated in the snubber resistor thereby contributing to additional losses. If the switching frequency is above 200 kHz, the energy associated with the switching transition is also more. Hence the snubber circuits are not useful. By connecting a simple snubber circuit parallel to the switching circuit, switching loss can be partly avoided.
In order to achieve higher energy conversion efficiency at high frequency switching the voltage or current at the moment of switching can be manipulated to become zero. This is called soft switching.

In zero voltage switching the voltage of the switching circuit is set to zero before the circuit is turned on thus the turn on switching loss is eliminated.

In zero current switching no current is allowed to flow through the circuit before turning it off thus the turn off switching loss is eliminated.

The voltage or current of the switching circuit can be made zero by using the resonance produced by an L-C resonant circuit. This topology is known as resonant converter.

An intelligent controller based closed loop control is essential to improve the productivity of an automatic control system.

In order to validate the analysis and design of the above converters and to verify the effectiveness of the control technique, simulation is done using MATLAB/SIMULINK software. Implementation is done using ATME6 and PIC microcontrollers to ascertain the effectiveness of the control techniques in real time.

The first criterion for achieving ZVS

\[ X_p \geq X_s \quad (1.8) \]

- \( C_r \) = Resonant capacitance
- \( C_{oss} \) = switch output capacitance
- \( C_{fmr} \) = Transformer capacitance
- \( L_r \) = Total resonant inductance
In order to obtain good efficiency at high switching frequency, lossless switching is to be achieved. Soft switching techniques are used to achieve lossless switching. Soft switching is obtained by adding resonant components (inductors and capacitors) or using the parasitic components of a DC-DC converter. Soft switching of a controllable switch can be provided by using either Zero current switching (ZCS) or Zero voltage switching (ZVS) technique.

The resonant converters have resonant tanks to create oscillatory voltage and/or current waveforms so that zero voltage switching (ZVS) or zero current switching (ZCS) conditions can be created for the power switches. The switching losses are reduced, hence the switching frequency can be increased (typically 100 kHz to 500 kHz). Since the magnetic sizes are reduced, the power density of the converters can be increased. The resonant current and voltage of resonant converters have high peak values, compared to PWM converters, leading to higher conduction loss.

New soft-switched converters combine the advantages of PWM converters and resonant converters. These soft-switched converters have switching waveforms similar to PWM converters but their rising and falling edges of the waveforms are ‘smoothed’ without transient spikes. Resonance is allowed to occur just before and during the turn-on and turn-off processes so as to create ZVS and ZCS conditions. Other than that, they behave just like conventional PWM converters. Because the switching loss and stress have been reduced, soft-switched converter can be operated at very high frequency (typically 500 kHz to a few Mega-Hertz). EMI is suppressed. Various forms of soft-switching techniques are ZVS, ZCS, voltage clamping, zero transition methods etc.
A resonant switch is a sub-circuit comprising a semiconductor switch S and resonant elements, $L_r$ and $C_r$. The switch S can be implemented by a unidirectional or bidirectional switch, which determines the operation mode of the resonant switch. Two types of resonant switches, including zero-current (ZC) resonant switch and zero-voltage (ZV) resonant switches, are shown in Figure 1.1 and Figure 1.2 respectively.

![Figure 1.1 Zero-current (ZC) resonant switch](image)

![Figure 1.2 Zero-voltage (ZV) resonant switch](image)

In ZC resonant switch, an inductor $L_r$ is connected in series with a power switch S in order to achieve zero-current-switching (ZCS). If a diode is connected in anti-parallel with the unidirectional switch, the switch current can flow in both directions. At turn-on, the switch current will rise slowly from zero. It will then oscillate, because of the resonance between $L_r$ and $C_r$ and commutated at the next zero current duration. The switch is used to shape the switch current waveform during conduction time in order to create a zero-current condition for the switch to turn off.
In ZV resonant switch, a capacitor $C_r$ is connected in parallel with the switch $S$ for achieving zero-voltage-switching (ZVS). If the switch $S$ is a unidirectional switch, the voltage across the capacitor $C_r$ can oscillate freely in both positive and negative half-cycle. If a diode is connected in anti-parallel with the unidirectional switch, the resonant capacitor voltage is clamped by the diode to zero during the negative half-cycle. A ZV switch, has a resonant circuit to shape the switch voltage waveform during the off time in order to create a zero-voltage condition for the switch to turn on.

