Performance Analysis of Three Phase On-Line UPS Using Single Stage Power Converter

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Abstract *- This paper proposes the performance improvement of the power converters in Uninterruptible Power Supply (UPS) based on size reduction, efficiency improvement and power quality. The traditional UPS consists of step up transformer or dc-dc chopper to boost the voltage which decreases the efficiency, reduces the power quality and leads to increase the cost of energy conversion. The proposed ZSI is a single stage power converter and it overcomes the limitations of traditional pwm inverter in UPS. In the three phase Z-source inverter a symmetrical LC network is employed to couple the main power circuit of an inverter to a battery bank. The ZSI having the advantages of operating at shoot through time period which is forbidden in the traditional VSI. By controlling the shoot through time the ZSI can operate in both buck and boost mode. The effectiveness of ZSI is greatly utilized in this research for UPS application. The analysis of proposed UPS system is based on cost effective, energy conversion efficiency and power quality. The proposed and conventional system of UPS is simulated in MATLAB/SIMULINK software and its results are validated with 2 kVA experimental setup in the laboratory.*

Key words: UPS, ZSI, THD, PowerQuality

I. INTRODUCTION

Uninterruptible Power Supplies (UPSs) provide clean and uninterrupted high quality power to critical loads such as communication systems, computers, life support systems in hospitals, data processing systems, industrial controls etc [1]-[4]. It provides emergency power under any normal or abnormal utility power conditions, including outages from a few milliseconds up to several hours duration [2]. Mainly there are two types of traditional UPS. The first type consists of ac/dc rectifier, battery, dc/ac inverter, step up transformer and filter[18]. The second type of UPS consists of ac/dc rectifier, battery, dc-dc booster, dc/ac inverter and filter[4]. The additionally used step up transformer and dc-dc booster in the conventional systems increases the weight, volume and cost of the system and also decreases the efficiency. The voltage source inverter (VSI) is used to convert dc to ac in UPS. VSI can be used only for buck the input voltage and not for boost function. In the traditional inverters upper and lower switches of each phase leg cannot be triggered simultaneously, otherwise shoot-through will occur[10]. Hence the dead time in the traditional inverter leads to waveform distortion [7].

In this paper a new approach that is Z-source inverter is used for the three phase uninterruptible power supply (UPS). This ZSI overcomes the conceptual and theoretical limitations of VSI and CSI. This new topology offers the following advantages [10]-[13]:

1. The step up transformer is not needed to boost the voltage. By introducing shoot through operation mode in ZSI which is not used in traditional UPS the output voltage can be increased.
2. The ZSI provides a cheaper, simpler and single stage power conversion by combining dc-dc booster and dc/ac inverter.
3. The ac output voltage waveform distortion is reduced because the shoot through is allowed and the dead time in the PWM signals is absent in ZSI.
4. The Total Harmonic Distortion (THD) of the output voltage waveform is less than 2% under the nonlinear load.
5. Fast transient response and good steady state performance even at voltage sag conditions can be achieved.

The uninterruptible power supply (UPS) is classified into on line UPS, off line UPS and Line interactive UPS [2]. In this paper on line UPS is used because the transfer time in the event of power failure is practically zero since the inverter is always ON [13]. On line UPS provides the

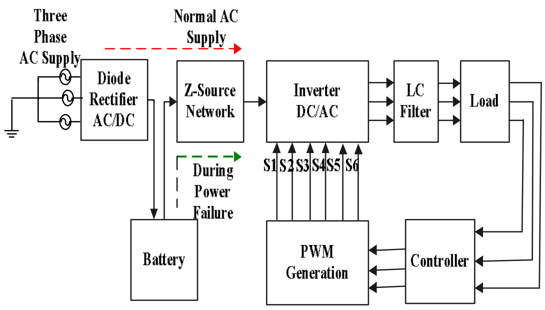

Fig.1. Block diagram of proposed UPS

The main objective of this project is to improve the performance of a three phase Uninterruptible Power Supply (UPS) with single stage power conversion, high efficiency, low harmonics, fast response, and low cost by incorporating a Z-Source inverter, where a symmetrical LC network is used to couple the inverter and main power supply. The output voltage is increased by adjusting the shoot through duty cycle without using step up transformer or dc-dc booster.

This paper deals with traditional and proposed power converters for UPS, Z-source inverter, pwm control scheme of ZSI based UPS, simulation and hardware results of proposed UPS system and conclusion.

II. TRADITIONAL AND PROPOSED POWER CONVERTERS FOR UPS

An uninterruptible power supply (UPS) is a device or system that maintains a continuous supply of electric power to certain essential equipment that must not be shut down unexpectedly [1]-[5]. The equipment is inserted between a primary power source, such as a commercial utility, and the primary power input of equipment to be protected, for the purpose of eliminating the effects of a temporary power outage and transient anomalies [2]. They are generally associated with telecommunications equipment, computer systems, medical intensive care systems, chemical plant process control and other facilities such as airport landing systems and air traffic control systems, where even a temporary loss of supply could have severe consequence, there is need to provide an uninterruptible power supply system which can maintain the supply under

highest level of protection when compared with off line UPS [1]. The block diagram of ZSI for three phase UPS is shown in Fig. 1.

all conditions. Therefore, the function of UPS is to provide clean, interrupt free supply of power to critical loads. This provides protection against power outages as well as suppressing incoming line transient and harmonic disturbances [4].

