Implementation of ZVS Concept in Four Wire Inverter for UPS Fed (Unbalanced) Star Connected Load

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Summary

A novel method of output voltage control of a 3 phase uninterruptible power supply (UPS) System with four leg inverter is proposed. This paper presents the feedback loop control scheme for a soft switched four wire voltage source inverter with filter for UPS system. The use of a four wire inverter increases the quality of the output whereas the implementation of soft switching technique increases the overall efficiency of the inverter by reducing switching losses. Further, in order to respond to the load variations a feedback loop is constructed with a PI controller to realize closed loop control. The four leg inverters effectively provide the neutral connection in three phase four wire system. They are used in many applications to handle the neutral current caused by the unbalanced and non-linear load. The four leg inverter produces the three output voltages independently.

The ability to deal with voltage imbalance in a 3 phase system is the main feature of three phase four wire inverter. The goal of the three phase four leg inverter is to maintain the desired sinusoidal output voltage waveform for all loading conditions and transients. The neutral connection is present to handle the ground current due to unbalanced loads. The feasibility of the proposed modulation technique is verified by computer simulation. The experimental analysis of the four wire inverter is also discussed in this paper.

Key words:

Four wire inverter, PLL, Soft Switching, THD, UPS.

1. Introduction

The four leg inverter is utilized in three phase four wire power converter and UPS applications due to its performance characteristics such as relatively low DC bus voltage and switching loss and capability to handle unbalanced load currents[1]. The fourth leg provides a path for the zero sequence currents for non-linear and unbalanced loads. Conventional three phase three wire inverters are suitable for supplying three phase balanced loads. For unbalanced three phase loads these four wire inverters able to provide a path for the neutral current.

The two main ways for neutral wire connection are

- Inverter with split dc link capacitors
- Inverter with fourth (neutral)leg[2].

The first way is simplest one but it generates the zero sequence harmonics and a high voltage ripple over supply capacitor is produced by neutral currents when the load is unbalanced or non-linear. The second way requires additional power switches and quite complex control strategy. It offers different advantages, such as increased maximum output voltage value, a reduction of neutral currents and the possibility of neutral point voltage control [3],[4],[5]. In four leg inverters the load neutral wire is connected to the fourth leg as shown in fig 2. This provides the flexibility to control the neutral voltage and hence produces balanced voltages across each phase is Vdc. The two additional power switches in four wire doubles the number of inverter output states from 8(=23) to 16(=24).This improves the quality output waveform[9].UPS requires sinusoidal output with minimum total harmonic distortion[10]. It is achieved by using sinusoidal pulse width modulation (SPWM) technique. In this technique, the load voltage is compared with a reference voltage and the difference in amplitude is used to control the modulating signal in the control circuit of the power inverter.

The three phase four wire inverter is suitable for high power UPS for its advantage of feeding unbalanced load and the higher dc voltage utilization [6]. The functional block diagram for four wire inverter is shown in Fig.1.The load neutral point voltage for the three phase four wire inverter is shown in Fig.2.

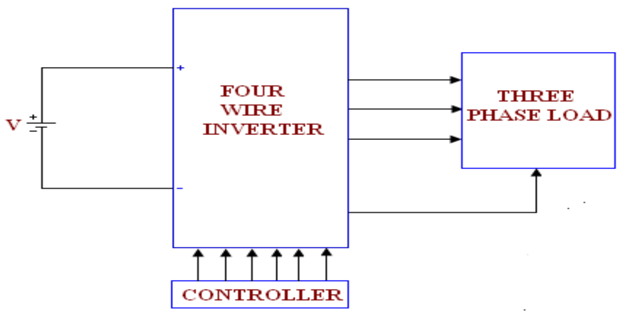

Fig.1.Functional Diagram for Four Wire Inverter

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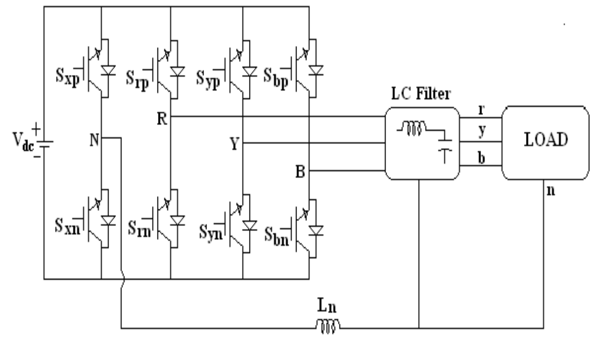


Fig.2.Three Phase Four Wire Inverter

The Fig.3 shows the block diagram for the four wire inverter for online UPS.

