International Journal of Innovative Research in Advanced Engineering (IJIRAE) ISSN: 2349-2163
Issue 5, Volume 2 (May 2015) www.ijirae.com

SVPWM BASED QUASI Z SOURCE INVERTER FOR POWER CONDITIONING OF PV SYSTEMS

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Abstract-- Quasi-Z Source Inverter (QZSI) an enhancement to Z Source Inverter (ZSI). The advantages of QZSI can be listed as lower component ratings, reduces switching ripples, reduced component count and simplified control methods. They can track the PhotoVoltaic (PV) panel maximum power, control the inverter output power and manage the battery power. In a single stage inverter operation the voltage boosting, inverting and energy storage are integrated. From the PV panel, QZSI draws a constant current. It controls the PV panel output power to maximize energy production. EMI problems and source stress are reduced, compared to the ZSI. QZSI is suitable, when implemented with the Space Vector Pulse Width Modulation (SVPWM) control techniques for photovoltaic power generation systems and could prove to be highly efficient.

Keywords: Maximum Power Point Tracking (MPPT), Z Source Inverter (ZSI), quasi-Z source inverter (QZSI), Shoot-Through (ST), Space Vector Pulse Width Modulation (SVPWM)

I. INTRODUCTION

The demand for electric energy is expected to increase rapidly due to the global population growth and industrialization. This increase in the energy demand requires electric utilities to increase their generation. The extensive use of fossil fuels has resulted in the global problem of greenhouse emissions. Moreover, as the supplies of fossil fuels are depleted in the future, they will become increasingly expensive. To overcome the problems associated with generation of electricity from fossil fuels, renewable energy sources can be participated in the energy mix. Thus solar energy is becoming more important since it produces less pollution and the cost of fossil fuel energy is rising, while the cost of solar arrays is decreasing.

The ever increasing energy consumption, fossil fuels soaring costs and exhaustible nature and worsening global environment have created a booming interest in renewable energy generation systems, one of which is photovoltaic. Such a system directly converts the solar radiation into electric power without hampering the environment. The worldwide installed photovoltaic power capacity shows nearly an exponential increase due to decreasing costs and to improvements in solar energy technology. In a conventional VSI and CSI, the constraint that triggering two input line switches leads to short circuit the source. The maximum obtainable output voltage cannot exceed the DC input and can produce a voltage lower than the DC input voltage. Voltage source inverter can assume only eight distinct topologies. Six topologies produces a non-zero output voltage and are known as non-zero switching states and the remaining two topologies produces zero output voltage and are known as zero switching states.

A. Quasi-Z-Source Inverter

The quasi z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter (ZSI) topology, employing an impedance network. The impedance network couples the source and the inverter to achieve voltage boost and inversion in a single stage. Both ZSI and qZSI overcome the drawbacks of VSI and CSI by utilizing several Shoot-Through (ST) zero states. A zero state is produced when the upper three or lower three switches are fired simultaneously to boost the output voltage. Sustaining the six permissible active switching states of a VSI, the zero states can be partially or completely replaced by the shoot through states depending upon the voltage boost requirement. The inverter draws a constant current from the PV array and is capable of handling a wide input voltage range. It also features lower component ratings, reduces switching ripples to the PV panels, causes less EMI problems and reduced source stress compared to the ZSI.

B. QZSI Network

The impedance network in QZSI differs from that of a ZSI. This network acts as an interface between the source and the inverter. The impedance network of QZSI is a two port network. It consists of inductors and capacitors. The LC impedance network and the diode connected to the inverter bridge modify the circuit operation, allowing the shoot-through state and protect the circuit from damage when the shoot through occurs. By using the shoot-though state, the quasi-Z-source network boosts the dc-link voltage. The dc source can be a battery, diode rectifier, thyristor converter or PV array. The output voltage of the QZSI is regulated and the output power is determined by corresponding load demands.

II. EXISTING TOPOLOGY

The solar irradiation and the PV panel temperature change randomly, the DC-link peak voltage will fluctuate accordingly. The additional backup is needed like battery to supply the continuous power to the load. Without requirements of any additional DC/DC converters or components, the qZSI was first proposed for PV power generation system.

