Simulation of Soft-Switched Three-Phase Inverter for RL and Induction Motor Load

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Abstract

In this paper a new Quasi-Resonant topology is proposed for soft-switching of all three-phase inverter switches for both positive and negative DC link current. This soft-switched three-phase inverter is proposed for a frequency of 400 Hz. The topology consists of four switches, two resonant inductors, and a capacitor. It will provide zero voltage switching condition for obtaining soft-switching in all inverter switches when the switching frequency is exceeding the limit. The soft-switching operation of inverter is explained in terms of modes for both positive and negative DC link current. A simulation model of soft-switched three-phase inverter for RL and induction motor load is developed using MATLAB software.

Keywords: *MATLAB, ZVS, Soft-Switching, Three-phase, Inverter, MOSFET*

1. Introduction

Inverter is a device which convert DC power into AC power at desired output voltage and frequency by using power electronic devices. When the power switches of conventional pulse width modulated (PWM) inverter operate in switch mode so that due to hard switching during turn on and turn off process, the power electronic device has to withstand high current and voltage simultaneously resulting high stress and switching power losses, These switching losses is proportional to switching frequency of PWM inverter, thus limiting the switching frequency of conventional PWM inverter. When switching power losses are increases the efficiency of inverter is reduce and also large amount of heat produce inside the inverter, which forces to use larger heat sink for industrial personnel which causes volume and weight of the system is increased and also system suffer from EMI.

Today soft-switching technique is very important in modern technology. In this technique zero voltage and zero current switching were used which improved the performance as compared to hard-switched PWM Inverter [1]. Soft switching technique developed from load resonant to quasi resonant reported in [2-5]. In quasi-resonant technique resonant network is activated during resonant interval to enable soft-switching [5]. Quasi-resonant DC link for voltage source inverter have been reported in [5-10].

A two switch resonant link inverter is reported for operates with unity power factor load [5]. A two switch quasi-resonant topology having displacement factor equal to 0.88 legging can be handle passive load [7]. A resonant snubber based topology in [8] is proposed for active and passive load. The modify topology of quasi-resonant technique [9], this modify topology has a limitation which restrict high power factor load operation. A current controlled soft-switching inverter which provides good sinusoidal waveform of current for induction machine in [10].

All above reported topology of the quasi-resonant link inverter have some limitation so that in this paper presented a new versatile quasi-resonant topology which provide soft-switching of all three-phase inverter switches for both positive DC link current and negative DC link current and also overcome the limitation of the above discussed topologies. This topology can handle low as well as high power factor active and passive load. The complete quasi-resonant soft-switched three phase inverter for RL and Induction motor load is simulated using a MATLAB simulator. Typical simulation result of RL load and Induction motor load is presented in this paper.

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2. Proposed Topology

The proposed quasi-resonant topology for three phase inverter of 400 Hz or 50 Hz is shown in Fig.1 which provides soft switching at the high range switching frequency. The resonant tank as shown in Fig.1 consist of main switch (SW_M), auxiliary switch (SW_A), two shunt switch ((SW_1-$_{SH}$) and (SW_2-$_{SH}$)), two resonant inductor (Lr and L_{SH}) and resonant capacitor C_r. So this resonant network is activated during resonant interval to enable soft-switching transition. This soft-switching transition is implemented by using zero-voltage transition. The circulating energy associated with soft-switching transition due to resonance is quite small. The resonant components which are used in this topology involved with load current only during the resonant interval and out of operation during non-resonant interval. The DC link voltage is always clamped to the source voltage in this topology. Since the resonant component are involved only during a small interval of switching cycle. The size and VA rating of these resonant components become quite small. This topology provide soft-switching operation when the link current is positive it means DC link current flow from resonant tank to inverter and also provide soft switching operation when the DC link current is negative it means DC link current flow from inverter to resonant tank. In this topology the DC link current is denoted by l_{Link}. In a switching cycle this DC link current is assumed to be ripple free.