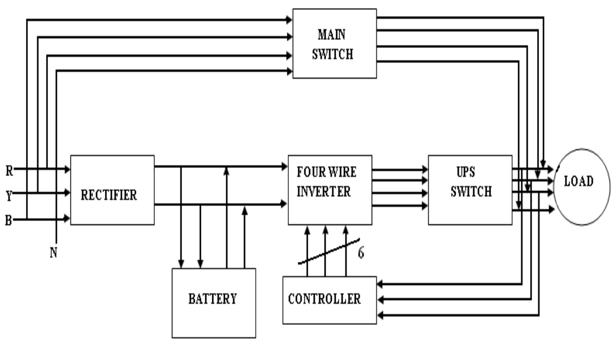


Fig.3.Block Diagram of Four Wire Inverter for Online UPS

The main components of the UPS are rectifier, battery, four wire inverter, switches and load. When the main supply is present, the rectifier provides power to an inverter as well as battery and it is charged. The inverter is on and feeds power to the load through UPS switch. The UPS switch is always ON and connects load to inverter output. The main switch is always off. But when the UPS fails, then load is connected directly to the mains through main switch. When the supply is not available, then battery bank supplies power to an inverter. Thus an inverter is always ON and it takes power from rectifier or battery.
This paper is organized as follows: Section 2 provides the description of the four wire voltage source inverter. Selecting a feedback variable for the closed loop control circuit structure, controller for the proposed control strategy, operation and simulation and zero voltage switching are proposed in section 3.Matlab implementation for the four wire inverter with system parameters are proposed in section 4 .Section 5 provides the simulation results for four wire inverter with controller. The four inverter is experimentally verified in section 6. Finally conclusion is drawn in section 7.

2. Description of Four Wire Voltage Source Inverter

The comparison of a three phase four wire voltage source inverter as shown in table 1.

Table 1: Comparison of 4 wire 3- phase inverter

S.no	Parameter	Three phase three wire load	Three phase four wire load WIRE
1.	Number of required power switches	6	8
2.	Equivalent topology	Three independent single phase half bridge.	Three dependent single phase full bridge.
3.	Number of the output vectors	6(no zero vectors)	16(14 active + 2 zero vectors)
4.	Maximum achievable peak value of line to neutral voltage.	0.5Vd	0.577Vd

There are sixteen switch combinations possible in four leg inverters. The switching vectors are represented by states [Sn, Sr, Sy, Sb] of the inverter legs. There are 14 non-zero voltage vectors and two zero vectors(1111),(0000).The three phase variables Kr, Ky and Kb can be transferred as orthogonal coordinates $K\alpha$,$K\beta$,$K\gamma$ using eq(1). Any three phase sinusoidal set of quantities can be transformed to an orthogonal reference.
For given switching states of the inverter, the voltage vector components can be calculated as,

$$\begin{pmatrix} K_\alpha \\ K_\beta \\ K\gamma \end{pmatrix} = 2/3 \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta - 4\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (1)$$

Where θ is the angle of orthogonal set $\alpha-\beta-\gamma$ with respect to arbitratory reference. If $\alpha-\beta-\gamma$ axes are stationary and the α -axis is aligned, then θ=0 at all times. Thus, we get

$$\begin{bmatrix} K_\alpha \\ K_\beta \\ K_\gamma \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} K_r \\ K_y \\ K_b \end{bmatrix} \quad (2)$$

The above matrix can be re-written as

$$K\alpha = \frac{1}{3}(2K_R - K_Y - K_B) \quad (3)$$

$$K\beta = \frac{1}{\sqrt{3}}(K_Y - K_B) \quad (4)$$

$$K\gamma = \frac{1}{3}(K_R + K_Y + K_B) \quad (5)$$

Table 2:Switching combination and output voltages for 4wire 3 phase inverter

Switching states	V_{rn}	V_{yn}	V_{bn}	V_α	V_β	V_γ
0000	0	0	0	0	0	0
0001	0	0	V_{dc}	$-1/3V_{dc}$	$1/\sqrt{3}V_d$	$1/3V_{dc}$
0010	0	V_{dc}	0	$-1/3V_{dc}$	$1/\sqrt{3}V_{dc}$	$1/3V_{dc}$
0011	0	V_{dc}	V_{dc}	$-2/3V_{dc}$	0	$2/3V_{dc}$
0100	V_{dc}	0	0	$2/3V_{dc}$	0	$1/3V_{dc}$
0101	V_{dc}	0	V_{dc}	$1/3V_{dc}$	$1/\sqrt{3}V_d$	$2/3V_{dc}$
0110	V_{dc}	V_{dc}	0	$1/3V_{dc}$	$1/\sqrt{3}V_{dc}$	$2/3V_{dc}$
0111	V_{dc}	V_{dc}	V_{dc}	0	0	V_{dc}
1000	$-V_{dc}$	$-V_{dc}$	$-V_{dc}$	0	0	$-V_{dc}$
1001	$-V_{dc}$	$-V_{dc}$	0	$-1/3V_{dc}$	$1/\sqrt{3}V_d$	$-2/3V_{dc}$
1010	$-V_{dc}$	0	$-V_{dc}$	$-1/3V_{dc}$	$1/\sqrt{3}V_{dc}$	$-2/3V_{dc}$
1011	$-V_{dc}$	0	0	$-2/3V_{dc}$	0	$-1/3V_{dc}$
1100	0	$-V_{dc}$	$-V_{dc}$	$2/3V_{dc}$	0	$-2/3V_{dc}$
1101	0	$-V_{dc}$	0	$1/3V_{dc}$	$1/\sqrt{3}V_d$	$-1/3V_{dc}$
1110	0	0	$-V_{dc}$	$1/3V_{dc}$	$1/\sqrt{3}V_{dc}$	$-1/3V_{dc}$
1111	0	0	0	0	0	0

When the leg is denoted by 1 the upper switch is closed when the leg is 0 the lower switch of the leg is closed. The switch positions determine the phase to neutral voltages, which are transformed to $\alpha-\beta-\gamma$ coordinates using eq(2).Table II shows the phase to neutral voltages and transformed $\alpha-\beta-\gamma$ voltages for each inverter switching state.

