Research Article
Design and Implementation of a Simple and Efficient Soft Switched PWM Inverter for Induction Motor Drives

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Abstract: The aim of study of this paper is design and implementation of a simple and efficient soft switched Pulse Width Modulation (PWM) for three-phase induction motor drives. Soft-switching techniques have gained popularity in recent times because they offer many advantages over hard-switched Pulse Width Modulated inverters such as higher efficiency, higher power density and better performances. The quasi-resonant DC-link is being designed, the simulation and experimental results prove that it achieves soft switching of all the main switches and resonant circuit switches at the same time it posses all the capabilities of conventional sinusoidal modulated PWM inverter. Finally, the efficiency of the Soft Switched Sinusoidal PWM (SSSPWM) inverter calculated from experimental results is compared with the conventional Hard Switched Sinusoidal PWM (HSSPWM) inverter, under identical load conditions. It is of great significance to improve the efficiency by reducing switching losses, high power density, high reliability and low electro management interference.

Keywords: Hard-switching inverter pulse width modulation, resonant DC-link inverter, soft-switching inverter pulse width modulation, Zero Voltage Switching (ZVS)

INTRODUCTION

A Voltage Source Inverter (VSI) is commonly used to supply power to variable speed three-phase induction motor drives. The most common and efficient method of doing variable frequency and variable voltage three phase supply is by Pulse PWM technique, which is used to control the VSI. PWM based variable speed drives are increasingly applied in many new industrial applications that require superior performance, so three-phase PWM inverters are recently showing the growing popularity for Induction motor drive in industrial applications. The sinusoidal modulation technique is simple control circuit and easy implementation on PWM inverters. In the conventional PWM power converters power switches were operated in a switched mode operation. PWM converters operate at a higher switching frequency, thus reducing the passive component size and eventually reduce the overall system cost. However, in association with the increased switching frequency, the converter switching loss also increases proportionally. The Power switches take the load current at turn-on and cut-off the load current at turn-off times this is referred as hard switching. The hard switching involves in high dv/dt and di/dt caused

by the increased switching speed will result in increased stress on switching devices and system Electro Magnetic Interface (EMI) noise. These limitations restricted the conventional hard-switched PWM converters from operating at a higher frequency. In the past several decades, lots of research works has been done to seek a better solution to shape the switch transition in order to overcome the inherent problems of hard switched PWM converters (Amini and Farzanehfard, 2011; Pan and Luo, 2005; Amini and Farzanehfard, 2009).

Lots of research efforts were taken to overcome drawback of hard switching PWM inverter, by incorporating resonant tanks with the converter circuit create oscillatory voltage and/or current waveforms, so that Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) conditions can be produced for the switching instants, this is referred as soft switching. The low switching loss in soft switching inverter allows increasing the switching frequency of the PWM Inverters, typically 15 to 20 kHz for inverter using IGBT as switching device. Consequently, power density of the converters increased and inductor size in the filter can be reduced (Wang *et al*., 2008; Bellar *et al*., 1998; Park *et al*., 2010).

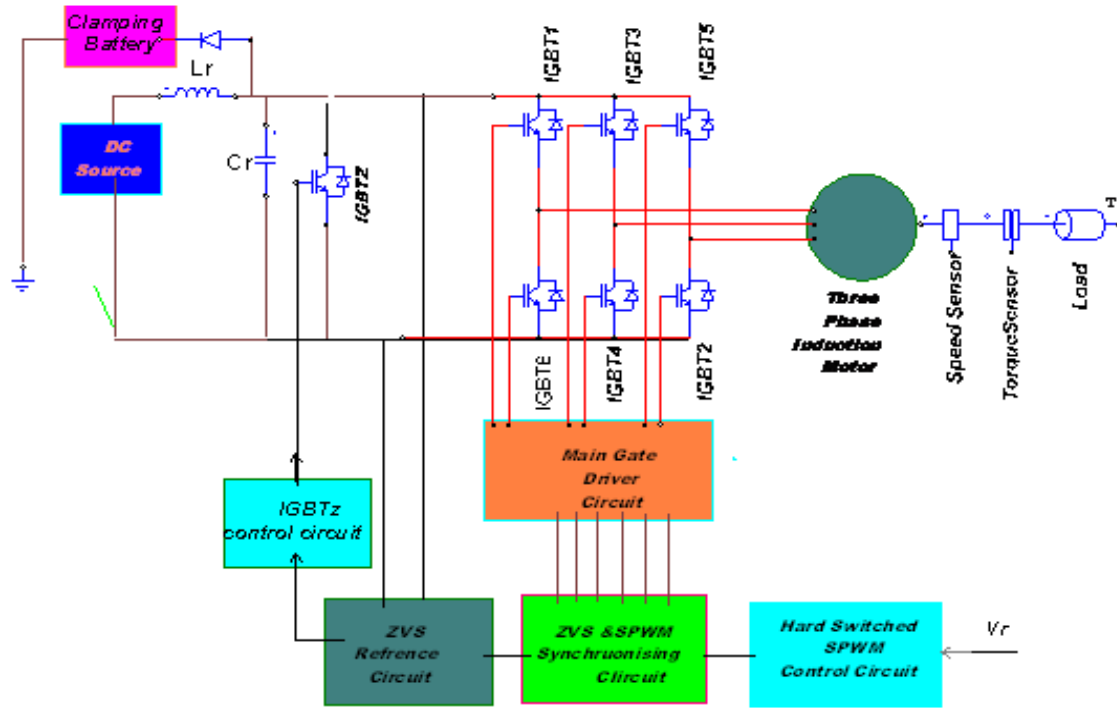Fig. 1: Block diagram of the proposed SSSPWM inverter-fed induction motor drive

Lower switching losses due to soft switching, less *dv/dt* and *di/dt* and thus low EMI emissions. The reliability of the drive has been improved due to reduced stress on the switching devices. The soft switching for PWM inverter fed three-phase induction motor drive is implemented with the features of reduced the ratings of the switching devices, design of simple resonance DC bus and simple control techniques.

PROPOSED METHODOLOGY

The system configuration of the proposed soft-switching sinusoidal modulated PWM inverter-fed induction motor drive is shown in Fig. 1. The Power circuit of the proposed soft switched PWM inverter is constructed same as a conventional PWM inverter. The simple resonant circuit is inserted between conventional PWM inverter and DC source for creating zero voltage intervals in DC input of the inverter. The resonance voltage clamping circuit is constructed with a standby battery and a diode. The inverter IGBTs switching control circuit of the three-phase SSSPWM inverter made with slight modification in control circuit of the conventional SPWM inverter and the output pulses of the SPWM are synchronized with zero voltage interval of DC resonance bus voltage by synchronized circuit.

