A Novel Quasi Z-Source Inverter Design for Grid-Tie Photovoltaic Power Generation

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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. This work proposes a new topology of the energy-stored qZSI to overcome the disadvantage of discontinuous conduction mode and delivers the continuous power to the grid/load. The quasi-Z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter topology, employing an impedance network which couples the source and the inverter to achieve voltage boost and inversion. In this new qZSI the voltage boost, inversion, and energy storage are integrated in a single stage inverter. Maximum Power Point Tracking (MPPT) is used to track the maximum power from PV when it is available and it can track the first local maximum point and stop progressing to the next maximum power point. The results are illustrated using MATLAB/Simulink environment.**

***Index term*— Energy storage, photovoltaic (PV) power generation, power conversion, quasi-Z-source inverter (qZSI).**

I. Introduction

In the PV Power generation system, the power converter topologies employed are mainly characterized by two stage inverters or single stage inverters. In the two stage topology, a boost converter is embedded into PV and inverter to boost the low voltage of the PV panel to a desired constant dc link voltage. This topology increases the complexity of the circuit, cost, space requirement and reduces the efficiency of the system, due to the usage of power switches.

ZSI(Z-Source Inverter) is a single stage structure which achieves voltage buck/boost in a single conversion without increasing or introducing the number of switching devices. It can handle range of input voltage fluctuation and also reduces the component count, cost with increased reliability.

A new topology called Quasi Z-Source inverter (Fig. 1) has been derived from the ZSI and have more advantage for application in PV system, as described in [9] because 1) it draws a constant current from the pv panel and thus there is no need for extra filtering capacitors, 2) features a lower component (capacitor) rating and 3) reduces switching ripples from PV panels.

Energy storage technique presents a vital role in the PV power system to mitigate fluctuations of PV power to get a continuous, stable and smooth power to the grid. A battery is connected in parallel to the capacitor C_2 (Fig. 1) for balancing the power production and consumption. It has a limited battery discharging ability due to discontinuous conduction mode which affects the inverter output. By employing a active switch rather than diode, DCM was avoided but the switching device increases the cost and losses. SPWM technique is essential to operate qZSI.

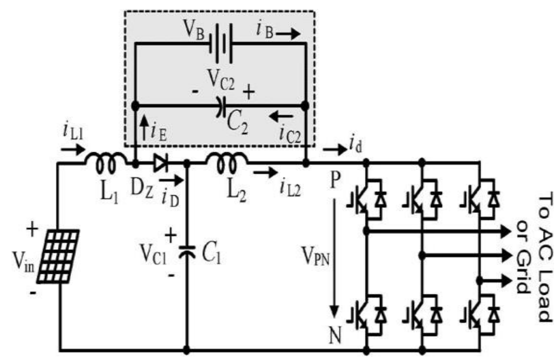

Fig. 1. Existing qZSI with battery for PV power generation

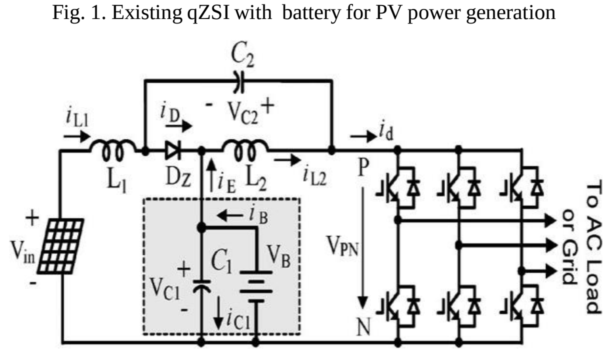

Fig. 2. Proposed qZSI with battery for PV power generation

This paper proposes a novel QZSI design for grid-tie PV power generation with a different storage connection method is proposed to overcome the above demerits.

II. QZSI

As a counterpart of Fig. 1, Fig. 2 shows a new topology. As in Fig. 1, Fig. 2 also has three power sources/consumers: PV panels, battery, and the grid/load. As long as controlling

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two power flows, the third one automatically matches the power difference through using

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

where P_{in}, P_{out}, and P_B are the PV power, the inverter output power, and the battery power, respectively.

