Available Online at www.ijcsmc.com

International Journal of Computer Science and Mobile Computing

A Monthly Journal of Computer Science and Information Technology

ISSN 2320–088X

IJCSMC, Vol. 4, Issue. 3, March 2015, pg.626 – 633

RESEARCH ARTICLE

Design and Implementation of Quasi-Z-Source Inverter for Off-grid Photovoltaic Systems

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Abstract

The quasi-Z-source inverter (qZSI) with the proposed battery operation can balance the turbulence of photovoltaic (PV) power injected to the load as in the existing topology, but overcomes the limitations in the rating, size and life of battery. This paper proposes a new topology that is optimized for off grid applications. The characteristics of the proposed idea are analyzed in detail. In the proposed model, voltage boost and inversion are integrated in a single-stage inverter. A prototype is built to experiment the proposed circuit and to test the control methods. The results obtained are verified with the theoretical analysis and proves the effectiveness of the proposed control of the inverter's input and output power and battery power. The PV panel and energy-stored qZSI, setup used in the experiment demonstrates three operating modes that make it suitable for off grid applications.

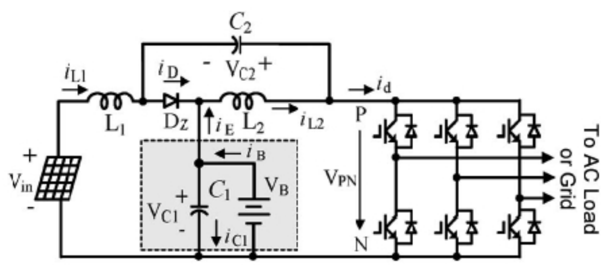
1. Introduction

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 benign 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.

These distributed power generation sources are widely accepted for micro grid applications. However, the reliability of the micro grid relies upon the interfacing power converter. Thus the proper power regulation from the interfacing power converter will ensure a stable and reliable micro grid system. Thus this paper focuses on the proposal of a new class of interfacing inverter, the quasi-Z-source inverter (qZSI) for off-grid applications.

There are several power converter topologies employed in PV systems; each of them with different characteristics: two-stage or single-stage, with transformer or transformer less, and with a two-level or multilevel inverter. Single-stage inverters are more desirable when compared to the two-stage models due to their compactness, low cost, and reliability. However, the conventional inverter has to be oversized to cope with the wide PV array voltage changes because a PV panel presents low output voltage with a wide range of variation based on irradiation and temperature, usually at a range of 1: 2. To interface the low voltage output of an inverter to the grid, a bulky low-frequency transformer is necessary at the cost of a large size, decrease in efficiency, loud acoustic noise, and high cost. The two-stage inverter applies a boost dc/dc converter instead of a transformer in order to minimize the required KVA rating of the inverter and boost the wide range of voltage to a constant desired value. Unfortunately, the switch in the dc/dc converter becomes the cost and efficiency killer of the system. For safety reasons, some PV systems have a galvanic isolation, either in the dc/dc boost converter using a high-frequency transformer, or in the ac output side of a line frequency transformer. Both of these added galvanic isolations increase the cost and size of the whole system, and decrease the overall efficiency. Transformer less topology is deserving attention because of its increased efficiency, reduced size, weight and price for the PV system. The Z-source inverter (ZSI), as a single-stage power converter with a step-up/down function, allows a wide range of PV voltages, and has been reported in applications in PV systems. It can handle the PV dc voltage variation in a wide range without overrating the inverter, at the same time it can carry out voltage boost and inversion simultaneously in a single power conversion stage, thus minimizing system cost and reducing component count and cost, and improving the reliability. Recently proposed quasi Z-source inverters have some new attractive advantages that will make the PV system much simpler and lower its cost because it : 1) draws a constant current from the PV panel, so no additional capacitor for filtering is needed; 2) features lower component (capacitor) rating; and 3) reduces switching ripples to the PV panels.
In the existing topology, the energy-stored qZSI shown in Fig.1 has the battery connected in parallel with the capacitor C_1.

Fig.1 Existing energy-stored qZSI for PV power generation.