In load resonant type ZVS, the combination of resonating elements (LC, LLC, and LCL) are used. The output oscillating voltage and current of the resonating elements are applied to the load to achieve resonance across the switch. In resonant switch type the internal capacitance present across the switch is used to achieve quasi resonance across the switch.

Zero voltage switching can be realized by Zero voltage switching for quasi resonant converters and Zero voltage switching resonated by LLC resonance elements, in order to achieve less total harmonic distortion (THD), less switching losses, high power density, and low EMI.

In resonant switches the internal capacitance of MOSFET is used to realize resonance. During one time period there are resonant as well as non resonant operating intervals resulting in quasi resonant converter.

A soft switching converter with increased power density reduces the switching stress across the switches. The converters must have high efficiency, high power density, high reliability and low EMI. But it is difficult to incorporate all the above features in a hard switching converter, because the high switching losses reduce the converter efficiency and suffers from reduced power density due to usage of high cooling requirements.
These drawbacks can be overcome by soft switching converters. To achieve high power density, switching frequencies needs to be made high but the oscillations caused by converter parasitic elements may cause high current and voltage stresses which cannot be predicted and depends on circuit layout. At increased frequency, the converter can employ smaller sized magnetic elements and filter components.

The two switching techniques used are zero voltage and zero current switching. Both these techniques reduce the switching losses and thereby increase converter efficiency.

Soft switching can mitigate some of the mechanisms of switching loss and possibly reduce the generation of EMI. Semiconductor devices are switched on or off at the zero crossing of their voltage or current waveforms. In Zero Current Switching (ZCS) transistor turn-off transition occurs at zero current. Zero-current switching eliminates the switching loss caused by IGBT current tailing and by stray inductances. It can also be used to commutate SCR’s. In Zero-Voltage Switching (ZVS) transistor turn-on transition occurs at zero voltage. Zero-voltage switching eliminates the switching loss induced by diode stored charge and device output capacitances. Zero-voltage switching is usually preferred in modern converters. Zero-voltage transition converters are modified PWM converters, in which an inductor charges and discharges the device capacitance.

1.3 QUASI-RESONANT CONVERTERS

Quasi-resonant converters (QRC) can be considered as a hybrid of resonant and PWM converters. The power switch in the PWM converter is replaced by a resonant switch. The current and/or voltage waveforms of the MOSFET switch are forced to oscillate in a quasi-sinusoidal manner, in order to achieve ZCS and ZVS. In ZCS quasi resonant converters the value of $L_f$ is
large, hence the current is constant. Before turning on output current $I_o$ freewheels through the output diode $D_f$. The resonant capacitor voltage $V_{Cr}$ equals zero. The switch is turned on with ZCS. A quasi-sinusoidal current $I_S$ flows through $L_r$ and $C_r$, the output filter, and the load. Switch is then softly commutated with ZCS again. During and after the gate pulse, the resonant capacitor voltage $V_{Cr}$ rises and then decays at a rate depending on the output current. Output voltage regulation is achieved by controlling the switching frequency. Operation of the converter depends on the resonant circuit $L_r$-$C_r$.

If $I_o > V_i / Z_r$, $I_S$ will not come back to zero naturally the switch will have to be forced off, thus resulting in turn-off losses. Voltage conversion ratio is sensitive to changes in load variation in half-wave. At light load conditions, the unused energy is stored in $C_r$, leading to an increase in the output voltage. The regulation of the output voltage is done by varying the switching frequency.

For full-wave mode of operation anti-parallel diode is connected across the switch. The circuit of full-wave quasi resonant converter is shown in Figure 1.3. The inductor current is reversed through the anti-parallel diode hence the resonant stage is lengthened. The excess energy in the resonant circuit at light loads will be transferred back to the voltage source $V_i$. The voltage conversion ratio is insensitive to load variation.

![Figure 1.3 Full-wave, quasi-resonant buck converter with ZVS](image-url)
In ZVS quasi resonant converters, quasi resonance is achieved by adding resonating elements to a PWM converter. Internal capacitance of the MOSFET switch and inductor connected in series are used to achieve ZVS. Quasi resonant converters can have resonant as well as non resonant operating intervals in a time period. Whenever MOSFET pulses are ON, the capacitor voltage across the MOSFET is zero. Hence switching losses are less. The quasi resonant converter gives a smooth sinusoidal waveform. They can be operated at comparatively high frequencies than PWM converters. As the operating frequency is high, there is a reduction in cost and size of the resonating components.