The PV power is unidirectional; is bidirectional, and positive when discharging and negative when charging; is

positive when the inverter delivers power to the grid.

A. Operating Principle

Similar to QZSI operating principle, Fig 2 also has two operating modes [6].

MODE 1:

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 doesn't get short circuit because of the presence of LC network while boosting output voltage. As a result, the diode(D_z) is turned off due to the reverse bias voltage. Its equivalent circuit is shown in fig

The circuit equation during this time interval is shown as

$C \frac{!"\#!}{} = i_B - i_{L2}$ (2)

$C \frac{!"\#!}{!"} = -i_{L1}$ (3)

$L \frac{!"\#!}{!"} = V_{in} + V_{C2}$ (4)

$L \frac{!"\#!}{!"} = V_{C1}$ (5)

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

MODE 2:

In the non-shoot through mode, the switching pattern for qZSI is similar to that of a VSI. Current flows through the diode D_z continuously, and its equivalent circuit is shown in fig 3(b). the circuit equation during the time interval is shown below

$C \frac{!"\#!}{!"} = i_B + i_{L1} - i_d$ (6)

$C \frac{!"\#!}{!"} = -i_L - i_d$ (7)

$L \frac{!"\#!}{!"} = V_i - V_{C1}$ (8)

$L \frac{!"\#!}{!"} = -V_{C2}$ (9)

Where i_d is the load current going to the inverter.

B. Inverter System model

Considering T_0 as the time interval for Mode I and T_1 as the time interval for Mode II, with the switching cycle T. The shoot-through duty ratio is $D=T_0/T$, and $T=T_0+T_1$.

The inverter's state space equation is formed using the state space average method.

$$\begin{bmatrix} C0 & 0 & 0 \\ 0 & C0 & \\ & 0 & \\ 0 & 0 & L0 \\ 0 & 0 & 0 & L \end{bmatrix} \dot{x} = \begin{bmatrix} 0 & 0 & 1-D-D \\ 0 & 0 & -D1-D \\ D-1 & D0 & 0 \\ DD-1 & & \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ & i_! \\ (&) \\ D-1 & i_! \\ !" & \\ 0 & \end{bmatrix} \quad (10)$$

At the steady state, the left side (10) is zero. Therefore average voltage and current have relationships as

$V_{C1}= \frac{!!!}{!!!!} V_{in}$, $V_{C1}=V_{C2}+V_{in}$ (11)

$V_{C2}= \frac{!!!"}{!!!!}$ (12)

$i_{L2}-i_{L1}=i_B$ (13)

The dc-link peak voltage of the qZSI is

$V_{PN}=\frac{!}{!!!!}V_{in}$, $V_{PN}=V_{C1}+V_{C2}$ (14)

The inverter output power can be controlled by the desired output voltage and the output peak phase voltage is

$V_{ln}=V_{PN}\frac{!}{!}$ (15)

where M is the modulation index

C. Analysis and Comparison

1) If $P_{in}<P_{out}$, $P_B>0$, and $i_{L2}>i_{L1}$, the battery is discharging.

2) If $P_{in}>P_{out}$, $P_B<0$, and $i_{L2}<i_{L1}$, the battery is charging.

3) If $P_{in}=P_{out}$, $P_B=0$, and $i_{L2}=i_{L1}$, the battery will not have energy exchange.

TABLE I. Comparing working modes of two circuits

Power relationship	Battery Power and Status	Inductor Current	
		Fig.1	Fig.2
$P_{in}<P_{out}$	$P_B>0$, discharge	$i_{L2}<i_{L1}$	$I_{L2}>i_{L1}$
$P_{in}>P_{out}$	$P_B<0$, charge	$i_{L2}>i_{L1}$	$I_{L2}<i_{L1}$
$P_{in}=P_{out}$	$P_B=0$, no exchange	$i_{L2}=i_{L1}$	$I_{L2}=i_{L1}$

Table 1 summarizes the current behavior of two inductors

when battery charges and discharges.

