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An Energy-Stored Quasi-Z-Source Inverter Using SVPWM Technique

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***Abstract*— The quasi-Z-source inverter (QZSI) with battery operation can balance the stochastic fluctuations of photovoltaic (PV) power injected to the grid/load. Two strategies are used to control the new energy-stored QZSI when applied to the PV power system. They can control the inverter output power, track the PV panel's maximum power point, and manage the battery power, simultaneously. The voltage boost and inversion, and energy storage are integrated in a single-stage inverter. The QZSI draws a constant current from the PV panel, and thus, there is no need for extra filtering capacitors. The QZSI features a lower component (capacitor) rating; and reduces switching ripples seen by the PV panels. It injects the active/reactive power into the grid by the inverter and regulates the battery state of charge (SOC). It controls the PV panel output power (or voltage) to maximize energy production. QZSI is best suited interface for photovoltaic power generation system and could prove to be highly efficient, when implemented with the improved space vector control techniques. This technique reduces the harmonics especially third and fifth order harmonics.**

***Index Terms*— Energy storage, Quasi-Z-source inverter (QZSI), SPWM, SVPWM.**

I. INTRODUCTION

The rapidly increasing environmental degradation across the globe is posing a major challenge to develop commercially feasible alternative sources of electrical energy generation. Thus, a huge research effort is being conducted worldwide to come up with a solution in developing an environmentally and long-term sustainable solution in electric power generation. The major players in renewable energy generation are photovoltaic (PV), wind farms, fuel cell, and biomass.

Photovoltaic (PV) are arrays (combination of cells) that contain a solar voltaic material that converts solar energy into electrical energy. PV cell is a basic device for Photovoltaic Systems. Such systems include multiple components like mechanical and electrical connections and mountings and various means of regulating and (if required) modifying the electrical output. The current and voltage available at the PV device terminals can be directly used to feed small loads like lighting systems or small DC motors. Energy sources such as solar, fuel cell, and wind have a wide voltage change.

The Z-source inverter (ZSI) presents a new single-stage structure to achieve the voltage boost/buck character in a single power conversion stage. This type of converter can handle the PV dc voltage variations over a wide range without overrating the inverter. As a result, the component count and system cost are reduced, with improved reliability due to the allowed shoot through state. Recently proposed quasi-Z-source inverters (QZSI) have some new attractive advantages more suitable for application in PV systems. Quasi-Z-source inverter (QZSI) is a power conversion technology suitable for interfacing of renewable sources. Two strategies are with the related design principles to control the new energy-stored QZSI when applied to the PV power system. They can control the inverter output power, track the PV panel's maximum power point, and manage the battery power, simultaneously. QZSI draws a constant current from the PV panel, and thus, there is no need for extra filtering capacitors. The voltage boost and inversion, and energy storage are integrated in a single-stage inverter.

In addition, the intermittent and unscheduled characteristics of solar power limit the applicability of PV systems. Therefore, much of the literature suggests the addition of an energy storage system (ESS) to work in conjunction with PV power generation to make its output power continuous, stable, and smooth. Moreover, when applied as a grid-connected system, it implements other important auxiliary services normally provided by special and expensive equipment. Most of the existing ESS technologies employ bidirectional dc/dc converter to manage the batteries which makes the system complex, increases its cost, and decreases its reliability.

A. Quasi-Z-Source Inverter

The quasi z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter topology, employing a unique impedance network. The conventional VSI and CSI suffer from the limitation that triggering two switches in the same leg or phase leads to a source short and in addition, the maximum obtainable output voltage cannot exceed the dc input, since they are buck converters and can produce a voltage lower than the dc input voltage.

Both Z-source inverters and quasi-Z-source inverters overcome these drawbacks; by utilizing several shoot-through 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.

Quasi-Z-source inverters (QZSI) acquire all the advantages of traditional Z source inverter. The impedance network couples the source and the inverter to achieve voltage boost and inversion in a single stage. By using this, 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

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panels, causes less EMI problems and reduced source stress compared to the traditional ZSI.