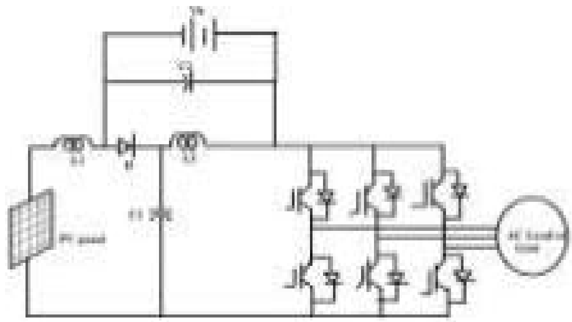

Fig.1. Existing QZSI for PV power generation

Fig.1 shows the Existing QZSI for PV power generation. This paper resolves the aforementioned problems, analyze all possible schemes of the energy-stored QZSI, compare their benefits and limitations and find a new topology more preferable to application in the PV power system.

III. PROPOSED TOPOLOGY

Fig.1 shows just one of the qZSI topologies, if the battery is connected in parallel with the capacitor C2 there is discontinuous mode will occur during battery discharge.

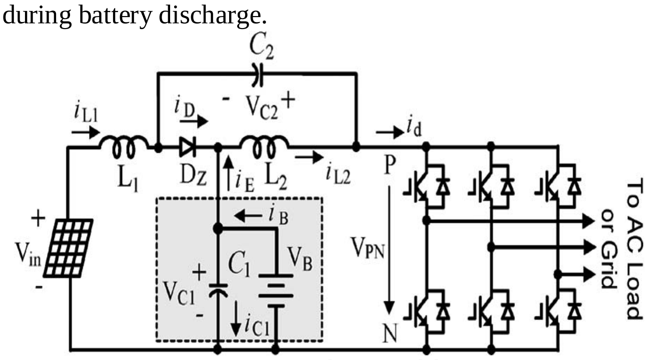

Fig.2. Energy-stored QZSI with battery

As a counterpart, connect the battery in parallel to the capacitor C1 as shown in Fig.2. They have common points:
1) there are three power sources i.e., PV panels, battery and the grid/load, 2) as long as controlling two power flows and
3) automatically matches the power difference, according to the power equation

$$P_{in} - P_{out} + P_B = 0 \qquad (1)$$

Where P_{in}, P_{out} and P_B are the PV panel power, output power of the inverter and the battery power respectively. The power P_{in} is always positive because the PV panel is single directional power supply, P_{out} is positive when the inverter injects power to the grid and P_B is positive when the battery delivers energy and negative when absorbing energy.

The Quasi z-source network makes the shoot-through zero states possible and provides the means by which boosting operation can be obtained. Critically, any of the shoot-through states can be substituted for normal zero states without affecting the PWM pattern seen by the load. Therefore, for a fixed switching cycle, Instead, with the shoot-through states inserted, the effective inverter dc link voltage V_i can be stepped up as given in (2) Consequently, taking also the PWM modulation index *M* into account, the phase ac output voltage V_x can be expressed by (3).

$$V_i = \frac{E}{1 - \frac{2T_{ST}}{T}} = B.E, B \geq 1 \qquad (2)$$

$$V_x = \frac{M.V_i}{\sqrt{3}} = B.\left\{\frac{ME}{\sqrt{3}}\right\} \qquad (3)$$

Where T_{ST} and T are the shoot-through interval and switching period respectively, B is the boost factor and the term in parenthesis represents the phase ac output voltage of a traditional VSI. Equations show that the ac output voltage of a Quasi Z-source inverter can be regulated from zero to the normal maximum by altering M and maintaining B = 1, or can be boosted above that obtainable with a traditional VSI by choosing B > 1.

A. Modes of operation:

The two modes of operation of a QZSI are:
(1) Non-shoot through mode (Active mode)
(2) Shoot through mode

1) Active mode: In this mode, the input DC voltage is available as DC link voltage input to the inverter, which makes the QZSI behaves similar to a VSI. This mode will make the inverter operate in one of the six active states and two traditional zero states, which is referred to as the non-shoot-through state. A continuous current flows through the diode D_Z. Its equivalent circuit is shown in Fig.3. During this time interval, the circuit equations are presented as follows:

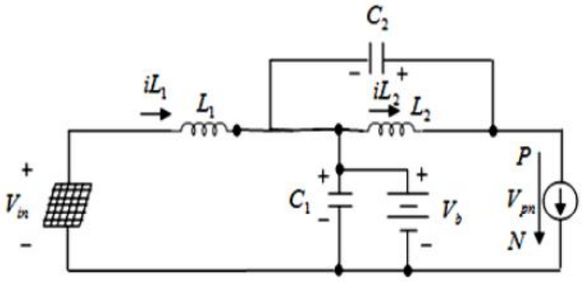

Fig.3. QZSI in Active mode

$$C\frac{dV_{C1}}{dt} = i_B + i_{L1} + i_d \quad (4)$$

$$C\frac{dV_{C2}}{dt} = i_{L2} - i_d \quad (5)$$

$$L\frac{di_{L1}}{dt} = V_{in} - V_{C1} \quad (6)$$

$$L\frac{di_{L2}}{dt} = -V_{C2} \quad (7)$$

Where i_d is the load current going to the inverter

2) Shoot through mode: In this mode, the switches of the same phase leg or combinations of any two phase legs in the inverter bridge are switched ON simultaneously for a very short duration which is referred to as the shoot through state. The source however does not get short circuited because of the presence of LC network, while boosting the output voltage. The DC link voltage during this mode, is boosted by a boost factor, whose value depends on the shoot through duty ratio for a given modulation index. Its equivalent circuit is shown in Fig.4. During this time interval, the circuit equations are presented as follows:

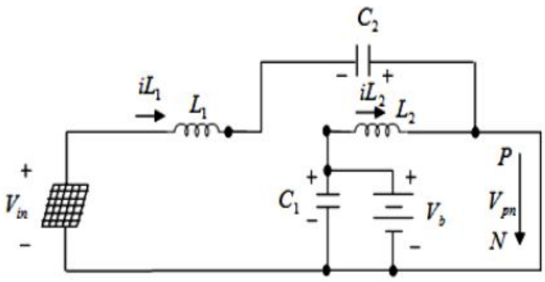

Fig.4. QZSI in Shoot through Mode

$$C\frac{dV_{C1}}{dt} = i_B - i_{L2} \quad (8)$$

$$C\frac{dV_{C2}}{dt} = -i_{L1} \quad (9)$$

$$L\frac{di_{L1}}{dt} = V_{in} - V_{C2} \quad (10)$$

$$L\frac{di_{L2}}{dt} = V_{C1} \quad (11)$$

Where i_{L1}, i_{L2} and i_B denotes the currents of inductors L_1 and L_2 and the battery, respectively; V_{C1} , V_{C2} , and V_{in} denotes the voltages of capacitors C_1 and C_2 and the PV panel, respectively; C denotes the capacitance of capacitors C_1 and C_2; and L denotes the inductance of inductors L_1 and L_2.

IV. SVPWM TECHNIQUES

The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. Space Vector Modulation (SVM) was developed as vector approach to PWM for three phase inverters.

It is a more sophisticated technique for generating sine wave that provides a higher voltage to the load with lower total harmonic distortion. Space Vector Pulse width Modulation (SVPWM) generates the appropriate gate drive waveform for each PWM cycle. The inverter is treated as one single unit and can combine different switching states.

SVPWM method is an advanced, computation intensive Pulse Width Modulation (PWM) method and possibly the best among all the PWM techniques for variable frequency drive applications. The SVPWM determines the switching pulse width and their position. The major advantage of SVPWM is that, there is a degree of freedom of space vector placement in a switching cycle. This feature improves the harmonic performance of this method. SVPWM method is an advantage because of increased flexibility in the choice of switching vector for both input current and output voltage control. It can yield useful advantage under unbalanced conditions.

A. SVPWM Representation

The circuit model of a typical three phase voltage source PWM inverter is shown in Fig.5. S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, a', b, b', c and c'. When an upper switch is switched ON, i.e., when a, b or c is 1, the corresponding lower transistor is switched OFF i.e., the corresponding a', b' or c' is 0. Therefore, the ON and OFF states of the upper switch S1, S3 and S5 can be used to determine the output voltage.