In ZVS-QRC converters, the resonant capacitor provides a zero-voltage condition for the switch to turn on and off. When the switch S is turned on, the output current flows. The supply voltage $V_i$ reverse-biases the diode $D_f$. When the switch is zero-voltage turned off, the output current starts to flow through the resonant capacitor $C_r$. When the resonant capacitor voltage $V_{Cr}$ is equal to $V_i$, $D_f$ turns on. This starts the resonant stage. When $V_{Cr}$ equals zero, the anti-parallel diode turns on. The resonant capacitor is shorted and the source voltage is applied to the resonant inductor $L_r$. The resonant inductor current $I_{Lr}$ increases linearly until it reaches $I_o$. Then $D_f$ turns off. In order to achieve ZVS, S should be triggered during the time when the anti-parallel diode conducts. The full-wave mode has the problem of capacitive turn-on loss, and is less in high frequency operation.

In Zero voltage switching resonated by LCL resonance elements, ZVS is achieved by using transformer leakage inductance ($L_{lkg}$), load side inductance (L) and load side capacitance(C). The CL components resonate with the leakage inductance of the transformer as twice the switching frequency of MOSFETs. By using good quality capacitor and air core inductor the resonant frequency will remain constant over the entire range of
converter loading. High frequency switching, reduces the size of the transformer; resonating elements become small; less stress on the MOSFET switches.

ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on. The limitations of ZCS are the capacitive turn-on losses. ZVS eliminates the capacitive turn-on loss. It is suitable for high-frequency operation.

Output regulations in many resonant-type converters, such as QRCs, are achieved by controlling the switching frequency. ZCS applications require controlled switch-on times while ZVS applications require controlled switch-off times.

1.4 LITERATURE REVIEW

The present direction of evolution in DC to DC converters is towards higher efficiency and higher power density. Both can be achieved by higher switching frequency and low overall losses. Soft switching results in zero switching losses and increases the switching frequency to 100 kHz and above.

Soft switching techniques are developed to reduce switching losses and electromagnetic interference (EMI). During soft switching, switching frequency can be increased to enhance the converter power density.

For PWM converters the soft switching conditions can be provided by zero-voltage switching and zero-current switching.

In zero voltage switching, a capacitor is placed in parallel with main switch. During turn off soft switching condition is provided by the capacitor.
The continuing success of square-wave PWM topology in switching converters can be attributed to its ease of operation (Lee et al 2008).

In zero current switching, an inductor is placed in series with converter main switch or main diode. During turn on soft switching condition is provided by the inductor. Before switch turn off, an auxiliary switch is turned on and the main switch current is reduced to zero. (Wang 2008 Das and Moschopoulos 2007)

In the research work carried out by (Jung et al 1996) Zero-voltage and zero-current switching full-bridge PWM converter using secondary active clamp, the harmonics can easily be eliminated by power filter and it has a capability in allowing continuous and linear control of the frequency and fundamental component of the output voltage.

But with the demands for higher power densities, the switching frequencies are approaching 1 MHz range. (Zhang et al 2006, Song and Huang 2005, Kim and Kim 2002, Seok and Kwon 2001) Increasing the frequency of operation of power converters is desirable as it allows the reduction in size of the circuit magnetics and capacitors, hence leading to cheaper and more compact circuits. However increasing the frequency of operation also increases the switching losses and hence reduces the system efficiency.

At high frequencies, square wave converter’s switching losses become very high leading to excessive heat dissipation. Even if the increased switching frequency does not cause unacceptable switching losses, the oscillations caused by converter parasitic elements may cause high current and voltage stresses, which are almost unpredictable, depending on circuit lay out (Sabate et al 1990, Borage et al 2005).
In the research work carried out by (Lu et al 2005) suitable snubber circuits must therefore be adopted, which affect power density and converter reliability.

The zero-voltage transition approach, as well as the active-clamp snubber approach, leads to zero-voltage switching of the transistors and zero-current switching of the diodes (Citko and Jalbrzykowski 2008, Yao et al 2004, Johan Park et al 2012). These approaches have been successful in substantially improving the efficiencies of transformer-isolated converters.

Wu et al (2008) deal with the analysis and derivations for a ZVS converter based on a new active clamp ZVS cell.

When the FB converter transits from zero state to active state, the clamping diode conducts and its initial current equals to the peak resonant current due to the resonance of the resonant inductor and the parasitic capacitor of the output filter rectifier diode. The increase in output filter inductor current leads to decaying in clamping diode current. The output filter inductor is always designed to be large. Since the rise rate of its current is very small, the conduction time of the clamping diode will be longer. Therefore the conduction loss will be more in clamping diodes, resonant inductor, and leading switches.

