

## Modelling, Impedance Design, and Efficiency Analysis of Battery Assists PV Tied Quasi-Z Source Inverter

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### Article Info

#### Article history:

Received Nov 12, 2015

Revised Mar 24, 2016

Accepted Apr 25, 2016

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#### Keyword:

Energy stored QZSI

Impedance network

Photovoltaic (PV)

Quasi-Z source inverter (QZSI)

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### ABSTRACT

The photovoltaic (PV) power cohort becoming more and more attractive in modern power systems era to meet out the power demand in the globe. Consequently, the extraction of maximum power and reduced power electronics stuff for PV based power generation system research studies are growing continuously to meet out the large power-scale/high-voltage grid-tie demands. In this junction, to improve the efficiency of the existing PV tied Quasi-Z source inverter (QZSI), in this paper the new attempt has proposed here by connecting two batteries across to the QZ capacitors. When a battery connected across each capacitor, this system can deliver power to the load power when the PV panel outputs a variable power with fluctuations. The battery can be charged or discharged without any extra circuit, because of the unique impedance network of QZSI. New PWM techniques and principles are proposed to control the new energy stored QZSI when applied to the PV power system. They can control the inverter output power and manage the battery power simultaneously. The operating principle and power flow of this system are analysed. The Simulated and experimental results through using the planned 0.2-kW prototype validate the proposed analytic model and the design method. In addition, this paper analyzes all of the functioning states for a QZSI and calculates the power loss.

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## 1. INTRODUCTION

The Z-source inverter employs a unique impedance network to couple the inverter main circuit to the power source, which provides a novel power conversion concept [1-7]. By controlling the shoot-through (ST) duty ratio and modulation index, the Z-source inverter can step up and down the input voltage using passive components with improved reliability and reduced cost, thus providing unique features, such as ride-through capability during voltage sags, reduced line harmonics, improved power factor and reliability, and Extended output voltage range [2]-[5]. In a basic quasi z source inverter (QZSI), circuit the total output of a PV system depends upon the light intensity, radiation. The output is provided not on the basis of load demand in a conventional QZSI. Due to disadvantages in the conventional QZSI and to meet the load demand, two batteries are connected across both the capacitors in boosting circuit. This provides the additional power required during low intensity period and charges itself during high intensity period. QZSIs have some new attractive advantages more suitable for application in PV systems [7]. QZSIs, as an improved ZSI, has some new advantages well suitable for application in PV systems [14]-[20], as it draws a constant

current from the PV panel, there is no need for extra filtering capacitors and reduces switching ripples seen by the PV panels.

This will make the PV system simpler and will lower cost, because of two reason. One is QZSI draws a constant current from the PV panel and thus, there is no need for extra filtering capacitors. Another is basically ZSI features a lower component (capacitor) rating and the QZSI reduces switching ripples seen by the PV panels. For the battery charging current control of the QZSI, there are several challenges for the controller design as follows: (1) Both output voltage and the battery charging current of the QZSI system with battery have to be controlled by the shoot-through state, which makes the design of a steady and fast regulator more difficult [18, 21]. (2) Similar to the boost converter, the QZSI operating in the continuous-condition mode, which limits the bandwidth of the controller and makes the dynamic reply of the system sluggish, and (3). Numerous control methods to achieve fast response and small overshoot have been proposed for the nonlinear system control [20]. Among them, nonlinear-carrier control and one-cycle control have been found practical in some applications. However, either method has some limitations. Given battery current control methods was seldom investigated in the literature, however the inverter performance is still suffering due to the single capacitors stability. Hence, in this paper is trying to cover the research gap by using two capacitor batteries and New PWM techniques and principles are proposed to control the new energy stored QZSI when applied to the PV power system. They can control the inverter output power and manage the battery power simultaneously. The operating principle and power flow of this system are analyzed. The Simulated and experimental results through using the planned 0.2-kW prototype validate the proposed analytic model and the design method. In addition, this paper analyzes all of the functioning states for a QZSI and calculates the power loss.