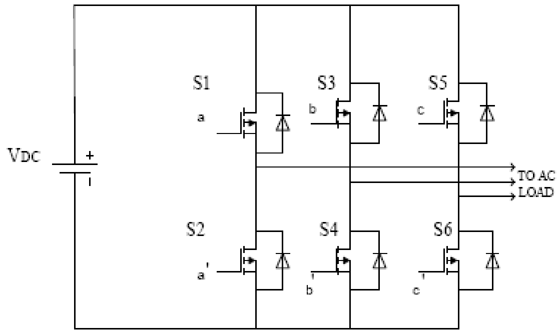

Fig.5. Three Phase Voltage Source PWM Inverter

There are eight possible combinations of ON and OFF patterns for the three upper power switches. The ON and OFF states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power transistors are determined. Space Vector Modulation was developed as vector approach to PWM for three phase inverters. It is a technique for generating sine wave that provides a higher voltage to the load with lower total harmonic distortion. Space Vector PWM (SVPWM) method is an advantage because of increased flexibility in the choice of switching vector for both input current and output voltage control. The eight switching vectors, output line to neutral voltage and output line to line voltages in terms of DC-link V_{dc}, are given in Table 1.

TABLE 1
SWITCHING VECTORS, PHASE VOLTAGES AND OUTPUT LINE TO LINE VOLTAGES

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary d-q reference frame. That consists of the horizontal (d) and vertical (q) axis as shown in Fig.6.

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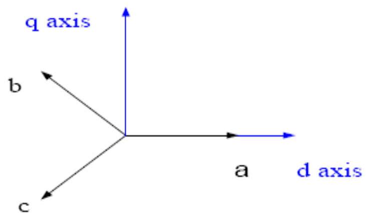

Fig.6. Relationship of abc and Stationary d-q Reference Frame

This transformation is equivalent to an orthogonal projection of $[a, b, c]^t$ onto the two dimensional perpendicular to the vector $[1, 1, 1]^t$ (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six non-zero vectors and two zero vectors are possible. Six non-zero vectors (V_1 - V_6) shape the axes of a hexagonal as shown in figure 4.4 and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V_0 and V_7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V_0, V_1, V_2, V_3, V_4, V_5, V_6, and V_7. The same d-q transformation can be applied to the desired output voltage to get the desired reference voltage vector V_{ref} in the d-q plane.

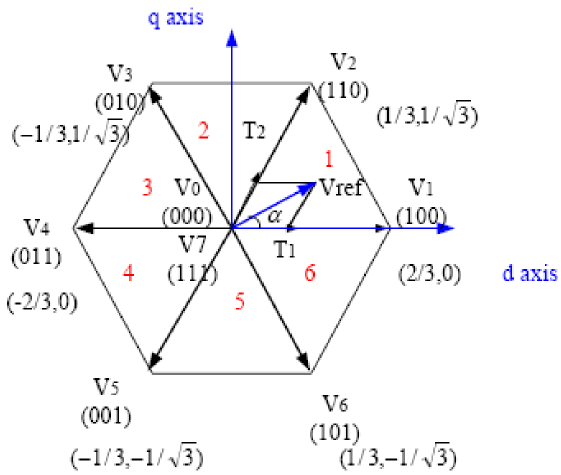

Fig.7. Space Vector Diagram with Sectors

B. SVPWM Algorithm

The objective of SVPWM technique is to approximate the reference voltage vector V_{ref} instantaneously by combination of the switching states corresponding the basic space vectors. One way to achieve this is to require, for any small period of time T, the average inverter output be the same as the average reference voltage V_{ref} in the same period. Therefore, SVPWM can be implemented by the following steps:

Step 1 : Determine V_d, V_q, V_{ref}, and angle (α)

Step 2 : Determine time duration T_1, T_2, T_0

Step 3 : Determine the switching time of each transistor (S1 to S6)

All sectors in SVPWM are shown in Fig.7. It uses a set of vectors that are defined as instantaneous space vectors of the voltages and currents at the input and output of the inverter. These vectors are created by various switching states that the inverter is capable of generating.

C. Determine of space vectors and angle (α)

To determine V_d, V_q, V_{ref} and angle (α) through the following equations which use abc to d-q Park transformation as shown in Fig.8.

