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Quasi-Z Source Inverter for Photovoltaic Power Generation System

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Abstract – This paper presents a modified Z-source inverter which is called as quasi-Z-source inverter (qZSI) that is a new topology derived from the traditional Z-source inverter (ZSI). The qZSI inherits all the advantages of the ZSI, which can realize buck/boost, inversion and power conditioning in a single stage with improved reliability. In addition, the proposed qZSI has the unique advantages of lower component ratings and constant dc current from the source. All of the boost control methods that have been developed for the ZSI can be used by the qZSI. The qZSI features a wide range of voltage gain which is suitable for applications in photovoltaic (PV) systems, due to the fact that the PV cell's output varies widely with temperature and solar irradiation. Theoretical analysis of voltage boost, control methods and a system design guide for the qZSI in PV systems are investigated in this paper. A prototype has been built in the laboratory. Both simulations and experimental results are presented to verify the proposed concept.

Index Terms- Z-Source Inverter, Quasi-Z-source Inverter, Voltage Source Inverter

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I. INTRODUCTION

Photovoltaic (PV) power generation is becoming more promising since the introduction of the thin film PV technology due to its lower cost, excellent high temperature performance, low weight, flexibility, and glass-free easy installation. However, there are still two primary factors limiting the widespread application of PV power systems. The first is the cost of the solar cell/module and the interface converter system; the second is the variability of the output (diurnal and seasonal) of the PV cells. A PV cell's voltage varies widely with temperature and irradiation, but the traditional voltage source inverter (VSI) cannot deal with this wide range without over-rating of the inverter, because the VSI is a buck converter whose input dc voltage must be greater than the peak ac output voltage.

Because of this, a transformer and/or a dc/dc converter is usually used in PV applications, in order to cope with the range of the PV voltage, reduce inverter ratings, and produce a desired voltage for the load or connection to the utility. This leads to a higher component count and low efficiency, which opposes the goal of cost reduction.

The Z-source inverter (ZSI) has been reported suitable for residential PV system because of the capability of voltage boost and inversion in a single stage. Recently, four new topologies, the quasi-Z-source inverters (qZSI), have been derived from the original ZSI. This paper analyzes one voltage fed topology of these four in detail and applies it to PV power generation systems. By using the new quasi-Z-source topology, 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 and reduced source stress compared to the traditional ZSI. A prototype which provides single phase 50-Hz, 230Vrms ac has been built in laboratory. It is demonstrated from the theoretical analysis, simulation and experimental results that the proposed qZSI can realize voltage buck or boost and dc-ac inversion in a single stage with high reliability and efficiency, which makes it well suited for PV power systems.

Merits of qZSI over ZSI:

1. The two capacitors in ZSI sustain the same high voltage; while the voltage on capacitor

C2 in qZSI is lower, which requires lower capacitor rating.

2. The ZSI has discontinuous input current in the boost mode; while the input current of the qZSI is continuous due to the input inductor L1, which will significantly reduce input stress.

3. For qZSI, there is a common dc rail between the source and inverter, which is easier to assemble and causes less EMI problems.

4. ZSI has more harmonics in the output than qZSI.

II. OPERATING PRINCIPLE AND CIRCUIT ANALYSIS OF qZSI

A. Quasi-Z-Source Inverter Circuit

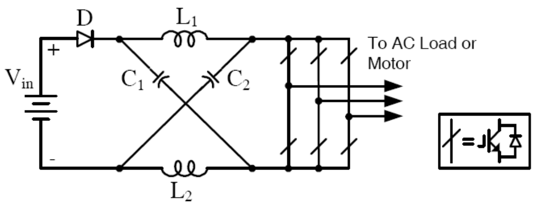

Fig. a. Voltage fed Z-source Inverter

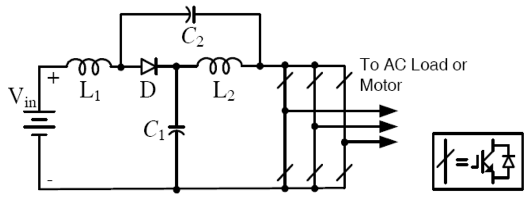

Fig. b. Voltage fed quasi Z-source Inverter

Figs. a and b shows the traditional voltage fed ZSI and the proposed voltage fed qZSI, respectively. In the same manner as the traditional ZSI, the qZSI has two types of operational states at the dc side: the non shoot-through states (i.e. the six active states and two conventional zero states of the traditional VSI) and the shoot-through state (i.e. both switches in at least one phase conduct simultaneously).