2. New qZSI-Battery topology

Fig. 1 shows the existing energy-stored qZSI topology where the battery is connected in parallel with the capacitor C_1, whereas in the proposed the battery is connected as shown in Fig. 2 leading to a new topology. The proposed model since optimized for direct load applications, it primarily focuses on the uninterrupted power supply to the connected load. It has three different cases in doing so, they are: 1) PV panel generates the power required to support the load and charge the battery; 2) if PV panel power becomes insufficient then the battery supports the load. 3) if both PV panel power and battery power become insufficient then the load is supplied with the AC mains.

Thus the proposed model achieves in providing continuous power the connected load at the same time keeps in check the battery voltage so that it doesn't go beyond the threshold limit which causes deterioration in recharging ability of the battery.

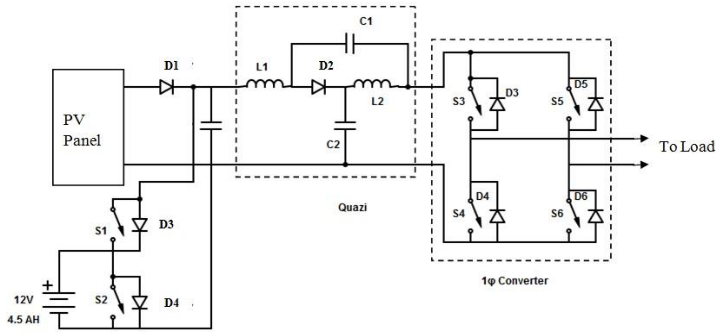


Fig.2 Optimized energy-stored qZSI for PV off-grid applications.

3. Operating modes of qZSI

The two modes of operation of a quasi z-source inverter are:
(1) Active mode
(2) Shoot through mode

3.1 Active mode

In the non-shoot through mode or active mode, the switching pattern for the QZSI is similar to that of Voltage Source Inverter (VSI). The input dc voltage is available as DC link voltage input to the inverter, which makes the QZSI behave similar to a VSI in this mode.

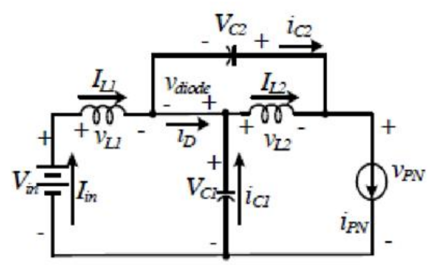


Fig.3.Equivalent circuit of QZSI in Active mode

3.2 Shoot through mode

In this mode, switches of the same phase in the inverter bridge are switched on simultaneously for a very short duration. The source however isn’t short circuited when attempted to do so because of the presence of LC network (quasi), that boosts 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.

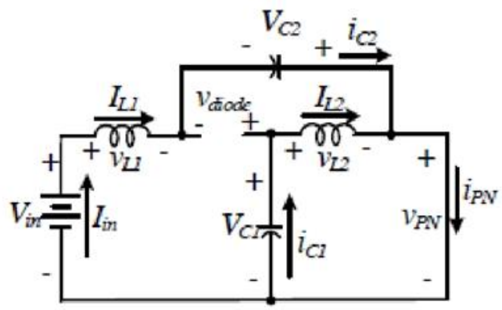


Fig.4.Equivalent circuit of QZSI in Shoot through mode

4. Design of quasi network

4.1 Design of Inductor

In active mode, the capacitor voltage is always equal to the input voltage. So there is no voltage across the inductor, whereas in the shoot through mode, the inductor current increases linearly and the voltage across the inductor is equal to the voltage across the capacitor. The average current through the inductor is given by,

$I_L = P/V_{dc}$ (1) (3.11)

Where P is the total power and V_{dc} is the input voltage.