Fig 1. shows different performances because the average currents of its two inductors and battery have the following expression:

$i_{L2}-i_{L1}= -i_B$ (16)

during mode II, Otherwise it works in the DCM if $i_D<0$ during mode II.

In steady state, the average current of capacitor C_1 is zero, and(above equation) will become

$$i_B<i_{L2} \text{ or } i_{L1}>0 \quad (18)$$

The power equation should satisfy

$$P_B<P_{out} \quad (19)$$

Fig 1 works in CCM if

$$I_D=i_{L1}+i_{C2}-i_B>0 \quad (20)$$

during nonshoot-through states. The average current of capacitor C_2 is zero at steady state and above eq will become

$$i_B<i_{L1} \quad (21)$$

$$P_B<P_{in};\ P_B<P_{out} \quad (22)$$

Both the circuit in Fig. 1 and Fig. 2 operates in CCM during battery charging. But they have different performance when battery is discharging. Therefore it shows the system in fig 2 always operates in the CCM during battery charging due to $P_B<0$, $i_B<0$, $i_{L2}>0$, and $i_D>0$.

By the equations (17) and (19) Fig. 2 is limited to operate in the CCM, and (19) will be true if (17) is met, but (17) may not be true if (19) is met. The instantaneous current flowing through the diode of the Z-source network may be decreased to zero during the nonshoot-through state, which causes the diode to turn OFF, so the DCM occurs, even though the average currents or powers meet (18) or (19). Fig. 1 is limited by (20) and (22) to operate in the CCM, and (22) will be true if (20) is met, but (20) may not be true if (22) is met. The instantaneous current flowing through the diode of the Z-source network may be decreased to zero during nonshoot-through state, which causes the diode to turn OFF, so the DCM occurs, even though the average currents or powers meet (21) or (22).

Fig. 1 shows the existing circuit's battery maximum discharging power over the inverter output power, and the resultant limited inverter output power is shown in Fig. 3(b). A DCM happens if the battery discharging power exceeds its limitation curve. From (19), (22), and Fig. 2, for the same inverter output power, Fig. 2 has a wider battery discharging power range when compared to Fig. 1.

TABLE II.

Parameters	Values
Temperature	25 °C
Irradiance	1000 W/m²
Series Connected Cell (Ns)	60 CELLS
Open Circuit Voltage (V_{oc})	44.816 V
Short Circuit Current (I_{sc})	7.244 A

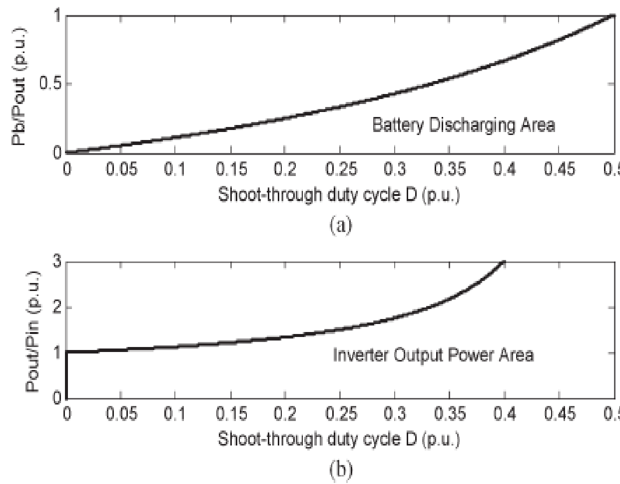

Fig. 3. Battery discharging power limitation and inverter output power limitation of the system in Fig. 1. (a) Battery discharging power ratio over the inverter output power. (b) Inverter output power ratio over the PV power.

III. Proposed System Design

In the PV based grid connected inverter system, the maximum point power tracking (MPPT), DC link voltage and current control and the battery storage connection are the main component to be designed and configured. The following subsections detail each of the components involved.

A. System Specification

Table II shows the specification used in the design of PV based qZSI system and Fig. 4 shows the overall PV inverter system. The source of the system is the PV array with the voltage of 90v. The voltage of the PV array terminal is boosted by the impedance network of L1, L2, C1and C2 to produce average 400V across the inverter input. The inverter then produces the sinusoidal current to be supplied to the grid and the synchronization is made.