Resonance link and control design considerations:

- Foremost design objective is that the DC bus voltage that is the input voltage to the PWM inverter must be reached zero in regular time interval for ZVS.

- The DC-link voltage, frequency must be very high compared to the switching frequency of the PWM inverter main devices.
- In order to reduce the voltage stress on the main devices, peak value of the resonance DC bus voltage must be maintained, below 1.5 times of the input voltage.
- The Zero voltage interval of the resonance DC bus voltage used for each and every switching operation all IGBTs.

Design procedure of resonant DC bus: Designing the proposed soft-switching sinusoidal modulated PWM inverter involves the selection of resonant inductance (L_r), resonant Capacitance (C_r) to provide a ZVS condition for turn-on and turn-off the inverter main switching devices and IGBT in resonance circuit. The resonant DC bus with the induction motor load was assumed constant current source is simulated using the Psim software package. First study the ZVS condition and use this zero interval reference turn on the resonance circuit IGBT to hold the zero voltage condition for required time at the same time the resonance inductor stored energy discharged to clamping battery (Chen, 1998; Divan and Wallace, 1997).

Design and parameter selection of simple resonance DC bus: The following basic specifications are used for resonance DC bus design:
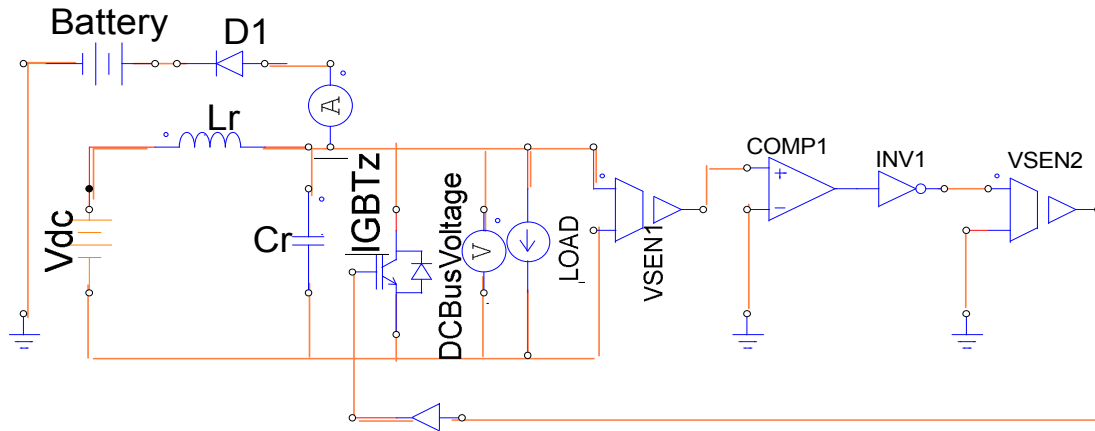
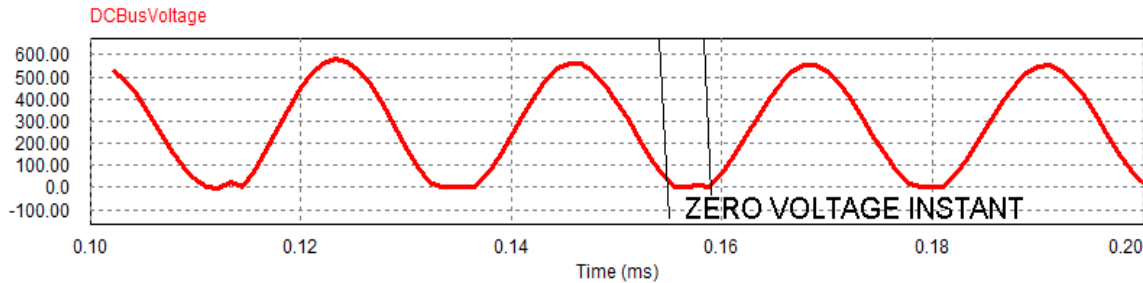Fig. 2: Circuit diagram for design the proposed SSSPWM inverter resonance DC bus

Fig. 3: Proposed resonance DC bus voltage simulated result

V_{dc} = DC-Input voltage of inverter = 275 V
Q = Quality factor of resonant component = 200
I_l = Line current of induction motor = 7.5 A
t_f = IGBT fall time = 0.9 µsec
f_r = Resonant frequency = 45 kHz

Determination of Resonant inductance (L_r) and resonant Capacitance (C_r) by using the following Eq. (1) and (2).
The impedance of the resonant tank is calculated by:

$$Z_r = \sqrt{\frac{Lr}{Cr}} \qquad (1)$$

For a chosen resonant frequency f_r the value of the Lr and *Cr* can be calculated from:

$$2\pi fr = \frac{1}{Lr\,Cr} \qquad (2)$$

Calculated parameters values are *Lr* = resonant inductance: 37 *µ*H, *Cr* = resonant capacitance is: 17 *n*F. The Fig. 2 shows simulation circuit of the resonant DC bus, the design values are found correct from the simulation results given in Fig. 3. The simulation results are analyzed each and every 0.02 msec zero voltage obtained in DC bus.

Controller design: The implementation of SSS PWM Inverter switching signal generating circuit with Resonance DC bus is shown in Fig. 4. The conventional sinusoidal PWM inverter control pulses are generated by comparing sinusoidal reference voltage wave V_r with carrier triangle voltage wave V_c. The Soft-switching control signal is easily obtained by synchronizing the rising and falling etches of the SPWM control pulse with zero voltage interval of the resonance DC bus voltage signal. The simulation wave form of SPWM and SSSPWM shown in Fig. 5 and 6. It is clear from the analysis the waveforms in Fig. 6, that the pulse is applied and removed to IGBTs at the zero voltage instant of the input DC voltage. The proposed soft switching control pulse can be achieved successfully; it is clearly shown in Fig. 6.

SIMULATION RESULTS AND DISCUSSION

Before performing the implementation, using Psim simulation software simulations is made on HSSPWM and SSSPWM fed induction motor for different load conditions the validity of the analysis and design presented above is checked and satisfied with the simulation.

