Chapter 3. Soft Switching Inverter

3.1 Introduction

The soft switching inverter normally uses the resonant technique to reduce or eliminate the switching loss so that the inverter can be operated at high switching frequencies. Soft switching improves the system performance with elimination of acoustic noises, alleviation of harmonics and electromagnetic interferences (EMIs) in a power system. However, the resonant circuit generally introduces either over-voltage or over-current in the main switches of the inverter. In resonant dc link inverter which employs a resonant inductor-capacitor circuit to supply a resonating voltage across inverter bridge, the resonant link voltage is twice the supply voltage at no load [Divan 1986]. This over voltage is clamped to 1.3 to 1.4 times with added components [Divan 1987], resulting in higher cost and reliability penalties. In clamped mode resonant pole inverter [Cheriti 1992], resonant inductors and capacitors are added at the output of each phase with diodes across each resonant capacitor to clamp the capacitor voltage. This diode causes a circulating current to flow in the main inverter devices, reducing the efficiency of inverter [Lai 1994]. To avoid over-voltage and over-current problems many soft switching techniques have been proposed [Lai 1990, DeDoncker 1991, McMurray 1993, Vlatovic 1993, Cuadros 1994]. The basic concept of these soft-switching techniques is to employ an auxiliary switch for zero-voltage transition control. The auxiliary switch does not turn-on until the main switches require a transition from one state to another state. When the auxiliary switch turns-on, a resonant pulse diverts the current from upper or lower switch to its opposite side diode, thus allowing the main switch to turn-on at zero voltage. The auxiliary switch is turned-off when the current swings back to zero. Among these soft switching inverters, the resonant snubber based inverter is a suitable choice for single phase UPS application. The required zero voltage operation is achieved with reduced components. The rating of auxiliary switch is only a fraction of the main switches, and the main switches do not have any over-voltage or over-current problem. For more accurate operation the parasitic capacitance of devices can be utilized as the resonant capacitor. Also this configuration has simple control strategy and with suitable choice of resonant inductor value it can be used for variable load current also.

3.2 Resonant Snubber Based Soft Switching Inverter [Lai 1996, Lai1997, and Yu 2002]

A single phase full bridge resonant snubber based soft switching inverter is shown in Fig.3.1.

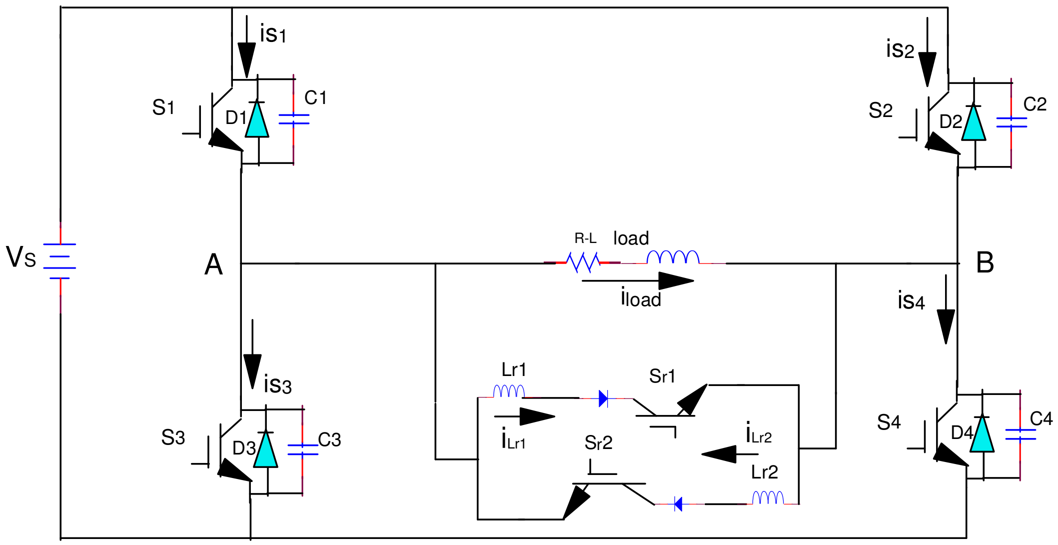

Fig.3.1 Resonant snubber based soft switching inverter

Zero voltage switching (ZVS) condition for the main switches S_1-S_4, are created by two auxiliary branches connected across the load. Auxiliary branch consists of one resonant inductor L_r, one auxiliary switch S_{r1} and one diode. Resonant capacitors C_1-C_4 are connected across the main switches. These resonant capacitors may be the internal capacitance of the devices. Resonant capacitors allow the main devices to turn-off at lossless condition. Anti-parallel diodes D_1-D_4 are connected across the main switches.

For ZVS, the auxiliary switch is turned-on with calculated pre turn-on time and delay time depending upon the load current and the maximum resonant current i_{Lr}. When the auxiliary switch is turned-on, it provides an additional path to the load current, forcing current in the resonant inductor to increase linearly. When the inductor current becomes equal to the load current, the main switch pair of one leg can be turned-off at zero current condition. When all devices are off, resonance occurs between the resonant inductor and resonant capacitor. The resonance creates the zero voltage condition for the main switches to achieve soft-switching condition at turn-on.

Various operating modes to achieve ZVS for main devices of one leg are described below.

Mode 0 (t_0-t_1): Analysis starts with an assumption that the positive load current is free-wheeling through diodes D_2 and D_3 while switches S_2 and S_3 remain on, as shown in Fig. 3.2(a). Capacitors C_1 and C_4 are charged to a voltage equal to V_s with polarity marked. Voltage and current status of main switches and resonant elements shown in fig. 3.2(b) for this mode are given below.

$i_{s1}= 0$; $i_{s2}= I_L$; $i_{s3}= I_L$; $i_{s4}= 0$; $i_{Lr1}= 0$; $i_{Lr2}= 0$; $v_{c1}= +V_s$; $v_{c2}= 0$; $v_{c3}= 0$; $v_{c4}= +V_s$

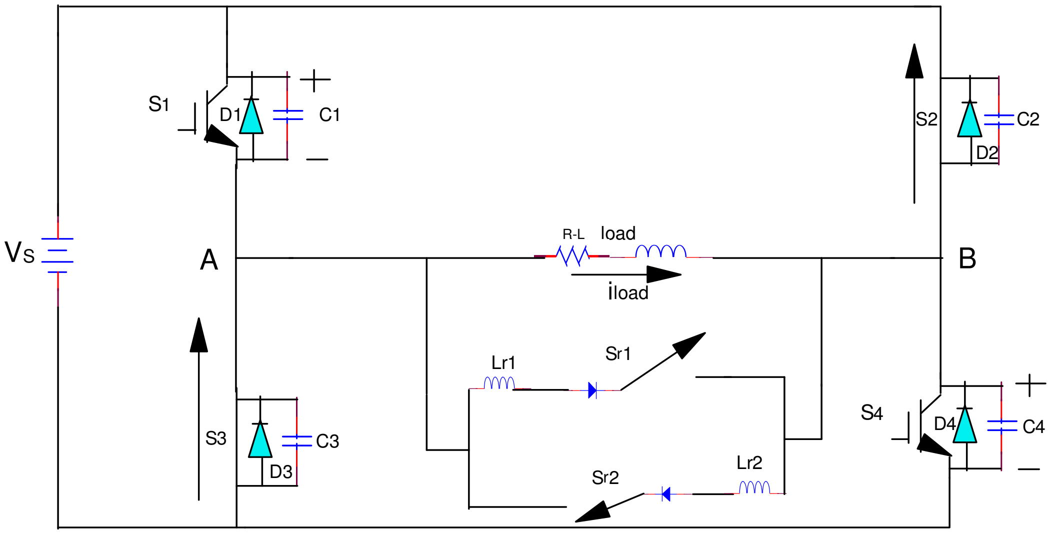

Fig. 3.2(a) Mode 0 (t_0-t_1)

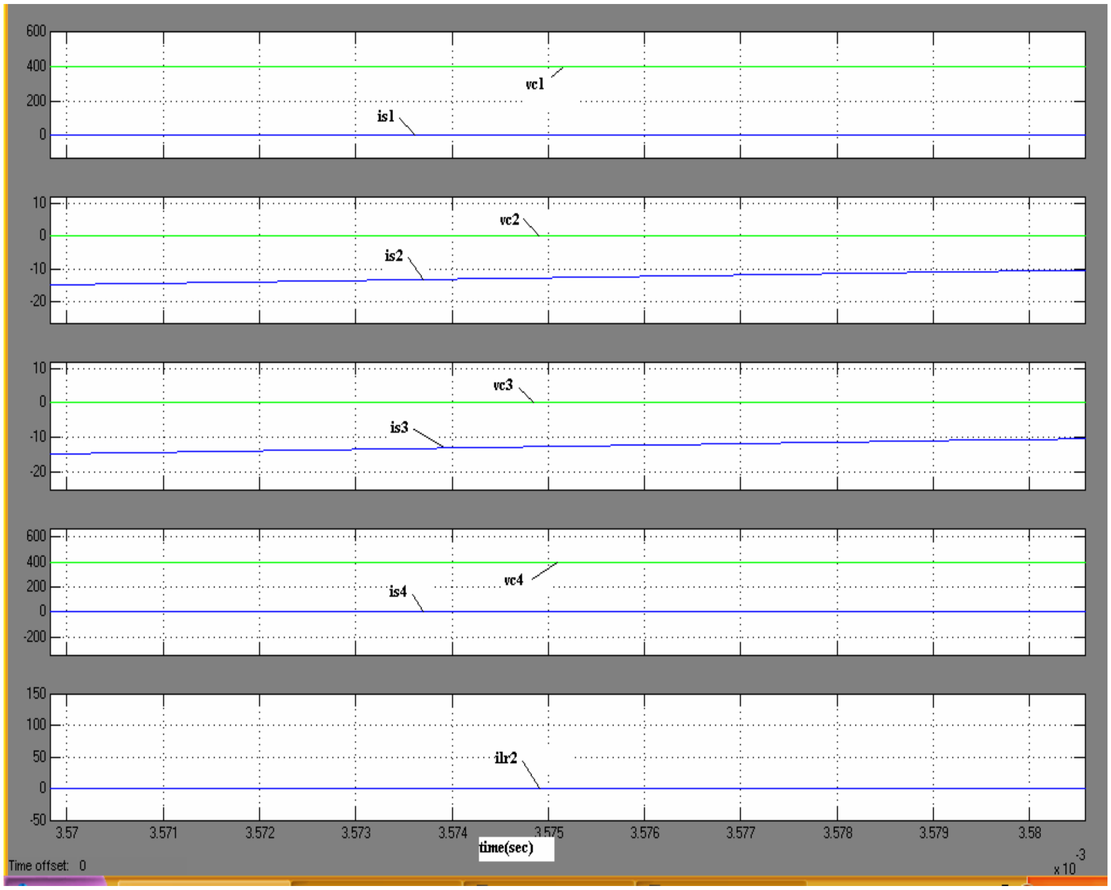

Fig. 3.2(b) Voltage and current status of devices and resonant elements in mode 0
(Voltage is in volts and current is in amp)

Mode 1 (t_1-t_2): The resonant switch S_{r2} is turned on at t_1. A part of the load current is now diverted through the resonant inductor L_{r2} which builds up linearly. Assuming the load current to be constant, current in switches S_2 and S_3 decrease linearly to zero at time t_2 when the resonant current becomes equal to the load current. Circuit for this mode is shown in Fig.3.3 (a). Voltage and current status of main switches and resonant elements shown in fig. 3.3(b) for this mode are given below.