## 2. QUASI-Z SOURCE INVERTER

Conventional QZSI, QZSI with battery connected across  $C_2$  and QZSI with battery connected across  $C_1$  as shown in Figure 1, Figure 2, and Figure 3. Both the voltage and current fed QZSIs can be controlled using methods used to control the traditional ZSIs. Regardless of the control strategy used, for the voltage fed ZSI and QZSIs, the operation can be listed into three modes; active, ST, and non-ST mode. In Active mode, one and only one device in each phase leg conducts. During the active mode, the inverter is controlled in the same manner as a standard VSI. The ST mode occurs when both switches in at least one phase conduct. The voltage across the inverter during this mode is zero. The discontinuous modes can occur when the inductors,  $L_1$  and  $L_2$ , have a small value relative to other system parameters. In general, the discontinuous modes occurs when the inverter is gated as if in the active mode, but one phase current is greater than or equal to the sum of the inductor currents. In this situation, no current flows through the diode,  $D1$ . For the current fed ZSI and QZSIs, the operation can be divided into modes in a similar manner. In the active mode one and only one upper device, and one and only one lower device conduct. During the active mode, the inverter is controlled in the same manner as a standard CSI. During the ST mode, the entire upper and/or all of the lower switches are gated off. During the discontinuous mode, the switches are gated as if in an active state, but one line-to-line voltage is greater than or equal to the sum of the capacitor voltages. When this occurs, the diode,  $D_1$ , conducts and the inverter behaves as if it is an open circuit. In the active state the current flows through the voltage source to the first inductor then the second inductor and finally to the source via the load. The diode is forward biased and allows the current flow.

In ST mode the both the inductors are already charged, the current flows from capacitor  $C_1$  through the inductor  $L_1$  and from capacitor  $C_2$  through the inductor  $L_2$ . For these reasons QZSI is used instead of other ZVSIs. In addition, the intermittent and unscheduled characteristics of solar power limit the applicability of PV systems. Therefore, addition of an energy storage system (ESS) to PV power generation to make its output power continuous, stable, and smooth Without requirements of any additional dc/dc converters or components, the QZSI with energy storage was first proposed for PV system in [1], [2]. By connecting the battery in parallel with capacitor  $C_2$  [2] of the QZSI, this system is able to do the following simultaneously.

- a. Produce the desired output ac voltage to the grid/load [20]
- b. Regulate the battery state of charge (SOC) and
- c. Control the PV panel output power (or voltage) to maximize energy production.

But it has a big discharging power limitation due to the existence of the DCM. This limits the inverter output power. As a counterpart, we connect the battery in parallel to the capacitor  $C_1$ , leading to a new topology. They have common points.

- d. There are three power sources, PV panels, batteries, and the grid/load
- e. As long as controlling two power flows, the third one automatically matches the power difference, according to the power equation

$$P_{in} - P_{out} + P_{B1} + P_{B2} = 0 \tag{1}$$

The output is provided not on the basis of load demand in a conventional quasi z source inverter for the PV system. To meet the load demand, a battery is connected across one of the capacitors in boosting circuit. This provides the additional power required during low intensity period and charges itself during high intensity period. The demerits of the existing system are,

$$P_{in} + P_B - P_{out} = 0 \tag{2}$$

- f. Based on the above equation, the Voltage stress on the capacitor which is connected across battery increases.
- g. To overcome this new circuit is proposed. In which two batteries are connected across both the capacitors in the boosting circuit.
- h. This will lessen the Voltage stress on the each capacitor.