B. MPPT

The MPPT method to be used is based on the perturbed and observed (P&O) method considering its simple algorithm which is widely used[8]. it is known that while regulating the capacitor voltage Vc1 constantly, the optimal voltage for the PV array $V_{pv} = V_{mpp}$ which result in maximum power can be obtained by adjusting the shoot-through duty ratio value D appropriately. The value of D is adjusted based on the algorithm in Fig. 4 and used in the form of modulation index m = 1 – D over the carrier signal which determine how long the gates are short-circuited during each cycle.

TABLE III

Values of components

	Parameters	Values
1.	L_1,L_2	500µF
2.	C_1,C_2	400µF
3.	L_f	1mH
4.	C_f	50 µF

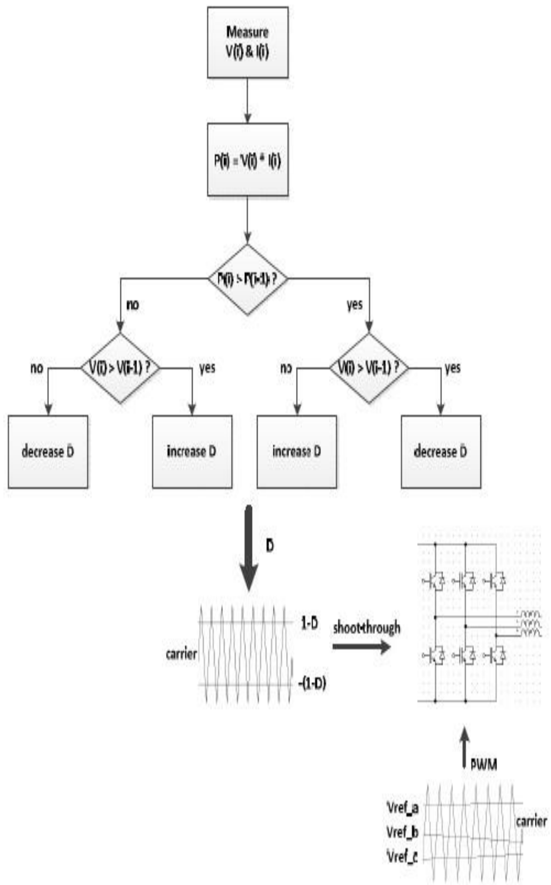

Fig. 4. Flow chart of P&O method of MPPT

C. Design of impedance network components

The values of two capacitors (C1 & C2) and two inductors (L1 & L2) at the impedance network are based on the required voltage and current ripple. The following equations (23) to (25) are used to determine the appropriate values [4].

ΔI_{L1} = [illegible] (23)

ΔV_{c1} = [illegible] (24)

$I_{L1(ave)}$ = [illegible] (25)

where D : shoot-through duty ratio, fs : switching frequency, Vdc : dc link voltage across the bridges, Pac : AC power to the grid, η: power efficiency, Vpv : output voltage of PV array.

IV. SIMULATION RESULTS

The simulation with MATLAB/SIMULINK is carried out to evaluate the PV inverter system behaviour based on the mode of operation described previously. Fig. 5 shows the power obtained from the PV array. Fig. 6 shows the voltage across the capacitor C_1. Fig. 7 shows the voltage obtained from the qZSI and Fig. 8 shows the current obatained from qZSI.