$i_{s1}= 0$; i_{s2} and i_{s3} start decreasing from the load current I_L; $i_{s4}= 0$;

$i_{Lr1}= 0$; i_{Lr2} starts increasing linearly and reaches the load current value I_L;

$v_{c1}= +V_s$; $v_{c2}= 0$; $v_{c3}= 0$; $v_{c4}= +V_s$.

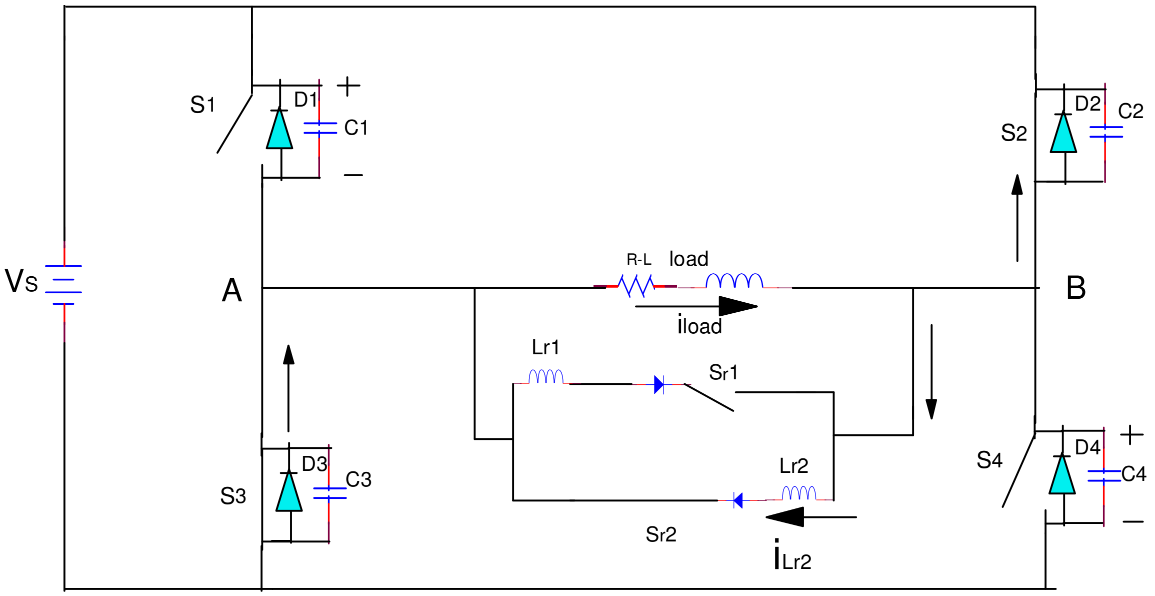

Fig. 3.3(a) Mode 1 (t_1-t_2)

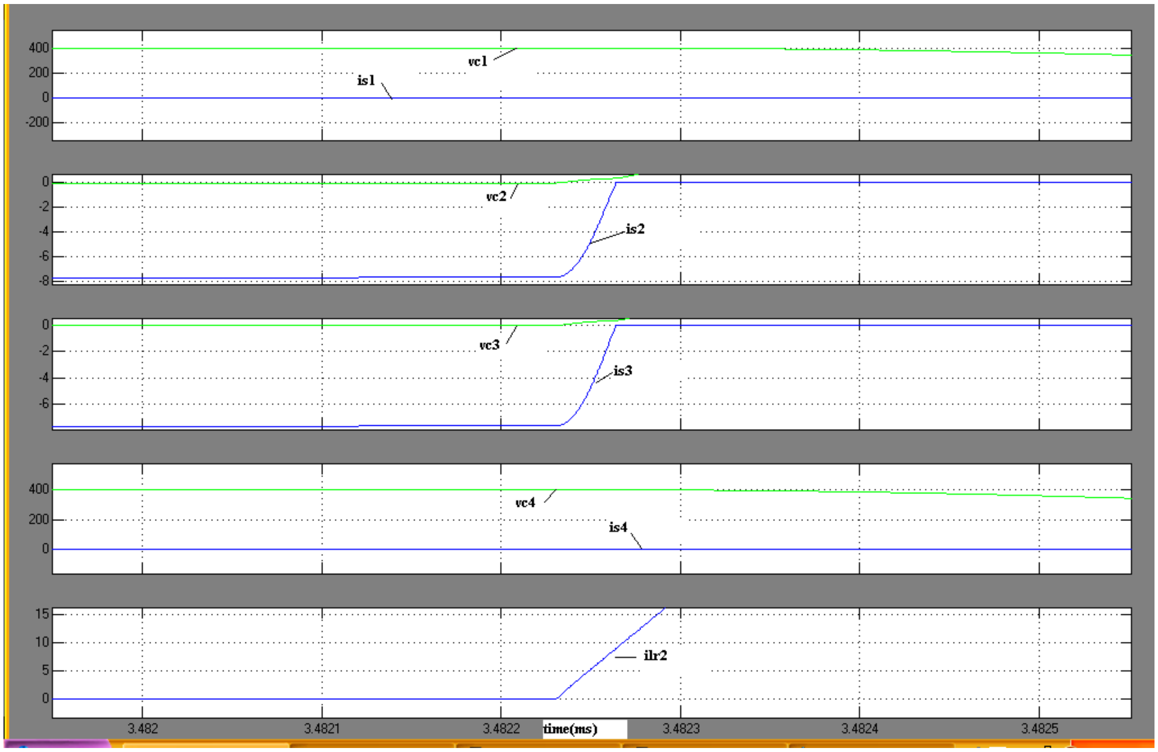

Fig. 3.3(b) Voltage and current status of devices and resonant elements in mode 1
(Voltage is in volts and current is in amp)

Mode 2 (t_2-t_3): Fig. 3.4. Shows circuit configuration for mode 2.

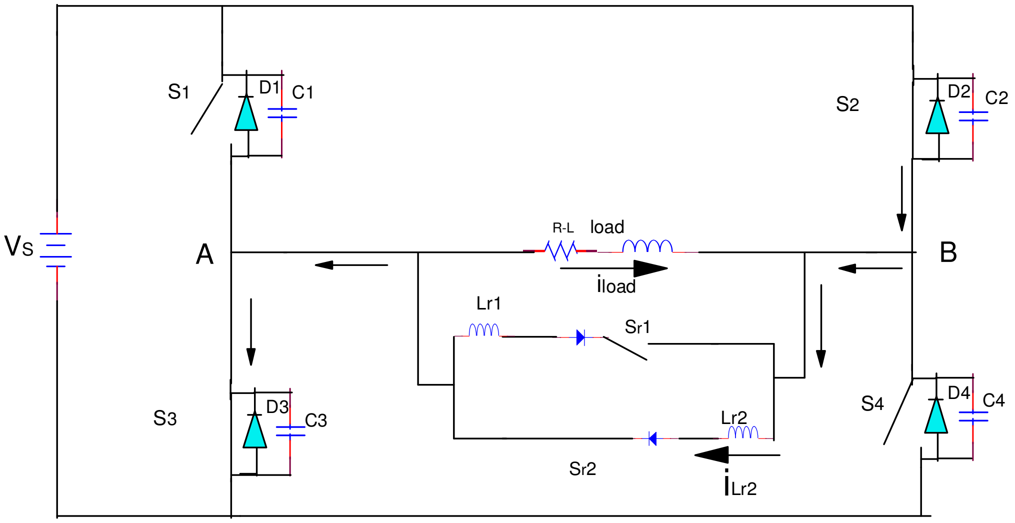

Fig. 3.4(a) Mode 2 (t_2-t_3)

In this mode, the inductor current exceeds the load current after t_2. This creates a zero-current turn-off condition for devices S_2 and S_3 and can be turned off after t_2.

Voltage and current status of main switches and resonant elements shown in fig. 3.4(b) for this mode are given below.

$i_{s1}= 0$; $i_{s2}= 0$; $i_{s3}= 0$; $i_{s4}= 0$; $i_{Lr1}= 0$; $i_{Lr2}= I_L$; $v_{c1}= +V_s$; $v_{c2}= 0$; $v_{c3}= 0$; $v_{c4}= +V_s$

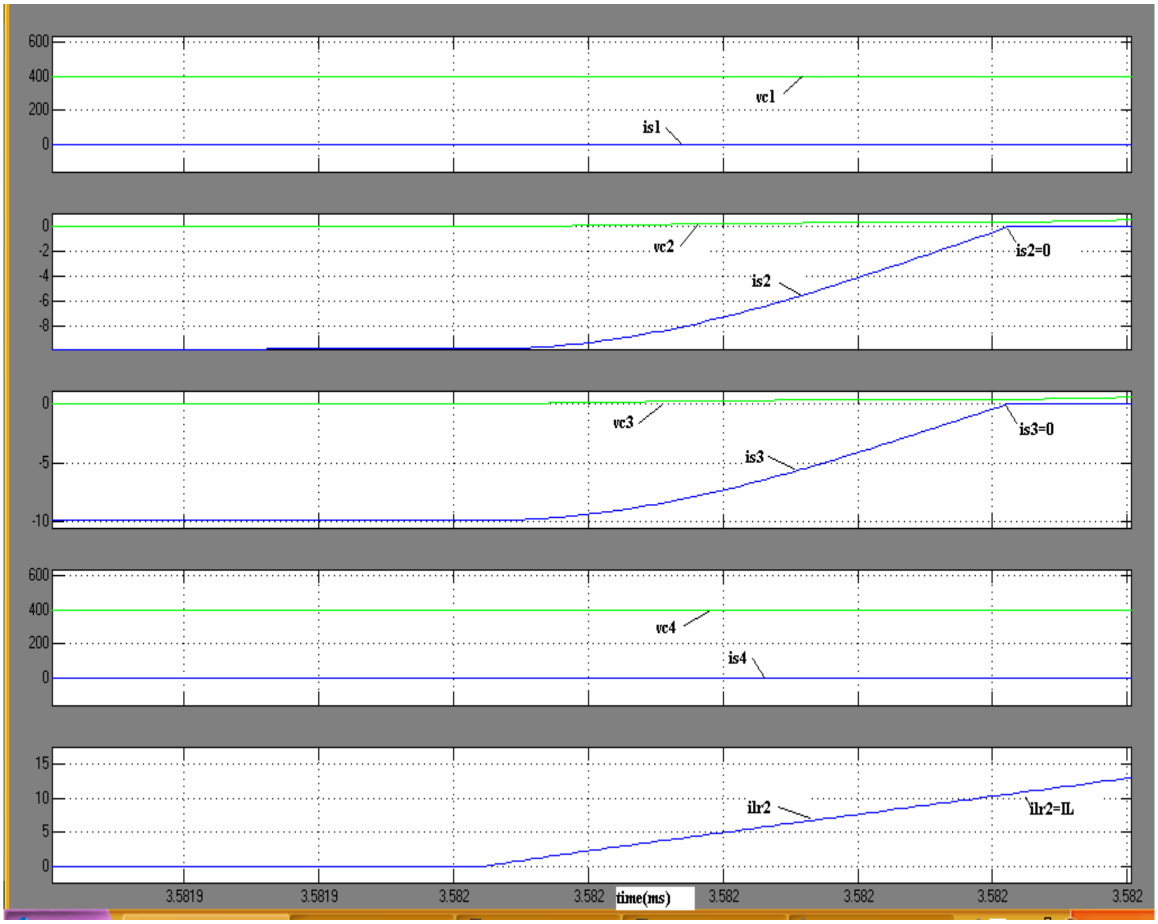

Fig. 3.4(b) Voltage and current status of devices and resonant elements in mode 2
(Voltage is in volts and current is in amp)

Mode 3 (t_3-t_4): During this mode, resonance starts between resonant inductor Lr2 and snubber capacitors**.** Current increases in the resonant inductor and reaches its peak value. Exchange of energy takes place between capacitors and inductor forcing capacitors C_2 and C_3 to charge to full voltage, V_S, and C_1 and C_4 to discharge to zero voltage at t_4. This creates a zero-voltage condition for switch1 and switch2. Circuit configuration for this mode is shown in Fig. 3.5(a).