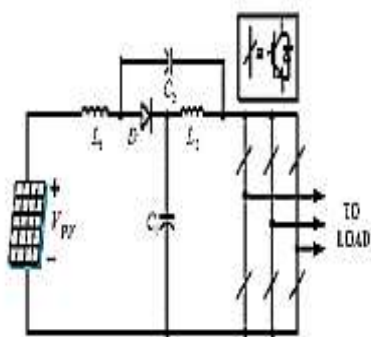


Figure 1. Conventional QZSI

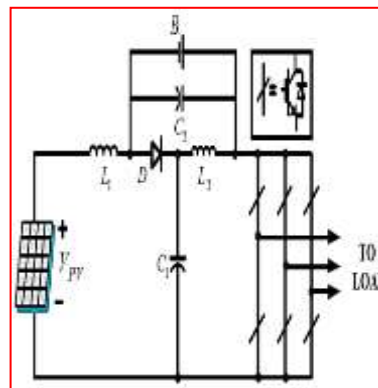


Figure 2. QZSI with battery connected across C<sub>2</sub>

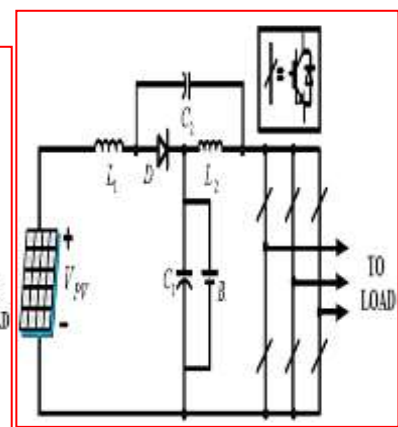


Figure 3. QZSI with battery connected across C<sub>1</sub>

### 3. PROPOSED TWO BATTERY CONNECTED QZSI

In The three topologies which we are going to use, for the reduction of leakage currents and the filter used for the inverter to grid connection is presented here. In the new system the two batteries are used each across individual capacitors in the boosting circuit. This prevents the voltage stress on individual capacitor. Based on the power equation

$$P_{in} + P_{B1} + P_{B2} - P_{out} = 0 \tag{3}$$

We have 3 modes of operation

- a.  $P_{in} > P_{out}$
- b.  $P_{in} < P_{out}$
- c.  $P_{in} = P_{out}$

Here, when both the batteries contributes towards the equation and hence the output resulting in low voltage stress on individual battery. This will in a way make the output smooth and constant as desired with no wear on the capacitors or the circuit. The following Table 1 shows the status of battery and inductor current during various modes. Proposed QZSI with B<sub>1</sub>, B<sub>2</sub>, Non Shoot through mode, Shoot through mode as shown in Figure 4, Figure 5, and Figure 6. This circuit have two modes of operation as a normal quasi z source inverter has;

- a. Shoot through mode
- b. Non shoot through mode

Table 1. Mode of operation for 2 battery connected QZSI

Input and output power	PB1	PB2	Inductor currents
$P_{in} < P_{out}$	$P_{B1} > 0$	$P_{B2} > 0$	$i_{L1} > 0, i_{L2} > 0$
$P_{in} > P_{out}$	$P_{B1} < 0$	$P_{B2} < 0$	$i_{L1} < 0, i_{L2} > 0$
$P_{in} = P_{out}$	$P_{B1} = 0$	$P_{B2} = 0$	$i_{L1} = i_{L2}$

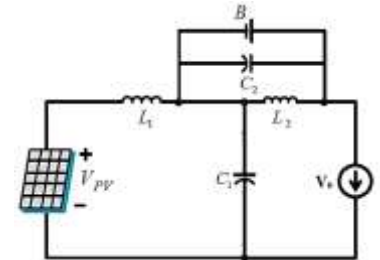
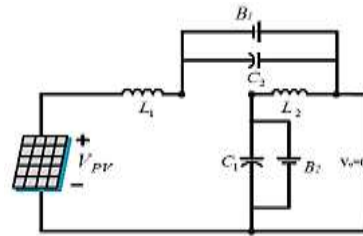
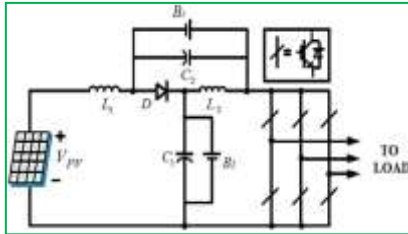
Figure 4. Proposed QZSI with B<sub>1</sub>, B<sub>2</sub>

Figure 5. Non Shoot through mode

Figure 6. Shoot through mode

### 3.1. Shoot Through Mode

In mode raises when two Thrusters of same leg or any pair of the two Thyristor legs or all the Thyristors are switched ON. Here a point arises that when an inverter is shorted there is no way of passing infinite current to the load, but this is not happening because of existing unique impedance network between source and inverter. During this stage the output voltage remains zero and the pre-charged inductor discharges by decreasing its current by raising the potentials of capacitors. Here inductor L1 charges C2 and L2 charges C1. During which the potentials across the diode gets reversed and hence it is reverse biased in shoot through mode. The net voltage stored in both the capacitors is applied across inverter arms. The amount of shoot through time period is  $0.25T$ . Where  $T$  is the total time period.  $T_0$  is the shoot through time period. The Comparison of Merits of Different Proposed QZSI as shown in Table 2.