In order to achieve full ZVS operation with unlimited load and wide input voltage range a large inductance is provided in series with the primary winding of the transformer. This increase in inductance causes an increased loss of duty cycle on the secondary side and voltage ringing across secondary side output rectifiers.

Citko and Jalbrzykowski(2009) have described bidirectional DC to DC converter which employs the two bridge configuration resonant
converters on both sides of the isolating transformer. The system has good
dynamic properties and high efficiency because the converter transistors are
switched in ZVS conditions..

Lin and Tseng (2007) have described the parallel-connected
asymmetrical soft-switching converter. A number of power converters
connected in parallel, share the load current so that each converter operates
with a load which is a fraction of its full load. The converter is able to
maintain a high efficiency at light loads.

Wang (2008) has presented a novel ZCS-PWM fly back converter
with a simple ZCSPWM Commutation cell. A LC resonant tank circuit is
utilized for shaping the device’s current wave form. Zero current condition is
created by allowing the device to switch under favourable conditions. These
circuits are hybrid converters between PWM converters and resonant
converters.

Zhang et al (2006) have presented a novel zero-current transition
full bridge DC-DC converter and C tank circuit is always present near the
power switch. It is used to shape the current and voltage waveforms of the
power switch and also to store and transfer energy from input to output
similar to the conventional resonant converters. However due to capacitor
turn on, the zero current transition has the problem of high switching loss.

Song and Huang (2005) have presented a novel zero-voltage and
zero-current switching full-bridge PWM converter. ZVS and ZCS techniques
are applied to PWM converters to improve efficiency and overcome the
reverse recovery problem. However, the main switches are suffering from
additional current stress and the auxiliary switch voltage stress is high.
The full bridge (FB) zero voltage switched (ZVS) converter is the most commonly used soft switched circuit in high power applications. A control circuit supplies pulsed control signals to the switching transistors of the converter. This constant frequency converter employs phase shift (PS) control. The primary switches of the converter features ZVS with small circulating energy.

Increasing the inductance value to enhance full ZVS operation for wide loads, increases voltage ringing across the secondary side output rectifiers. In order to suppress secondary ringing active snubber or passive snubber is proposed in (Sabate et al 1990). This paper presents analysis, design, and application of a high voltage, high power, zero voltage switched, full-bridge PWM converter with an active snubber in the secondary circuit. But active snubber increases the complexity and cost of the circuit.

The research work carried out by Ayyanar and Mohan (2001) have presented a novel soft switched DC-DC converter with full ZVS-Range and reduced filter requirement - Part I-regulated-output applications.

The ZVS range can be extended by the energy stored in the magnetizing inductance of the auxiliary transformer. The soft switched DC-DC converter is a hybrid combination of an uncontrolled half bridge section and a phase-shift controlled full bridge section.

Ayyanar and Mohan (2001) Part II have presented a novel soft switched DC-DC converter with full ZVS Range and reduce filter requirement. The performance of the hybrid converter for constant-input and variable-output applications has been analyzed.
Lee et al (2008) has described a new phase shift full bridge converter with voltage doubler type rectifier. The circulating current can be significantly reduced. However, it is difficult to achieve ZVS using magnetizing current. Therefore, dead time is dramatically increased.

Borage et al (2008) have described a new topology of FBZVS converter to achieve ZVS over entire conversion range with minimum additional conduction loss. This converter does not use auxiliary coupled inductor or transformer, rather, the main power transformer is divided into two half rated transformers and an uncoupled inductor is used to achieve ZVS over entire conversion range. It is particularly suitable in applications where the output is required to be adjustable over a wide range and the load resistance is fixed.

The Zero-voltage switching (ZVS) phase shift modulated full bridge (PSM-FB) DC-DC converter with MOSFET switches has been proposed in (Lee et al 2008, Wu et al 2008). The circulating current can be significantly reduced. Low component count and zero full load switching losses enable this topology to achieve low cost, high power density, high efficiency, and low EMI, so for medium to high power DC-DC applications it is a good choice. However, it is difficult to achieve ZVS using magnetizing current. Therefore, dead time is increased. The phase-shifted PWM full bridge converter incorporates the leakage inductance of the transformer to achieve zero-voltage switching, but only achieves it near the full load condition. Several new techniques for high frequency DC-DC conversion are there to reduce component stresses and switching losses while achieving high power density and improved performance.