Voltage and current status of main switches and resonant elements shown in fig. 3.5(b) for this mode are given below.

$i_{s1}= 0$; $i_{s2} = 0$; $i_{s3} = 0$; $i_{s4}= 0$;

$i_{Lr1}= 0$; i_{Lr2} = resonant current; v_{c1} and v_{c4} start decreasing and discharge to zero voltage; v_{c2} and v_{c3} start increasing and charge to full voltage V_s;

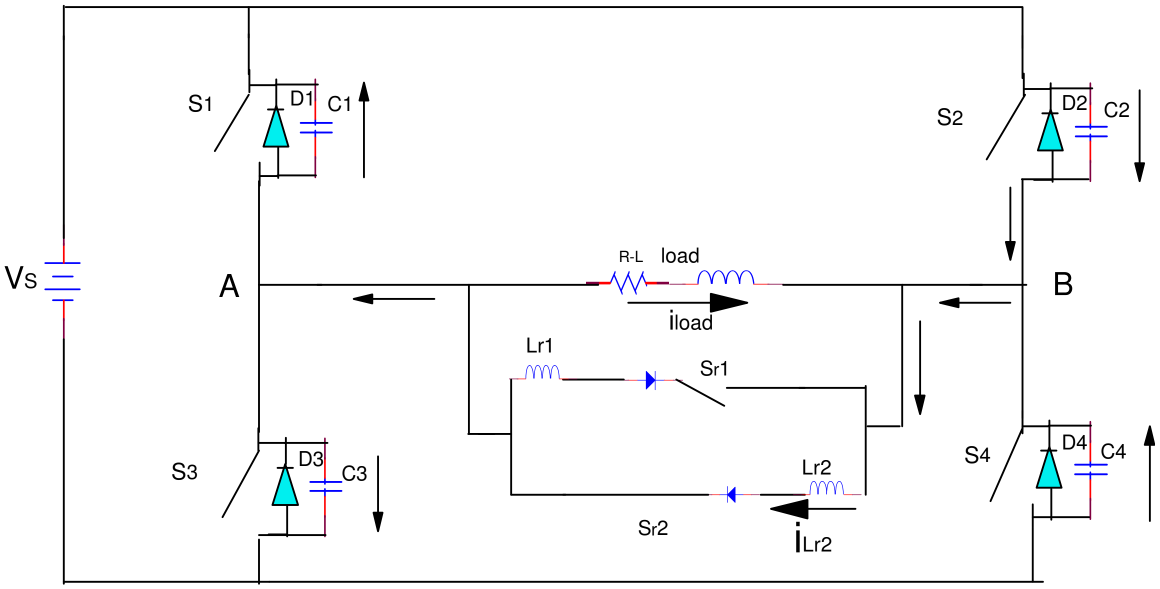

Fig. 3.5(a) Mode 3 (t_3-t_4)

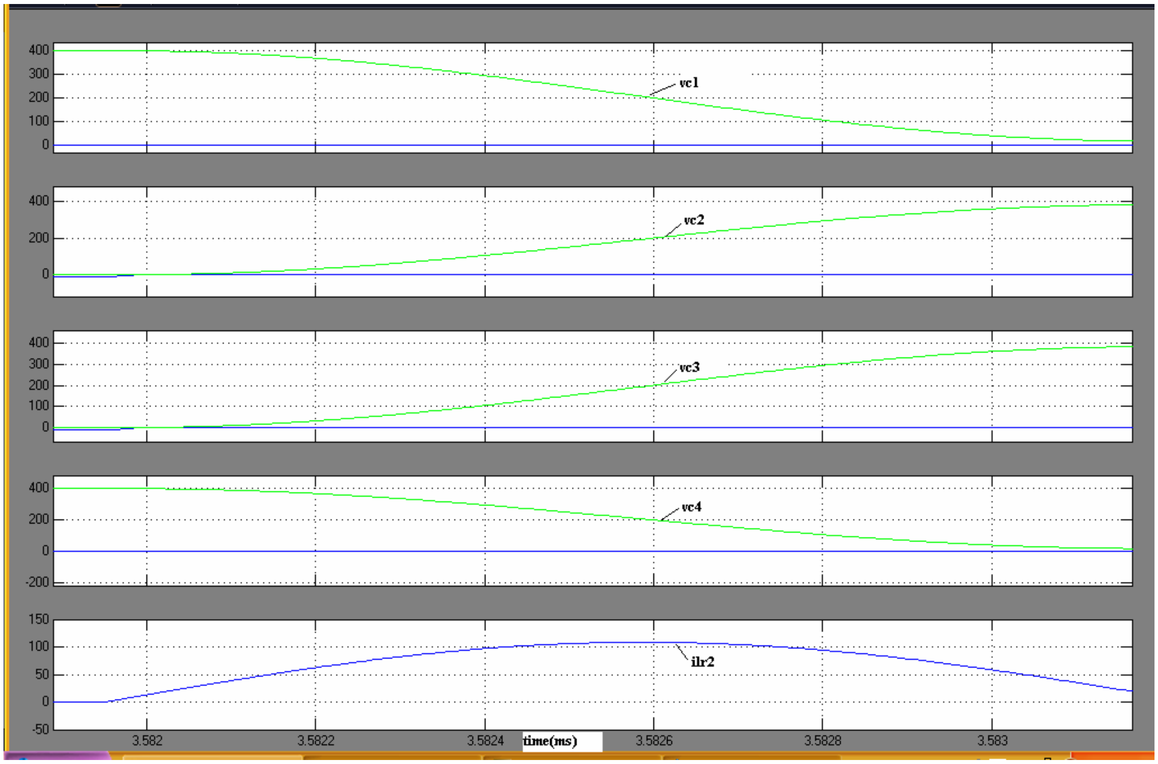

Fig. 3.5(b) Voltage and current status of devices and resonant elements in mode 3
(Voltage is in volts and current is in amp)

Mode 4 (t_4-t_5): In this mode, load current is diverted to diodes D1 and D4 due to decrease in resonant current. At time t_5, the resonant current equals the load current, and the diode current is diverted to the switch. Circuit for this mode is shown in Fig. 3.6.

Mode 5 (t_5-t_6): In this mode of operation switch current increases linearly and reaches the load current at t_6. Resonant inductor current $i_{Lr2,}$ decreases to zero, making a zero-current turn-off condition for auxiliary switch S_{r2}. This is shown in Fig. 3.7.

Some oscillation is seen in voltage and current waveforms during turn-on transition. This oscillation is due to snubber resistance in the block parameter of MOSFET in the SIMULINK block which can not be avoided. This is shown in Fig. 3.8

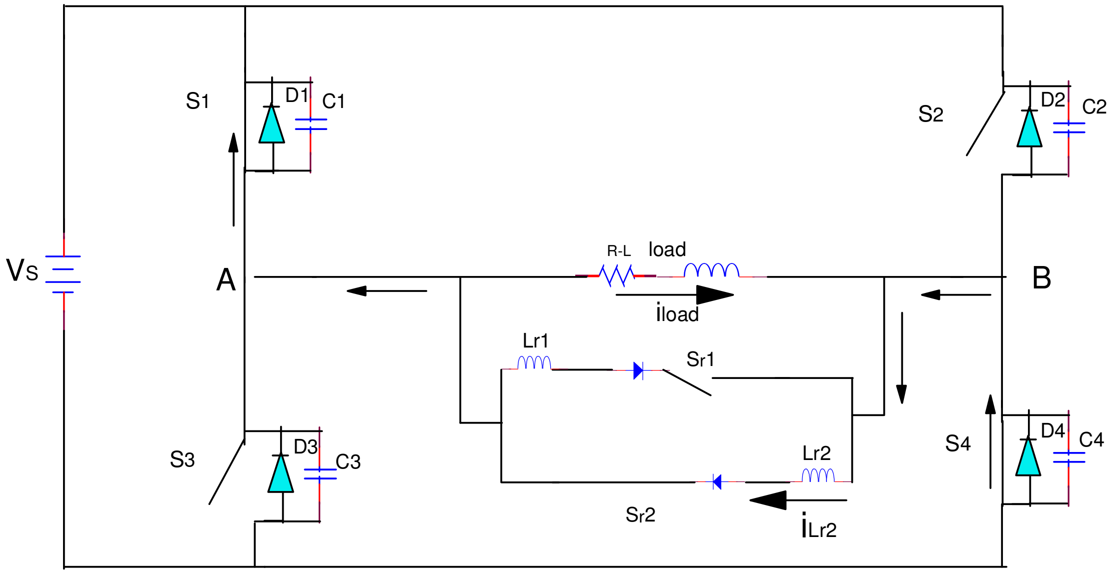

Fig. 3.6 Mode 4 (t_4-t_5)

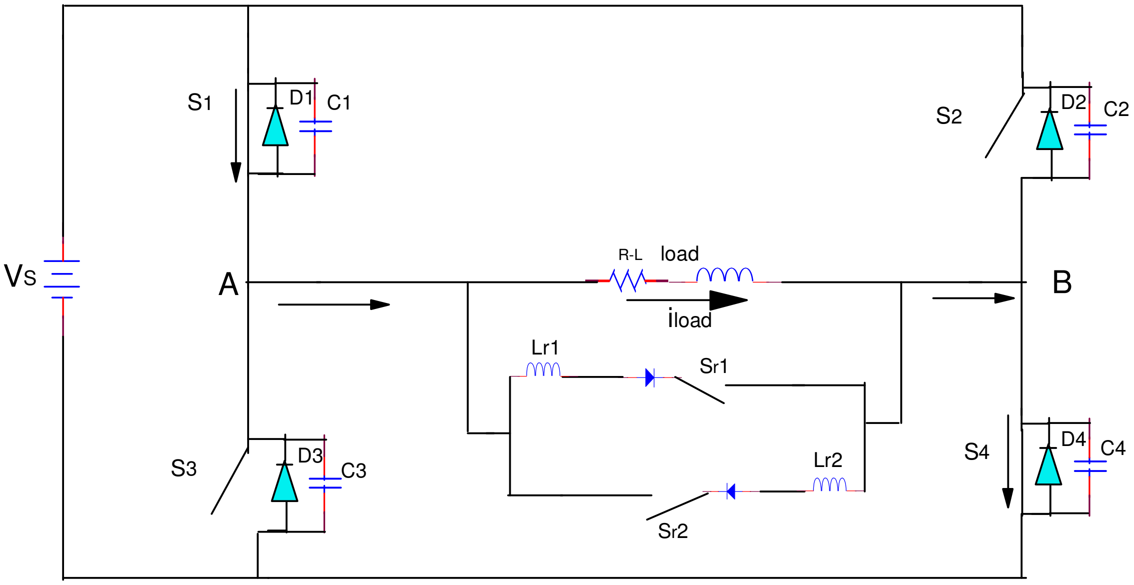

Fig. 3.7 Mode 5 (t_5-t_6)