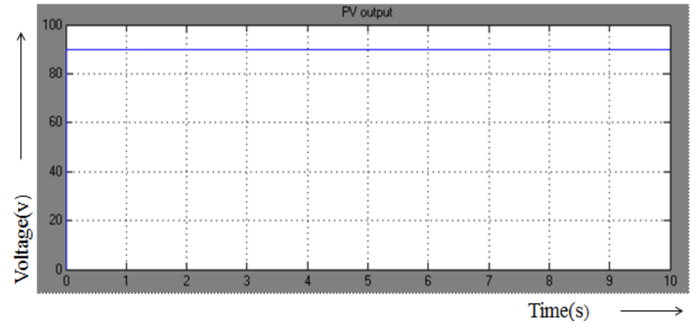

Fig. 5. Simulation result of PV output voltage

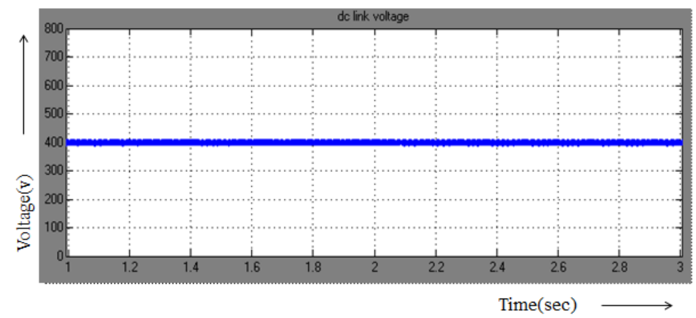

Fig. 6. Simulation result of dc link voltage

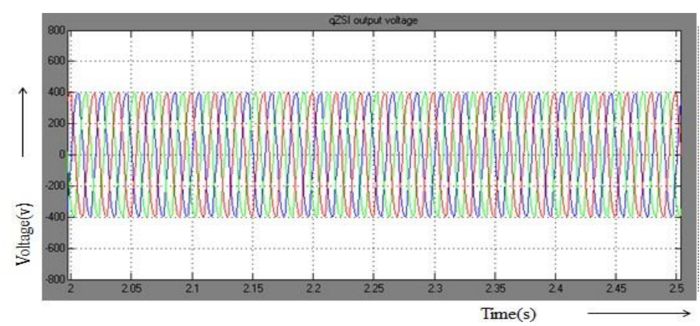

Fig. 7. Simulation result of qZSI output voltage

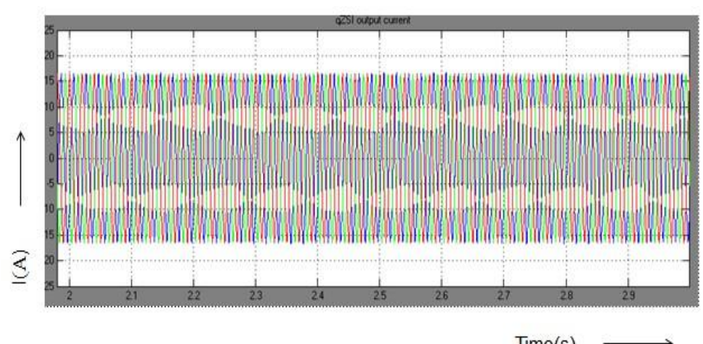

Fig. 8. Simulation result of qZSI output current

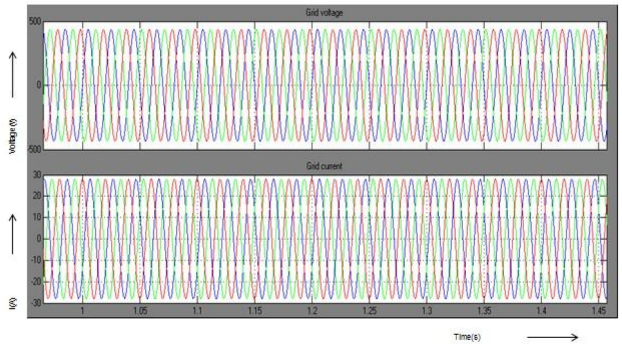

Fig. 9. simulation result of grid voltage and current

V. CONCLUSION

In this thesis, quasi z-source inverter design for grid-tie photovoltaic power generation is proposed. The energy stored QZSI overcome the shortcoming of existing topology, with wider power compensation range. It also ensured a constant dc-link peak voltage no matter what PV panel voltage varied. At the same time, the maximum PV power was harvested and the smooth power was injected to the grid/load even though PV power presented stochastic fluctuations. Experimental results shows effectiveness of proposed system novel energy stored QZSI-based PV power system.

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