The three phase four wire voltage source inverter, commonly used for three phase voltage generation as shown in Fig.4. It consists of eight switches Srp-Sxn and inductor LR-LX and capacitors CR-CB.The LC filter filters out the switching harmonics. The voltage source inverter able to generate balanced and high quality ac output voltage, shown in Fig.4.

The three phase output voltage waveform shown in Fig.4. One line cycle is divided into six regions. In region 0°–60°, 120°–180°and 240°–300°, the voltage waveforms in Fig. 4 have similar pattern, i.e., one-phase voltage is always lower than the other two [7].

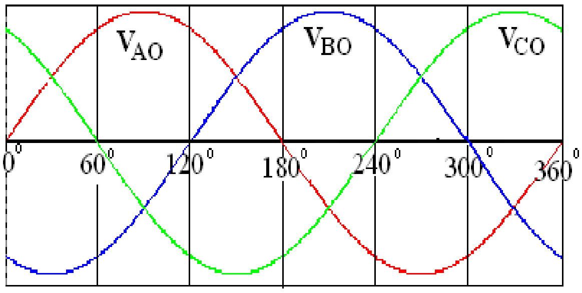
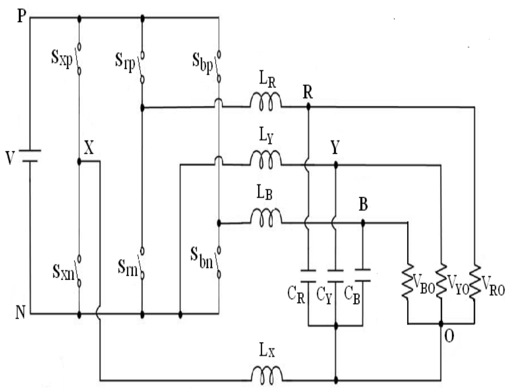
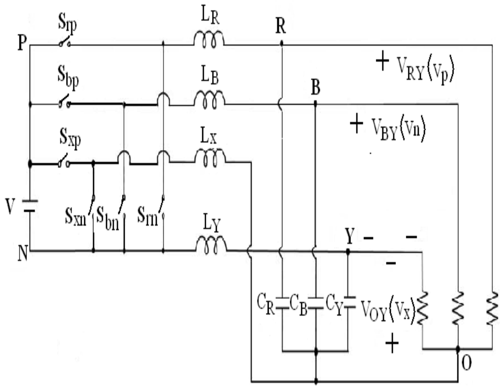


Fig.4. Three phase output voltages

The main circuit diagram Fig.2 is equivalent to Fig.5 (a) in 0°–60° region, which can be further organized into Fig.5 (b). The same equivalent circuit is also applicable to 120°–180° and 240°–300° regions. The switching of inverter is shown in table 3



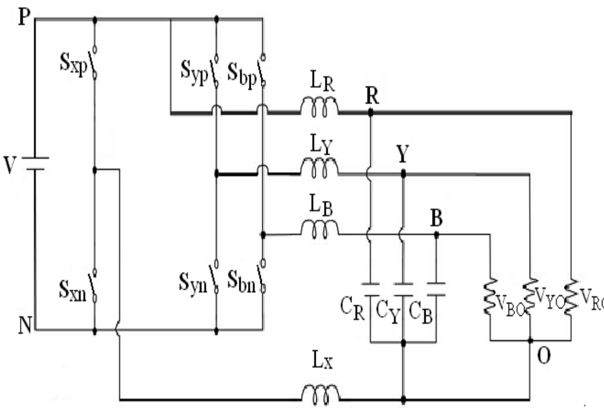
5(a)



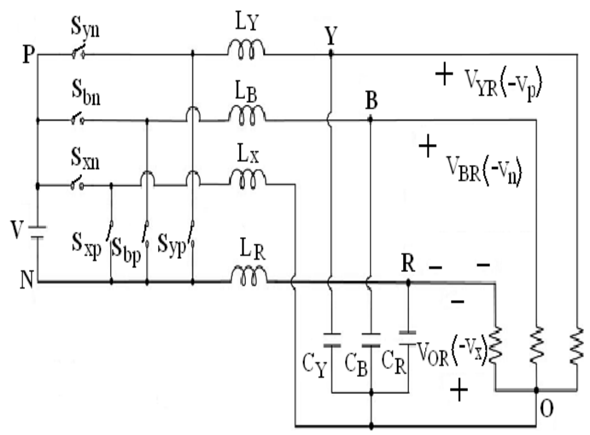
5(b)

Fig.5. Equivalent circuit for four wire VSI for 0°–60°

In region 60°–120°, 180°–240°, and 300°–360°, the voltage waveforms in Fig.5 have another pattern, i.e., one phase voltage is always higher than the other two[1]. With this Fig.2 is equivalent to Fig.6(a) in 60°–120° region, which can be further organized into Fig. 6(b).The same equivalent circuit is also applicable to 180°–240°and 300°–360° regions. The switching of inverter is shown in table 3.