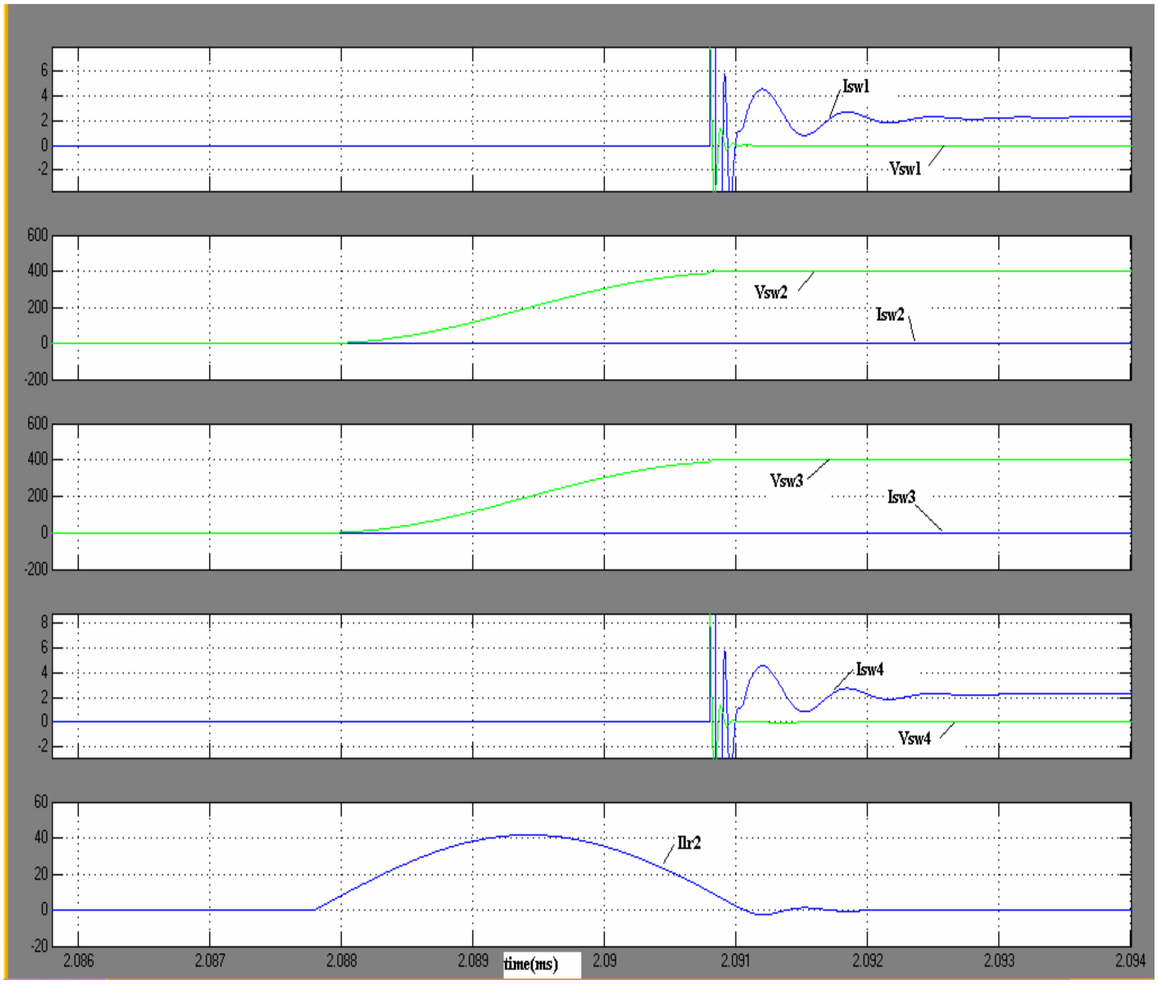

Fig. 3.8 Oscillations in switch voltage and current during turn-on transition

(Voltage is in volts and current is in amp)

Fig. 3.9 shows theoretical waveforms at different operating modes for the auxiliary resonant snubber based soft switching inverter.

A simplified theoretical waveform for one switch pair under ZVT of resonant snubber based soft switching inverter is shown in Fig. 3.10.

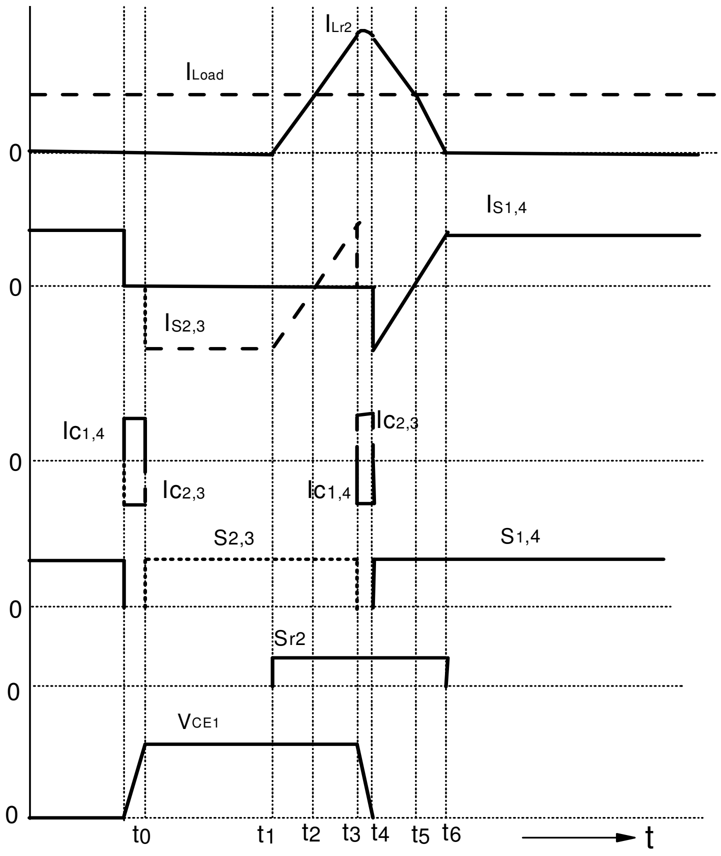

Fig.3.9. Waveforms showing different operating modes

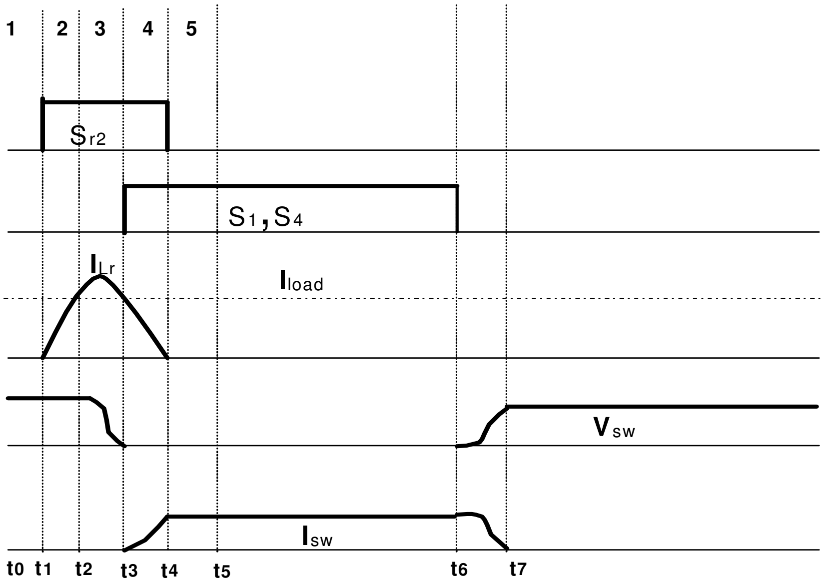

Fig. 3.10 Theoretical waveform for one switch pair under ZVT

3.3 Design Criteria [Yu 2002]

The main aim is to achieve zero voltage instant during the resonant stage so that, the main switches can be turned-on at or near zero voltage condition. Precise switching instant is obtained by suitable selection of resonant inductor and resonant capacitors depending on the load current and on-time of auxiliary and main switches. Current in resonant inductor starts building at time t_1 (fig. 3.10) in a linear fashion given by

$$i_{Lr} = \frac{V_{DC}}{L_r}(t_2 - t_1) \tag{1}$$

At time t_2, (fig. 3.9) when inductor current becomes equal to the load current, resonance starts and current in the inductor is given by

$$i_{L_r}(t) = i_L + \frac{V_{DC}}{Z}\sin(\omega t) \tag{2}$$

Voltage across the resonant capacitor is given by

$$V_{C_r}(t) = V_{DC}(1 - \cos(\omega t)) \tag{3}$$

Where

$$Z = \sqrt{\frac{L_r^*}{C_r^*}} \quad ; \quad \omega = \frac{1}{\sqrt{L^*_r C^*_r}} \quad ; \quad T_r = 2\pi\sqrt{L^*_r C^*_r} \tag{4}$$

And, T_r is duration of natural resonant cycle.

The equivalent circuit of resonant stage is given in the fig. 3.11

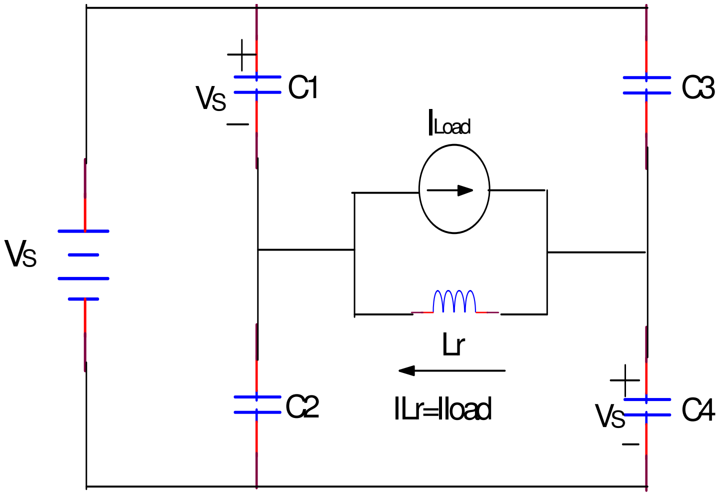

Fig. 3.11 Equivalent circuit of resonant stage

The equivalent resonant inductor and capacitor, L_r^* and C_r^* respectively are given by

$$C_r^* = \frac{(C_1 + C_2)(C_3 + C_4)}{C_1 + C_2 + C_3 + C_4} \qquad L_r^* = L_r \tag{5}$$

The simplified circuit of resonant stage with initial conditions is shown in Fig. 3.12.