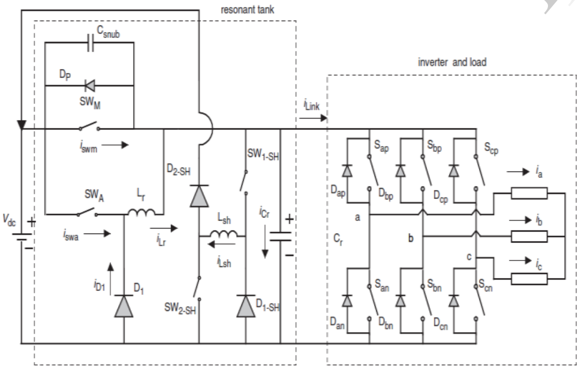


Figure 1. Proposed Quasi-Resonant soft-switched three phase inverter

3. Operating principal

Paper proposed quasi-resonant topology which provide soft-switching of all three phase inverter switches and also provide soft-switching operation in independent direction of DC link current so that there are two operation one in which DC link current is positive (i.e. resonant tank to inverter) and other operation where DC link current is negative (i.e. inverter to resonant tank).

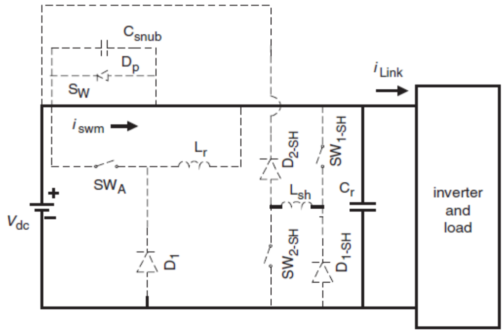


Figure 2. Initial condition under positive DC link current

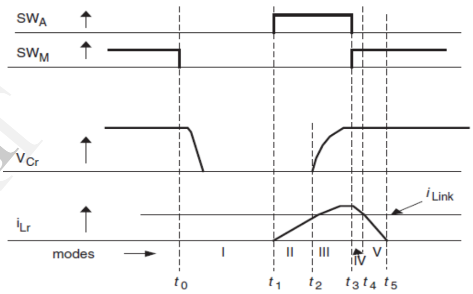


Figure 3. Switching waveform under positive DC link current

2.1 Case I: The DC Link Current is Positive

The DC link current is positive it means that link current flow from resonant tank to inverter and load. Fig.2 shows the initial condition under positive link current at this condition resonant capacitor clamped to source voltage and only main switch was conduct. For obtaining soft-switching of three-phase inverter switches the circuit goes through various modes of operation, shows in Fig. 3 various modes of operation switching waveform.

MODE I (t_o-t_1)

This mode is started when the gate signal to main switch SW_M is withdrawal at to. During small interval of this mode resonant capacitor discharges to zero, because of zero-voltage diode which is anti-parallel across the inverter switches get forward-biased. At the instant of ZVS, switching status of inverter is changed. End of this mode at t_1 gate pulse to auxiliary switch is released. The circuit topology of this mode is shown in Fig. 4(a).

MODE II (t_1 - t_2)

At starting of this mode auxiliary switch is turn-on. Current increases linearly from zero when flowing through the resonant inductor Lr, while the current which is flowing through diode in the inverter decreasing. At the end of this mode resonant inductor current is equal to link current and also the current becomes zero which is flowing through the anti-parallel diodes of inverter switches. The circuit topology of this mode is shown in Fig. 4(b).

MODE III (t_2 - t_3)

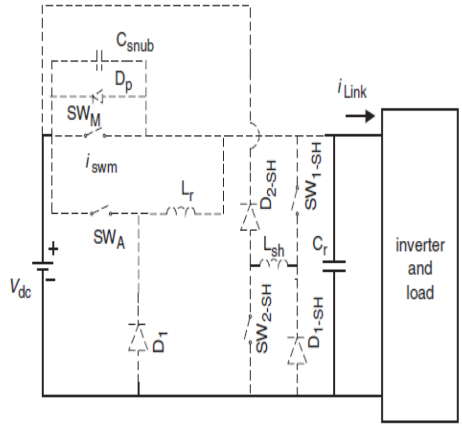
This mode starts at t_2 with charging capacitor C_r because resonance of L_r and C_r and the. Voltage across the DC link / resonant capacitor C_r gradually increases from zero to source voltage V_{DC} .The resonant inductor current is equal to the sum of the link current and charging current of capacitor C_r. Due to resonance of L_r and C_r link voltage is further increases causes diode D_p to be forward-biased. End of this mode at t_3 main switch is turned on and auxiliary switch is turned off. The circuit topology of this mode is shown in Fig. 4(c).