B. QZSI Network

The QZSI circuit differs from that of a conventional ZSI in the LC impedance network interface between the source and inverter. The unique LC and diode network connected to the inverter bridge modify the operation of the circuit, allowing the shoot-through state which is forbidden in traditional VSI. This network will effectively protect the circuit from damage when the shoot through occurs and by using the shoot-though state, the (quasi-) Z-source network boosts the dc-link voltage.

The impedance network of QZSI is a two port network. It consists of inductors and capacitors. This network is employed to provide an impedance source, coupling the converter to the load. 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.

C. Operating Principle of QZSI

The two modes of operation of a quasi z-source inverter are:

(1) Non-shoot through mode (active mode).

(2) Shoot through mode.

1) Active mode

In the non-shoot through mode, the switching pattern for the QZSI is similar to that of a VSI. The inverter bridge, viewed from the DC side is equivalent to a current source, the input dc voltage is available as DC link voltage input to the inverter, which makes the QZSI behave similar to a VSI. A continuous current flows through the diode D_1.

2) Shoot Through Mode

In the shoot through mode, switches of the same phase in the inverter bridge are switched ON simultaneously for a very short duration. The source however does not get short circuited when attempted to do so because of the presence LC network, while boosting the output voltage. The DC link voltage during the shoot through states, is boosted by a boost factor, whose value depends on the shoot through duty ratio for a given modulation index. The diode D_1 is turned off due to the reverse-bias voltage.

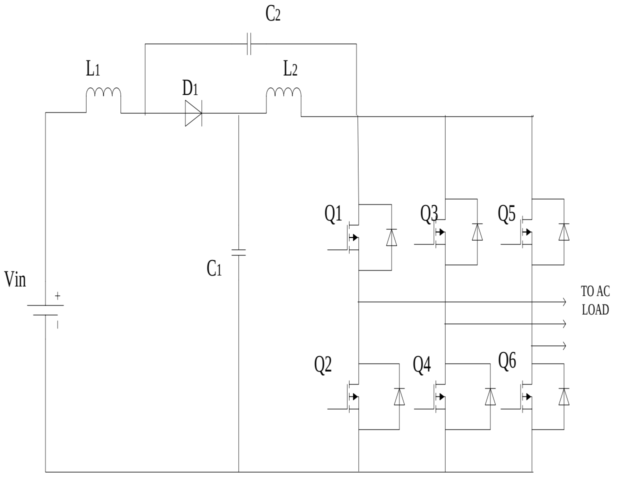

Fig.1. Quasi Z source inverter

II. QZSI–BATTERY USING SPWM

Fig. 2 shows just one of the energy-stored QZSI topologies, we connect the battery in parallel to the capacitor *C*1.They have common points: 1) There are three power sources/consumers, i.e., PV panels, battery, and the grid/load, and 2) as long as controlling two power flows, the third one automatically matches the power difference, according to the power equation

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

where P_{in}, P_{out}, and P_B are the PV panel power, the 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_B is positive when the battery delivers energy and negative when absorbing energy, and *P*out is positive when the inverter injects power to the grid.