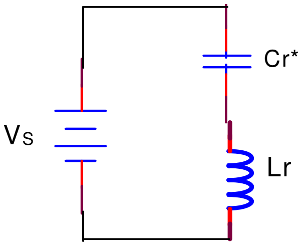

Fig. 3.12 Simplification of resonant stage circuit

For $C_1 = C_2 = C_3 = C_4$, we have $C_r^* = C_r = C_1$. The final equivalent circuit is simply LC resonant tank .

The maximum current in resonant inductor is given by

$$I_{MAX} = I_{Load} + \frac{V_{DC}}{Z} \tag{6}$$

The auxiliary switch is turned-on before the main switch with a pre-turn-on time (T_{pre}). This is the interval from t_1 to t_3, which is the sum of inductor charging time T_1 and the resonant stage duration, T_2.

$$T_1 = L_r^* \frac{I_{Load}}{V_{DC}}; \qquad T_2 = \pi\sqrt{L_r^* C_r^*} \tag{7}$$

A quality factor Q (Z) is defined as the ratio of T_2 to T_1, as given by

$$Q(Z) = \frac{T_2}{T_1} = \frac{V_{DC}}{I_{Load}} \frac{\pi}{Z} \tag{8}$$

The exact zero voltage instant for the main switch can be calculated for by calculating T_1 and T_2. This is the ideal condition for ZVS instant when we have lossless circuit components. Further, since this calculation depends on the load current also, any variation in loading condition will cause deviation in the switching instant of zero voltage instant. To achieve exact zero voltage instant under variable loading condition, a variable timing control with extra sensing elements is needed. To meet this condition without variable timing control, resonant inductor and resonant capacitors are chosen such that the resonant duration is much greater than the inductor charging time i.e. the quality factor is sufficiently large with fixed pre-turn-on time, $T_{pre} = T_{1(normal)} + T_2$, where $T_{1(normal)}$ is the charging time under normal load condition.

If the main switch is turned-on a little earlier or later due to the load current variation, the voltage will only swing back to a finite amplitude, but close enough to zero-voltage condition.

Peak resonant current depends on the tank impedance Z. For lower value of peak resonant current higher value of Z is required which is obtained by small resonant capacitor and large resonant inductor. Zero voltage turn-on condition for a wide range of loading condition is achieved when $T_2 >> T_1$. It requires large L_r and small C_r so that condition is satisfied. So, a suitable value of tank impedance becomes an important parameter.The capacitor value can be selected based on dv/dt requirement and turn-off loss. The resonant inductor value can be calculated with predetermined Z, and the pre-turn-on time of auxiliary switch is optimized at the rated load condition.

3.4 Design Procedure [Yu 2002]

To avoid variable timing control which depends on the loading condition, quality factor Q (Z) of resonant tank impedance Z is kept large enough to meet zero voltage turn-on condition. The peak resonant current I_{MAX} is kept near four times the load current.

Resonant inductor L_r and capacitors C_r are selected to minimize dv/dt and to obtain proper resonant time T_r. Snubber capacitor C_r value is selected to minimize the turn-off loss. After selecting the resonant elements, the pre turn-on time of the auxiliary switch, T_{pre} , and the turn-on duration of the auxiliary switch, T_{aux} is determined. T_{pre} is the sum of the pre-charging time T_1 and resonant period T_2. T_1 is load current dependent and is chosen under static load current condition. Since T_2 is much larger than T_1, the variation of T_1 will not affect much of the near zero voltage condition. T_{aux} is the turn-on duration of the auxiliary switch and is kept larger than $2T_1 + T_2$ duration.

3.5 Simulation Results

Fig. 3.13 shows the SIMULINK block which generates the control pulses for main and auxiliary switches to achieve ZVT and Fig. 3.14 shows the SIMULINK block of soft-switching inverter.

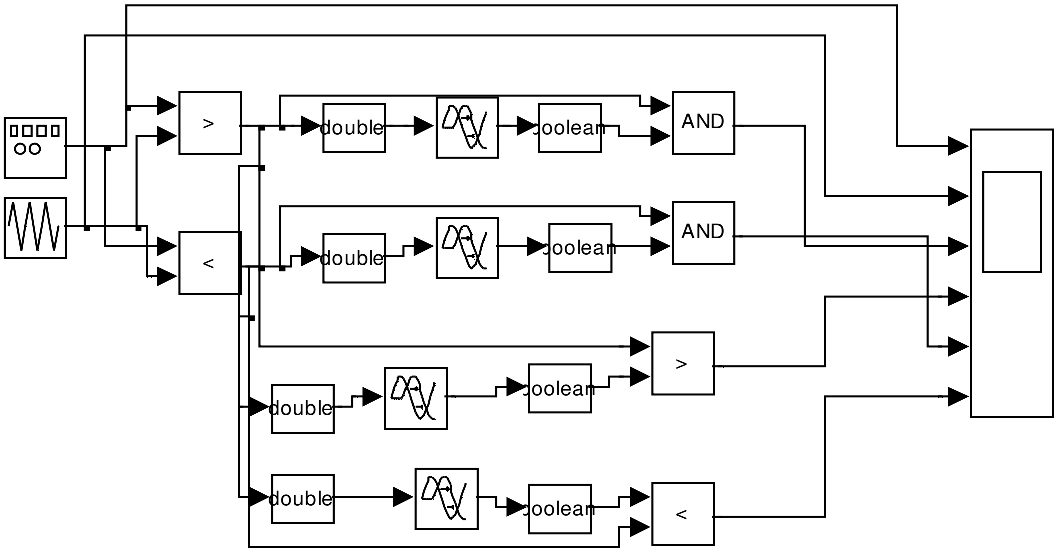

Fig.3.13 SIMULINK block for main and auxiliary pulse generation

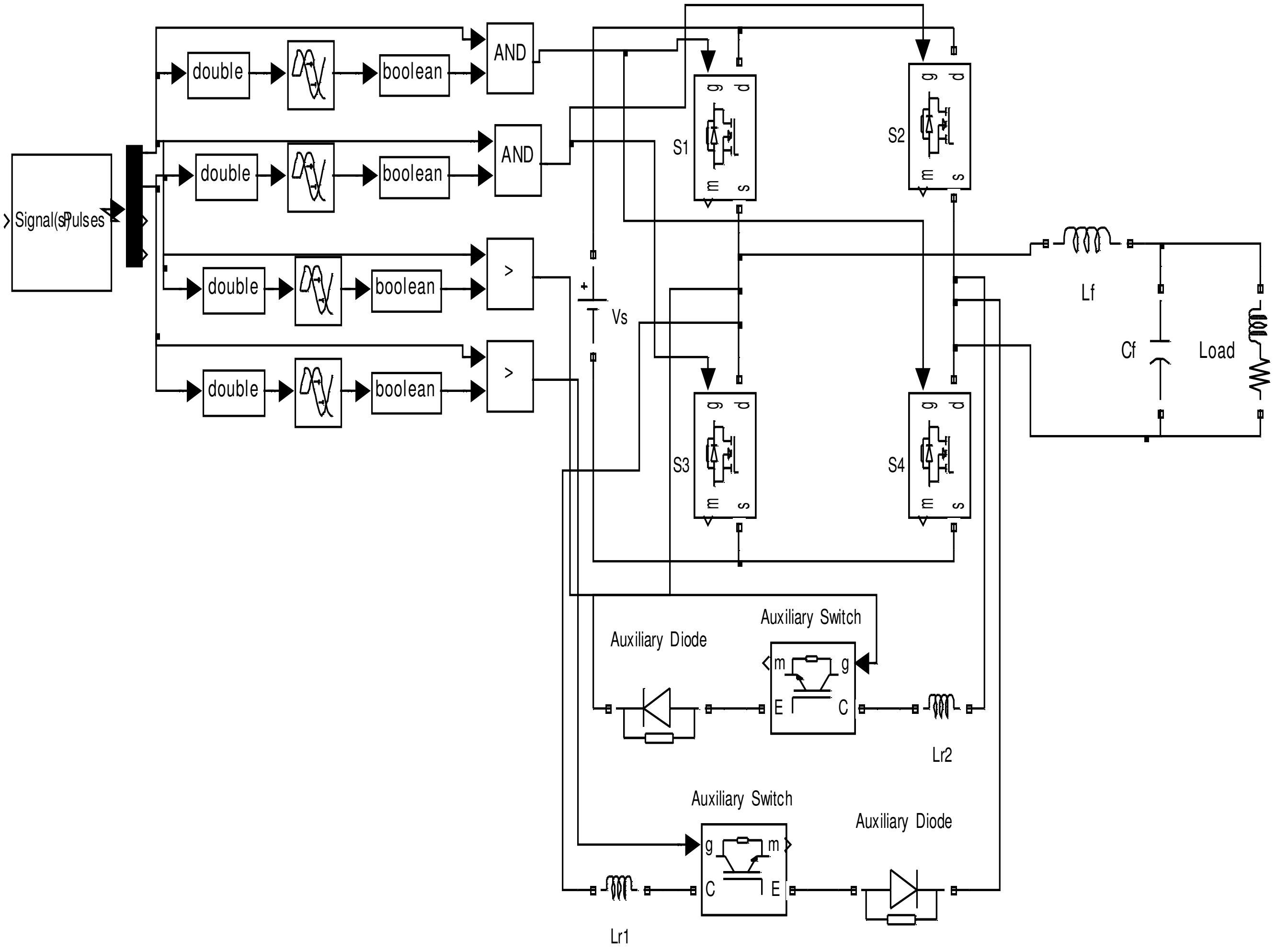

Fig.3.14 SIMULINK block of soft-switching inverter

Control pulses generated by SIMULINK block are shown in Fig. 3.15 and Fig. 3.16. It shows control pulses for one cycle and a closer view.