### 3.2. Non Shoot Through Mode

This mode is applied to operate the inverter in normal operating state, during which output voltage appears across the inverter. The voltage across both the capacitors gets added and hence boosted voltage is applied to the inverter circuit. This occurs for  $0.75T$ .  $T_1$  is denoted as active mode time period or non-shoot through time period. In this mode the capacitor delivers voltage along with inductor and both the inductors gets pre-charged for next stage of shoot through period.

#### 3.2.1. Loop equations in shoot through mode

$$L_1 \frac{di_{L1}}{dt} = V_{in} + V_{C2} \quad (4)$$

$$L_2 \frac{di_{L2}}{dt} = V_{C1} \quad (5)$$

$$C_1 \frac{dV_{C1}}{dt} = i_{B1} - i_{L2} \quad (6)$$

$$C_2 \frac{dV_{C2}}{dt} = -i_{L1} - i_{B1} \quad (7)$$

#### 3.2.2. Loop equations in non-shoot through mode

$$L_1 \frac{di_{L1}}{dt} = V_{in} - V_{C1} \quad (8)$$

$$L_2 \frac{di_{L2}}{dt} = -V_{C2} \quad (9)$$

$$C_1 \frac{dV_{C1}}{dt} = i_{B2} + i_{L1} - i_o \quad (10)$$

$$C_2 \frac{dV_{C2}}{dt} = i_{L2} - i_{B2} - I_o \quad (11)$$

From above equations we can derive that voltage across capacitor C1 and C2 is

$$V_{C1} = \frac{1-D}{1-2D} \cdot V_{in}; \quad V_{C2} = \frac{D}{1-2D} \cdot V_{in}$$

Difference in the capacitor voltages

$$V_{C1} - V_{C2} = V_{in}$$

Power equation of circuit is

$$P_{in} + P_{B1} + P_{B2} = P_{out} \quad (12)$$

Table 2. Comparison of Merits of Different Proposed QZSI

B <sub>1</sub> across C <sub>1</sub>	B <sub>2</sub> across C <sub>2</sub>	B <sub>2</sub> Across C <sub>2</sub> and B <sub>1</sub> Across C <sub>1</sub>
<ol style="list-style-type: none"> <li>1. Output power continuous, stable, and smooth in spite fluctuating input by PV panel</li> <li>2. Produce the desired output ac voltage to the grid/load</li> <li>3. Regulate the battery state of charge (SOC)</li> </ol>	<ol style="list-style-type: none"> <li>1. Output power continuous, stable, and smooth in spite of fluctuating input by PV panel</li> <li>2. Produce the desired output ac voltage to the grid/load</li> <li>3. Regulate the battery state of charge (SOC)</li> <li>4. The discharging battery is limited to ensure that the system</li> <li>5. Operates in the CCM always operates in the CCM during battery charging</li> <li>6. A wider battery discharging power range</li> <li>7. Can be used to high voltage</li> </ol>	<ol style="list-style-type: none"> <li>1. Output power continuous, stable, and smooth in spite of fluctuating input by PV panel</li> <li>2. Produce the desired output ac voltage to the grid/load</li> <li>3. Regulate the battery state of charge (SOC)</li> <li>4. The discharging battery is limited to ensure that the system</li> <li>5. Operates in the CCM always operates in the CCM during battery charging</li> <li>6. A wider battery discharging power range</li> <li>7. Can be used to high voltage</li> <li>8. Reduces the stress on one battery</li> <li>9. Better THD performance</li> </ol>