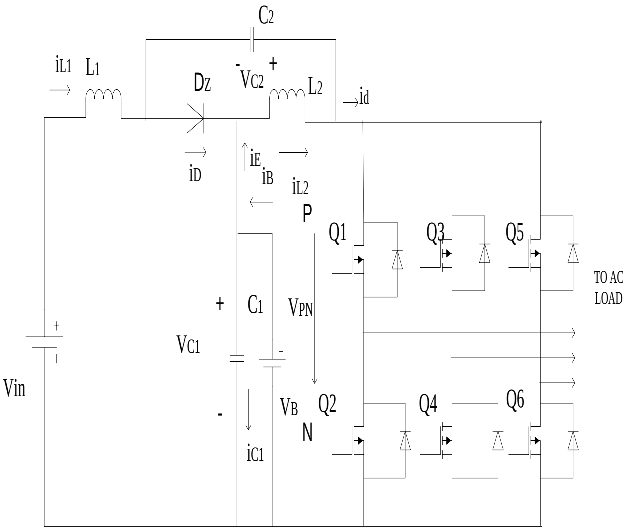

Fig.2. New energy-stored QZSI for PV power generation

There are three operating states of the battery. When the battery is charging, thus $i_b>0$, $i_{L2}>i_{L1}$,$P_{battery}>0$, and $P_{PV}>P_{load}$; when the battery is discharging ,$i_b<0$,$i_{L2}<i_{L1}$,$P_{battery}<0$, and $P_{PV}<P_{load}$;no charging and discharging, $i_b = 0$, $i_{L2} = i_{L1}$,$P_{battery} = 0$, and $P_{PV} = P_{load}$.

The grid-injected active power is changed to achieve the designed operating modes. Three cases have been investigated:

1) Battery charging mode
2) Neither charging nor discharging mode
3) Battery discharging mode

1. Battery Charging Mode

The PV panel received high solar irradiation. With the MPPT algorithm, the PV panel outputs high output current i_{L1} and power $P_{in}$to the energy-stored inverter. Light grid-injected power P_{out} results in $P_{in} > P_{out}$. The power difference ($P_{in} - P_{out} = P_b$) presents the superfluous PV power that is charged into the battery in the negative battery current.

2. Battery Neither Charging Nor Discharging Mode

The PV panel received low solar irradiation. As a result, the PV panel produced low output current i_{L1} and power P_{in} to the energy-stored inverter. The grid-injected active power is adjusted to match the PV power, i.e., $P_{in} = P_{out}$. For this case, there is no active power difference inputted into the battery, i.e., $P_b = P_{in} - P_{out} = 0$ W. The battery will be neither charging nor discharging for the zero battery current.

3. Battery Discharging Mode

The PV panel received low solar irradiation, leading to low current i_{L1} and power P_{in}. The grid-injected active power is increased to a high level, such that $P_{in} < P_{out}$. The grid requires much more active power than that PV panel could provide to track the desired value. For this situation, the battery will discharge, providing a positive current to supply the power shortfall. Finally, the grid injected active power reaches its desired value through the combination ($P_{out} = P_b + P_{in}$) of the PV panel and battery powers.

A. Sinusoidal pulse width modulation

The voltage source inverter that use PWM switching techniques have a DC input voltage (VDC = VS) that is usually constant in magnitude. The inverter job is to take this DC input and to give AC output, where the magnitude and frequency can be controlled. There are several techniques of Pulse Width Modulation (PWM).The efficiency parameters of an inverter such as switching losses and harmonic reduction are principally depended on the modulation strategies used to control the inverter.

In this the Sinusoidal Pulse Width Modulation (SPWM) technique has been used for controlling the inverter as it can be directly controlled the inverter output voltage and output frequency according to the sine functions. Sinusoidal pulse width modulation (SPWM) is widely used in power electronics to digitize the power so that a sequence of voltage pulses can be generated by the on and off of the power switches. The PWM inverter has been the main choice in power electronic for decades, because of its circuit simplicity and rugged control scheme. Sinusoidal Pulse Width Modulation switching technique is commonly used in industrial applications or solar electric vehicle applications.

SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. Sinusoidal pulse width modulation is the mostly used method in motor control and inverter application.

In SPWM technique three sine waves and a high frequency triangular carrier wave are used to generate PWM signal. Generally, three sinusoidal waves are used for three phase inverter. The sinusoidal waves are called reference signal and they have 120˚ phase difference with each other. The frequency of these sinusoidal waves is chosen based on the required inverter output frequency (50/60 Hz). The carrier triangular wave is usually a high frequency (in several KHz) wave. The switching signal is generated by comparing the sinusoidal waves with the triangular wave. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches.

In order to avoid undefined switching states and undefined AC output line voltages in the VSI, the switches of any leg in the inverter cannot be switched off simultaneously. The phase outputs are mutually phase shifted by 120˚ angles.