MODE IV (t_3 - t_4)

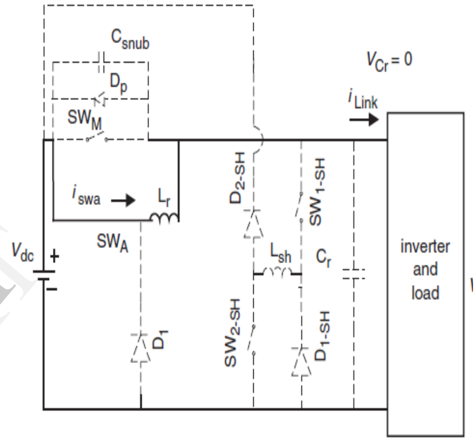
This mode starts at t_3 with turned on with main switch and turned off with auxiliary switch. When current in the resonant inductor grater then the DC link current, the excess current which is more than the link current is flowing through the diode D_p. At the end of this mode at $t_4$current in the resonant inductor is equal to load current. The circuit topology of this mode is shown in fig. 4(d).

MODE V (t_4 - t_5)

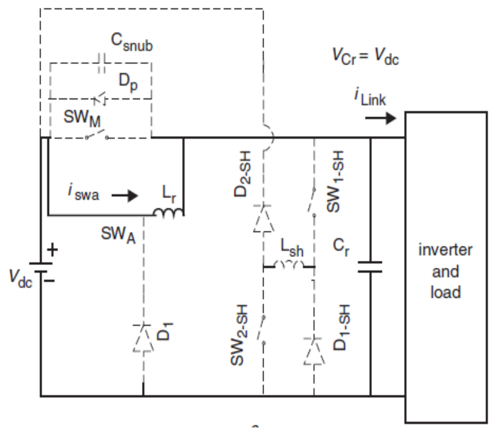
This mode starts at t_4 with turned off of diode D_p and main switch SW_M at the same time stats conducting. Now current in the Link is a some of the main switch current and current in the resonant inductor Lr. End of this mode at t_5 main switch SW_M conducts total link current and energy which is stored in resonant inductor is recovered. The circuit topology of this mode is shown in Fig. 4(e) which is changes in to initial state and same mode is repeated.



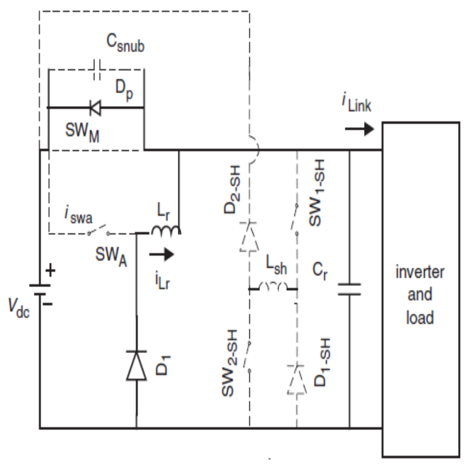
(a) MODE I



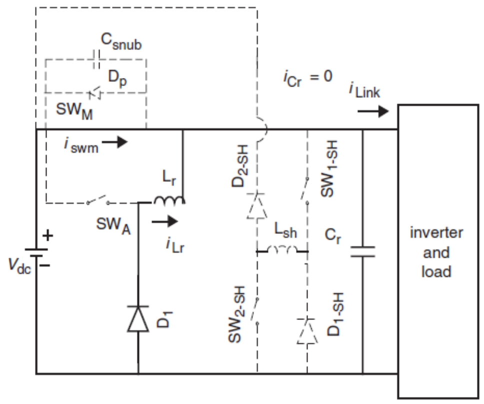
(b) MODE II



(c) MODE III



(d) MODE IV



(e) MODE V

Figure 4. Modes under positive DC link current (a) Mode I (b) Mode II (c) Mode III (d) Mode IV (e) Mode V