Matrix form of the equations is after solving the transfer function of proposed two battery connected QZSI

$$\text{Let } \begin{bmatrix} C1 & 0 & 0 & 0 \\ 0 & C2 & 0 & 0 \\ 0 & 0 & L1 & 0 \\ 0 & 0 & 0 & L2 \end{bmatrix} = X \cdot \begin{bmatrix} 0 & 0 & 1-D & D \\ 0 & 0 & -D & 1-D \\ D-1 & D & 0 & 0 \\ D & 1-D & 0 & 0 \end{bmatrix} = Y \quad (13)$$

$$X \begin{bmatrix} VC1 \\ VC2 \\ iL1 \\ iL2 \end{bmatrix} = Y \begin{bmatrix} VC1 \\ VC2 \\ iL1 \\ iL2 \end{bmatrix} + \begin{bmatrix} iB1 + iB2(1-D) + i(D-1) \\ iB1(-D) + iB2(D-1) + i(D-1) \\ V_{in} \\ 0 \end{bmatrix} \quad (14)$$

#### 4. SIMULATION STUDY

The aforesaid energy stored QZSI and its control scheme are performed in MATLAB / SIMULINK. The main simulation parameters are: the quasi-Z-source capacitor is  $C_1=C_2=400\mu\text{F}$ ; inductor is  $L1=L2=50\text{mH}$ ; the grid line voltage is 208 V, and the grid frequency is 50 Hz; the command peak dc-link voltage,  $V_{ac}$  is fixed as 400 V. The Simulation test is carried out in three cases, where battery connected in  $C_1$  alone,  $C_2$  alone and battery connected for both  $C_1$  and  $C_2$ . For the input voltage source for the proposed QZSI uses the P&O- MMPT based PV based 1kW structure. The simulation initially carried out with 800W PV output with 400 V DC-link. The test is carried out for the variation of the power and voltage of the PV output. The variation has been achieved through variation of the irradiation. All the simulation is carried out for the same variation to test the predominance of the inverter. The Figure 7 displays the Mat lab/SIMULINK simulation

Diagram for QZSI with  $B_1$  connected across  $C_1$  and  $B_2$  connected across  $C_2$ . In Figure 8, shows the PWM control scheme for proposed inverter.

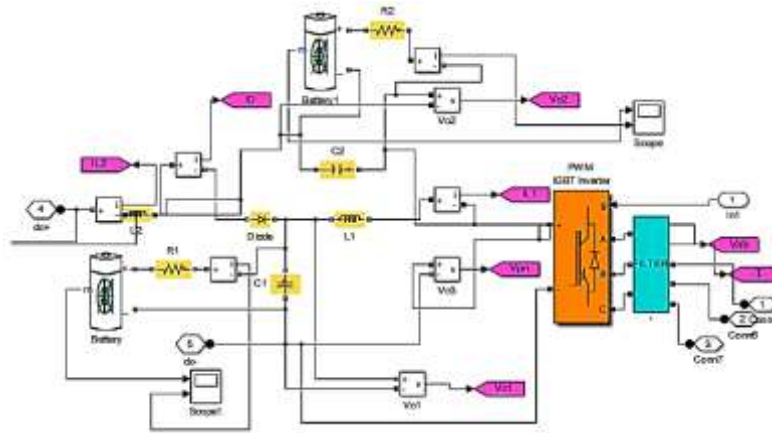


Figure 7. Simulation Diagram for QZSI with B1 connected across C1 and B2 connected across C2