In the non-shoot-through states, the inverter bridge viewed from the dc side is equivalent to a current source. The equivalent circuits of the two states are as shown in Figs. c and d. The shoot-through state is forbidden in the traditional VSI, because it will cause a short circuit of the voltage source and damage the devices. With the qZSI and ZSI, the unique LC and diode network connected to the inverter bridge modify the operation of the circuit, allowing the shoot-through state. 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 major differences between the ZSI and qZSI are

(1) The qZSI draws a continuous constant dc current from the source while the ZSI draws a discontinuous current and

(2) The voltage on capacitor C2 is greatly reduced. The continuous and constant dc current drawn from the source with this qZSI make this system especially well suited for PV power conditioning systems.

B. Circuit Analysis

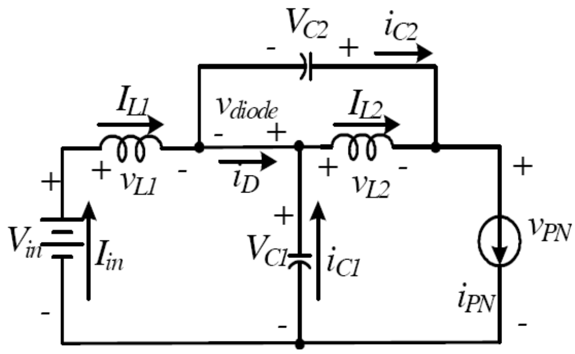

Fig. c. Equivalent circuit of the qZSI in non shoot through states

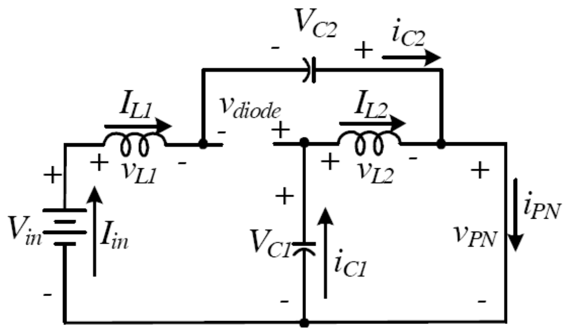

Fig. d. Equivalent circuit of the qZSI in shoot through states.

All the voltages as well as the currents are defined in Figs c and d and the polarities are shown with arrows. Assuming that during one switching cycle, T, the interval of the shoot through state is To; the interval of non-shoot-through states is T1; thus one has T= To + T1 and the shoot-through duty ratio, D= To/T. From Fig. c. which is a representation of the inverter during the interval of the non-shoot through states, T1 , one can get

$v_{L1} = Vin – V_{C1}$, $v_{L2} = -V_{C2}$, and (1)

$V_{PN} = V_{C1} – v_{L2} = V_{C1} + V_{C2}$ Vdiode =0 (2)

From Fig d. which is a representation of the system during the interval of the shoot-through states, To, one can get

$v_{L1} = V_{C2} + Vin$, $v_{L2} = V_{C1}$, and (3)

$V_{PN} = 0$, Vdiode $= V_{C1} + V_{C2}$ (4)

At steady state, the average voltage of the inductors over one switching cycle is zero. From (1), (3), one has

$$\begin{cases} V_{L1} = \overline{v}_{L1} = \dfrac{T_0(V_{C2} + V_{in}) + T_1(V_{in} - V_{C1})}{T} = 0 \\ V_{L2} = \overline{v}_{L2} = \dfrac{T_0(V_{C1}) + T_1(-V_{C2})}{T} = 0 \end{cases}$$