The maximum current occurs through the inductor when the maximum shoot-through happens, that results in maximum ripple current. In order to limit the allowable ripple current within 4A and the maximum current within 10.67A the design was so made that only 30% current ripple occur through the inductors during maximum power operation

For a switching frequency of 10 kHz, the average capacitor voltage is,

$V_C = (1-T_O/T) * V_{dc} / (1-2T_O/T)$ (2) (3.12)

Substituting the values in the inductance equation, the average capacitor voltage would be 300V. So the inductance must be no less than

$L_1 = L_2 = (0.1*10*300 / 10.67) = 3mH$

4.2 Design of Capacitor

The main function of the capacitor is to absorb the voltage ripple and maintain a fairly constant voltage. During shoot-through the capacitor charges the inductors and the current through the capacitor equals the current in the inductor. Therefore the voltage ripple across the capacitor is,

$V_c = [I_{L(avg)}T_S] * (1/C)$ (3)

The capacitor voltage ripple is 0.17%.
Substituting the above values in the equation, the required capacitance was found to be

C = 6.67*0.1*10(300*0.0017)=3.401

Therefore the impedance network of the Quasi Z-Source inverter consists of inductors of 3mH and capacitors of 1000µF.

5. Control strategy

The QZSI configuration 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 lower or upper two switches. These switching states and their combinations have been spawned many PWM control schemes. Sinusoidal PWM is the most commonly used PWM technique in the VSI. On the other hand, QZSI has additional zero vectors or shoot through switching states that are forbidden in traditional VSI. In order to boost the output voltage, the shoot through state should always be followed by active state. This requirement may be met by the complimentary operations of the switches within a leg. The simple boost control method used here employs two constant voltage envelopes which are compared with the sine carrier wave. Whenever the magnitude of sine carrier wave becomes greater than or equal to the positive constant magnitude envelope (or) lesser than or equal to the negative constant magnitude envelope, pulses are generated which control the shoot through duty ratio D_O. These serve as the firing signals for the switches in the inverter. This control technique has shoot through states spread uniformly which makes output free of frequency ripples.

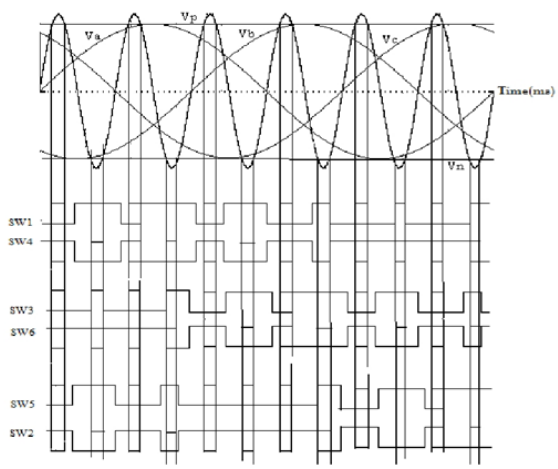


Fig.5. Schematic of Sine PWM

The sine wave carrier PWM provides high shoot through duty ratio than the triangular wave carrier, for the same modulation index, that results in reduced voltage stress on the device and gives high peak output voltage. The use of sine carrier suppresses the harmonics that results in reduction of THD in output voltage.

$$G = \frac{\text{Output peak AC voltage}}{\text{DC link voltage}} \qquad (4)$$

$$\mathrm{V_{Link}} = \frac{\mathrm{V_s}}{2} \qquad (5)$$

$$\mathrm{V_{ac}} = \mathrm{MB} * \frac{\mathrm{V_s}}{2} \qquad (6)$$

Where V_{Link} is the DC link voltage of inverter
$V_{ac}$is the peak ac output voltage
B is the boost factor
M is modulation index

The boost factor is given by,

$$B = \frac{1}{T_1 - T_0} = \frac{1}{1-2\frac{T_0}{T}} = \frac{1}{1-2D_0} \qquad (7)$$

where *Do* is the shoot through duty ratio of QZSI *To* is the shoot through interval *T* is the switching cycle.

When sine wave carrier PWM is implemented for control, the shoot through duty ratio, the boost factor and voltage gain of QZSI are derived as

$$D_0 = \frac{T_0}{T} = 1 - \frac{2}{\pi}\sin^{-1} M \qquad (8)$$

$$B = \frac{\pi}{4\sin^{-1} M - \pi} \qquad (9)$$

$$G = \frac{\pi M}{4\sin^{-1} M - \pi} \qquad (10)$$

It is observed that sine carrier PWM gives high shoot through duty ratio compared to triangular carrier, for the same modulation index, which reduces the voltage stress on the device and gives high peak output voltage. The simple boost control method has shoot through states spread uniformly which makes output free of low frequency ripples and the use of sine carrier wave has resulted in reduced THD in output voltage.