Among them, the full-bridge zero-voltage-switched converter is one of the most attractive techniques. It is the most widely used soft-switched circuit in high-power applications (Lee et al 2008, Wu et al 2008, Lin and
Tseng 2007). This constant-frequency converter employs phase-shift control and features ZVS of the primary switches with relatively small circulating energy. However, full ZVS operation can only be achieved with a limited load and input-voltage range, unless a relatively large inductance is provided in series with the primary winding of the transformer either by an increased leakage inductance of the transformer and/or by an additional external inductor.

Cho (1994) has described that the increased inductance has a detrimental effect on the performance of the converter since it causes an increased loss of the duty cycle on the secondary side, as well as severe voltage ringing across the secondary side output rectifiers due to the resonance between the inductance and the junction capacitance of the rectifier.

Forsyth et al (1991) have described an active snubber to suppress the secondary-side ringing.

For implementations with an external primary inductor, the ringing can also be effectively controlled by employing primary-side clamp, as proposed in (Song et al 2006).

While the snubber approaches in (Hamada and Nakaoka 1994, Xu et al 2006) offer practical and efficient solutions to the secondary-side ringing problem, they do not offer any improvement of the secondary-side duty-cycle loss.

Lee et al (2008) and Han et al (2002) have proposed techniques to extend the ZVS range of FBZVS converters without the loss of duty cycle and secondary-side ringing.
Russi et al (2009) have described achieving ZVS circuits for all primary switches by utilizing energy stored in the inductive components of an auxiliary circuit in an extended load and input voltage range.

Ideally, the auxiliary circuit needs to provide very little energy, if any, at full load because the full-load current stores enough energy in the converter’s inductive components to achieve complete ZVS for all switches. As the load current decreases, the energy provided by the auxiliary circuit must increase to maintain ZVS, with the maximum energy required at no load. The energy stored for ZVS is independent of load as described in (Wang 2008 and Jain et al 2002).

Adaptive energy storage in the auxiliary circuit have been introduced in (Borage 2007 and Eid et al 2006). However, these converters have to use large inductors so, high circulating energy is needed to achieve no load ZVS and that is due to a relatively large inductor employed to assist ZVS.

Soft-switching DC-DC converter using Phase-Shifted Pulse Width Modulation (PS-PWM) on secondary side of high frequency transformer was proposed by (Shih-Ming Chen et al 2011). This converter consists of a full-bridge inverter fitted with fast IGBT transistors. The output power of the converter is controlled by rectifier made up of two snap-off diodes in series with MOSFET transistors which is connected on secondary side of high-frequency power transformer. This topology can easily achieve soft-switching operation also under low commutating current. The conduction losses are substantially reduced compared with conventional soft-switching DC-DC converters (Johan Park et al 2012, Yang et al 2009)

Kim and Kim (2002) have described half bridge (HB) DC-DC converter topology for middle power level applications owing to its
simplicity. There are two conventional control schemes for the HB DC-DC converter, namely, symmetric control and asymmetric (complimentary) control (Steigerwald 1988, Xu et al 2004, Chen et al 2005, Zhou and Ruan 2003). The main drawback of the conventional symmetric control is that both primary switches in the converter operate at hard switching condition. Moreover, during the off-time period of two switches, the oscillation between the transformer leakage inductance and junction capacitance of the switches results in energy dissipation and electromagnetic interface (EMI) emissions due to reverse recovery of MOSFETs body diodes. To suppress the ringing, resistive snubbers are usually added. As a result, energy in the transformer leakage inductance is significantly dissipated in snubbers. Therefore, the symmetric-control half bridge is not a good candidate for high switching frequency power conversion.

The asymmetric (complimentary) control was proposed to achieve ZVS operation for HB switches (Zhang et al 2006, Song and Huang 2005, Kim and Kim 2002, Seok and Kwon 2001 and Wu et al 2008). Two drive signals are complementarily generated and applied to high side and low side switches which may be turned on at ZVS conditions owing to the fact that the transformer primary current charges and discharges the junction capacitance.

However, asymmetric stresses distribution on the corresponding components may occur due to the asymmetric duty cycle distribution for the two primary switches which are not identical and voltage and current stresses on secondary rectifiers with higher voltage rating are needed at the penalty of degrading the performance and efficiency of the rectifier stage (Seok and Kwon 2001).

Oruganti and Lee (1985) have described that the DC gain ratio of the converter is nonlinear, thus higher duty cycle variation is needed for the same input voltage variation in comparison with symmetric PWM control
scheme, which makes the converter operate further beyond the optimum operation point at high input voltage.