UPS provides emergency power under any normal or abnormal utility power conditions, including outages from a few milliseconds up to several hours duration. Mainly there are two types of traditional three phase UPS [4]-[6].

1. The first type consists of ac/dc rectifier, battery, dc/ac inverter, step up transformer and filter shown in Fig. 2.
2. The second type of UPS consists of ac/dc rectifier, battery, dc-dc booster, dc/ac inverter and filter shown in Fig. 3.

In the first type of UPS to get the boosted ac output voltage a step-up transformer is required. Due to this step up transformer the stress on the switches of the inverter is increased because the inverter current is much higher than the load current. The transformer also increases the weight, volume, and cost of the system and decreases the efficiency [5]. In the second type of UPSs, the booster is used to boost the voltage this also increases the high cost and decreases the efficiency. In both the cases the output voltage distortion is high.

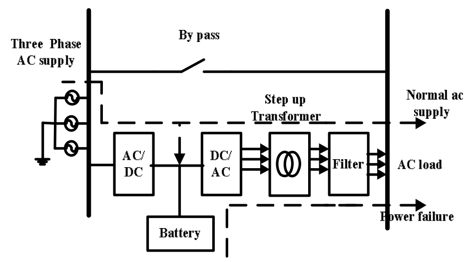

Fig. 2. Traditional UPS with step up transformer.

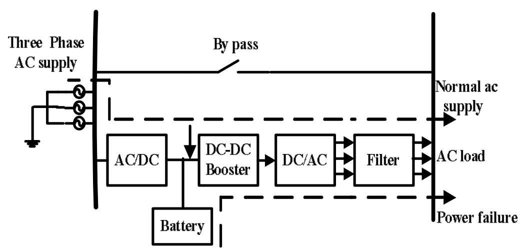

Fig. 3. Traditional UPS with DC-DC Booster.

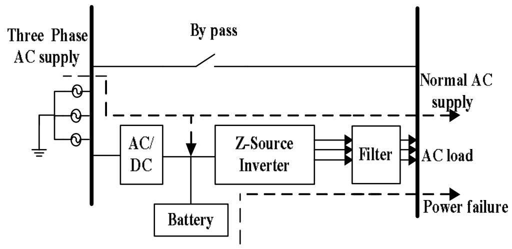

Fig. 4. Proposed UPS with Z-source inverter.

In this paper a new approach that is Z-souce inverter is used for the three phase uninterruptible power supply (UPS) as shown in Fig. 4. This ZSI overcomes the limitations of traditional UPS. By increasing the shoot through time period in Z-source inverter the output voltage can be increased [10]. Hence, this new topology does not require step up transformer or dc-dc booster to boost the voltage [19]. The circuit diagrams for proposed UPS during normal power supply and power outage are shown in Fig. 5 & 6. During normal power supply the rectifier provides the power to the inverter. During power outage, the battery bank supplies the power to the inverter.

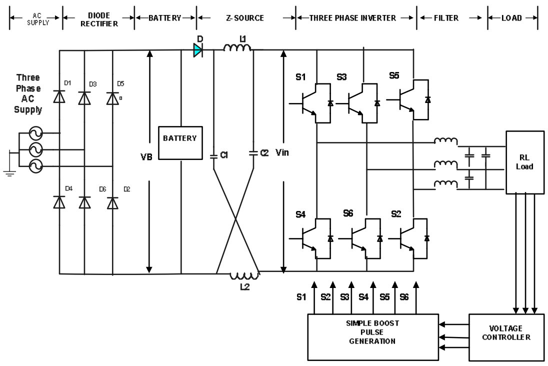

Fig. 5. Proposed UPS with ZSI during normal power supply

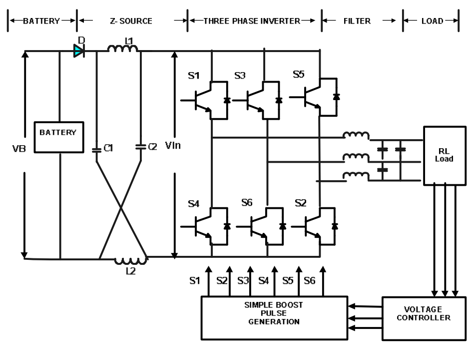

Fig. 6. Proposed UPS with ZSI during power outage

3. Z-SOURCE INVERTER

The Z-source inverter employs a unique impedance network (LC network) to link the power source and inverter main circuit to provide both voltage buck and boost properties which cannot be obtained in traditional voltage source inverter (VSI) where a capacitor and inductor are used respectively [10]. The Z-source inverter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage source inverter (VSI) [10]. The Z-source inverter system provides ride-through capability under voltage sag, reduces line harmonics, and extends output voltage range [11]. The Fig. 7 shows the general Z-source inverter structure proposed and the table I shows the corresponding switching states for the ZSI. In Fig. 7, a two-port network that consists of a inductors (L_1, L_2) and capacitors (C_1, C_2) and connected in X shape is employed to provide an impedance source (Z-Source) coupling the inverter to the dc source. The dc source is the three phase uncontrolled rectifier. Switches used in the inverter can be a combination of switching devices and diodes. The inductance and can be provided through a split inductor or two separate inductors. The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion [10].