6. Simulation result

The block of the proposed model is shown in fig.6, from which it's evident that the thyristors shown in fig.2 are bidirectional in function and hence stated as converter. The single phase converter works as inverter in the 1 & 2 and as rectifier in case 3 of the proposed system operation.

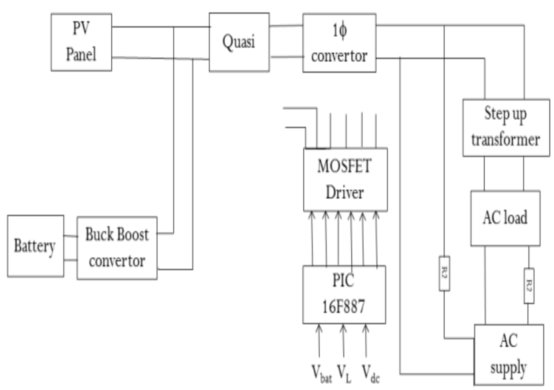


Fig.6 Block Diagram

For the purpose of simulation the PV panel was replaced by DC source.

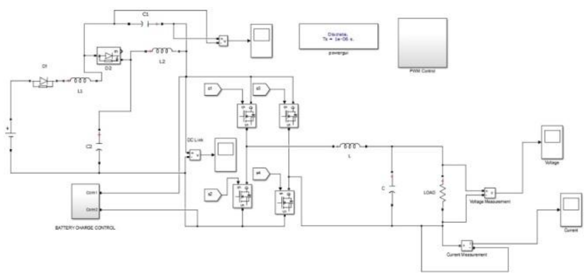


Fig.7 Simulation Block Diagram

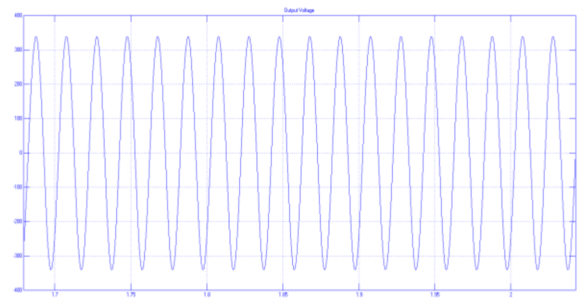


Fig.8 Output voltage waveform

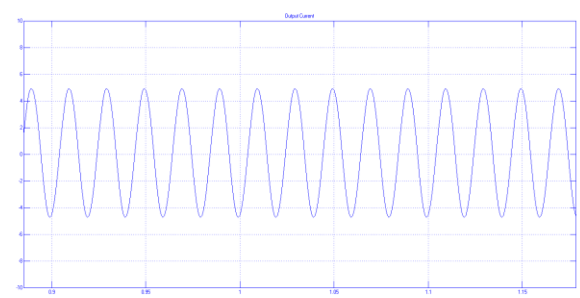


Fig.9 Output current waveform

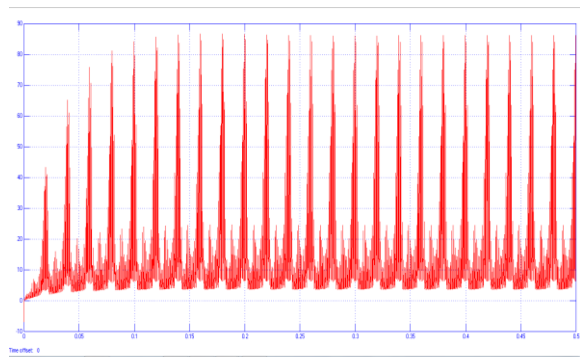


Fig.10 D.C. link Voltage

7. Conclusion

This paper proposes a new topology for energy stored Quasi Z-source Inverter that is more suitable for Photovoltaic power systems that are directly connected to load. The three operating modes of the proposed model make sure that the power supply to the load is uninterrupted and satisfies the load requirement. A prototype for the proposed model has been developed and its simulation and experimental results shown in this paper clearly demonstrate the effectiveness of this topology for PV power systems directly connected to the load.

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