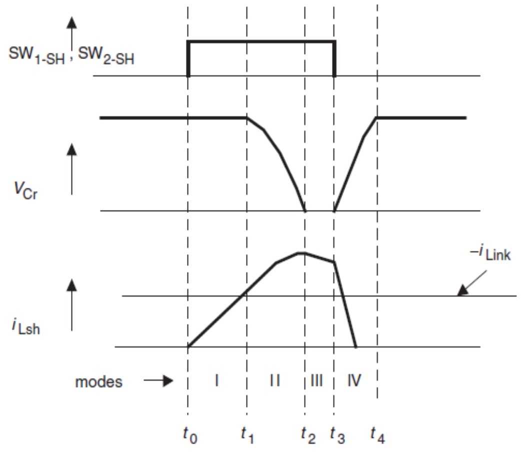


Figure 5. Switching waveform under negative DC link current

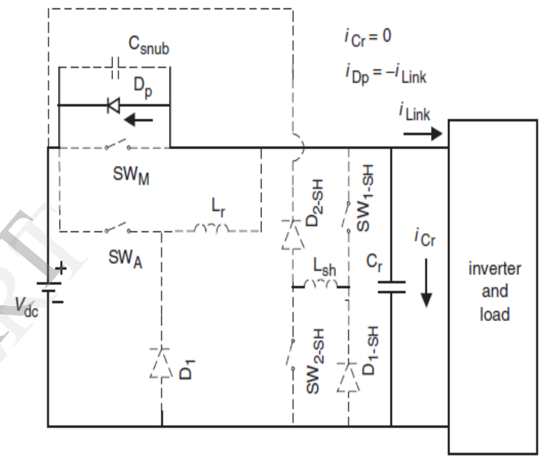


Figure 6. Initial condition under negative DC link current

3.1 Case II: The DC Link Current is Negative

When the DC link current is negative under these condition link current is flowing from inverter to resonant tank (i.e. negative). For negative DC link current during soft-switching of inverter switches circuit goes through various modes of operation. The switching waveform of gate pulse to shunt switches, resonant capacitor voltage and shunt inductor current are shown in the Fig. 5. The circuit topology of initial condition under negative link current is shown in fig 6. Initially due to conduction of diode D_p DC link voltage is clamped to source voltage and all the switching devices are off state in the resonant tank.

Now explain each mode which shows how switching status of inverter devices is changed when DC link current is negative.

MODE I (t_0 - t_1)

This mode starts at t_0 with release of gate pulse to shunt switches ($SW_{1\text{-}SH}$, $SW_{2\text{-}SH}$). In this mode dc-link voltage is clamped to the source voltage. Shunt inductor current i_{Lsh} linearly starts increasing from zero. In this mode DC Link is the sum of current in shunt inductor i_{Lsh} and current in diode D_p. At the end of this mode shunt inductor current equal to load current and diode D_p turn-off. The circuit topology of this mode is shown in Fig. 7(a).

MODE II (t_1 - t_2)

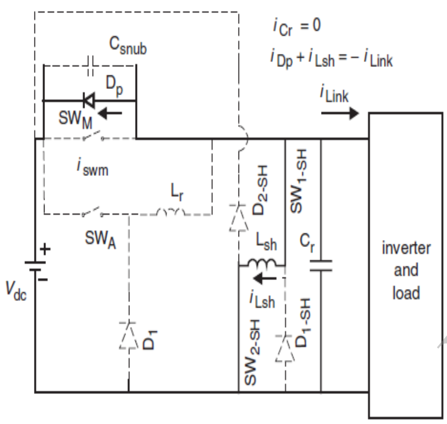
This mode starts at t_1 with turn off of diode D_p and discharging of resonant capacitor C_r. current in the shunt inductor is sum of the discharging capacitor current and dc-link current. At the end of this mode t_2 the resonant capacitor C_r discharges to zero voltage. The circuit topology of this mode is shown in Fig. 7(b).

MODE III (t_2 - t_3)

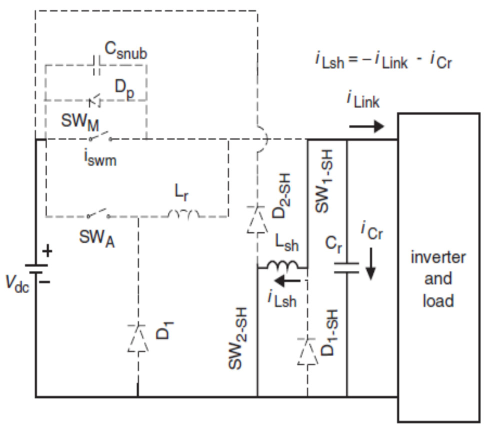
This mode starts at t_2 with discharging of resonant capacitor to zero voltage, at this instant switching status of inverter devices is changed under ZVS and diode D_{1SH} get forward-biased through SW_{I-SH} because of energy in the shunt inductor L_{sh}. The current which is flowing through diode D_{1-SH} is the difference between dc link current and shunt inductor current. Shunt inductor current i_{Lsh} is conducted by the switch SW_{2-SH}. End of this mode at t_3 gate pulse from shunt switch is released SW_{1-SH} and SW_{2-SH} is released. The circuit topology of this mode is shown in Fig. 7(c).