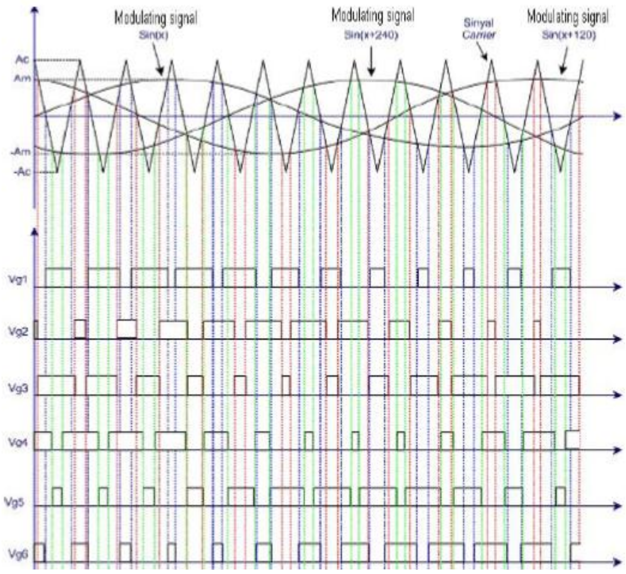

Fig.3. SPWM Signal Generation Technique for Three Phase Voltage Source Inverter

III. PROPOSED CONTROL STRUCTURE

B. Space vector pulse width modulation

Space Vector Modulation (SVM) was originally developed as vector approach to Pulse Width Modulation (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. The main aim of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics. Space Vector PWM (SVPWM) method is an advanced computation intensive PWM method and possibly the best techniques for variable frequency drive application.

C. A space vector PWM

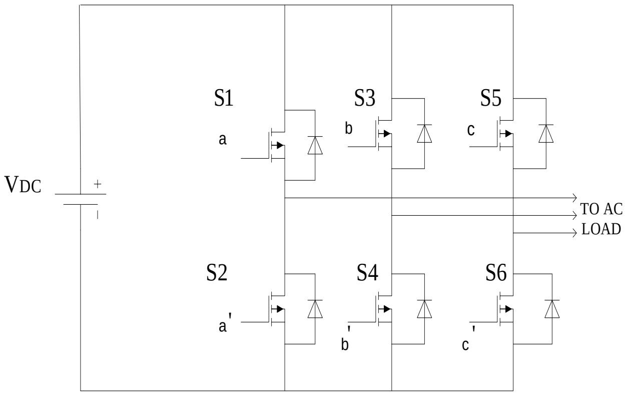

Fig.4. Three-Phase Voltage Source PWM Inverter

The circuit model of a typical three-phase voltage source PWM inverter is shown in Figure-4. S_1 to S_6 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 S_1, S_3 and S_5 can be used to determine the output voltage.

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

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. The eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC-link V dc, are given in Table 1

To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axis.