6(a)



6(b)

Fig.6. Equivalent circuit for four wire VSI for 60˚–120˚

For further analysis, following assumptions are made.

1) LR = LY = LB = LX = L.
2) CR = CY = CB = C.
3) Switching frequency is much higher than fundamental frequency

Table3:Switching logic for proposed controller

Switches	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*N1*	*N2*
0˚-60˚	ON	OFF	OFF	OFF	OFF	ON	ON	OFF
60˚-120˚	ON	ON	OFF	OFF	OFF	OFF	OFF	ON
120˚-180˚	OFF	ON	ON	OFF	OFF	OFF	ON	OFF
180˚-240˚	OFF	OFF	ON	ON	OFF	OFF	OFF	ON
240˚-300˚	OFF	OFF	OFF	ON	ON	OFF	ON	OFF
300˚-360˚	OFF	OFF	OFF	OFF	ON	ON	OFF	ON

3. Control Circuit Structure

3.1 Controller For Four Wire Inverter

The block diagram for the proposed controller is shown in Fig.7.The component of proposed controller are phase lock loop, comparator, voltage controller, and gain control signal distributor. The input for the phase lock loop is the voltage feedback. The PLL responds to both the frequency and phase of the input signals automatically raising or lowering the frequency of a controlled oscillator until it is maintained to the reference in both frequency and phase. The comparator is used to compare the actual output voltage with the reference voltage and that output is fed into the voltage controller. The voltage controller is the PI controller. The PI controller is used to minimize the steady state error. The output of PI controller again compared with the reference voltage. The output of the voltage controller is given to the control signal distributor which distributes the signal to the inverter.

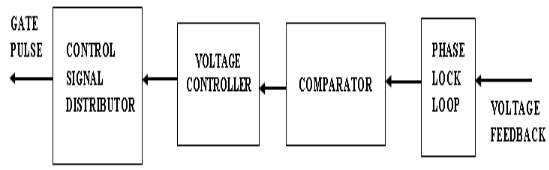


Fig.7.proposed controller for four wire inverter

The control block diagram for the inverter is shown in Fig.8. The control blocks are simulated through MATLAB/SIMULINK.

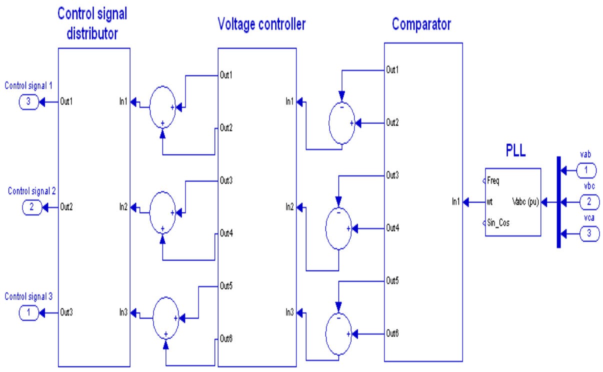


Fig.8. Control block diagram for inverter

The implemented feedback loop makes use of Park transformation on the measured three-phase output voltages. This conversion is also referred to as abc-to-dqo transformation. The following equations are used for the said transformation:

$$V_d = \frac{2}{3} * \begin{bmatrix} V_a * \sin(\omega t) + V_b * \sin(\omega t - 2pi/3) \\ + V_c * \sin(\omega t + 2pi/3) \end{bmatrix} \quad (6)$$

$$V_q = \frac{2}{3} * \begin{bmatrix} V_a * \cos(\omega t) + V_b * \cos(\omega t - 2pi/3) \\ + V_c * \cos(\omega t + 2pi/3) \end{bmatrix} \quad (7)$$

$$V_o = \frac{1}{3} * [V_a + V_b + V_c] \quad (8)$$

The instantaneous line to line voltage for three phase sinusoidal waveform is

$$V_{ab} = \sum_{n=1,3,5}^{\alpha} \frac{4Vs}{n} \sin\frac{n\pi}{3} \sin n\left(\omega t + \frac{\pi}{6}\right) \quad (9)$$

$$V_{bc} = \sum_{n=1,3,5}^{\alpha} \frac{4Vs}{n\pi} \sin\frac{n\pi}{3} \sin n\left(\omega t - \frac{\pi}{2}\right) \quad (10)$$

$$V_{ca} = \sum_{n=1,3,5}^{\alpha} \frac{4Vs}{n\pi} \sin\frac{n\pi}{3} \sin n\left(\omega t - \frac{7\pi}{6}\right) \quad (11)$$

In the eq (9),(10),(11) triplen harmonics (n= 3, 6, 9, 12) would be zero in the line-line voltages.