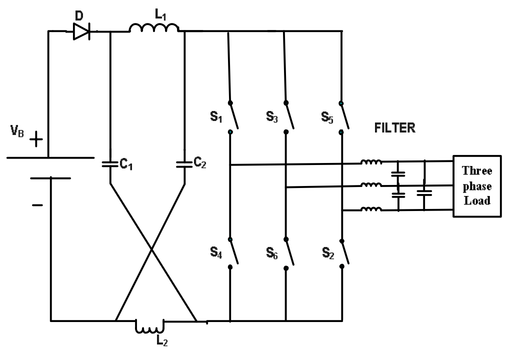

Fig. 7. Z-Source Inverter (ZSI)

A. *Operating Principle & Equivalent Circuit of ZSI*

The Z-source inverter is a buck–boost inverter in which the output voltage can be of any value between zero and infinity [10]. The traditional voltage and current source inverters are either buck or boost inverters. The three phase Z-Source inverter bridge has fifteen permissible switching states (vectors) unlike the traditional three phase voltage source inverter that has only eight[11]. The traditional three phase voltage source inverter has six active vectors when the dc voltage is impressed across the load and two zero vectors when the load terminals are shorted through either the lower or upper two devices, respectively. However, the three phase Z-source inverter bridge has seven extra zero state (or vector) when the load terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are gated on) or any two phase legs [10]-[14]. This shoot-through state (or vector) is forbidden in the traditional voltage source inverter, because it would cause a shoot-through. This zero state (vector) is called as the shoot-through state (or vector). The Z-source network makes the shoot-through state possible. This shoot-through state provides the unique buck-boost feature to the inverter. This shoot through state can be generated by three different ways 1. Shoot-through via first phase leg 2. Shoot-through via second phase leg 3. Combinations of two phase legs.

B. Circuit Analysis and Output Voltage of ZSI

Assumptions for the analysis of Z-source Inverter shown in Fig. 5. [10].

1. Inductors L_1 and L_2 have the same values.

$$L_1 = L_2 = L \quad (1)$$

$$V_{L1} = V_{L2} = V_L \quad (2)$$

2. Capacitors C_1 and C_2 have the same values.

$$C_1 = C_2 = C \quad (3)$$

$$V_{C1} = V_{C2} = V_C \quad (4)$$

3. Z-Source network is a symmetrical network.

The two operating states of the ZSI are shoot through state and non shoot through state [10]-[14]. The shoot through state of the ZSI is the operating state at which the switches in the same phase leg are turned ON. The H- bridge inverter is equivalent to a short circuit when the inverter is in the shoot-through zero state. During shoot through state the diode D is off. The Z-source inverter is working in shoot through states during time interval T_0, during a switching period $T_{s.}$ Shoot through time period (T_0) is defined as the duration at which the switches in the same phase leg are turned on at the same time. Non Shoot through time period (T_1) is the duration at which the Z-Source inverter is operating in any one of the Six active states. The switching time period (T_s) is the sum of shoot through time period (T_0) and non shoot through time period (T_1)[10].

$$T_S = T_1 + T_0 \quad (5)$$

$$T_0 = T_S - T_1 \quad (6)$$

The equivalent circuit of the ZSI in shoot through zero state is given in Fig. 9.

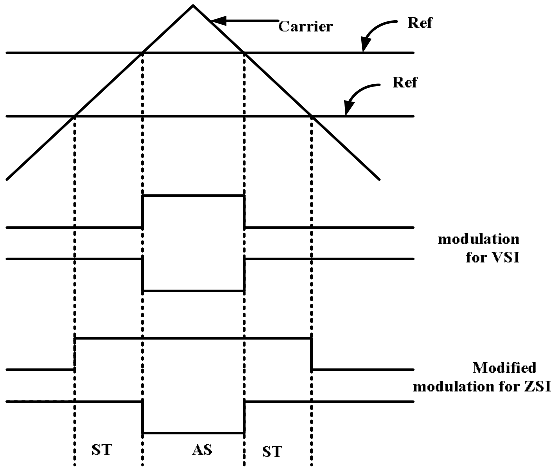

Fig.8.Modulation for VSI & ZSI

Table I switching states of ZSI

Switching States	S_1	S_4	S_3	S_6	S_5	S_2
Active state {1 0 0}	1	0	0	1	0	1
Active state {1 1 0}	1	0	1	0	0	1
Active state {0 1 0}	0	1	1	0	0	1
Active state {0 1 1}	0	1	1	0	1	0
Active state {0 0 1}	0	1	0	1	1	0
Active state {1 0 1}	1	0	0	1	1	0
Null state {0 0 0} 0V	0	1	0	1	0	1
Null state {1 1 1} 0V	1	0	1	0	1	0
Shoot Through E1 0V	1	1	S_3	S_3!	S_5	S_5!
Shoot Through E2 0V	S_1	S_1!	1	1	S_5	S_5!
Shoot Through E3 0V	S_1	S_1!	S_3	S_3!	1	1
Shoot Through E4 0V	1	1	1	1	S_5	S_5!
Shoot Through E5 0V	1	1	S_3	S_3!	1	1
Shoot Through E6 0V	S_1	S_1!	1	1	1	1
Shoot Through E7 0V	1	1	1	1	1	1

In the ZSI as in the case of VSI the capacitor provides stiff voltage across the inverter bridge, during the active state. Only the zero state which is unused in VSI, is used as shoot through period in the ZSI. During this period, the switches in any one phase leg or two phase legs or all the three phase legs are turned on resulting in short circuit. Hence a large value of emf is induced in the inductor. The capacitors are charged equal to the inductor voltage as shown in fig.(9).