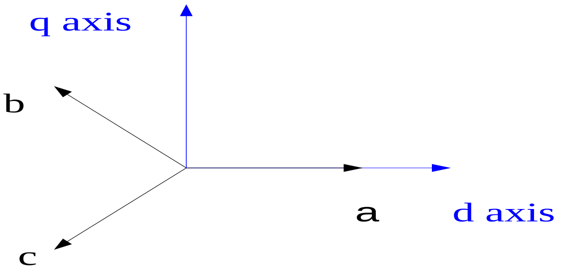

Fig.5. The Relationship of abc Reference Frame and Stationary dq Reference Frame

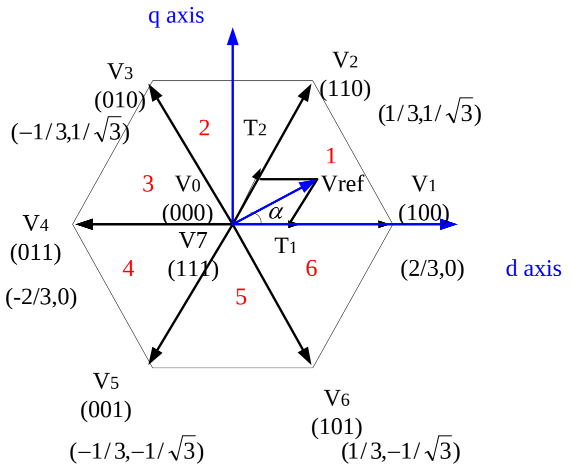

Fig.6. Basic Switching Vectors and Sectors

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 nonzero vectors (V1 - V6) shape the axes of a hexagonal as depicted in Fig.5.3 and feed electric power to the load. The angle between any adjacent two non-zero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6, and V7. The same transformation can be applied to the desired output voltage to get the desired reference voltage vector Vref in the d-q plane.

The objective of space vector PWM technique is to approximate the reference voltage vector Vref using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of Vref in the same period.

Therefore, space vector PWM can be implemented by the following steps:

- Step 1. Determine Vd, Vq, Vref, and angle (α)
- Step 2. Determine time duration T1, T2, T0
- Step 3. Determine the switching time of each transistor (S1 to S6)

5.2.1 STEP 1: Determine Vd, Vq, Vref, and angle (α)

Vd, Vq, Vref, and angle (α) can be determined as follows

$$V_d = V_{an} - V_{bn}.\cos 60 - V_{cn}.\cos 60$$

$$= V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn} \qquad (1)$$

$$V_q = V_{an} + V_{bn}.\cos 30 - V_{cn}.\cos 30$$

$$= V_{an} + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn} \qquad (2)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$\left|V_{ref}\right| = \sqrt{V_d^2 + V_q^2} \qquad (3)$$

$\alpha = \tan^{-1}\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \omega t =$ 2πft, where f = fundamental frequency

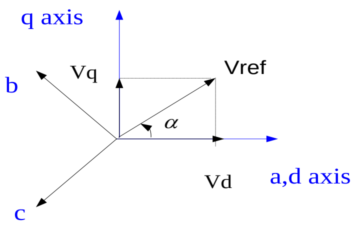

Fig.7. Voltage Space Vector and its Components in (d, q).

5.2.2 STEP 2: Determine time duration T1, T2, T0

The switching time duration can be calculated as follows:

- Switching time duration at Sector 1

$$\int_0^{T_Z} V_{ref} = \int_0^{T_1} V_1 dt + \int_{T1}^{T_1+T_2} V_2 dt + \int_{T_1+T_2}^{T_Z} V_0$$

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

$$T_Z . \left| V_{ref} \right| . \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 . \frac{2}{3} . V_{dc} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 . \frac{2}{3} . V_{dc} \begin{bmatrix} \cos\left(\frac{\Pi}{3}\right) \\ \sin\left(\frac{\Pi}{3}\right) \end{bmatrix}$$

Where, $(0 \leq \alpha \leq 60^{\circ})$

$$T_1 = T_Z . a . \frac{\sin\left(\frac{\Pi}{3} - \alpha\right)}{\sin\left(\frac{\Pi}{3}\right)} \quad (4)$$

$$T_2 = T_Z . a . \frac{\sin(\alpha)}{\sin\left(\frac{\Pi}{3}\right)} \quad (5)$$

$$T_0 = T_Z - (T_1 + T_2), \text{ where, } T_Z = \frac{1}{fz} \text{ and } a = \frac{\left| V_{ref} \right|}{\frac{2}{3} V_{dc}} \quad (6)$$

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

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	$s_1 = T_1 + T_2 + T_0/2$ $s_3 = T_0/2$ $s_5 = T_1 + T_0/2$	$s_4 = T_0/2$ $s_6 = T_1 + T_2 + T_0/2$ $s_2 = T_2 + T_0/2$