Thus

$$V_{C1} = \frac{T_1}{T_1 - T_0} V_{in} \qquad V_{C2} = \frac{T_0}{T_1 - T_0} V_{in} \tag{5}$$

From (2), (4) and (5), the peak dc-link voltage across the inverter bridge is

$$\hat{v}_{PN} = V_{C1} + V_{C2} = \frac{T}{T_1 - T_0} V_{in} = \frac{1}{1 - 2\dfrac{T_0}{T}} V_{in} = BV_{in} \tag{6}$$

where B is the boost factor of the qZSI. This is also the peak voltage across the diode.

The average current of the inductors L_1, L_2 can be calculated by the system power rating P

$I_{L1} = I_{L2} =$ Iin = P/Vin (7)

According to Kirchhoff's current law and (7), we also can get that

$I_{C1} = I_{C2} = I_{PN} - I_{L1}$ $I_D = 2I_{L1} - I_{PN}$ (8)

In summary, the voltage and current stress of the qZSI are shown in Table 1. The stress on the ZSI is shown as well for comparison, where

(1) M is the modulation index; v_{ln} is the ac peak phase voltage; P is the system power rating.

(2) m = T1/(T1 – To); n = To/(T1 – To); thus m>1; m – n=1.

(3) B = T/ (T1 – To), thus m + n = B, 1<m<B.

From Table 1 we can find that the qZSI inherits all the advantages of the ZSI. It can buck or boost a voltage with a given boost factor. It is able to handle a shoot through state, and therefore it is more reliable than the traditional VSI. It is unnecessary to add a dead band into control schemes, which reduces the output distortion.

Table 1. Voltage and average current of the qZSI and ZSI network

	$v_{L1} = v_{L2}$		v_{PN}		v_{diode}	
	T_0	T_1	T_0	T_1	T_0	T_1
ZSI	mV_{in}	$-nV_{in}$	0	BV_{in}	BV_{in}	0
qZSI	mV_{in}	$-nV_{in}$	0	BV_{in}	BV_{in}	0
	V_{C1}		V_{C2}		$\hat{v}_{ln}$	
ZSI	mV_{in}		mV_{in}		$MBV_{in}/2$	
qZSI	mV_{in}		nV_{in}		$MBV_{in}/2$	
	$I_{in} = I_{L1} = I_{L2}$		$I_{C1} = I_{C2}$		I_D	
ZSI	P/V_{in}		$I_{PN} - I_{L1}$		$2I_{L1} - I_{PN}$	
qZSI	P/V_{in}		$I_{PN} - I_{L1}$		$2I_{L1} - I_{PN}$	

In addition, there are some unique merits of the qZSI when compared to the ZSI:

(1) The two capacitors in ZSI sustain the same high voltage; while the voltage on capacitor C_2 in qZSI is lower, which requires lower capacitor rating.

(2) The ZSI has discontinuous input current in the boost mode; while the input current of the qZSI is continuous due to the input inductor L_1, which will significantly reduce input stress.

(3) For the qZSI, there is a common dc rail between the source and inverter, which is easier to assemble and causes less EMI problems.

III. CONTROL METHODS

A. Buck/Boost Conversion Mode

If the inverter is operated entirely in the non-shoot-through states (Fig. c) the diode will conduct and the voltage on capacitor C_1 will be equal to the input voltage while the voltage on capacitor C_2 will be zero. Therefore, v_{PN} = Vin and the qZSI acts as a traditional VSI:

$$\hat{v}_{ln} = \frac{\hat{v}_{PN}}{2} \cdot M = \frac{V_{in}}{2} \cdot M \tag{9}$$

For SPWM $0 \le M \le 1$; and for SVPWM $0 \le M \le 2/\sqrt{3}$. Thus when D = 0, V_{ln} always less than Vin/√3 and this is called the buck conversion mode of the qZSI.