3.2 Zero Voltage Switching

Hard switching refers to stressful behavior of the power electronics device. During the turn on and turn off process, the power device has to withstand high voltage and high current simultaneously. This results in high switching losses and stress.

a) Low switching frequency
b) High switching loss
c) High EMI
d) Acoustic noise

The drawbacks in hard switching can be overcome by using the method called soft switching. Soft switching converters constrain the switching of power devices to time intervals when the voltage across the device or the current through it is zero. It reduces the device switching losses and hence allows higher switching frequencies and wider control bandwidths simultaneously lowering dv/dt and EMI problems.

The switching strategy for the inverter is shown in Fig.8. In this Fig.8 the control signals are compared with the carrier signal and produce the switching patterns for the inverter. The gating signals for each switches is shown in Fig (b)-(g).It can be seen that all the switching patterns possess half-wave symmetry where the switches in the same arm do not conduct[8].

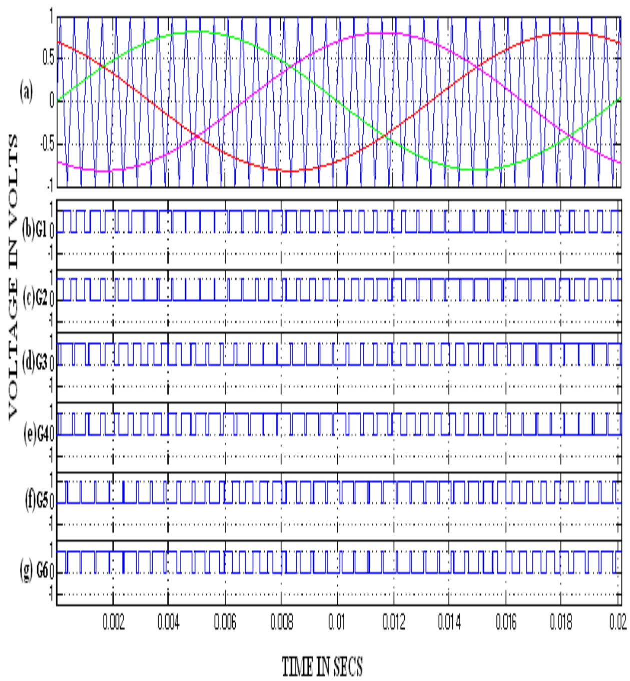


Fig.8.Generation of Pulses for Switches

Benefits of ZVS:

- Zero power “Lossless” switching transitions.
- Reduced EMI / RFI at transitions.
- High efficiency with high voltage inputs at any frequency.
- Can incorporate parasitic circuit and component L and C.

The overall switching pattern for the inverter is simulated through simulink. The time variation of gate pulse, voltage and current of switches Srp and Srn are shown in Fig.9 and Fig.10 where ZVS operation can be clearly observed. When the switch is on i.e., the gate pulse is given to the switches the voltage across the switch and current is zero.

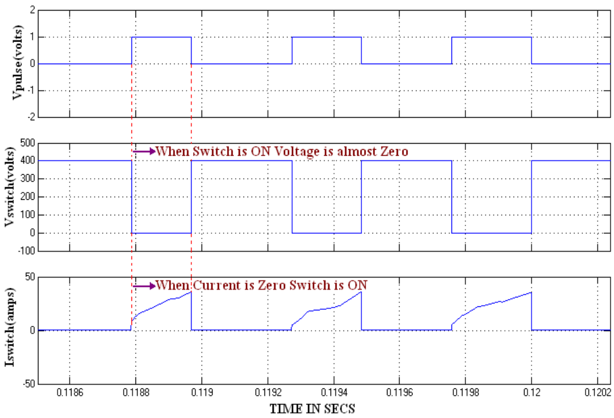


Fig. 9.Gate signal, voltage and current of Srp

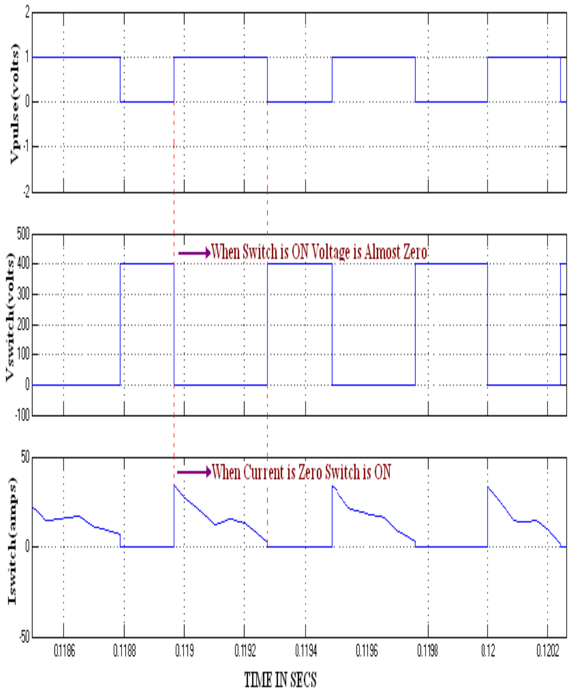


Fig.10.Gate signal, voltage and current of Srn

4.Matalab Implementation

The proposed three phase four wire inverter is tested on online UPS system simulated on Matlab/simulink implementation. The Fig.11 shows the closed loop circuit in which control signals are given as input to the gate for the four wire inverter and the output of the inverter are the voltage taken after filter and before filter and line currents.