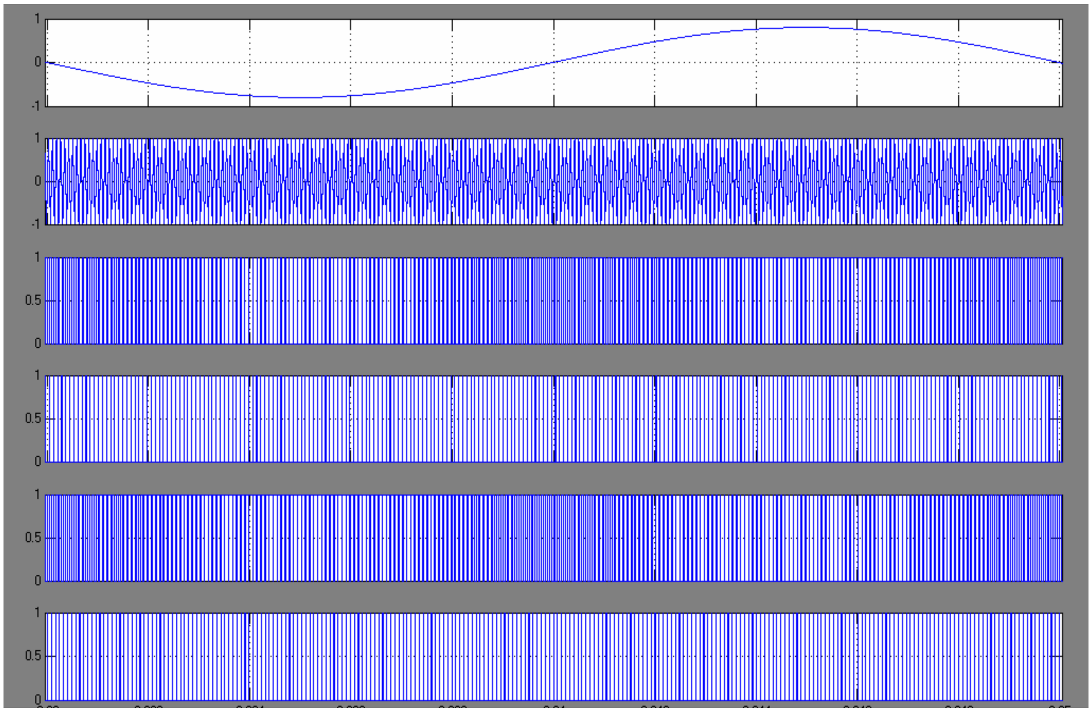

Fig. 3.15 SPWM control pulses for auxiliary and main switches for one cycle

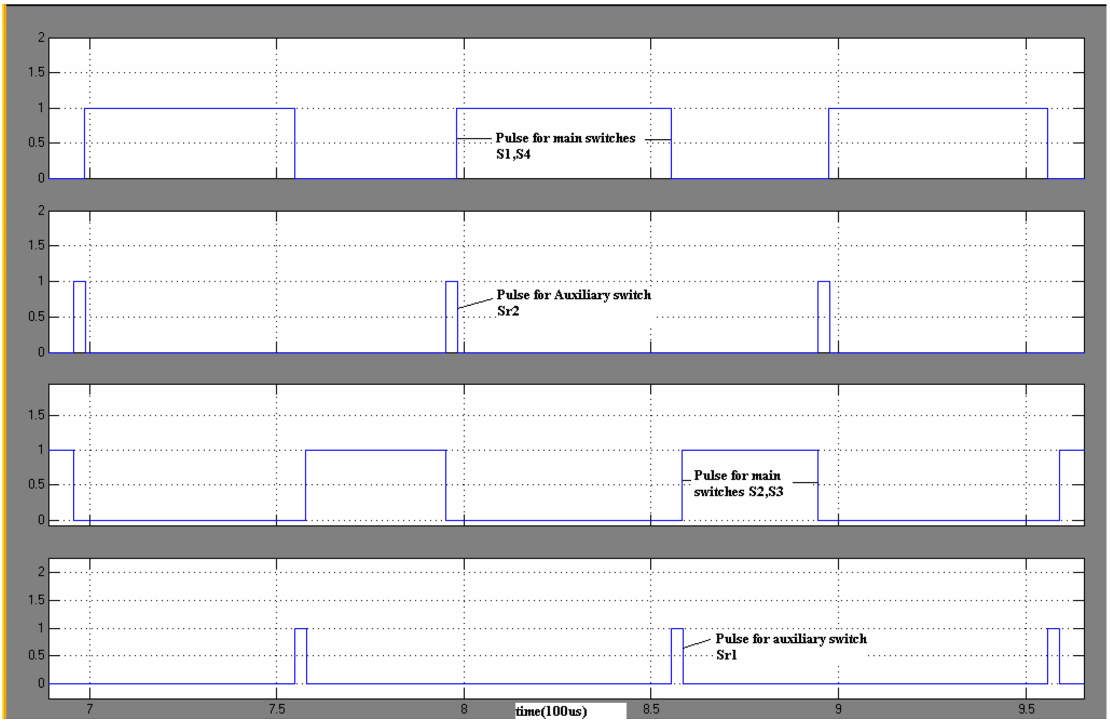

Fig. 3.16 Control pulses for main and auxiliary switches

Fig. 3.17 shows the simulated waveforms under ZVT scheme. Switch voltage, resonant inductor current and load currents are shown to verify the design.

Fig. 3.18 shows resonant inductor current with main and auxiliary switch gate pulses. Resonant inductor current is there for the auxiliary switch pulse duration and it extends for short duration of main switch pulse also as desired.

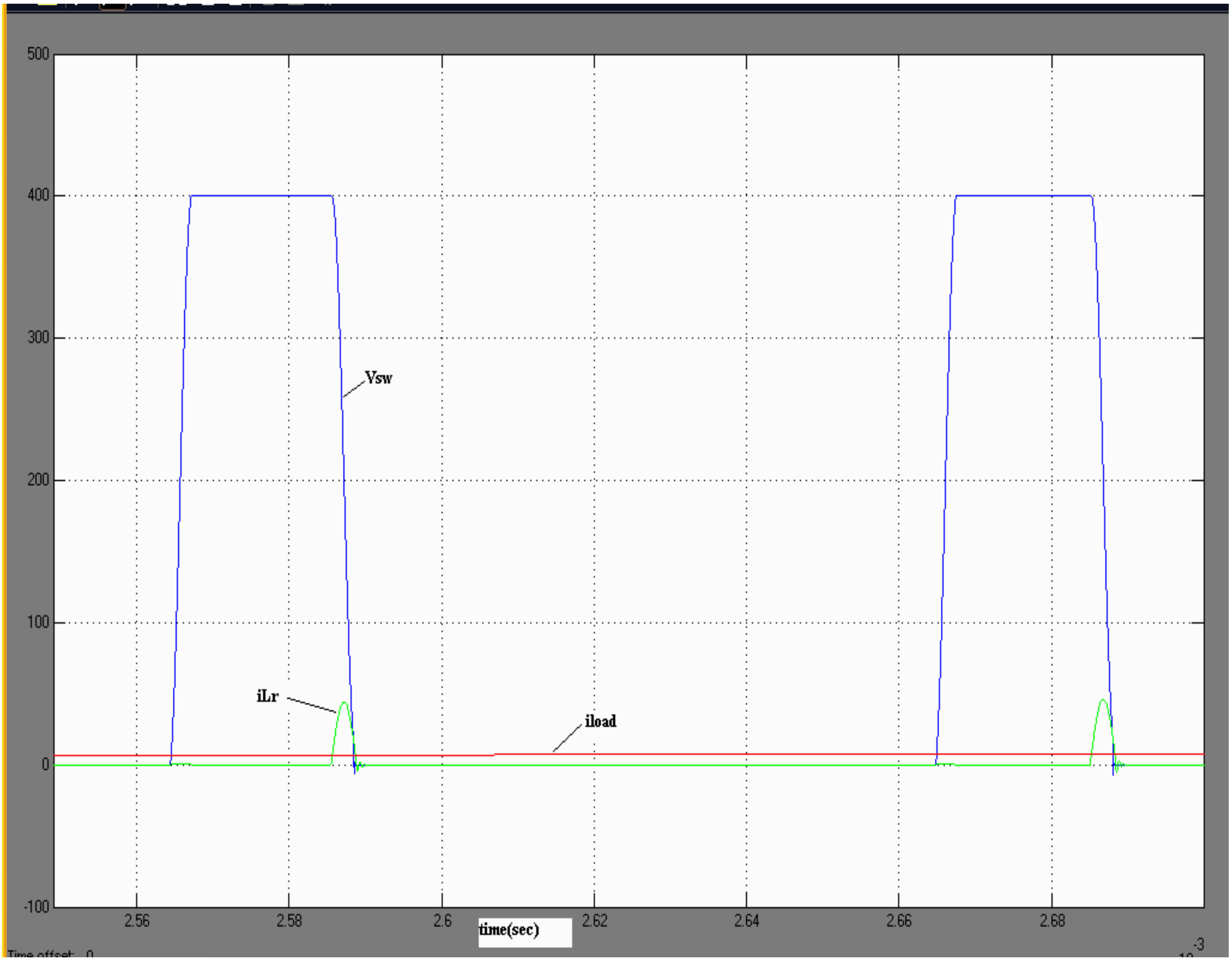

Fig.3.17 Simulated waveform under ZVT scheme (Current is in amperes and voltage is in volts)

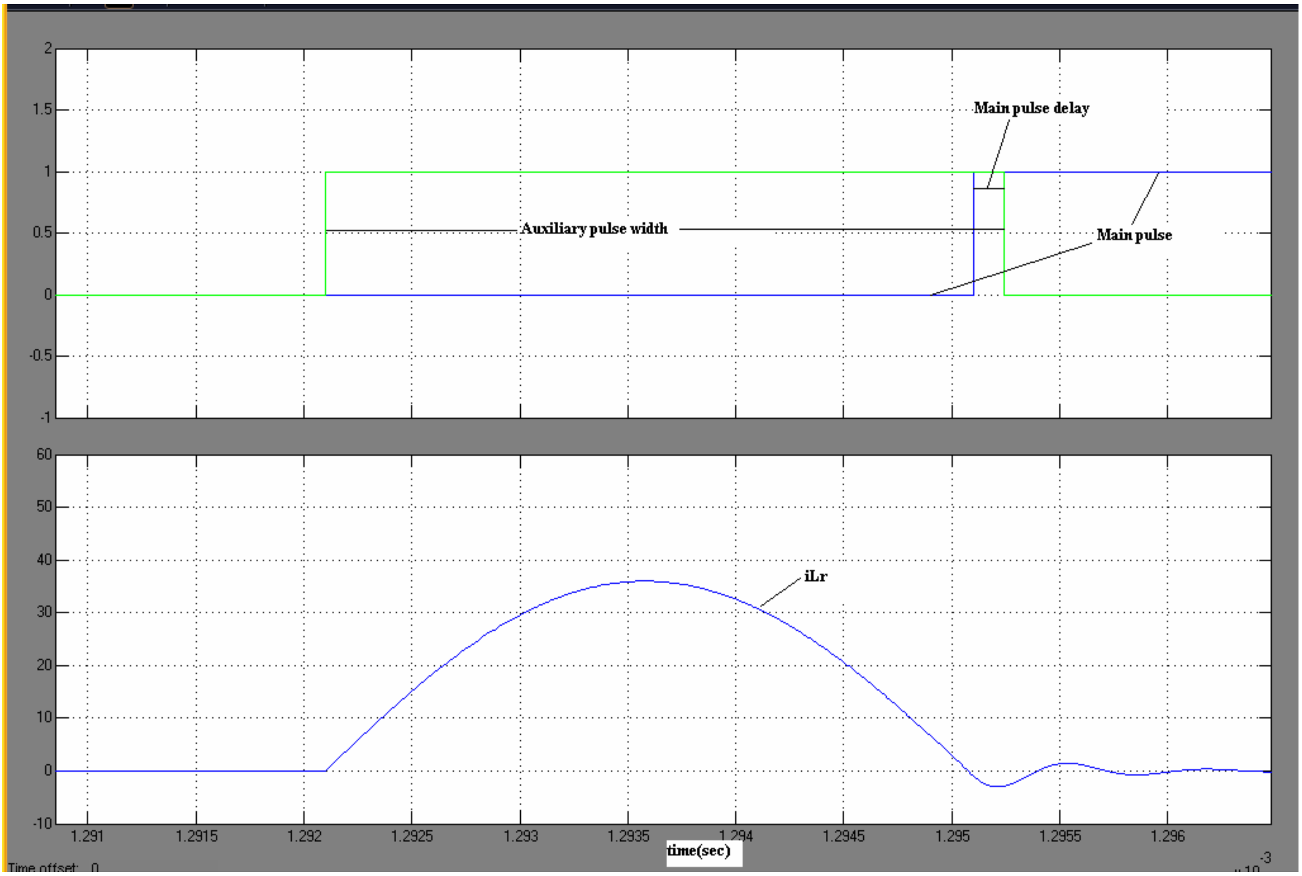

Fig. 3.18 Resonant current waveform with main and auxiliary switch pulses (current is in amperes)

Fig. 3.19 (a) - (f) shows switch voltage and resonant inductor current at different loading conditions. Distortion is observed when the load current is much higher than the rated current as shown in Fig. 3.19 (e) and (e). For clarity the switch voltage has been scaled down to 100V to adjust in the graph.