MODE IV (t_3 - t_4)

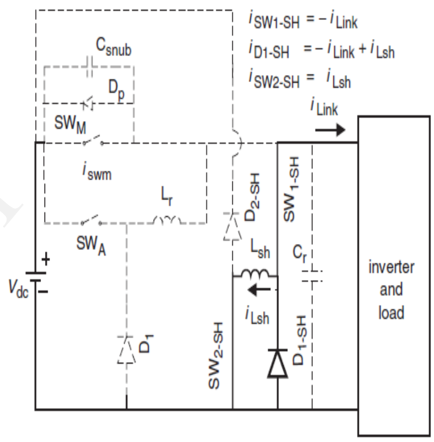
This mode starts at t_3 with withdrawal of gate pulse from the shunt switches SW_{1-SH} , SW_{2-SH}. Shunt inductor energy recovered to source through diode D_{1-SH} and D_{2-SH} so that conduction of diode D_{1-SH} and D_{2-SH}.The shunt inductor current decay to zero simultaneously resonant capacitor charged with dc link current. End of the mode at t4 resonant capacitor voltage equal to source voltage. The circuit topology of this mode is shown in Fig. 7(d). Diode D_p conduct full DC link current when becomes forward biased.



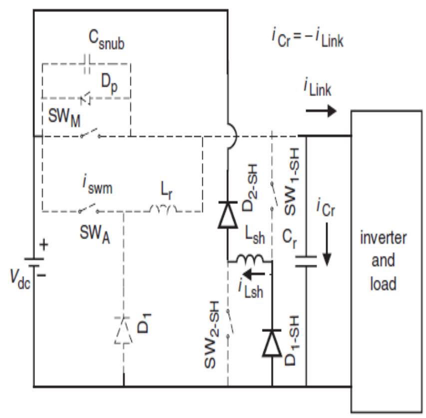
(a) MODE I



(b) MODE II



(c) MODE III



(d) MODE IV

Figure 7. Modes under negative dc link current (a) Mode I (b) Mode II (c) Mode III (d) Mode IV

4. Simulation Result

The Proposed soft-switched three phase inverter has been simulated for RL and induction motor load using MATLAB. Fundamental frequency of 400 Hz, switching frequency of link is 40 KHz and modulation index of 0.9 are used. In Quasi-Resonant topology resonant parameters of small size and weight are used L_r = 1μH, L_{sh} = 0.5μH, C_r = 50nF. The source voltage is 150 V DC. Due to high frequency and low power operating capability MOSFET is selected as power switch in proposed soft-switched inverter.

Gate pulse for main and auxiliary switch is given from two pulse generator and these pulses are given such that when main switch is on auxiliary switch is off. Gate pulse for two shunt switches are given from one pulse generator because these two shunt switches are on at same time. Gate pulse for three-phase inverter switches is given from discrete PWM generator. Voltage across the resonant capacitor providing zero voltage switching, when zero voltage condition is obtained across resonant capacitor switching status of inverter device is changed.