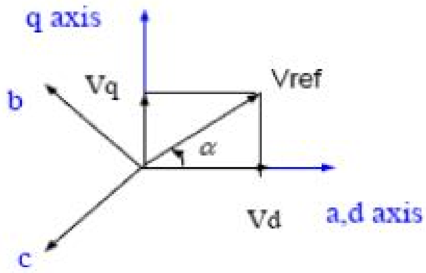

Fig.8. Voltage Space Vector and its Components in (d,q)

$$V_d = V_{an} - V_{bn} . \text{Cos } 60 - V_{cn} . \text{Cos } 60$$
$$= V_{an} - (1/2)\, V_{bn} - (1/2)\, V_{cn} \qquad (12)$$
$$V_q = V_{an} + V_{bn} . \text{Cos } 30 - V_{cn} . \text{Cos } 30$$
$$= V_{an} + (\sqrt{3}/2)\, V_{bn} - (\sqrt{3}/2)\, V_{cn} \qquad (13)$$

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix}\begin{pmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{pmatrix} \qquad (14)$$

$$|V_{ref}| = \sqrt{V_d^2 + V_q^2} \qquad (15)$$

$$\propto = tan^{-1}\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \omega t = 2\pi f t$$

Where f = fundamental frequency.

D. Time duration

At sector I, V_1 and V_2 are voltage vectors. Assume V_{ref} makes 'α' phase angle difference with V1. This V_{ref} can be calculated using vector calculus by referring Fig.9. T_z is the switching time interval at which output voltage of inverter is constant. T_1 and T_2 are switching time duration of voltage space vectors V_1 and V_2.

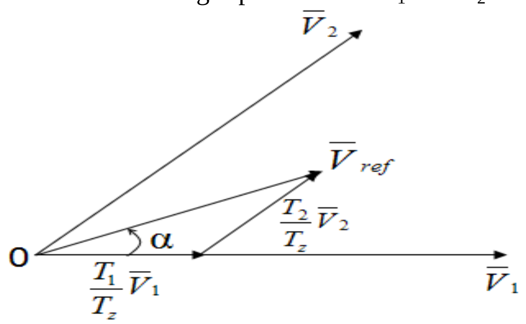

Fig.9. Reference Vector with Respect to Sector I

$$\int_0^{T_Z} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T_1}^{T_1+T_2} V_2\, dt + \int_{T_1+T_2}^{T_Z} V_0 \qquad (16)$$

$$T_Z . V_{ref} = T_1 . V_1 + T_2 . V_2$$

$$T_Z . |V_{ref}| . \begin{bmatrix} \cos(\propto) \\ \sin(\propto) \end{bmatrix} = T_1 . \tfrac{2}{3} . V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 . \tfrac{2}{3} . V_{dc} \begin{bmatrix} \cos\frac{\pi}{3} \\ \sin\frac{\pi}{3} \end{bmatrix} \qquad (17)$$

$$where\ (0 \leq \propto \leq 60^o)$$

$$T_Z . |V_{ref}| . [\cos \propto] = T_1 . \frac{2}{3} . V_c [1] + T_2 . \frac{2}{3} . V_C \cos\left(\frac{\pi}{3}\right)$$

$$T_Z . |V_{ref}| . [\sin \propto] = T_2 . \tfrac{2}{3} . V_C \sin\left(\tfrac{\pi}{3}\right)$$

$$T_1 = T_Z . a . \frac{\sin\left(\frac{\pi}{3} - \alpha\right)}{\sin\left(\frac{\pi}{3}\right)} \qquad (18)$$

$$T_2 = T_Z . a . \frac{\sin(\alpha)}{\sin\left(\frac{\pi}{3}\right)} \qquad (19)$$

$$T_0 = T_Z - (T_1 + T_2) \qquad (20)$$

$$where\ T_Z = \frac{1}{f_z}\ and\ a = \frac{|V_{ref}|}{\frac{2}{3} V_{dc}}$$

E. Switching Time at Any Duration (T1, T2, T0)

Switching time at any instant can be illustrated here. For n number of samples T1, T2 and T0 are,

$$T_1 = \frac{\sqrt{3}T_Z|V_{ref}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha + \frac{-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}T_Z|V_{ref}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha\right)\right)$$

$$= \frac{\sqrt{3}T_Z|V_{ref}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3}\cos\propto - \cos\frac{\pi}{3}\sin\alpha\right)\right) \quad (21)$$

$$T_2 = \frac{\sqrt{3}T_Z|V_{ref}|}{V_{dc}}\left(\sin\left(\alpha - \frac{-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}T_Z|V_{ref}|}{V_{dc}}\left(-\cos\propto.\sin\left(\frac{-1}{3}\pi\right) + \sin\propto\right) \quad (22)$$

$$T_0 = T_Z + (T_1 + T_2) \quad (23)$$

where n=1 through 6 (that is sector 1 to 6), $0 \leq \alpha \leq 60^0$

F. Switching Time

Table 2 shows the six sectors and the time calculation of each switch. This can be easily calculated using the switching states.