Simulation of HSSS PWM: The Simulation circuit of the HSSPWM Inverter fed three-phase induction motor
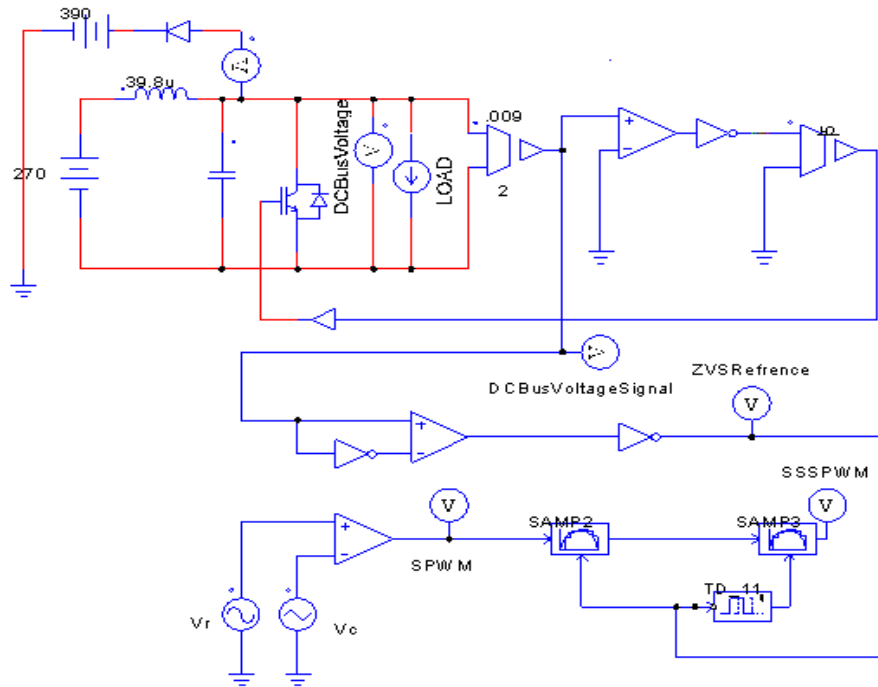
Fig. 4: Circuit diagram for design the proposed resonance DC bus and ZVS synchronized SSSPWM inverter gating signal
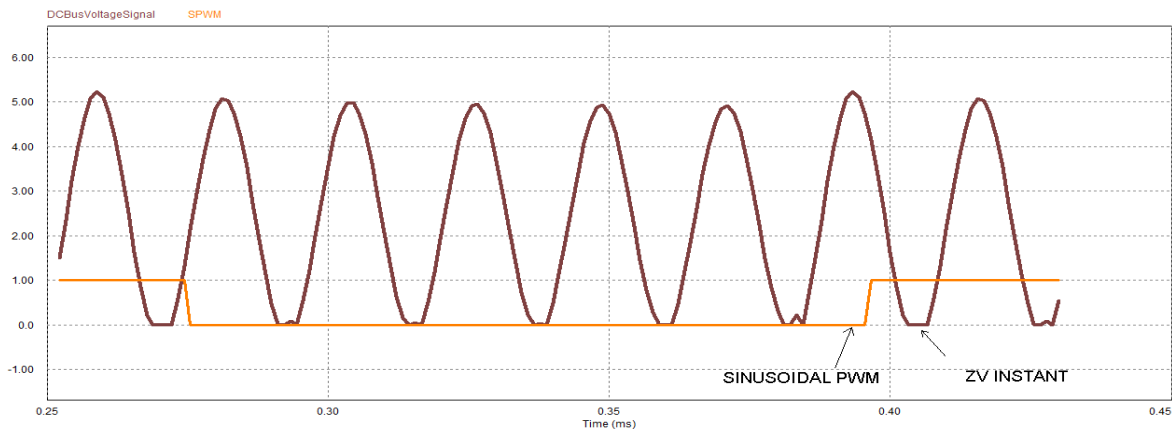

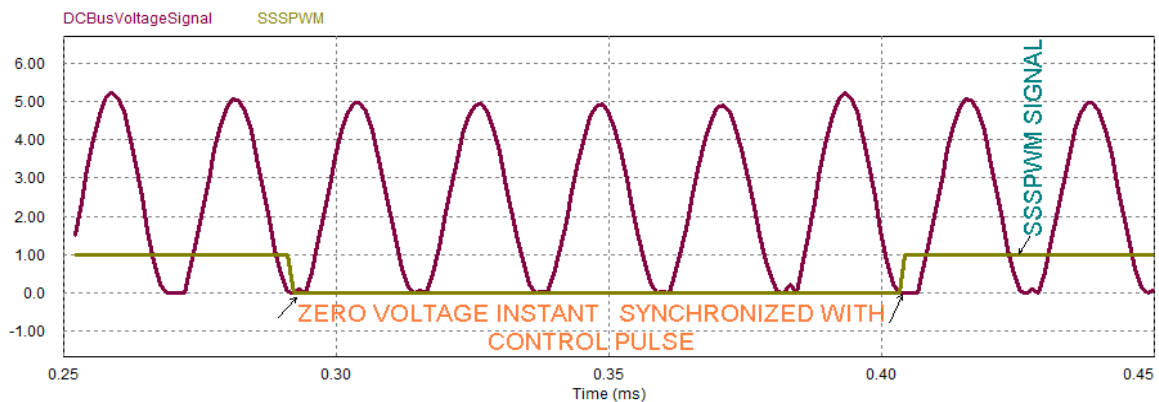Fig. 5: Simulated wave form of proposed SPWM