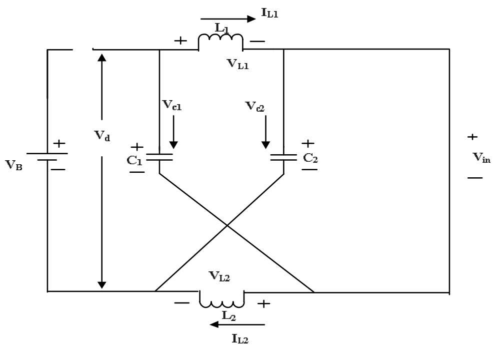

Fig. 9. Equivalent circuit of ZSI in the shoot through state.

During the shoot through state the L_1 and C_1 are connected in parallel similarly L_2 and C_2 are connected in parallel which is shown in Fig. 10[16]. From the equivalent circuit of Z-Source inverter during the shoot through zero state, the voltage equations are,

$$V_L = V_C \quad (7)$$

$$V_{in} = 0 \quad (8)$$

$$V_d = 2V_C \quad (9)$$

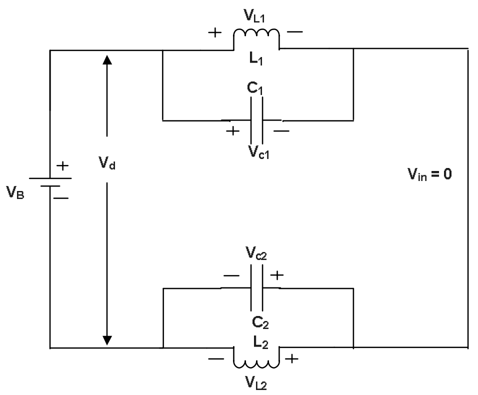

Fig. 10. Representation of ZSI in the shoot through zero state.

The non shoot through state of the Z-Source is the one of the active switching states of the ZSI. When the Z-source inverter is working in non shoot through states during time interval T_1, the diode D is on, and the H-bridge inverter can be considered as a current source I_{in}. The equivalent circuit of ZSI in the non shoot through zero state is shown in Fig. 11, and the voltage equations are[10]

$$V_B = V_d \quad (10)$$

$$V_B = V_d = V_C + V_L \quad (11)$$

$$V_L = V_B - V_C \quad (12)$$

$$V_{in} = V_C - V_L \quad (13)$$

Substituting the equation (12) in (13)

$$V_{in} = 2V_C - V_B \quad (14)$$

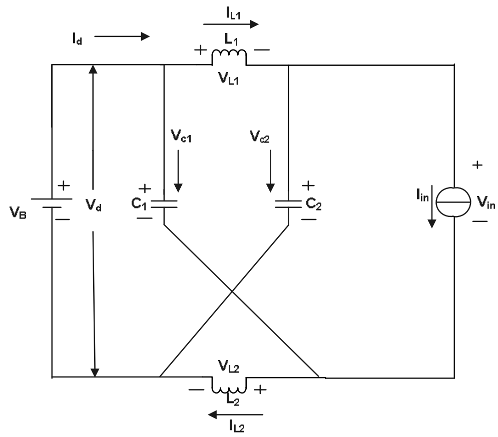

Fig. 11. Equivalent circuit of ZSI in the non shoot through state

The average voltage of inductor L_1 (or L_2) over one switching period in steady state operation is zero [10].

$$(V_B - V_C)T_1 + V_C T_0 = 0 \quad (15)$$

$$V_C = \frac{T_1}{T_1 - T_0} V_B \quad (16)$$

Substituting (16) in (14)

$$V_{in} = \frac{T_S}{T_1 - T_0} V_B \quad (17)$$

$$V_{in} = BV_B \quad (18)$$

Where B is the boost factor.

$$B = \frac{T_S}{T_1 - T_0} \quad (19)$$

$$B = \frac{1}{1 - 2\frac{T_0}{T_S}} \quad (20)$$

$$B=\frac{1}{1-2d} \tag{21}$$

$$d=\frac{T_0}{T_S} \tag{22}$$

Where, **d** is the shoot through duty ratio.

Boost factor is defined as the ratio of switching time period to the difference in duration between active state time and the shoot through time period. Boost factor value is always greater than or equal to one. By adjusting the boost factor the output voltage of the Z-source inverter can be increased or decreased.

If the voltage across the filter inductor is ignored, the output peak voltage of the inverter is given by [15],

$$V_{ac}=M\frac{V_{in}}{2} \tag{23}$$

From the equation (18)

$$V_{ac}=MB\frac{V_B}{2} \tag{24}$$

$$B_B=MB \tag{25}$$

$$V_{ac}=MB\frac{V_B}{2}=B_B\frac{V_B}{2} \tag{26}$$

Where,
M is the modulation index. $M \leq 1$.
B is the boost factor $B \geq 1$
B_B is the Buck –Boost factor.
From the equation (26) the voltage gain of the Z-Source inverter is given by,

$$\frac{V_{ac}}{V_B}=\frac{MB}{2}=\frac{B_B}{2} \tag{27}$$

Thus, any desired output voltage can be obtained by properly selecting the boost factor and the modulation index regardless of the battery bank voltage.