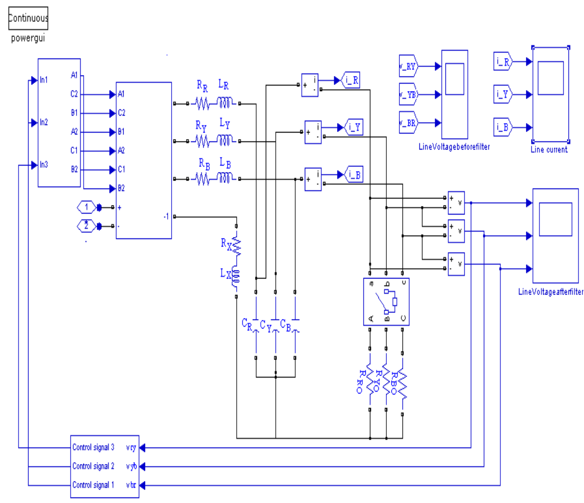


Fig. 11.Simulation circuit for three phase four wire inverter From the above simulation analysis

(i) The neutral leg provides a lower impedance loop for unbalanced current and triplen harmonics, so the imbalance of output is dramatically reduced.

(ii) The neutral inductance L_X can reduce the current that flows through the switching components of neutral leg.

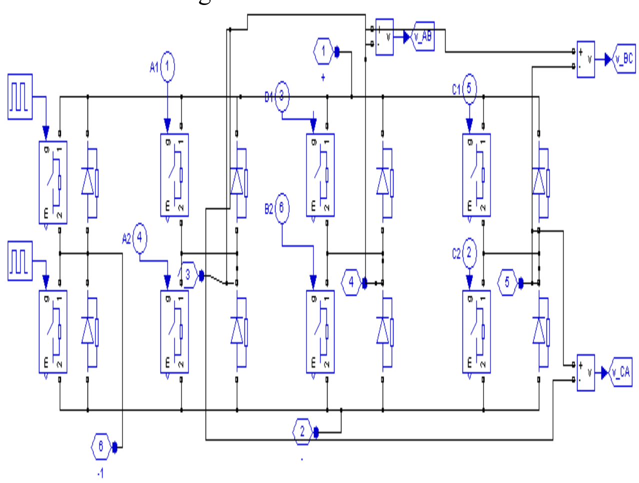


Fig.12. Simulation of gate pulse for four wire inverter

The Fig.12 is the simulation of gate pulse for four wire inverter in which the input of the gatting signals is taken from the control signal distributor. The simulation parameter is shown in table 4.

Table 4:Parameter for Simulation Analysis

Parameter	Values
DC bus	400V
Output voltage	300V
Output frequency	50HZ
Switching frequency	2000HZ
Inductor resistance	1Ω
Filter inductance	800e-5H
Filter capacitance	400µF
Rated resistive load	100Ω

5.Simulation results

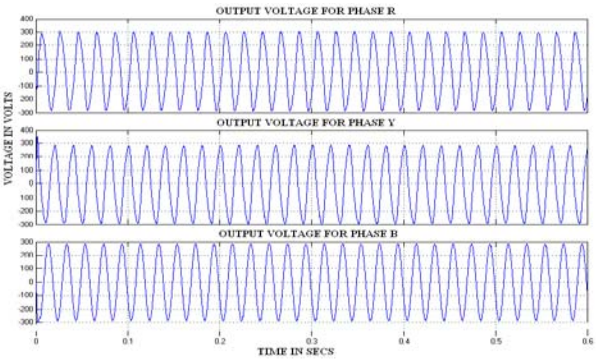


Fig.13. Simulation result for output line voltage

The above waveform as shown in Fig.13 is the output line voltages. The output waveform is a sinusoidal and it is taken by using filter component and to reduce the harmonic in the output.

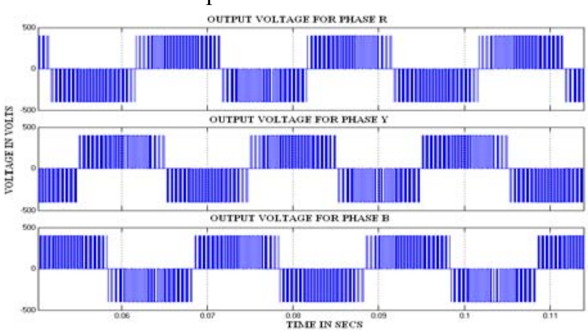


Fig.14.Simulation result for output line voltage before filter

The above Fig.14 is the simulation result for output line voltage. The output is the stepped wave and it is taken without any filter components. The Fig.15 is the waveform for three phase four wire inverter output current which is taken between load and no load condition.