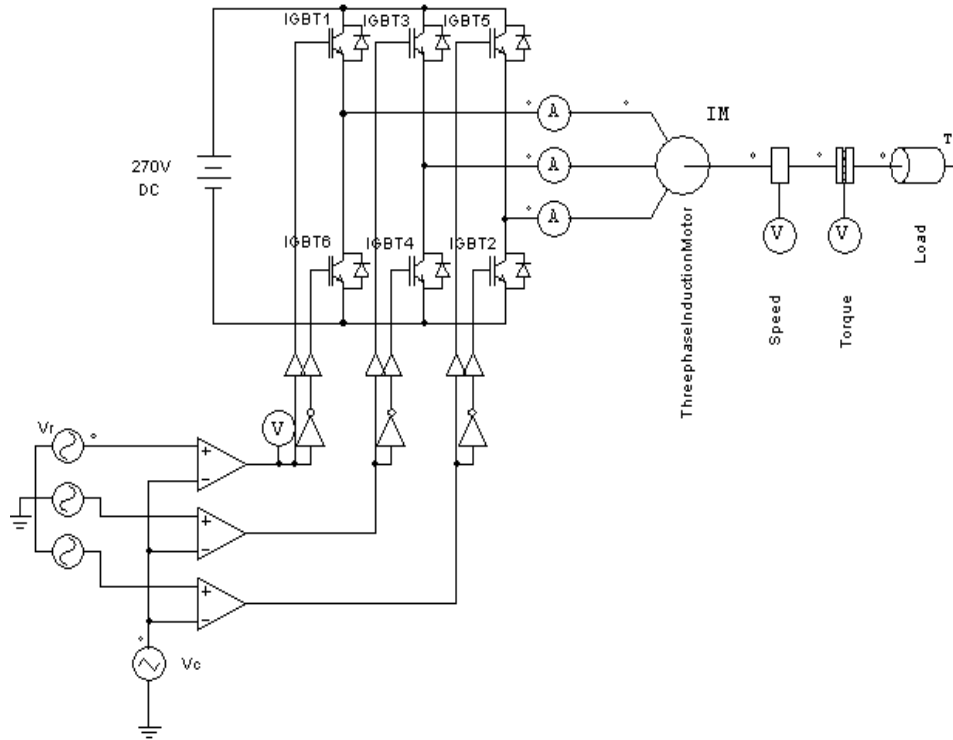Fig. 6: Simulated wave form of proposed SSSPWM

Fig. 7: Simulation circuit of the HSSPWM inverter fed three phase induction motor drives

Table 1: Specification of SPWM inverter circuit components and name plate detail of 3-phase induction motor

	Parameters	Value
SPWM inverter circuit	Dc input voltage	270 V
	Reference voltage	0.9 V
	Reference frequency	50 Hz
	Carrier voltage (triangle peak to peak)	2 V
	Carrier frequency	15000 Hz
3-phase induction motor	Motor capacity	5HP/3.7 kW
	Nominal line voltage	415 volts
	Nominal line current	8.2 Amps
	Nominal speed	1440 Rpm
	Motor winding connection	Delta

drive is and simulated by Psim. The specification of SPWM inverter circuit components name plate detail of three-phase induction motor is given in Table 1.

The HSSPWM Inverter fed three-phase Induction motor drive simulation circuit is given in Fig. 7 and its simulation results of line current of the HSSPWM Inverter fed three phase Induction motor is shown in Fig. 8 and speed and torque is shown in Fig. 9 and 10 respectively.

Calculation of power losses in the hard switching PWM inverter: The power losses, in the HSSPWM inverter, are the conduction and switching losses in the IGBTs in the inverter. The conduction losses are due to the voltage drop across the device as well as the current flow through the device during the on state period of IGBT. The switching losses in the hard switching inverter have three components, they are IGBT turn on

losses, IGBT turn off losses and the losses due to diode reverse recovery. Evaluation of the switching losses in the hard switching inverter can be done using the measured values of switching energy from the data sheets:

V_{ce} = Voltage across the IGBT
I_{q-} = The current flowing through the IGBT
V_{ak} = Voltage across the Diode
I_d = Current flowing through the diode
$I_{0(pk)}$ = Peak load current
Φ = Power factor angle
P_{qcl} = Conduction loss in IGBT
P_{qsl} = Switching loss in IGBT
P_{dcl} = Conduction losses in the diode
P_{tclh} = Total conduction losses in HSSPWM
$P_{tsl\,h}$ = Total switching losses in HSSPWM
P_{tl} (HSPWM) = Total losses in (HSSPWM)
$P_{tsl\,s}$ = Total switching in (SSSPWM)
P_{tl} (SSPWM) = Total losses in (SSSPWM)
Vdc = DC input voltage
Kc = Correction factor

V_q, R_q, V_d and R_d parameters are given in the data sheet.
$I_{o(pk)}$ = Peak load current.
Conduction and switching losses:

$$V_{ce} = V_q + I_q R_q \qquad (3)$$
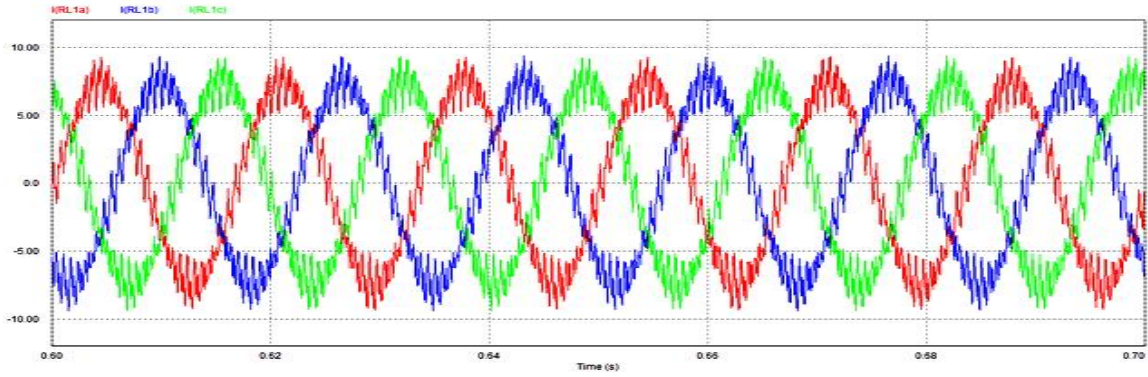
$$V_{ak} = V_d + I_d R_d \qquad (4)$$