4. PWM CONTROL SCHEME OF ZSI BASED UPS

The firing pulses generated using a modified pwm scheme is shown in Fig. 11. The three phase sinusoidal reference signals and two constant DC voltages are compared with the triangular carrier wave to generate the firing pulse with the shoot through state. The amplitude of the two straight lines is equal to or greater than the peak amplitude of the reference wave. When the carrier waves is greater than the upper envelope V_P, or lower than the bottom envelope V_n the circuit turns into shoot through state [17]-[20] otherwise it operates as a conventional inverter. For this simple boost control the obtainable shoot through duty ratio decreases with the increase of modulation index M. The maximum shoot through duty ratio of the simple boost method is limited to 1-M, thus reaching zero at a modulation index of one. In order to produce an output voltage that requires a high voltage gain, a small modulation index has to be used [18].

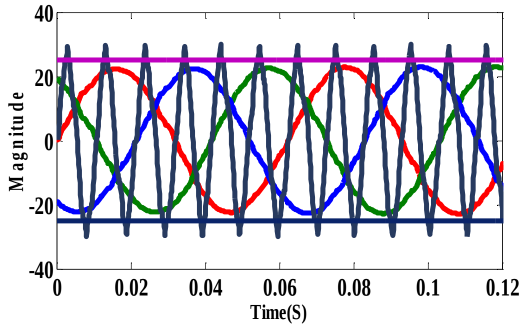

Fig. 12. PWM control scheme for ZSI.

Modulation Index is given by,

$$M=\frac{T_1}{T_S} \tag{28}$$

The boost factor of the Z-Source inverter is given by,

$$B=\frac{1}{1-2\left(\frac{T_S-T_1}{T_1}\right)} \tag{29}$$

$$B=\frac{1}{1-2(1-M)} \tag{30}$$

$$B=\frac{1}{(2M-1)} \tag{31}$$

The voltage gain of the single phase Z-Source inverter with simple boost algorithm is given by[15],

$$G=\frac{V_{ac}}{V_B}=\frac{MB}{2}=\frac{B_B}{2} \tag{32}$$

$$G=\frac{M}{2(2M-1)} \tag{33}$$

For any desired voltage gain G, the maximum modulation index can be used is,

$$M = \frac{2G}{2G-1} \qquad (34)$$

5. SIMULATION AND EXPERIMENTAL RESULTS

The simulation model of three phase on line UPS with step up transformer is shown in Fig. 13(a). The input current and output voltage harmonics of this UPS are compared with the proposed UPS. In this traditional UPS step-up transformer is additionally used which leads to more waveform distortion and high cost.

The simulation of proposed three phase on line UPS with the Z-Source inverter have been performed. During the normal power supply the supply is given from three phase ac supply. During the power outage the battery gives supply to the inverter. The simulation model of the three phase UPS is shown in Fig. 13(b) and 13(c). The total harmonic distortion (THD) of the output voltage in the steady state under the nonlinear load is less than the 2%.

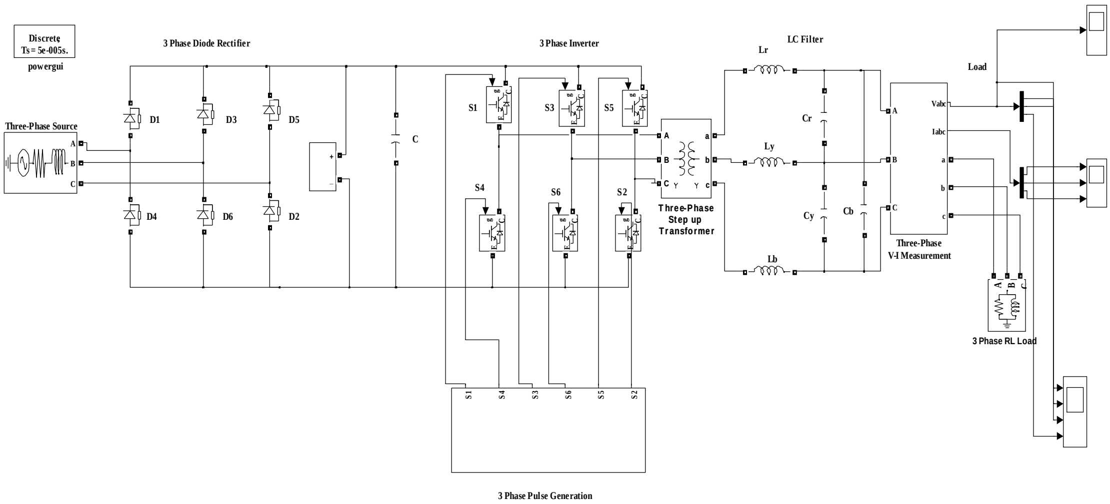

Fig. 13(a). Simulation of traditional UPS with step up transformer.