Seok and Kwon (2001) and Oruganti and Lee (1985) have proposed the complementary (asymmetric) PWM control more suitable for applications where the input voltage is fixed. As a solution to reduce the duty cycle variation for wide input voltage range, an asymmetric transformer turns ratio together with integrated-magnetic structure. Rectifiers with lower withstanding voltage may be used to improve the performance. However, the power delivery of the current stresses in the switches and rectifiers are still uneven.

A new auxiliary circuit was introduced that can be applied to current fed full bridge and half bridge converters. The auxiliary circuit provides ZVS condition for the main switches while its semiconductor elements are also soft switched. (Adib 2009)

There are three major types of high frequency transformer isolated soft switching converter configurations: a) Voltage fed resonant converters b) Current fed resonant converters c) Fixed frequency resonant transition zero voltage switching PWM bridge converter (Steigerwald 1988)

Increasing the frequency of operation increases the switching losses and hence reduces the system efficiency. One solution to this problem is to replace the chopper switch of the converter by resonant switch. The resonant switch uses the resonances of circuit capacitances and inductances to shape the waveform of either the current or the voltage across the switching element. When switching takes place, there is no current through or voltage across it. Therefore there is no power dissipation across the switch. A converter employing this technique is known as quasi resonant converter, as only part of the resonant sinusoid is utilized.
Xie et al (2007) and Xu et al (2006) have been investigated resonant converters to achieve the prominent characteristics of miniaturization, high efficiency, and low noise. However, since a large variation in switching frequency is needed to control the output voltage, these converters have some difficulties from the viewpoints of size reduction and noise (Zhang et al (2006), Eid et al (2006), Fathy et al (2006), Yao et al (2004), Singh (2002), and Ren et al (2003)). To overcome the above problems, recently a half-bridge LLC resonant converter has been discussed because it has many unique characteristics and improvements over previous topologies.

Dalal (1990) has proposed a full bridge phase shifted converter topology. Its control features are similar to regular PWM converter and it uses parasitic elements (transformer leakage inductance) to control switching transition for ZVS. The resonant peaks are absent thus limiting the stresses on the converter components. However the converter suffers from severe voltage overshoot and ringing due to the interaction of the transformer leakage inductance with the reverse recovery process of the rectifier diode, loss of duty cycle on the secondary side of the transformer and loses ZVS for wide variation in line and load condition. The rectifier ringing and overshoot can be controlled by using fast recovery diodes.

Hu et al (2005) and Yang et al (2002) have proposed a half-bridge LLC resonant converter with a voltage doubler rectifier which has a simple structure and low-voltage stress on primary power switches. Moreover, since there is no secondary filter inductor, the voltage across the secondary rectifier can be effectively clamped to the output voltage. Employing rectifier diodes with a low-voltage rating, the conduction loss can be greatly reduced. Also, its zero-voltage switching capability is excellent from zero to full load condition. These features make the half-bridge LLC resonant converter very suitable for use as a Plasma display panels sustaining power module.
However, this converter has a small magnetizing inductance in order to have a narrow variation in switching frequency. This results in not only considerable higher circulating energy on the primary side of the transformer but also in more conduction loss. In the case of light load conditions, high circulating energy can be a serious problem that reduces the system efficiency. In addition, a variable frequency control method makes the control circuits much more complicated than those using the pulse width modulation control method.

Even though the half bridge LLC resonant converter has such good features, it shows lower efficiency under light load condition. This problem can be resolved effectively by using PWM-controlled quasi-resonant converter which has simpler control circuits and less conduction loss compared to a half bridge LLC resonant converter under light load conditions.

Emrani et al (2012) have proposed a new single switch soft switched isolated DC-DC converter. In the proposed converter, the transformer parasitic elements are used as resonant elements to transfer energy and to attain soft-switching condition.

Pecelj et al (2012) and Kavin et al (2013) have proposed converter that does not require output inductor just like the flyback converter, and the transformer core does not store energy just like the forward converter.

In high frequency converters soft switching are widely used to reduce the switching loss that results from high switching frequency. A full bridge series resonant converter (SRC) is simple because all switches of the converter are turned on at zero voltage, the conversion efficiency is high. The limitation of SRC is that the output voltage cannot be regulated for no load.
The phase shift control of SRC based FBZVS achieves constant frequency operation, no regulation problem but the range of ZVS is not wide.