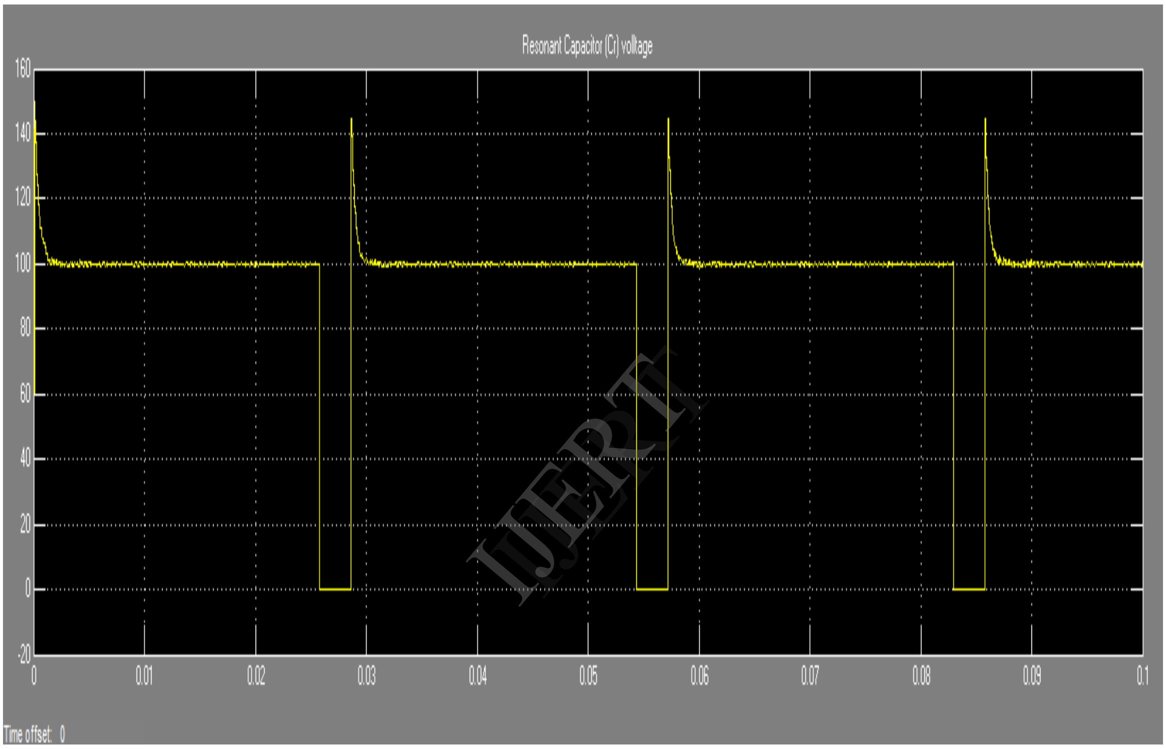


Figure 8. Voltage across the resonant capacitor

The proposed quasi-resonant topology provide zero-voltage switching condition across the resonant capacitor for obtaining soft-switching in all inverter switches so now shown in Fig.8 zero voltage switching waveform across the resonant capacitor C_r.

4.1 For RL load

For RL load R=5Ω, L= 5mH and source voltage of 150V DC is taken. Fundamental frequency, switching frequency, and modulation index were 400 Hz, 40 KHz and 0.9 taken respectively. Fig 9 shown simulation model of soft-switched three-phase inverter for RL load and three-phase current and voltage wave form shown in Fig.10 when RL load is used.