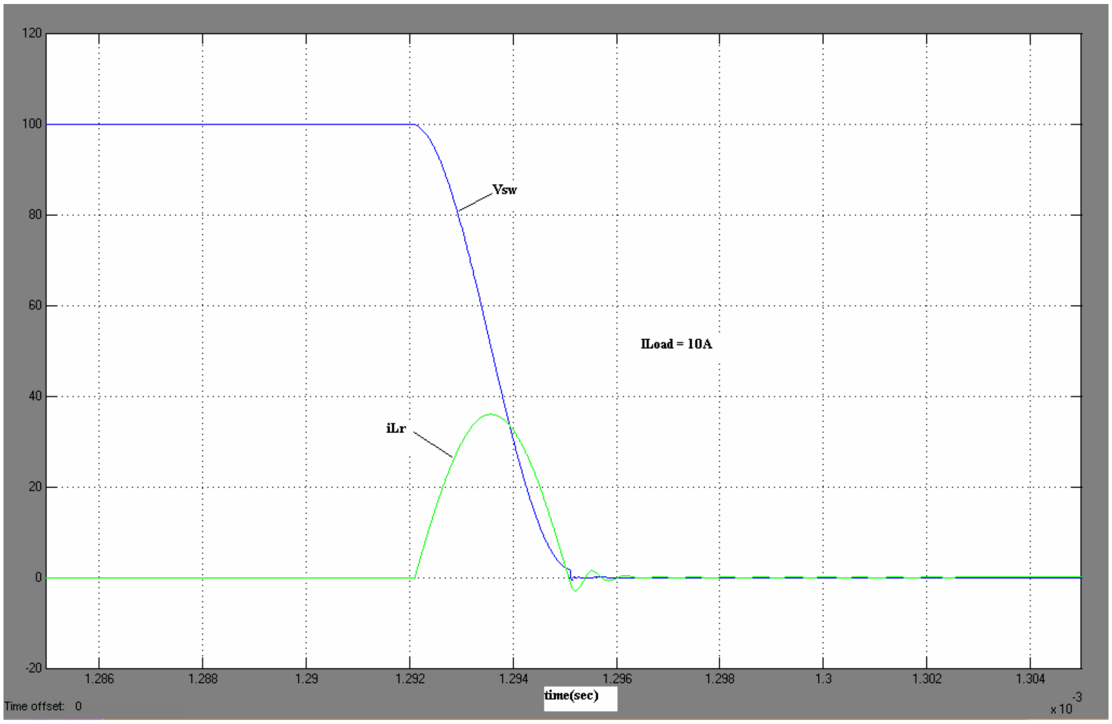

Fig. 3.19 (a)

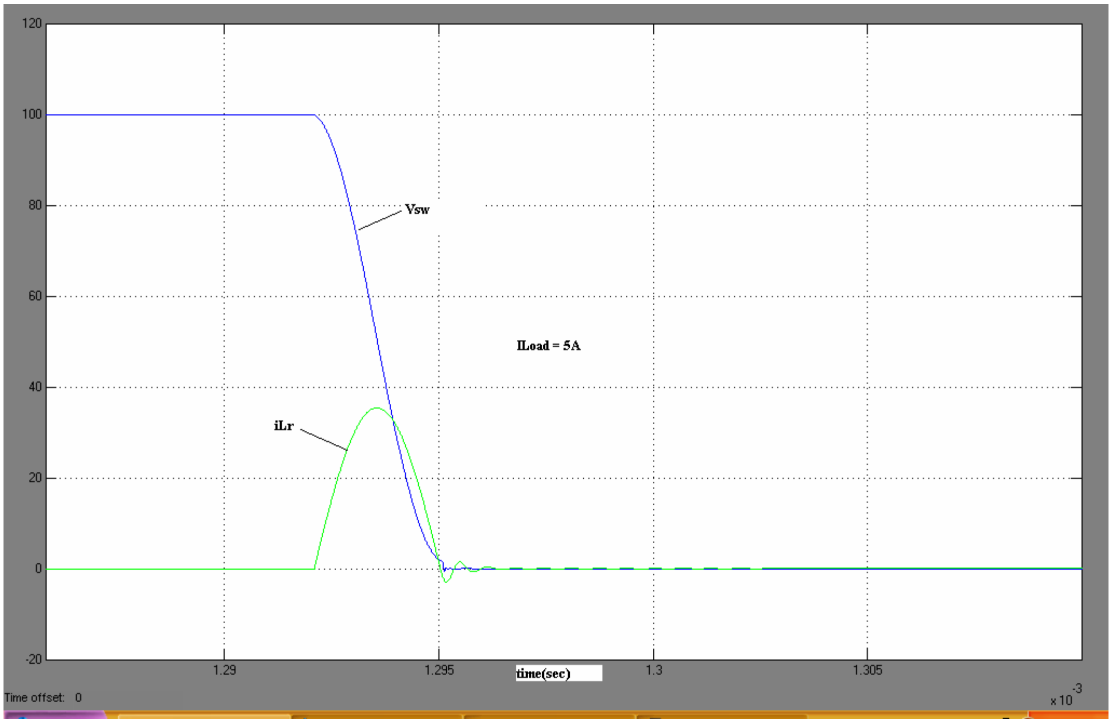

Fig. 3.19 (b)

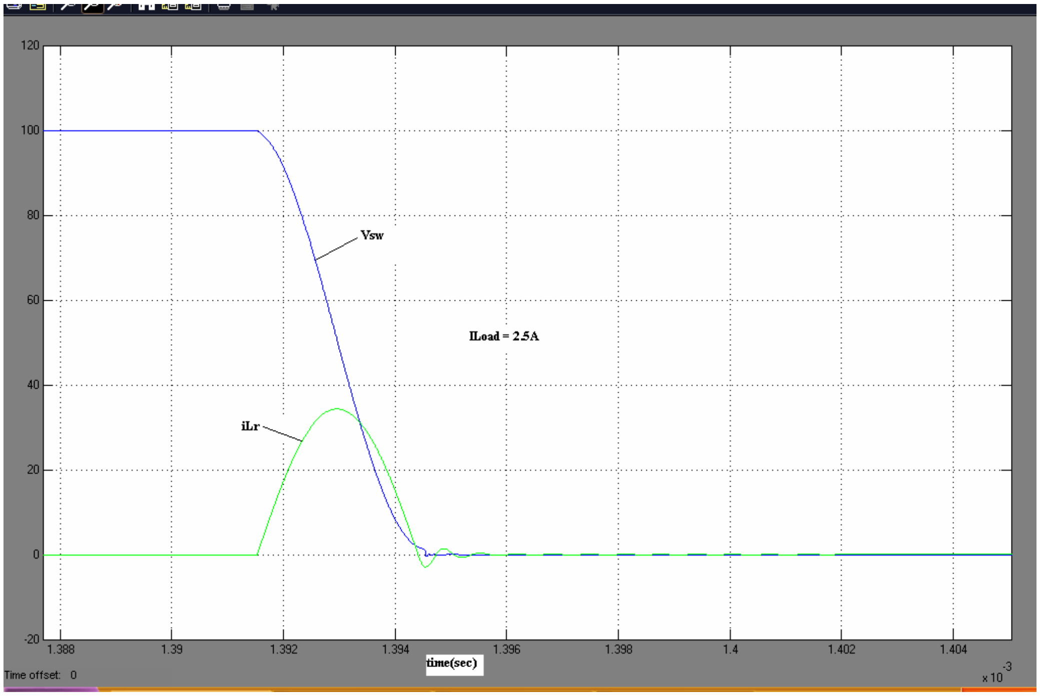

Fig. 3.19 (c)

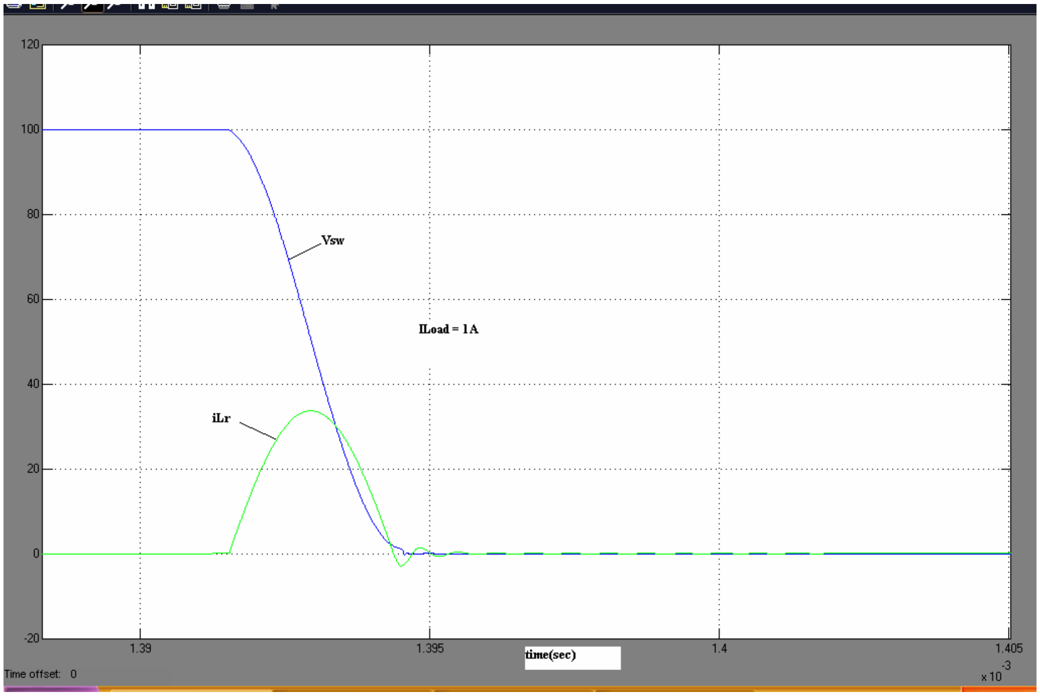

Fig. 3.19 (d)