In Zero voltage switching resonated by LCL resonance elements, ZVS is achieved by using transformer leakage inductance ($L_{tkg}$), load side inductance ($L$) and load side capacitance($C$). The CL components resonate with the leakage inductance of the transformer as twice the switching frequency of MOSFETs. By using good quality capacitor and air core inductor the resonant frequency will remain constant over the entire range of converter loading. High frequency switching, reduces the size of the transformer; the resonating elements become small; less stress on the MOSFET switches.

In Full bridge converter with secondary resonance, the transformer’s parasitic elements (transformer leakage inductance) are used as resonant elements to transfer energy and to attain soft-switching condition.

High frequency rectifiers are needed to build high power density DC -DC converters. Bridge rectifiers provide a full wave rectification and require a simple transformer with only one secondary winding. However, two diodes are simultaneously ON during each half period. This results in high power losses at a high output current operation. Moreover, voltage drops across the diodes make the full bridge rectifier unsuitable for low output voltage applications. Rectifier losses can be reduced using the centre tapped rectifier.

Constant-frequency, phase-shifted operation of the primary side switches provides a convenient method for achieving zero-voltage turn on of the switches, significantly reducing switching losses where as ZCS cannot be achieved in this arrangement.
A modified version of Full bridge converter for fixed load, acts as a current doubler and the inductor volume is reduced. This converter can replace the conventional FBZVS converter but it has the limitation that two transformer windings are required which will add additional cost, additional leakage inductance and hence the switches of high ratings have to be selected to sustain the leakage currents. FBZVS are not suitable to drive light loads.

PWM based quasi resonant DC-DC converter employs a voltage doubler type rectifier which has no output inductor. Due to the lack of an output inductor, there is no high voltage ringing across the rectifier diode. The variation of the resonant voltage ripple is controlled by the auxiliary circuit and there is no DC offset of the magnetizing current. Thus PWM based quasi resonant DC-DC converter shows efficiency enhancement in case of light loads only.

A current fed full bridge zero current switching converter (FBZCS) will support wide load range with zero current switching based on constant on time. Due to high switching frequency, the size of the transformer is reduced. The inductor volume required is also less; therefore the cost and size of the converter is reduced. The FBZCS converter is devoid of parasitic oscillations, as all of the parasitic capacitances and inductances are included in a resonant tank circuit. The main advantage of such systems is that they include a capacitive output filter, which is preferred in higher voltage applications. Moreover, it achieves ZCS for all active switches and zero-voltage switching (ZVS) operation for all diodes on high voltage side, which is an additional benefit. Still the efficiency and power density has to be improved.

A full bridge buck converter with secondary resonance using secondary side leakage inductance of the transformer is used for soft switching of primary side switches which helps in reducing the stress across the primary switches. The output voltage of this converter is high compared to
conventional FBZVS DC-DC converter. Though it has less loss and higher efficiency, the presence of spikes in the output voltage and current is the major draw back. Moreover high peak to peak ripples will increase heat in the load.

The objective of this research work is to overcome the shortcomings of the earlier configurations such as extending the ZVS range of phase shifted series resonant DC-DC converter. To extend the operation of modified FBZVS for changes in output load. To improvise the efficiency of Quasi resonant PWM converter at high loads. To overcome high reverse recovery losses caused by the diode and to remove the output voltage and current spikes of Full bridge DC-DC converter with secondary resonance. This research work also aims to compare the performance of the above converters to find the best converter for low power applications.

The above literature does not deal with the modeling of closed loop controlled Phase shifted series resonant DC-DC converter (PSRC), modified Full bridge zero voltage switching DC-DC converter (modified FBZVS), Quasi resonant PWM converter (QRPWM), Current-fed full-bridge DC-DC converter with zero current switching (FBZCS), Full bridge DC-DC converter with secondary resonance and Half bridge secondary resonance DC-DC converter with pi filter. The comparison between Phase shifted series resonant DC-DC converter, modified Full bridge zero voltage switching DC-DC converter, Quasi resonant PWM converter, Current-fed full-bridge DC-DC converter with zero current switching and Half bridge secondary resonance DC-DC converter with pi filter.

The configuration of the converter adopted here is soft-switched quasi-resonant converters (QRCs). The rising and falling edges of the waveforms are ‘smoothed’ without transient spikes. The switch current and voltage waveforms are forced to oscillate in a quasi-sinusoidal manner, so that
ZCS and ZVS can be achieved. Output voltage regulation is achieved by controlling the switching frequency. Operation and characteristics of the converter depend mainly on the design of the resonant circuit inductance and capacitance. It has overcome the shortcomings of the early configurations such as switching losses and stresses, electromagnetic interference during the hard switching conditions.