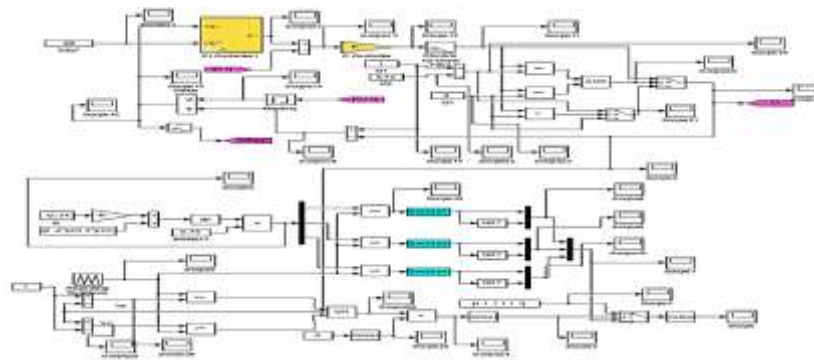


Figure 8. SVPWM generated for the proposed two battery connected QZSI

The Figure 11 shows the capacitor voltage response ( $V_{C1}$  and  $V_{C2}$ ), when battery connected only cross  $C_1$  and Figure 12, shows the capacitor voltage response, when battery connected only cross  $C_2$ . Based on the results, it could understand that, through the inverter stability is increased. The capacitors' not balanced due to the influence of the battery voltages on  $C_1$  and  $C_2$ . Here, Capacitor charging and discharging gives the boosted voltage at the inverting legs. When a battery is connected across one of the capacitor then the voltage that appears across that capacitor is large when compared with the other capacitor. This shows that the capacitor holds large voltage and stress on it increases. The harmonic distortion of the output at the inverter circuit is measured and is found very high. Hence the distortion of wave is high when compared with fundamental frequency which is shown in Figure 9 and 10.

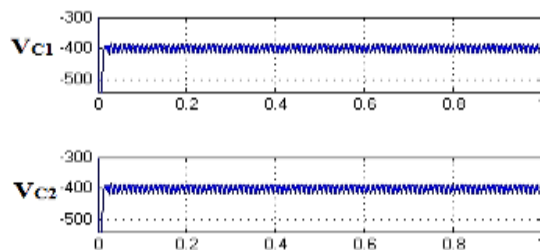


Figure 9. QZSI  $V_{C1}$  and  $V_{C2}$  performance with B

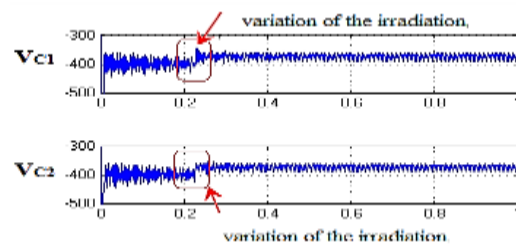


Figure 10. QZSI  $V_{C1}$  and  $V_{C2}$  performance, with affect irradiation

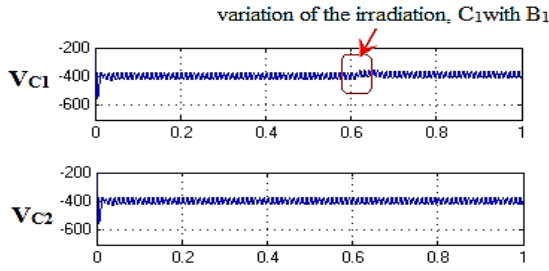


Figure 11.  $V_{C1}$  and  $V_{C2}$  performance with B across  $C_2$

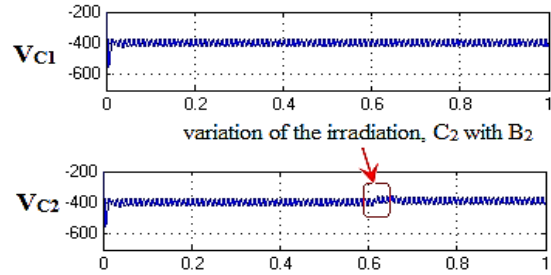


Figure 12.  $V_{C1}$  and  $V_{C2}$  performance with B across  $C_1$

$V_{THD}$  spectra, when QZSI B across  $C_2$  as shown in Figure 13, and in Figure 14 as show  $V_{THD}$  spectra, when QZSI B across  $C_1$ . The Figure 15 and Figure 16 illustrations the inverter capacitors balancing for both irritation effect and constant solar power. The live voltage profile for proposed proposed two battery QZSI and its harmonics spectra. Due to the capacitor balancing the help of  $B_1$  and  $B_2$  for the proposed inverter is much better then, one can compare with battery connected only in  $C_1$  and  $C_2$ . The proposed QZSI performance and capacitor voltage regulation, when two batteries are operating across the capacitors. In the proposed circuit, the batteries are connected across both the capacitors in which the power that is deficient at the load is supplied from the batteries. Batteries deliver power to the circuit by discharging current into the inductors further which is dissipated to the capacitor. Here the voltage across both the capacitors is almost decreased from the previous comparison. Hence the stress on the capacitors is decreased. In this circuit, THD value has been decreased 7.8%, which is a large value when compared with the other two topologies. Hence the output wave form is with less distortion, continuous. The voltage across the inverter is with less distortion. The distortion in this wave is due to the high frequency carrier wave interference. The Table 3 shown the comparison of QZSI, when operating single battery connected and proposed two battery connected QZSI. Based the table data, the proposed inverter is proving the advantages all way comparing with other battery connected topology (note, these values are measured for the maximum modulation depth of the inverter. Line Voltage for proposed two battery QZSI, and  $V_{THD}$  spectra, Proposed two battery QZSI as shown in Figure 17 and Figure 18.