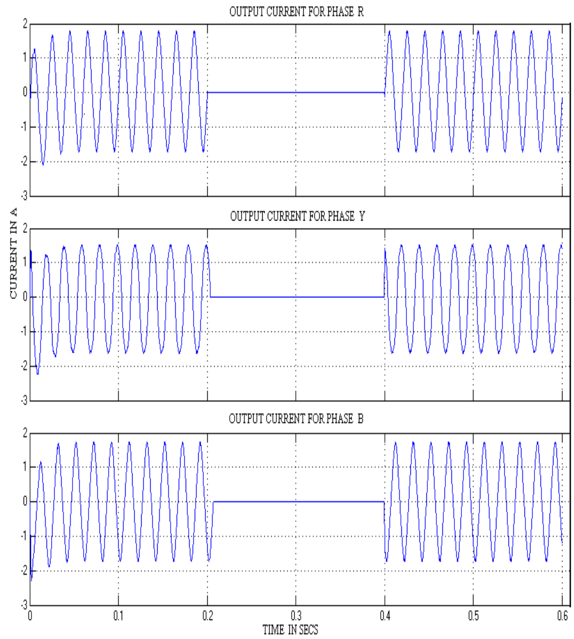


Fig.15.Simulation result for output current

The THD analysis of four wire inverter is shown in Fig.16 and the THD level is 2.70%.The amount of harmonic is reduced in this inverter.

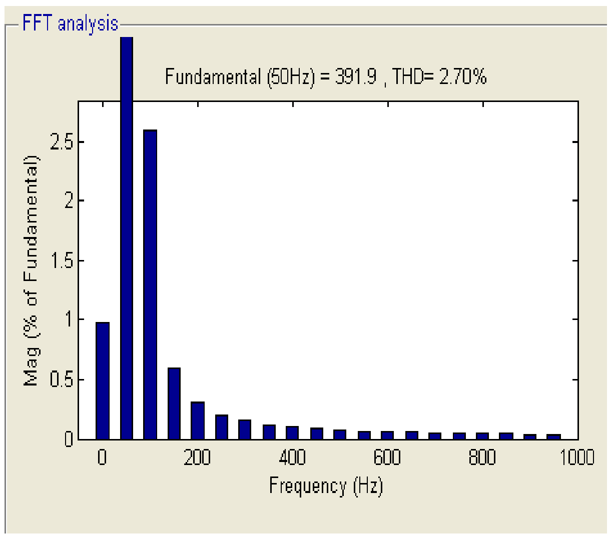


Fig.16. THD for four wire inverter

6.Experimental results

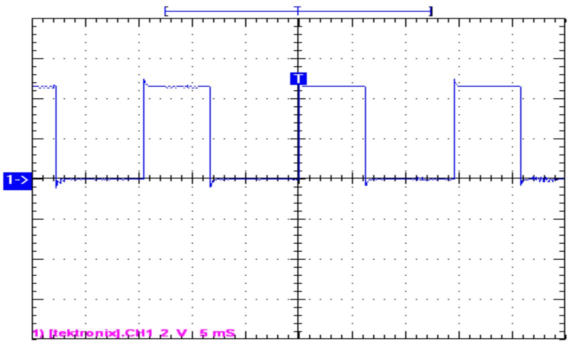


Fig.17.Gate pulse for the four wire inverter switches

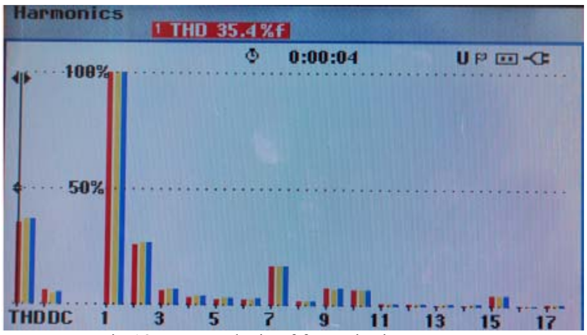


Fig.18.THD analysis of four wire inverter

The hardware output for the gate pulse of the inverter switches (srp-sbn) and neutral wire switch (sxp-sxn) as shown in Fig.17 and Fig.18 respectively.
The output line voltage result for the phase R, Y, B is shown in Fig.19, 20, 21 respectively. The three phase line output voltage waveforms are phase shifted by 120°.