Fig. 8: Simulation results of the HSSPWM inverter fed three phase three phase line currents
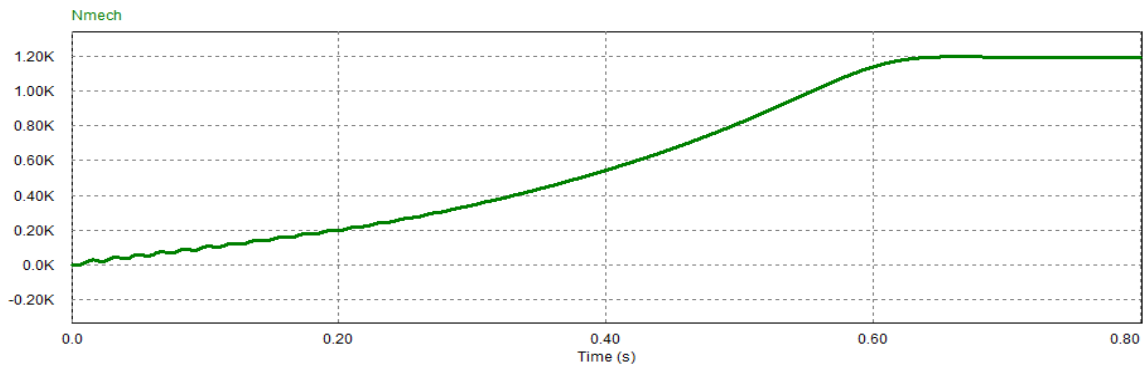

Fig. 9: Simulation results of the HSSPWM inverter fed three-phase induction motor drives speed curve
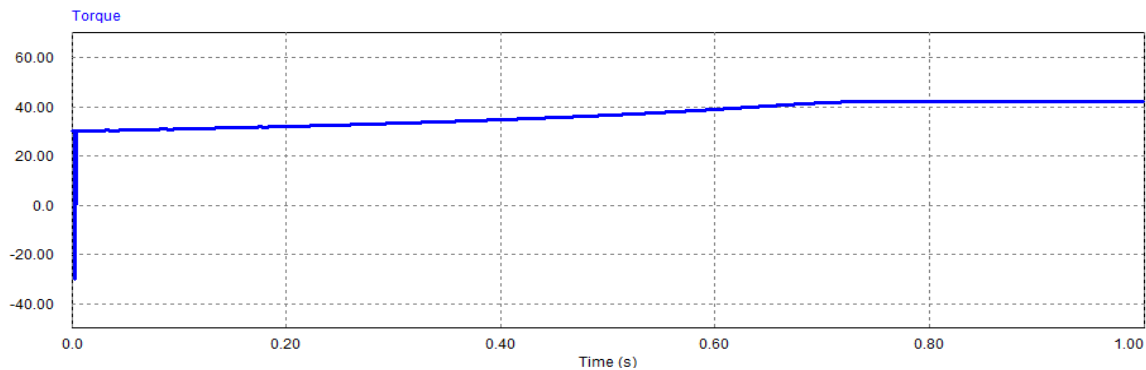

Fig. 10: Simulation results of the HSSPWM inverter fed three-phase induction motor drives torque cure

$$I_{q(av)} = I_{O(pk)}(\frac{1}{2\pi} + \frac{m_a \cos\emptyset}{8}) \qquad (5)$$

$$I_{q(rms)} = I_{O(pk)}\sqrt{(\frac{1}{8}) + \frac{ma\cos\emptyset}{3\pi}} \qquad (6)$$

$$I_{d(rms)} = I_{O(pk)}\sqrt{(\frac{1}{8}) - \frac{ma\cos\emptyset}{3\pi}} \qquad (7)$$

$$I_{d(av)} = I_{O(pk)}(\frac{1}{2\pi} - \frac{m_a \cos\emptyset}{8}) \; (1) \qquad (8)$$

$$P_{qcl} = V_q . I_{q(av)} + R_q . I_{q(rms)}^2 \qquad (9)$$

$$P_{dcl} = V_d . I_{d(av)} + R_d . I_{d(rms)}^2 \qquad (10)$$

Total conduction losses in HSPWM, therefore, conduction losses of the six numbers of IGBTs and six numbers of diodes in PWM inverter:

$$P_{tl} = 6 (P_{qcl} + P_{dcl}) \qquad (11)$$

The calculated values of the (E_{on}) turn-on and (E_{off}) turn-off energy proportional to test voltage and current (Vtest and Itest) are provided in the data sheets data:

$$E_{tl} = K_g (E_{on} + E_{off}) . \frac{Vs}{Vtest} * \frac{Io(pk)}{Itest} \qquad (12)$$
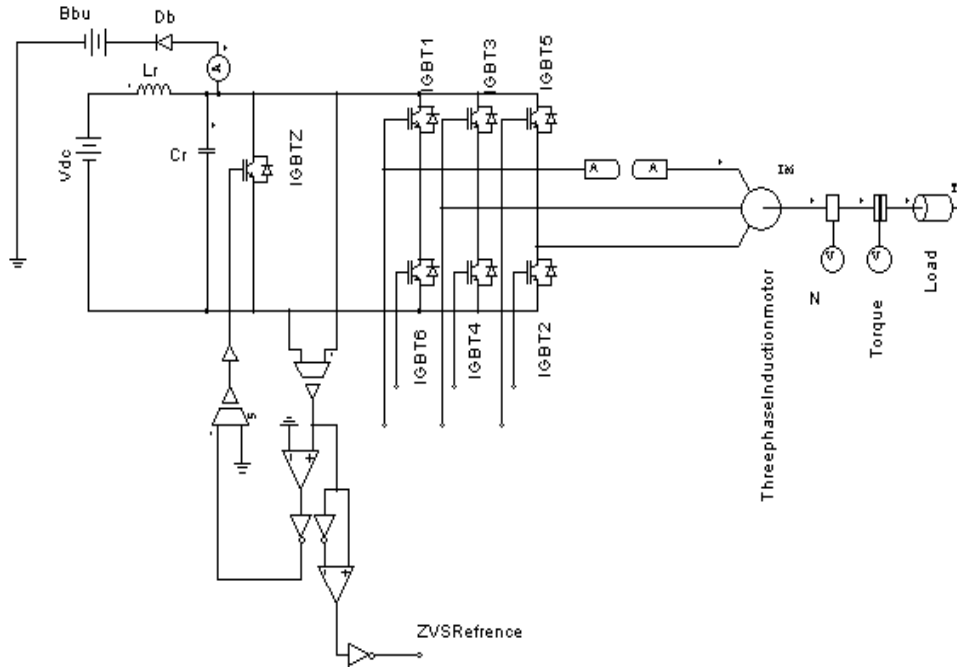
Fig. 11: Simulation power circuit of the SSS PWM inverter fed three phase induction motor drives
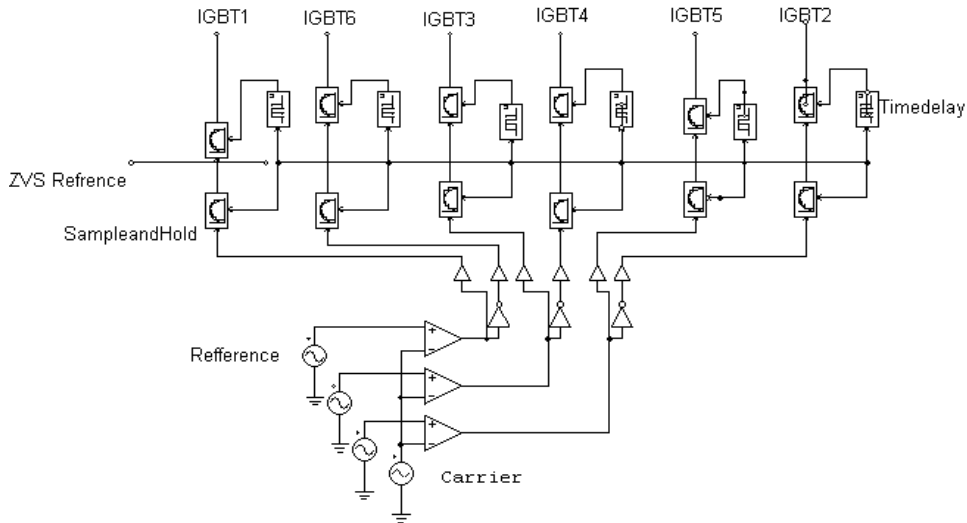