TABLE 2
SWITCHING TIME CALCULATION AT EACH SECTOR

Sector	Upper Switches (S_1, S_3, S_5)	Lower Switches (S_4, S_6, S_2)
1	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_0/2$ $S_6 = T_1 + T_0/2$ $S_2 = T_1+T_2+T_0/2$
2	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	$S_4 = T_2 + T_0/2$ $S_6 = T_0/2$ $S_2 = T_1+T_2+T_0/2$
3	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_0/2$ $S_2 = T_1 + T_0/2$
4	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1+T_2+T_0/2$ $S_6 = T_2 + T_0/2$ $S_2 = T_0/2$
5	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	$S_4 = T_1 + T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_0/2$
6	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	$S_4 = T_0/2$ $S_6 = T_1+T_2+T_0/2$ $S_2 = T_2 + T_0/2$

V. SIMULATION RESULTS

Output voltage of PV panel is a low voltage DC, which is given to the inverter through a z source network. Inverter boosts this voltage by shoot-through-mode and converts the DC voltage into AC voltage. This conversion is done with the help of the inverter based on SVPWM. The inverter has MOSFET switches which are switched by the SVPWM. The universal bridge inverter converting the DC to AC three phase voltage by using the space vector pulse width modulation from the SVPWM generator. This circuit takes the reference voltage from the three phase inverter output. The Z-source inductor and capacitors are act as a filter and they generate resonant to the switches. Output voltage obtained three phase AC which is given to the grid or to the load. Obtaining AC contains ripples which are filtered by LC filter. The battery is connected in parallel with the capacitor C1. This circuit is analyzed in the SIMULINK software. The simulation circuit is shown in the Fig.10.

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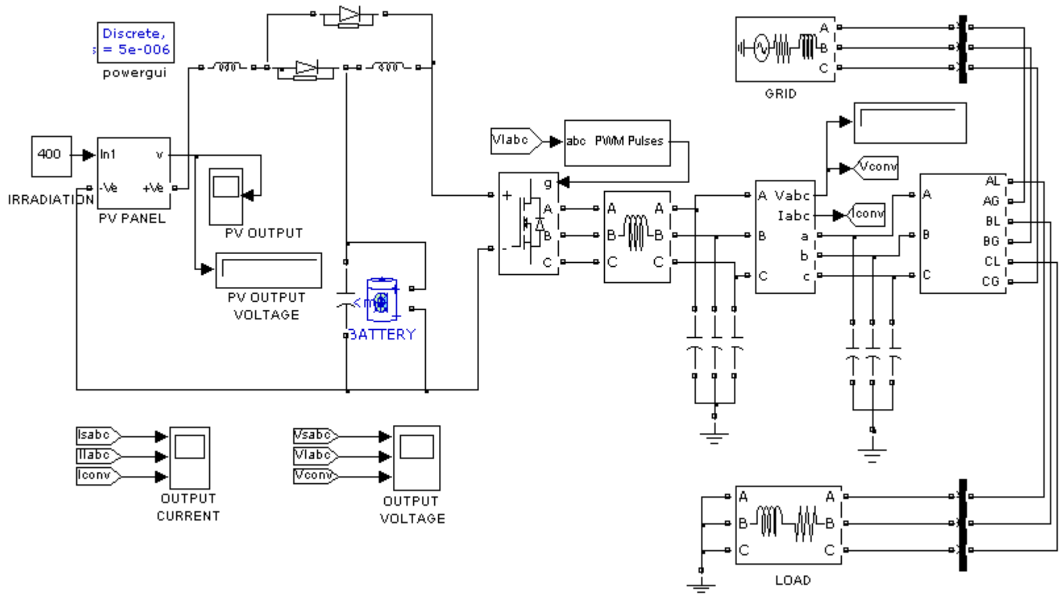