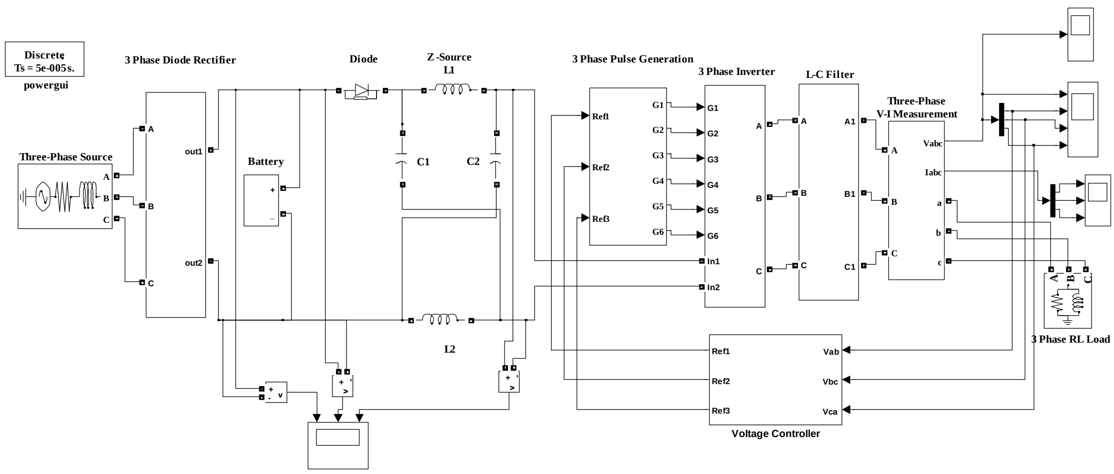

Fig. 13(b). Simulation of proposed UPS during normal power supply.

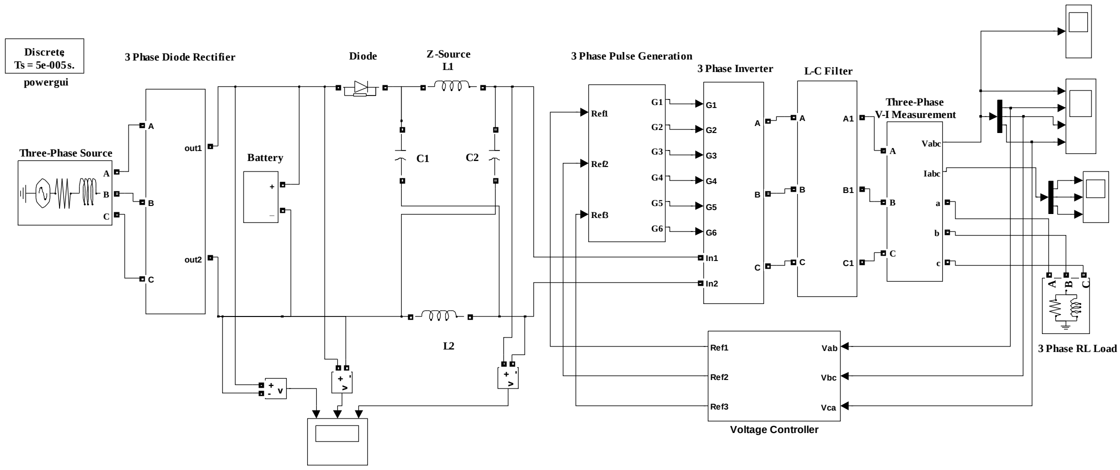

Fig. 13(c). Simulation of proposed UPS during power outage.

The pulse pattern for the single phase ZSI is shown in Fig. 14. The pulses are generated by using simple boost control technique.

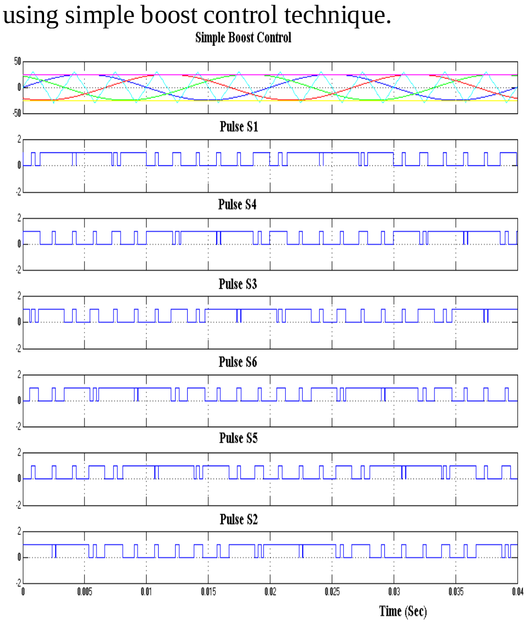

Fig. 14. Switching pulses for S1, S2, S3, S4, S5, S6.

The Fig. 15(a) and 15(b) shows the output voltage and current waveform of the proposed UPS with ZSI during the normal power supply and power outage. During the power outage the battery gives supply to the inverter and the output is not interrupted. The input voltage given is 415V (rms). The output voltage of the proposed UPS is 580V (peak-peak) with the boost factor of B=1.2.