Fig. 12: SSSPWM inverter control circuit for synchronizing inverter IGBTs switching ON and OFF operation with zero instants of DC-link voltage

P_{tsl} = Total switching losses in HSSPWM:

$$P_{tsl} = 4fs * \frac{E(tol)}{\pi} \qquad (13)$$

Total losses of HSSPWM inverter: The total loss in HSSPWM Inverter is sum of the total conduction and switching losses:

$$P_{tl}\,(HSI) = P_{tcl}\,(HSI) + P_{tsl}\,(HSI) \qquad (14)$$

Simulation of proposed SSSPWM inverter: The complete SSS PWM inverter-fed induction motor drive

system has been formulated and simulated on a computer with Psim simulation software. Figure 11 shows the power circuit of the SSS PWM Inverter fed three phase Induction motor drives, Fig. 12 SSS PWM Inverter Control circuit for synchronizing inverter IGBTs switching control pulse with zero instants of DC-link voltage and Fig. 13 shows simulation results of PWM Inverter fed three phase Induction motor drives. Figure 13 shows the line current and line to line voltage of the SSSPWM Inverter fed three phase Induction motor drives. Figure 14 shows the simulation results of the SSSPWM Inverter fed three phase Induction motor
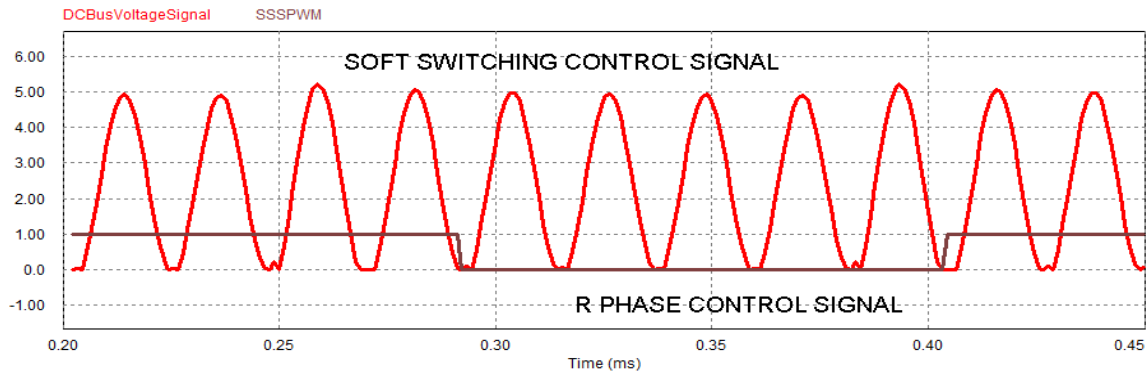
(a)
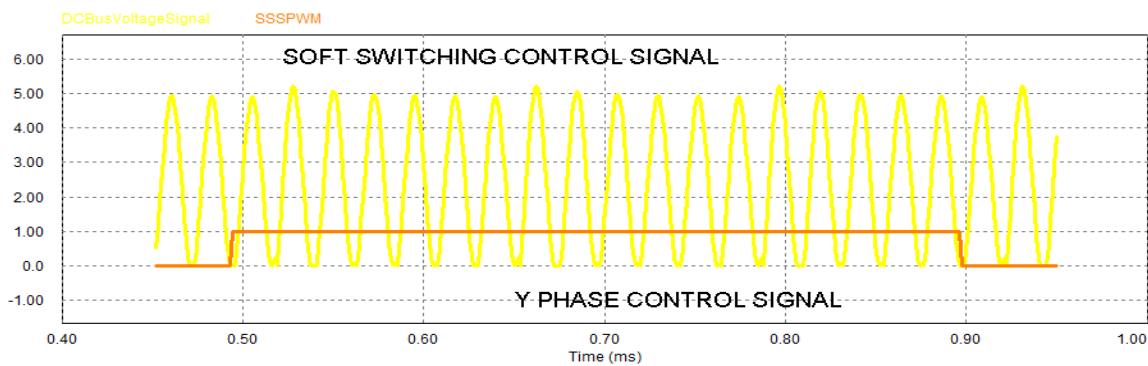
(b)
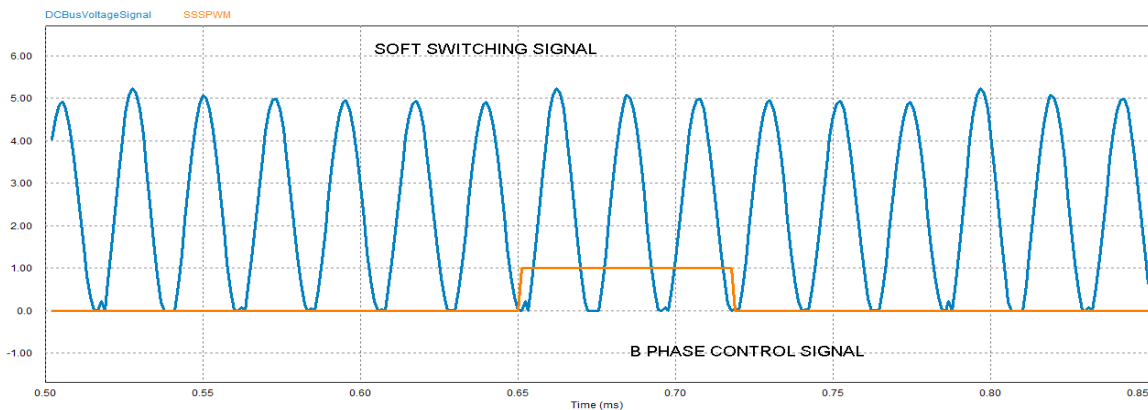
(c)