Fig.10. Quasi Z-Source Inverter using PV Module

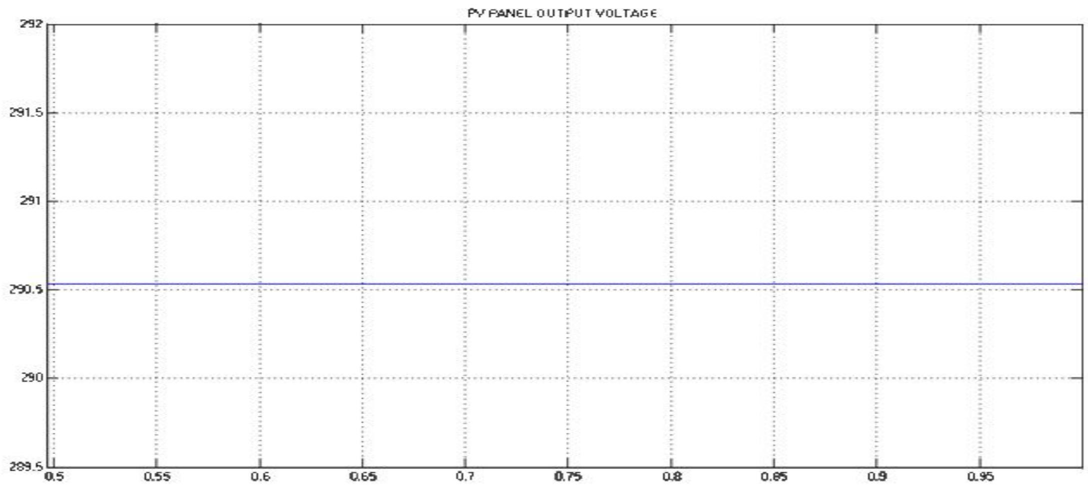

Fig.11 Input voltage waveform

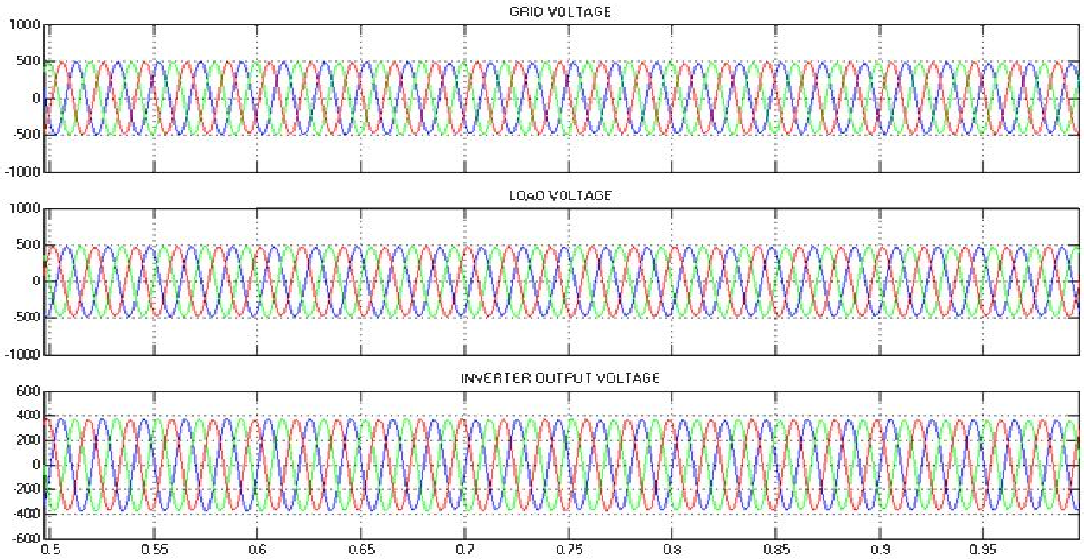

Fig.12 Output Voltage Waveforms

VI. CONCLUSIONS

In this paper, a novel topology for energy stored QZSI has been proposed to overcome the shortcoming of the existing solutions in PV power system. The theoretical analysis, simulations results presented in this work clearly demonstrate the proposed energy-stored QZSI with SVPWM technique. QZSI used for solar power applications, where both boosting and inverting can be done in a single stage. The battery operation can balance the fluctuations from PV panel and supply the continuous power to the grid/load, whenever PV panel cannot generate the power due to some low irradiation. There are three power sources i.e., PV panels, battery and the grid/load. Controlling the two power flow, the third one automatically matches the power difference. The proposed energy stored QZSI have some new advantages more suitable for application in PV systems. This will make the PV system simpler and lower cost.

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