4.1.1 Simulation circuit

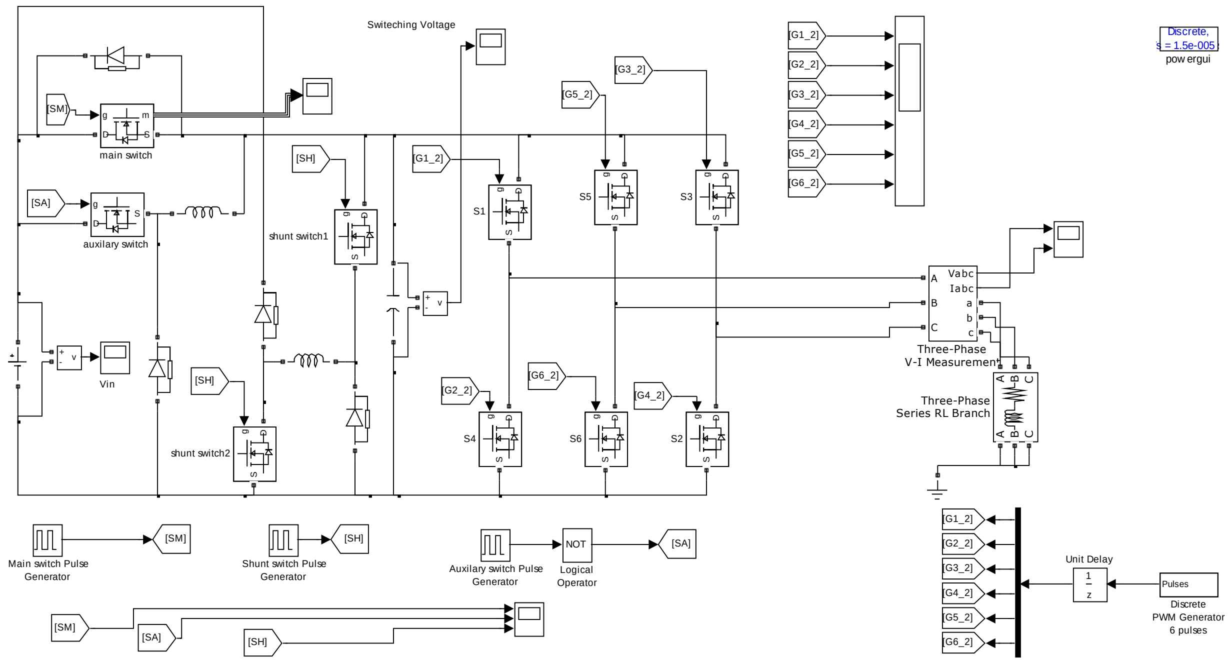


Figure 9. Simulation model of soft-switched three-phase inverter for RL load

4.1.2 Simulation result for RL load

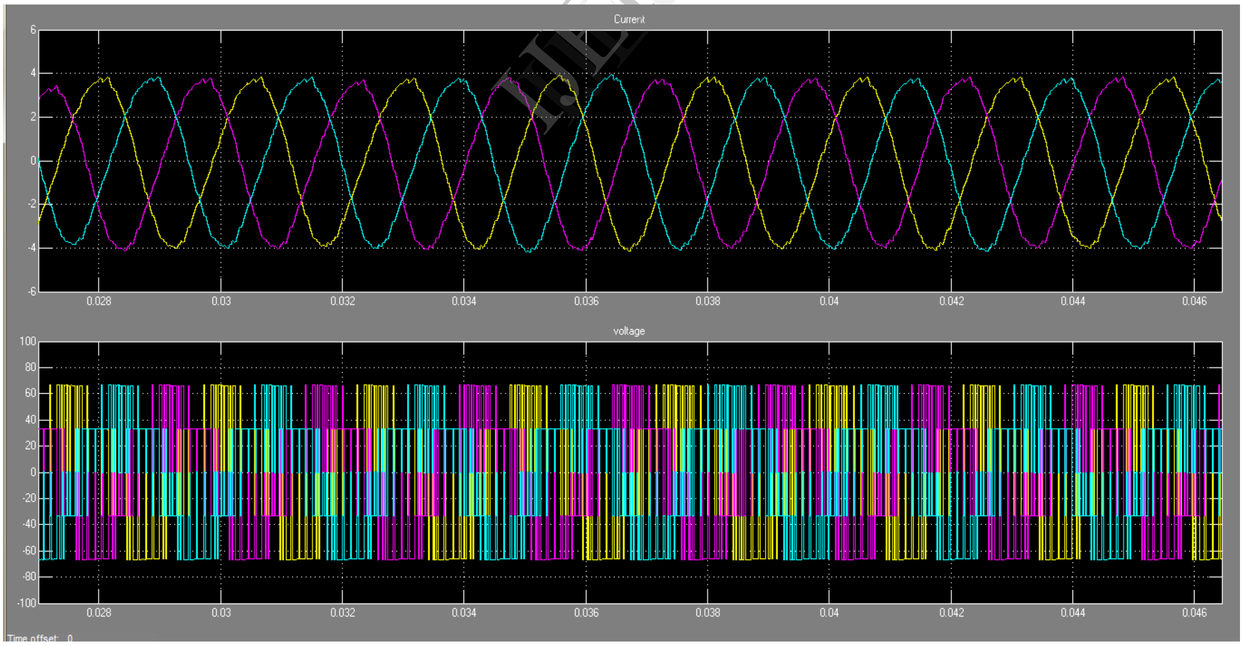


Figure 10. Three phase current and voltage waveform for RL load

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4.2 For Induction motor load

For Induction motor load source voltage of 150V DC is taken. Fundamental frequency (400Hz) and switching frequency (40 Khz) at modulation index 0.9 are considered. Fig11 showed simulation model of soft-switched three phase inverter for induction motor load and three phases current and voltage waveform in Fig.12 when Induction motor load is used. The current waveform is found sinusoidal.