Fig. 13: SSSPWM inverter three phase control signal for synchronizing inverter IGBTs switching ON and OFF operation with zero instants of DC-link voltage

drives: line current, Speed and torque. Simulation results of the SSSPWM Inverter fed three phase Induction motor drives: line current and line to line voltage depicted in the Fig. 15.

Losses calculation of SSSPWM inverter: The main power losses, in the soft switching inverter are diodes recovery losses, switching losses in the devices, that is IGBTs turn-on loss and turn-off loss. In soft switched

PWM Inverter the diodes recovery losses and the IGBTs turn-on losses are very small and neglected only. Only turn-off losses of IGBTs under zero voltage switching condition to be considered for losses calculation (Chen and Lipo, 1996; Pattnaik and Mahapatra, 2010).

Calculation of switching losses in the SSSPWM inverter: The switching losses in the soft switching
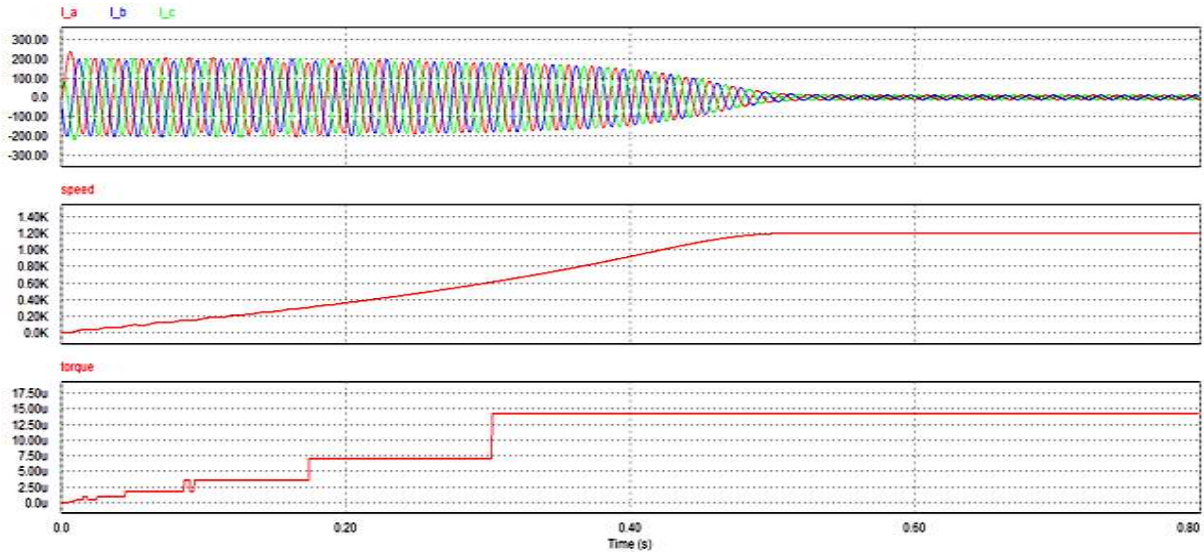
Fig. 14: Simulation results of the SSSPWM inverter fed three phase induction motor drives: line current, speed and torque
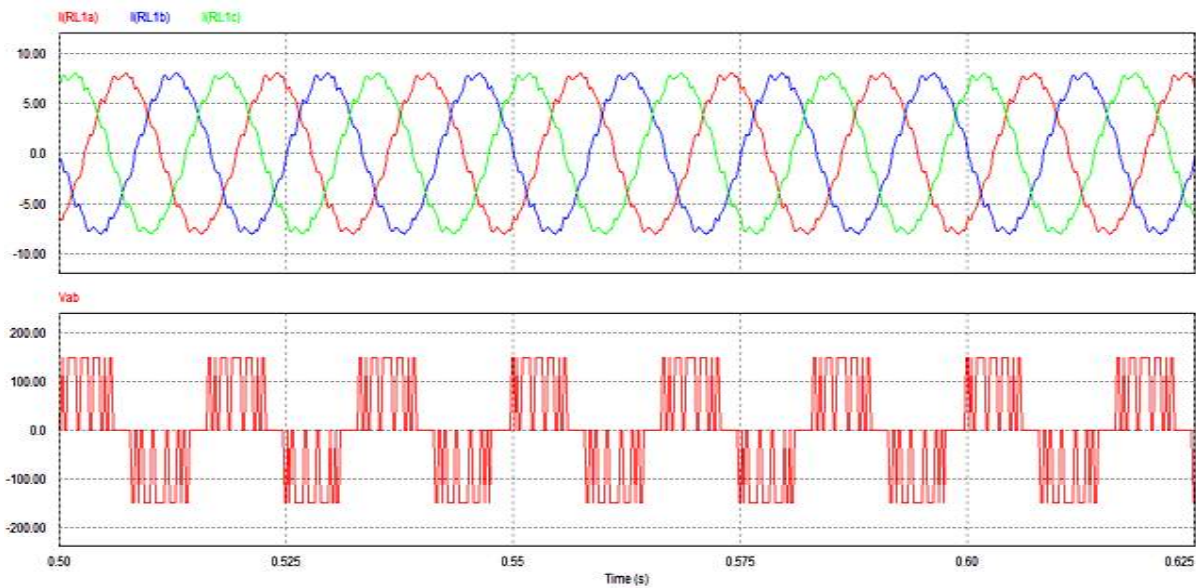

Fig. 15: Simulation results of the SSSPWM inverter fed three phase induction motor drives: line current and line to line voltage

PWM inverter defend on resonant Capacitance (C_r) and indirectly depends on the resonant inductance (L_r). As explained in 4.3 only turn-off losses of IGBTs under zero voltage switching condition to be calculated at peak load current $I_{0(pk)}$, the switching losses also depends on the resonance frequency (f_r), the switching losses in SSSPWM inverter can be calculated using the Eq. (15):