The present work aims to develop soft switching Simulink model for Phase shifted series resonant DC-DC converter, Modified Full bridge zero voltage switching DC-DC converter, Quasi resonant PWM converter, Current-fed full-bridge DC-DC converter with zero current switching, and Full bridge DC-DC converter with secondary resonance to develop the Simulink model of closed loop system for the above converters and to compare them with the open loop system. This work also aims to find the best converter for low power applications.

1.5 OBJECTIVE OF THE THESIS

The objectives of the research work are summarized as follows:

- To model phase shifted series resonant DC-DC converter, Full bridge zero voltage switching DC-DC converter, Quasi resonant PWM converter, Current-fed full-bridge DC-DC converter with zero current switching, Full bridge DC-DC converter with secondary resonance using blocks of simulink and to implement the hardware using Atmel microcontroller and PIC microcontroller.

- To overcome the shortcomings of the earlier configurations such as extending the ZVS range of phase shifted series resonant DC-DC converter. To extend the operation of
modified FBZVS for changes in output load. To improvise the efficiency of Quasi resonant PWM converter at high loads. To remove the voltage spikes and ripples of Full bridge secondary resonance converter.

- To compare phase shifted series resonant DC-DC converter, Full bridge zero voltage switching DC-DC converter, Quasi resonant PWM converter, Current-fed full-bridge DC-DC converter with zero current switching and Half bridge secondary resonance DC-DC converter with pi filter.

Design validation is done using MATLAB/SIMULINK then experimental design is executed. Atmel 89c2051 Microcontroller and 16F84A PIC are used as controllers for generating pulses. Based on input and output design values the transformer is selected. Cut toroidal ferrite core features exact air gap avoiding saturation. The leakage inductance of the transformer is calculated and for a desired switching frequency a range of L and C components are found. Larger the value of inductance lesser the ripples. Larger the value of capacitance lesser the voltage stress on the rectifier side and induces high ripple current. Tuning of the capacitor and resistor in the PI controller to optimum value, results in better performance.

1.6 ORGANIZATION OF THE THESIS

The thesis includes eight chapters. The organization of the thesis is as follows:

The first chapter presents the importance of soft switching, types of soft switching methods, Quasi resonant converters, the general introduction to the problem and the previous investigations reported in the literature. The
difficulties and draw backs in present converters are identified. It concludes with the statement of the main objective of the work presented in the thesis.

Phase shifted series resonant DC-DC converter is analysed, simulated, tested, and the results are presented in the second chapter.

The third chapter presents the modeling, simulation and hardware implementation of the modified full bridge zero voltage switching DC-DC.

The fourth chapter presents the modeling, simulation and hardware implementation of the Quasi resonant PWM converter.

The fifth chapter presents the modeling, simulation and hardware implementation of the Current-fed full-bridge DC-DC converter with zero current switching.

The sixth chapter presents the modeling, simulation and hardware implementation of the full bridge DC-DC converter with secondary resonance and proposed half bridge secondary resonance DC-DC converter with pi filter. The suitable converter is designed using MATLAB.

The seventh chapter compares the performance of the phase shifted series resonant DC-DC converter, Full bridge zero voltage switching DC-DC, Quasi resonant PWM converter, Current-fed full-bridge DC-DC converter with zero current switching, and Half bridge secondary resonance DC-DC converter with pi filter.

Chapter eight concludes with the work done in this research and discusses scope for further research in this area.
1.7 METHODOLOGY

Based on theoretical calculations, using analytical equations for switching frequency the value of capacitance and inductance are calculated. These theoretical values are used in simulation tool for validating the design parameters.

Assumptions and constraints are defined and followed. When the applied values give results matching the theoretical ones, experimental phase commences. Once the hardware prototype matches with the verified simulation results, the cycle ends. To analyze the converter, mathematical design is done followed by design validation using MATLAB and then finally experimented.

The converter’s operating range of switching frequency varies from 30 kHz to 300 kHz. The switching stresses of the converters are analyzed. Conversion of 48V to 12V is done at a switching frequency of 38.3 kHz. The results are compared using simulation and experiment.

1.8 SUMMARY

This chapter builds the basic background for understanding DC to DC converters. Importance of soft switching and types of soft switching are discussed. Quasi resonant converters are discussed. The introduction, objectives, concepts such as ZCS and ZVS and the organization of the thesis are presented in this chapter. Details of the literature on DC to DC converters are also presented.