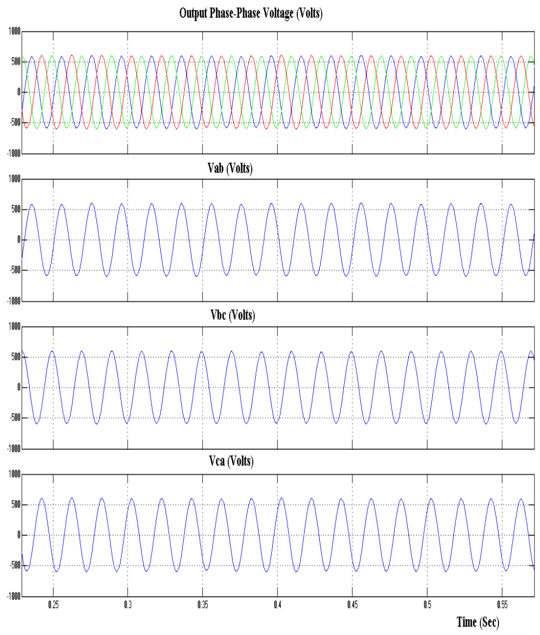

Fig. 15(a). Output voltage and current waveform during normal power supply.

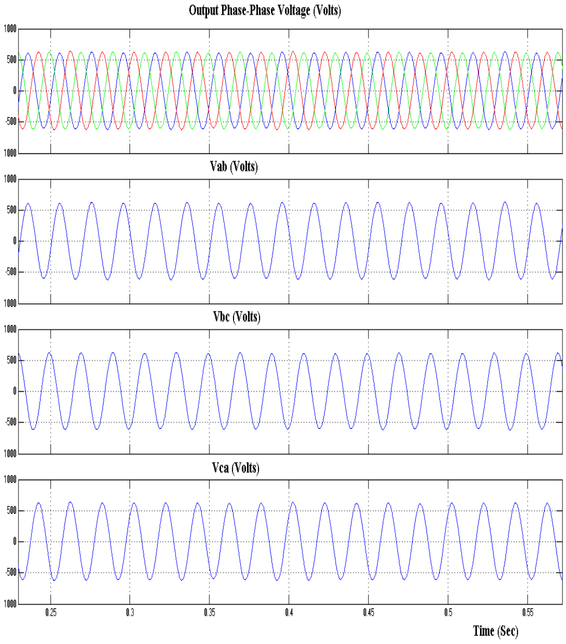

Fig. 15(b). Output voltage and current waveform during power outage.

The sinusoidal waveform is obtained for the proposed UPS without the waveform distortion. The sine wave output voltage can be obtained with the THD value of 1.04%, 1.06%, 0.88% in V_{ab}, V_{bc}, V_{ca} respectively which is shown in Fig. 16a, 16b and 16c. The total harmonic distortion (THD) of the output voltage in the steady state under the nonlinear load is less than the 2%.

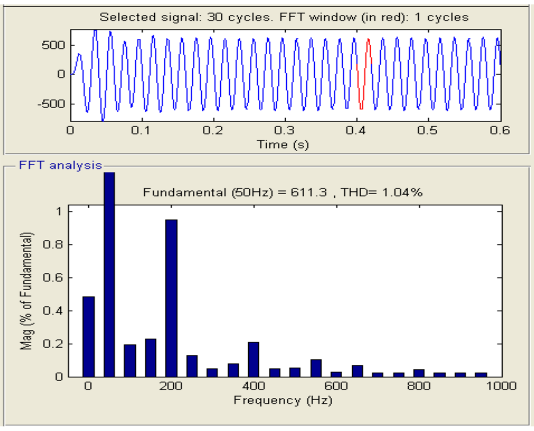

Fig. 16(a) Output voltage (V_{ab}) THD for 5 kVA.

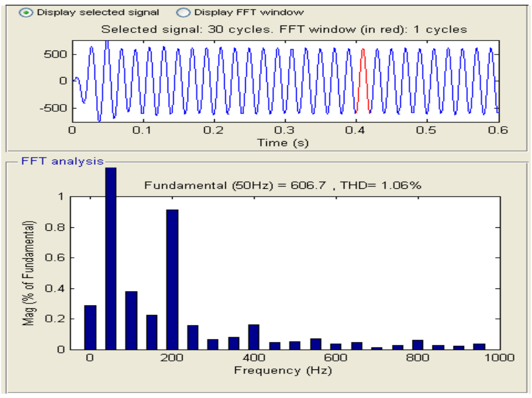

Fig. 16(b). Output voltage (V_{bc}) THD for 5 kVA.

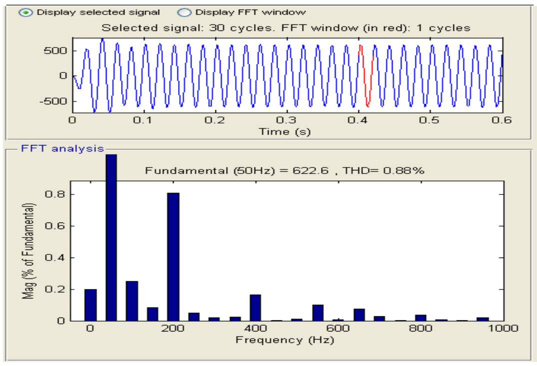

Fig. 16(c). Output voltage (V_{ca}) THD for 5 kVA.