Total switching in (SSSPWM)
$$= P_{tsl\ s} = 6\ (0,5F_r)\ E_{off}I_{opk} \tag{15}$$

Calculation of resonance inductor losses: When the resonant circuit operates with a load, the current flow

through the inductor oscillates tracking the changes of the input DC current of SSSPWM inverter. So the current flow through the inductor is considered for a loss calculation in inductor and it is given by Eq. (16):

$$I_r(t) = \frac{1}{\phi\ 12}\theta\ (\theta_{12}.I_o + \theta_{12}.V_s) \tag{16}$$

The resonant inductor losses P_{Lr}, can be achieved by using Eq. (17):

$$P_{Lr} = \frac{zr}{Q}I_r^2 \tag{17}$$

Total losses in the SSSPWM inverter: The total losses of the SSSPWM inverter can be calculated by
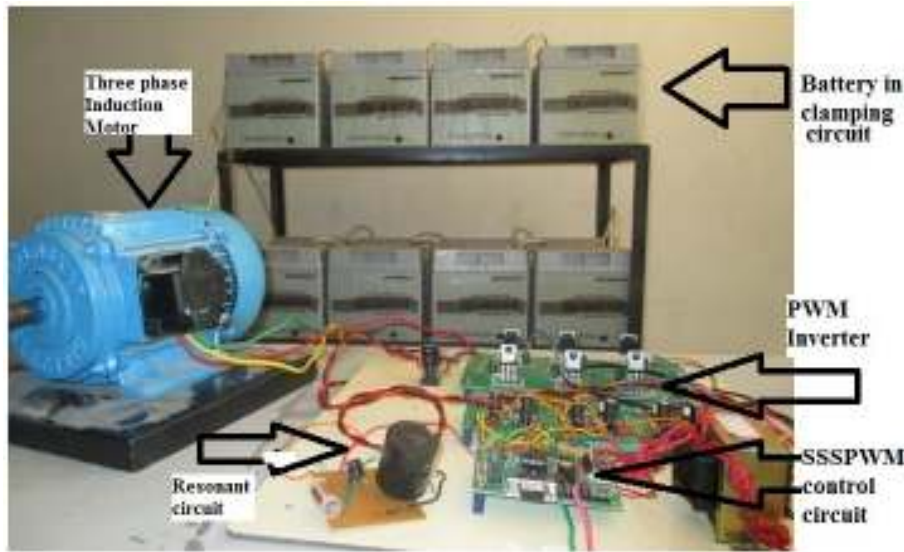
Fig. 16: Photograph of the proposed SSSPWM experimental set-up

Table 2: Performance analysis of HSSPWM and SSSPWM topology

Output power in watts	Efficiency of the inverter	
	HSSPWM	SSSPWM
1050	83.32	88.87
2156	85.16	89.94
2976	87.92	91.57
3426	88.72	92.54
3728	88.08	92.31

adding the main device losses resonant inductor losses and are represented in Eq. (18):

$$P_{tl}(SSPWM) = P_{tsls} + P_{Lr} \qquad (18)$$

Experimental results and discussion: To check the validity of the design and simulated results presented in previous chapters, a laboratory prototype HSSPWM and SSSPWM inverter shown in Fig. 16 was built and tested with 5 HP three phase induction motor under various load conditions. The input DC voltage (V_{dc}) is 270 V, the switching frequency of the inverter was maintained at 15 kHz the load current vary from 4.2 to 7.43 A.

The load current of the three phase induction motor is sinusoidal, torque is maintained constant and the performance of the DC link is found satisfactory. The resonant DC-link voltage reaches zero voltage for every 21 sec, the resonant peak voltage is effectively clamped within expected limits using 300 volt battery in clamping circuit and the inductor energy is discharged during ZVS period and utilized for charging the battery. The zero-voltage instant of the resonance DC link voltage is synchronized with switching pulse. The efficiency of the SSSPWM inverter fed three phase induction drives are calculated for five different load
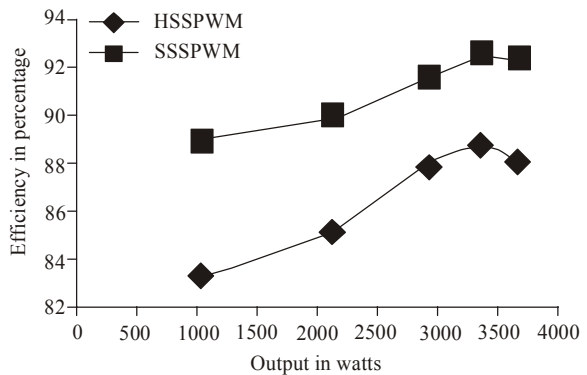

Fig. 17: Efficiency of HSSPWM and SSSPWM for different power ratings

conditions that is shown in Table 2 and shown in Fig. 17 the proposed concept is verified experimentally and found satisfactory.

CONCLUSION

In this study, a three- phase volts per hertz three phase induction motor drive using simple DC link resonance circuit, new voltage clamping circuit, new as well as simple zero voltage and SPWM control pulse synchronizing circuit are designed and simulated, from the simulation results study, following points are observed:

• A Perfect zero voltage turn-on and turned off conditions were achieved for the main switches.
• Turn-off losses were considerably reduced.
• The reverse recovery problem of the diodes greatly reduced and found negligible.

- Soft switching results in considerably less noise than in the hard switching case.
- SSSPWM inverter operation is easier.

A prototype of SSSPWM inverter has been implemented. The experimental results confirm the above said theoretical and simulation analysis. The efficiency of the soft switched sinusoidal modulated PWM inverter was compared with conventional hard switched sinusoidal modulated PWM inverter for similar load conditions, its shows abrupt reduction in switching losses and enhanced the quality of the output waveforms. Soft switched PWM inverter improved the efficiency around 15%, although it has a lesser number of elements than the previous soft-switching PWM inverters. In addition, that the soft switching inverter greatly reduces EMI noise because all the main switches are turned on and off under ZVS condition, which reduces the switching dv/dt and di/dt. In the future, this simple circuit will be implemented on various PWM techniques. It will also improve the efficiency of SSPWM inverter, further The proposed clamping circuit battery may be used with UPS system it improve the overall efficiency of the drives.

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