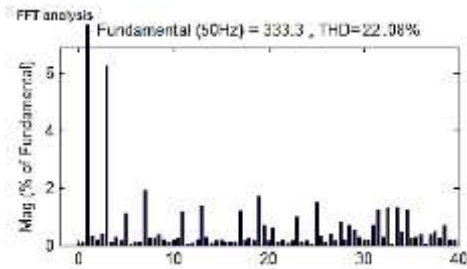


Figure 13.  $V_{THD}$  spectra, when QZSI B across  $C_2$

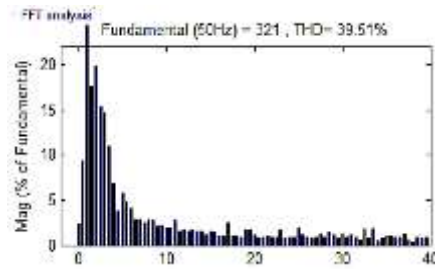


Figure 14.  $V_{THD}$  spectra, when QZSI B across  $C_1$

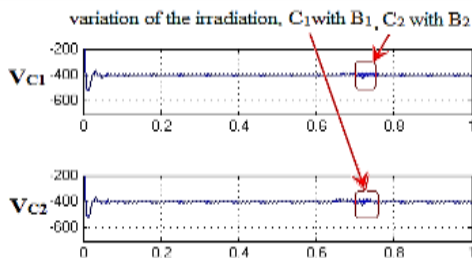


Figure 15. Proposed two battery QZSI  $V_{C1}$  and  $V_{C2}$  Performance

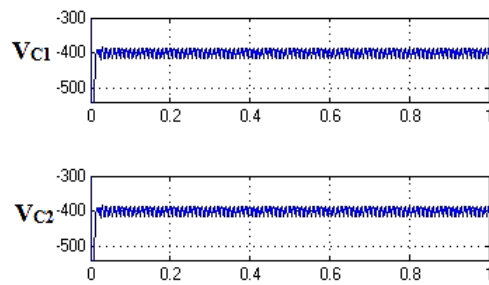


Figure 16. Proposed two battery QZSI  $V_{C1}$  and  $V_{C2}$  performance with change in solar irradiation at 0,78sec



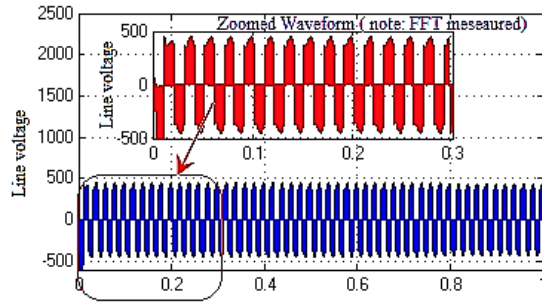


Figure 17. Line Voltage for proposed two battery QZSI

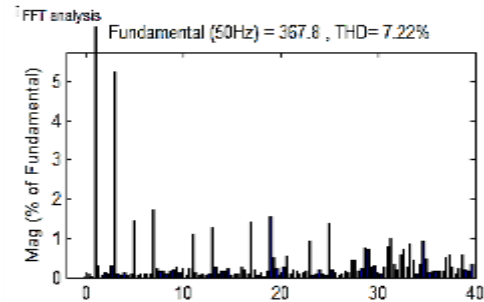
Figure 18.  $V_{THD}$  spectra, Proposed two battery QZSI