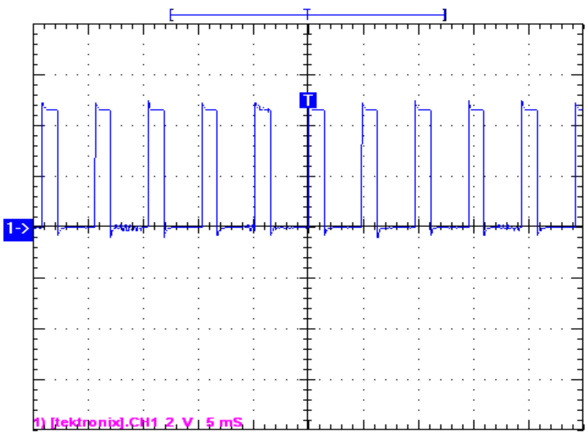


Fig.19. Gate pulse for neutral wire switches

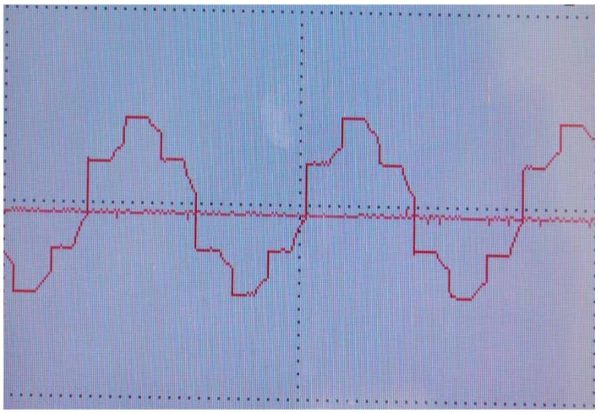


Fig.20.Output line voltage waveform for phase R

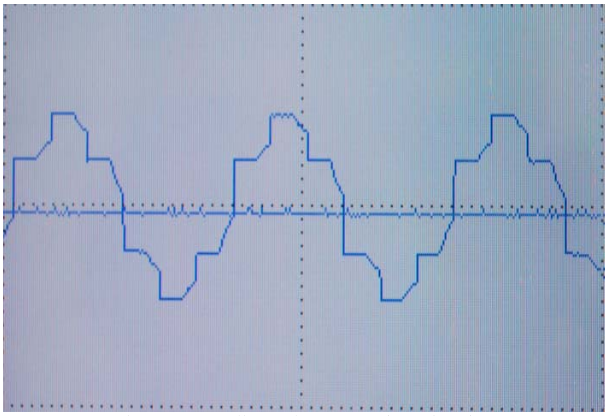


Fig.21.Output line voltage waveform for phase Y

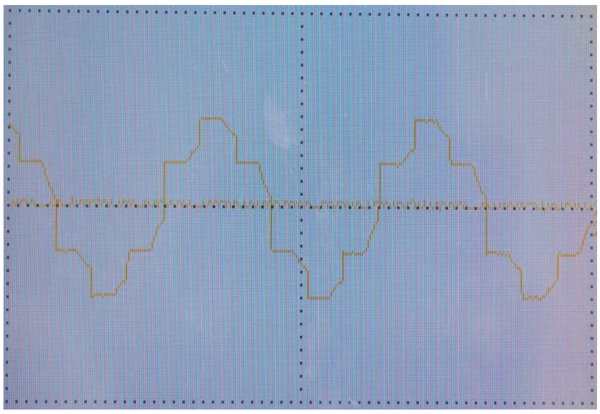


Fig.22. Output line voltage waveform for phase B

The results are experimentally verified and the setup for four wire inverter is shown in Fig.23

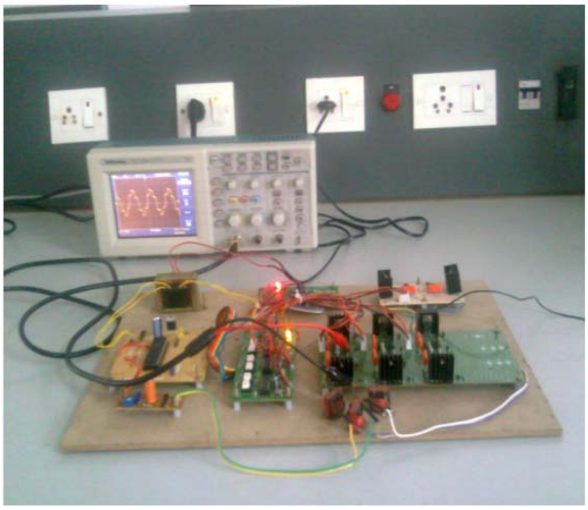


Fig.23.Experimental setup for four wire inverter

7.Conclusion

A feedback loop control strategy for four wire voltage source UPS system has been described in this paper. The basic features of feedback control systems, such as insensitivity to parameter variations and robustness, this scheme is capable of producing nearly perfect sinusoidal load voltage. The closed-loop controller produced output voltage waveforms that have lower harmonic content than the open loop controller. Moreover, the zero-voltage switching makes a great contribution to reducing dv/dt and di/dt of each switching device, thus resulting in reduced EM1 and switching losses. The fourth leg of the topology makes the inverter have the ability of handling unbalancing loads The inductor in fourth leg reduces the current through the switching components. The experimental results for four wire inverter are analysed in this paper.

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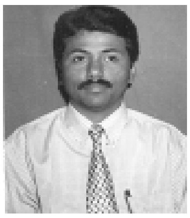

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