From the Fig.17 it is evident that the output voltage THD of proposed UPS is almost 15% lesser than the traditional UPS. This increases the power quality on the output side.

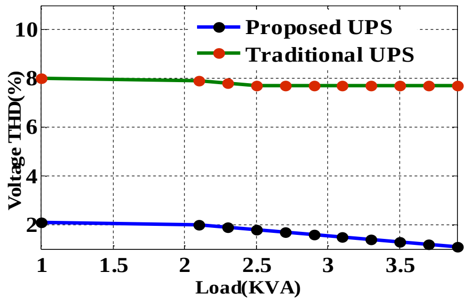

Fig. 17. Comparison of output voltage THD as a function of load power.

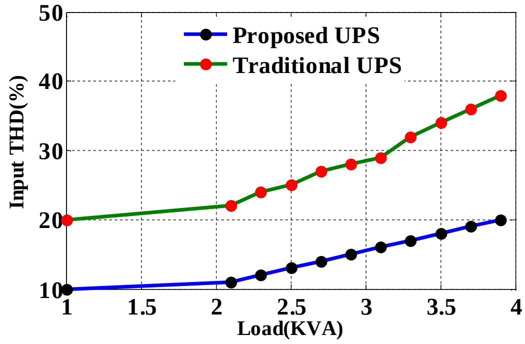

Fig. 18.Comparison of input current THD as a function of load power.

The input THD of the proposed system is almost 12% lesser than the traditional UPS which is shown in Fig.18. So the input power factor is higher and hence conduction loss in the switches is decreased.

The Fig.19 shows the efficiency of the proposed UPS and the traditional UPS. In the traditional UPS the step up transformer is used to increase the output voltage, which increases the losses and poor power factor and hence reduces the efficiency. Because of single stage conversion in the proposed UPS the losses are reduced and the overall efficiency is improved.

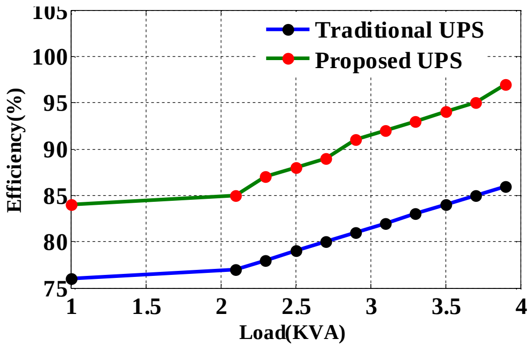

Fig.19. Efficiency of proposed and traditional UPS.

The Fig.20 and Fig.21 shows the laboratory experimental results of the proposed UPS. The pulses to turn on the switches T_1 and T_4 of the ZSI is shown in Fig.20.

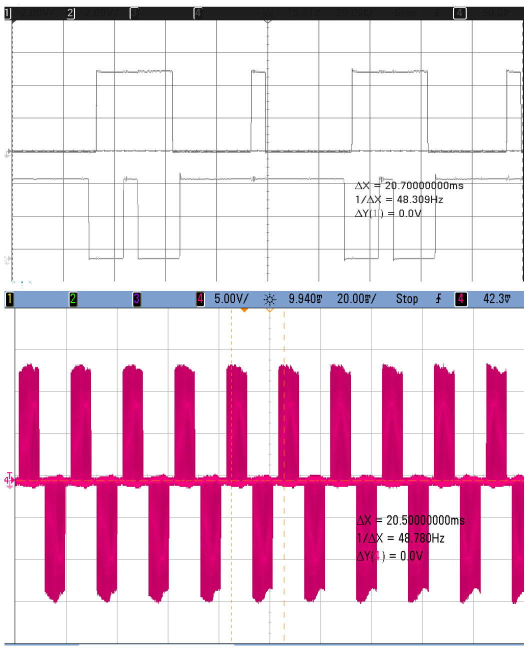

Fig. 20. Pulse pattern from experimental setup for switches T_1 and T_4

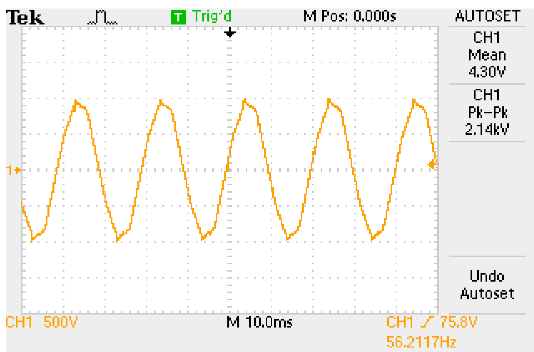

Fig.21. Output voltage of ZSI from experimental setup

6. CONCLUSION

In this paper the ZSI based UPS system is presented. The ZSI is a single stage dc-ac converter which has low switching stress. The output voltage of the ZSI entirely depends on the boost factor. The simulation of the proposed UPS is carried out for different loading conditions. Finally the comparison between traditional and proposed system is made based on power quality, efficiency and cost effective. The input THD (12%)and output THD(1.06%) of the proposed UPS is lesser than the traditional UPS. This decreases the conduction losses in the switches. Due to low switching stress, low conduction loss, low value of inductors and capacitors in the Z-source inverter the efficiency of the proposed UPS is higher than the traditional UPS.

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