Table 3. Comparison of QZSI, when Operating Single Battery Connected and Proposed Two Battery -QZSI

PROPERTY	QUASI	B1 across C1	B2 across C2	Both B1&B2 at C1&C2
$V_{in}$	388V	394V	395V	400V
$I_n$	16.7A	18A	12A	13A
$V_{DC}$	475V	471	514	490
$V_{C1}$	357	370	350	390
$V_{C2}$	3669	350	376	3870
$V_{inv}$	500	484	515	501
$I_{out}$	16.9	17.3	15	12.36
THD %	85.72	86.28	85.63	39.88

## 5. EXPERIMENTAL STUDY

In the experiments, the Solar powered to the two battery connected QZSI is verified with a laboratory prototype of 200W with constant lamp load as shown in Figure 19. Here, the DC-link voltage is set as 80V to 45V from fixed solar plant. The solar plant is used here as single string type with TI-C2000 microcontroller MMPT. Here the MMPT is giving the boosted function to the inverter ST. According to the miniature level circuit the hardware parameters are calculated and used: the quasi-Z-source capacitor is  $C_1 = C_2 = 400 \mu\text{F}$ ; inductor is  $L_1 = L_2 = 2.8 \text{ mH}$ . The input voltage can be changed from range between 0 to 80 V by adjusting the solar irradiation through (test bench lamp arrangement), which provides a general bench to achieve various experiments. The two 30-V Niche-Metal battery is connected across to  $C_1$  and  $C_2$  of qZSI network. Here the PWM generation PIC MC is used for the PWM generation to control the proposed inverter.



Figure 19. Experimental setup for qZSI

The R-load is connected to QZSI output terminals through an LC-filter. The switching frequency of the inverter is 3 kHz. Due to the batteries ( $B_1$  and  $B_2$ ) are connected across both the capacitors in which the power that is deficient at the load is supplied from the batteries. Batteries deliver power to the circuit by discharging current into the inductors further which is dissipated to the capacitor. The batteries ( $B_1$  and  $B_2$ ) ensure the reliability of the inverter, whenever the voltage tip in the solar plant. Hence the stress on the capacitors is decreased. The Figure 14 shows the qZSI line voltage profile. Here, the measured harmonics



spectra (THD=9.5%) for the 3kHz switching frequency. These values are measured, when the irradiation came 30% tip from the maximum values of the solar plant. The inverter perform uninterruptedly for the different case of solar variation. Hence the stress on the capacitors is decreased.

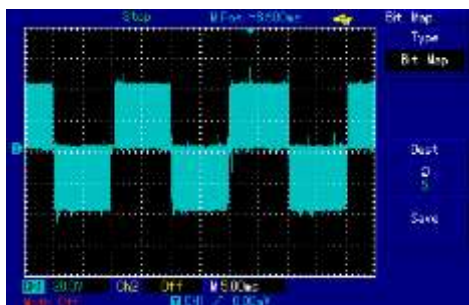


Figure 20. Experimental setup for QZSI

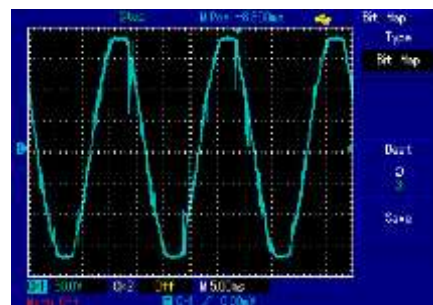


Figure 21. Experimental setup for QZSI

## 6. CONCLUSION

The PV power generation system based on the QZSI with two battery connected topology is proposed, and its principle and operating states are analyzed. The battery can be charged and discharged through the QZSI-network. The MPPT can be implemented through adjusting shoot-through duty ratio to change the PV panel's voltage. The modulation signal is controlled to ensure a constant output voltage. The battery will balance the difference between the input power and output power. The simulated and experimental results verified the proposed PV power generation system. A novel topology for an energy-stored QZSI has been proposed to overcome the shortcoming of the existing solutions in PV power system. The effectiveness of the proposed controllers were verified by both the simulation and experimental results.

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