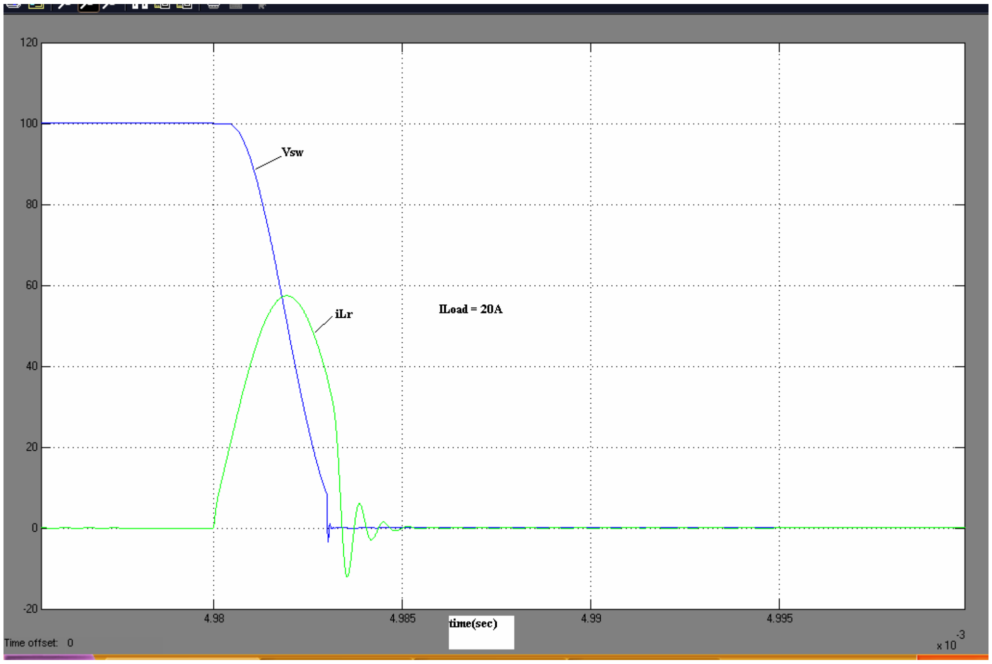

Fig. 3.19 (e)

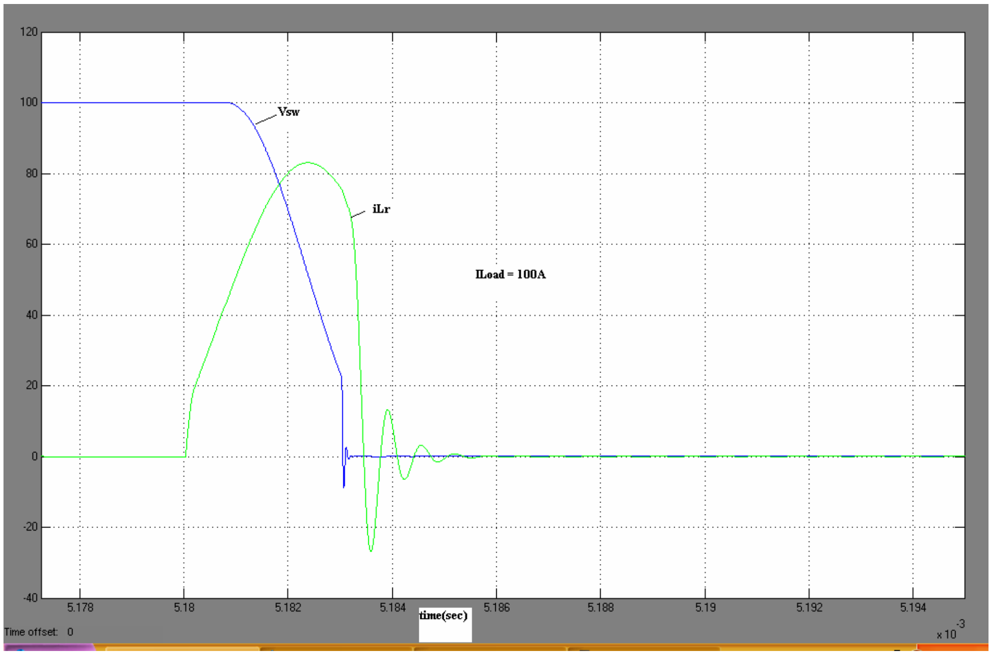

Fig. 3.19 (f)

Fig. 3.19 (a)-(f) Switch voltage and resonant current at various load currents (voltage is in volts and scaled down to ¼ th of its value and current is in amperes)

Device voltage and current for hard and soft switch conditions are shown in Fig. 3.20 and Fig. 3.21 respectively. Switch waveforms under hard switching condition clearly shows the overlap of voltage and current waveform for a longer duration with more spike in the current waveform. However, the switch waveforms under soft switching condition have reduced overlap with low spike in the current waveform, leading to lower switching loss.

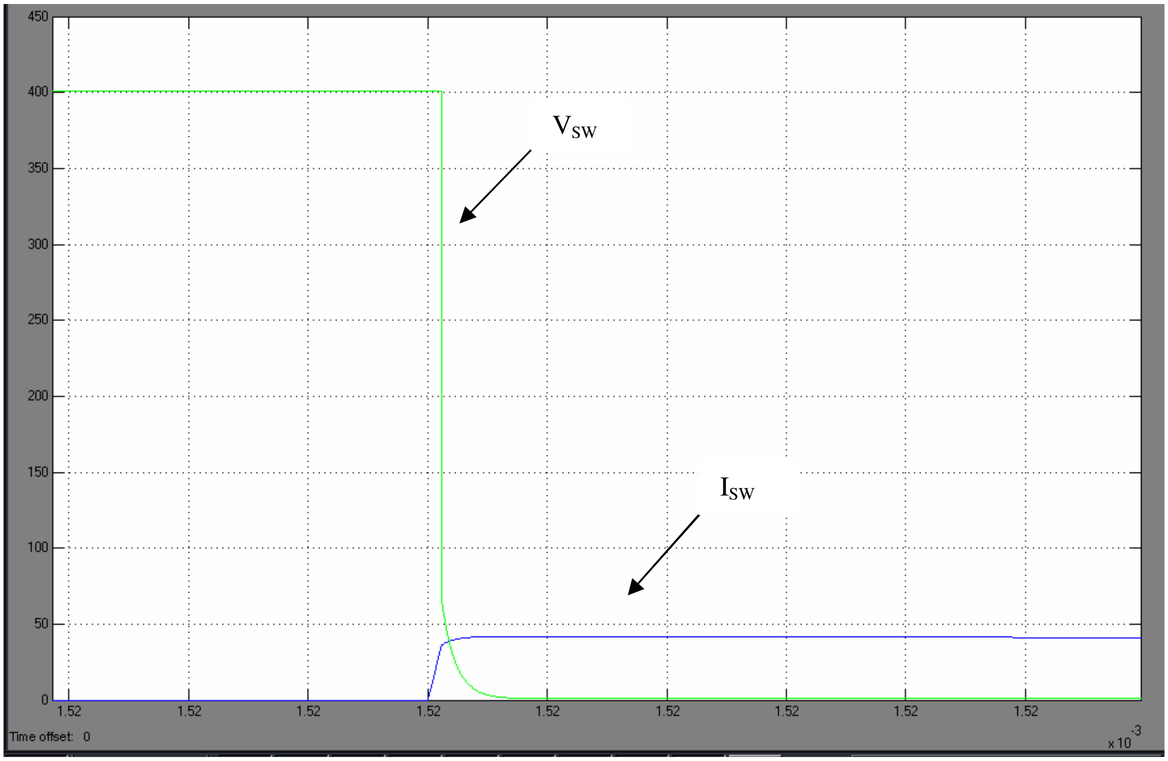

Fig. 3.20 Device voltage (volts) and current (amp) waveform during turn-on for hard switching (time axis scale is in sec)

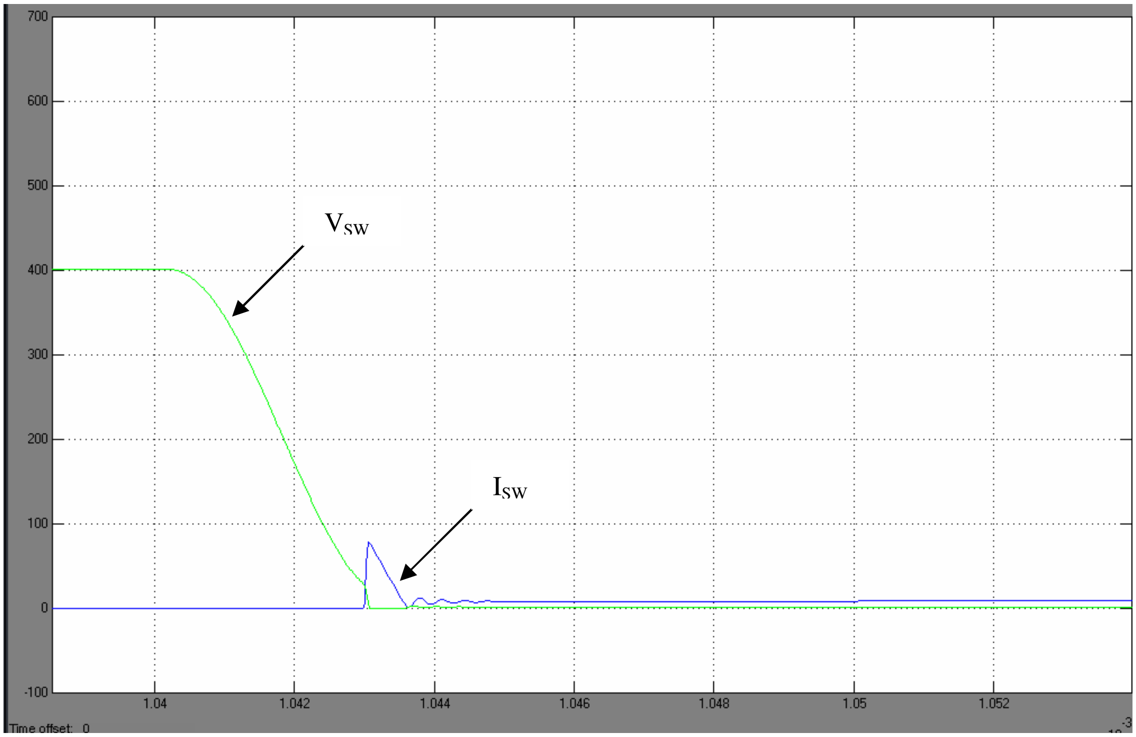

Fig. 3.21 Device voltage (volts) and current (amp) waveform during turn-on for soft switching (time axis scale is in msec)

Designed Parameters:

V_{dc} = 400V **I_{load} = 10A**

R_{load} = 25Ω **L_{load} = 15mH**

L_r = 10µH **C_r = 0.1µF**

Z= 10 **Q = 12.56**

T_{aux} = 4µs **T_{pre} = 3µs**

T_1 = 0.25µs **T_2 = 3.14µs**

3.6 Conclusions

Simulation results are presented for a soft switching SPWM inverter with an output voltage of 230V at a frequency of 50 Hz. Soft switching is achieved by connecting two auxiliary branches in parallel to the load. Auxiliary (resonant) branch parameters are calculated to meet the ZVT condition. Switching waveforms are observed under ZVT condition and found to be satisfactory to meet the requirement of near zero voltage condition. Resonant inductor current for various load currents are also measured with switch voltage to confirm the ZVT condition under variable load conditions.