4.2.1 Simulation circuit

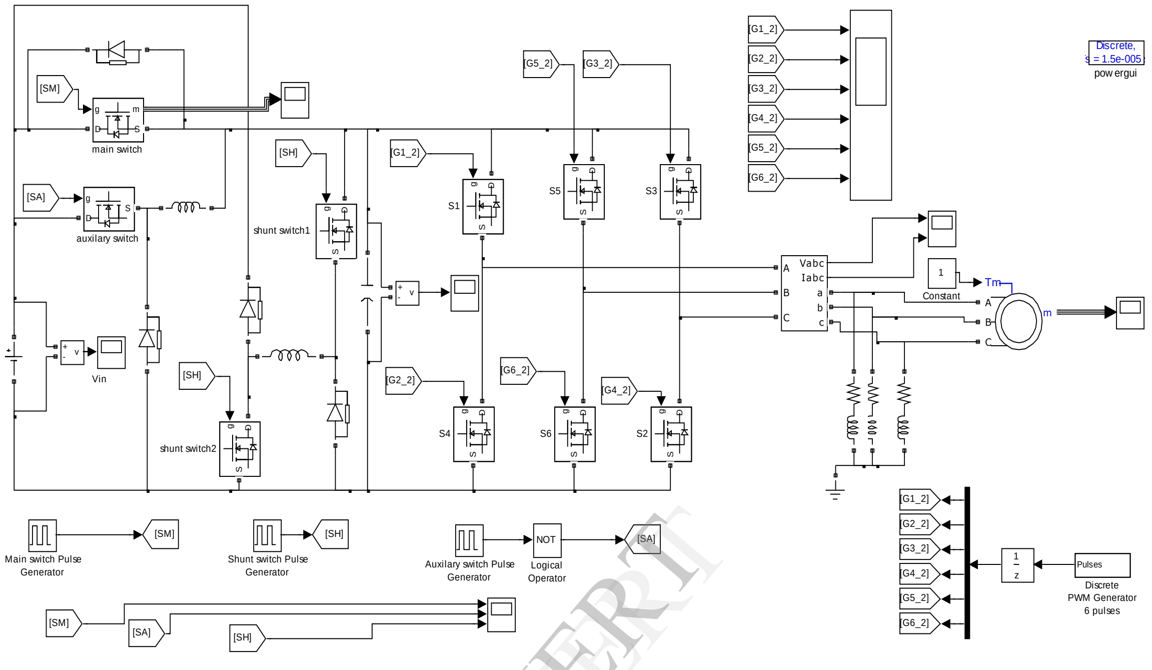

Figure 11. Simulation model of soft-switched three-phase inverter for induction motor load

4.2.2 Simulation result for Induction motor load

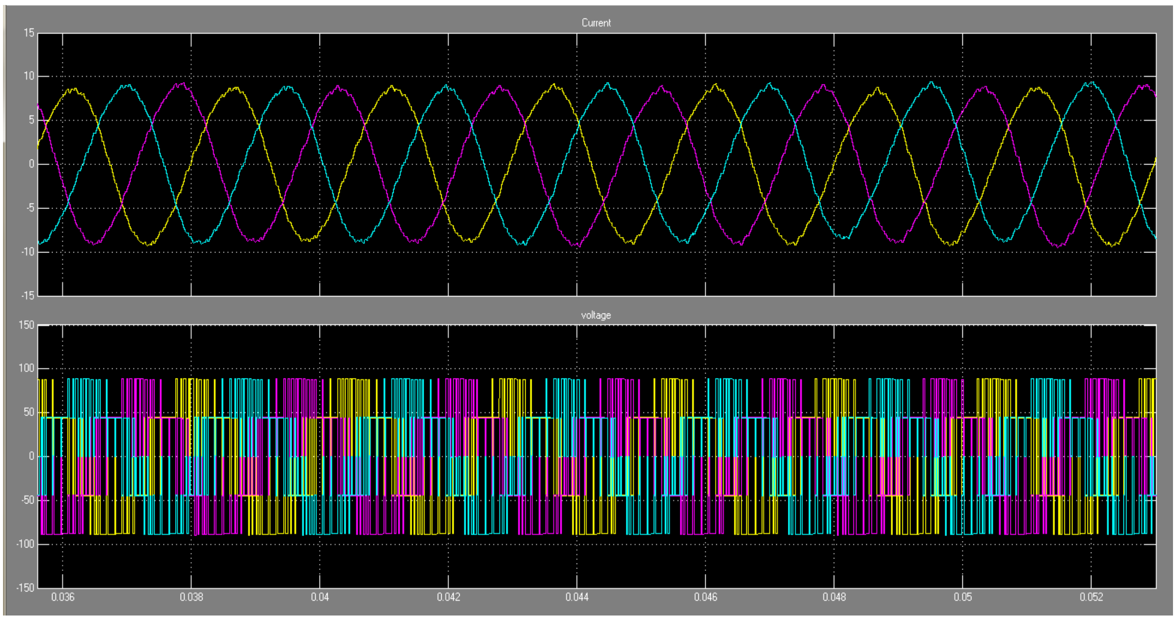

Figure 12. Three phase current and voltage waveform for Induction motor load

5. Conclusion

In this paper a soft-switched three-phase inverter is simulated in MATLAB for RL and Induction motor loads. The switching sequence of various switches in the resonant link is allowed soft-switching of switches in the three-phase inverter. This soft-switching is ensured independent of DC link current direction by the quasi-resonant topology and its control strategy. The proposed quasi-resonant topology is attractive over other topology as it can work for both RL and induction motor loads.These soft-switched three-phase inverter is operated at high frequency and resonant component of small size and weight are used which is attractive for airborne power supplies.

6. References

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