IV. SIMULATIONS AND RESULTS

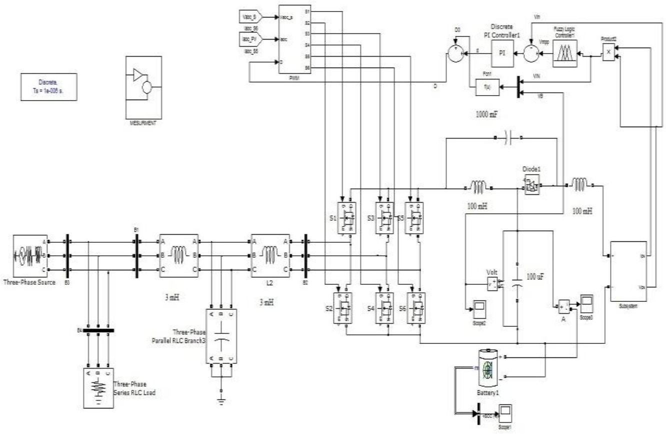

Fig.8. Energy-stored QZSI for PV power generation

Fig.8. shows just one of the energy-stored QZSI topology, where the battery is connected in parallel with the capacitor C_1. Output voltage of PV panel is 200 V dc, which is given to the QUASI-Z-source, that boost the voltage and given to the inverter. Inverter converts the dc voltage into ac voltage, obtaining ac contain ripples which is filtered by LCL filter. Output voltage obtained is 200 V three phase ac, which is given to the ac grid or to the load. Output also contains the power factor, active power and reactive power. PV panel uses MPPT technique, which produces duty ratio for the switching of the QUASI-Z-Source inverter. Duty ratio is obtained by using ANFIS controller.

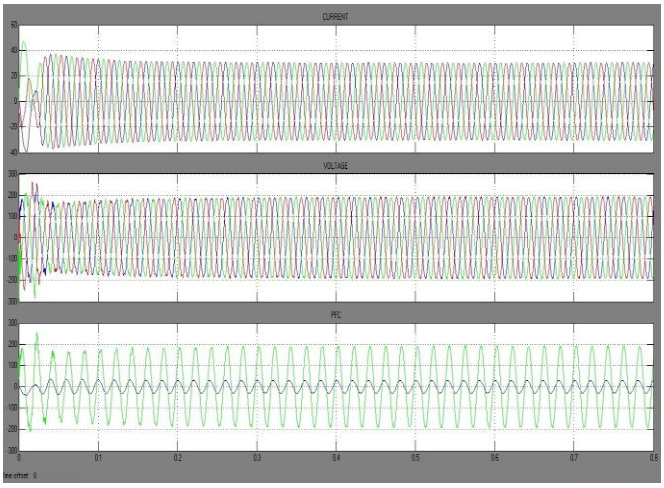

Fig.9. Output voltage, current, PFC waveforms

In Fig.9 output voltage is 200V three phase ac voltages and output current is 35 Ampere three phase current. In power factor correction the voltage and current of any one phase is taken, and are almost in phase with each other.

Analysis:

1. The total harmonic distortion was calculated to be 1.1 for SPWM and .40 for SVPWM.
2. The power factor was obtained as 0.92 for SPWM and .97 for SVPWM.

Table 3.Simulation Parameters of SVPWM & SPWM

Technique Name	Power factor Value	THD%
SPWM	.92	1.10%
SVPWM	.97	.40%

V. CONCLUSIONS

PV array has been simulated and integrated to the QZSI with maximum power point tracking algorithm (ANFIS method). The QZSI inherits all the advantages of the ZSI and features its unique merits. It can realize buck/boost power conversion in a single stage with a wide range of gain that is suited well for application in PV power generation systems. Furthermore, QZSI with battery has advantages of continuous input current, reduced source stress, and lower component ratings when compared to the traditional ZSI. Compared to SPWM the Total harmonic distortion (THD) and lower order harmonics (LOH) contents are decreased in SVPWM. Space Vector PWM provides more efficient use of supply voltage in comparison with sine PWM. Energy-stored QZSI using SVPWM technique was simulated in MATLAB/SIMULINK, the output of simulated diagram and experimental results was observed and analysed.

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