By keeping the six active states unchanged and replacing part or all of the two conventional zero states with shoot through states, one can boost by a factor of B , the value of which is related to the shoot-through duty ratio, as shown in (6). This is called the boost conversion mode of the qZSI. The peak ac voltage becomes

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$$\hat{v}_{1n} = \frac{\hat{v}_{PN}}{2} \cdot M = \frac{V_{in}}{2} \cdot BM \qquad (10)$$

B. Boost Control Methods

All the boost control methods that have been explored for the traditional ZSI (i.e. simple boost, maximum boost, and maximum constant boost) can be utilized for qZSI control in the same manner. Generally speaking, the voltage gain of the qZSI is $G=v_{ln}/0v_{pn}.=MB$**,** whereas the voltage stress across the inverter bridge is BVin . In order to maximize the voltage gain and minimize the voltage stress on the inverter bridge, one needs to decrease the boost factor B and increase the modulation index M as much as possible.

In the proposed PV power generation system, in order to lower the voltage stress on the inverter bridge and keep a high voltage gain, the maximum constant boost control with third harmonic injection was chosen as the control method. Fig. e. shows the sketch map. At (1/6) third harmonic injection, the maximum modulation index M = (2/√3) can be achieved. The shoot-through states are introduced into the switching cycle when the carrier is either greater than V_P or less than V_N, which is evenly spread in each switching cycle. Thus the qZSI network doesn't involve low-frequency ripples. In this case, the shoot-through duty ratio is

$$D = \frac{T_0}{T} = 1 - \frac{\sqrt{3}M}{2} \qquad (11)$$

The boost factor is

$$B = \frac{1}{1-2D} = \frac{1}{\sqrt{3}M - 1} \qquad (12)$$

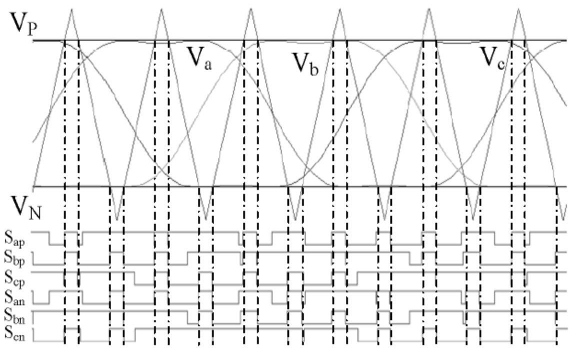

Fig.e. Sketch map of constant boost control for qZSI

And the voltage gain equals

$$\hat{v}_{1n} = \frac{V_{in}}{2} G = \frac{MV_{in}}{2\sqrt{3M} - 2} \qquad (13)$$

The peak ac phase voltage can be calculated

$$\hat{v}_{1n} = \frac{V_{in}}{2} G = \frac{MV_{in}}{2\sqrt{3M} - 2} \qquad (14)$$

IV. RESULTS AND ANALYSIS

SIMULATION RESULTS

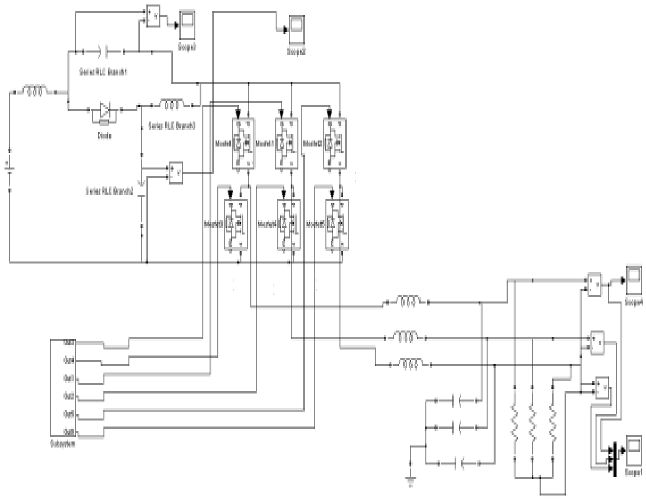

Fig. f. Open loop simulation circuit of qZSI

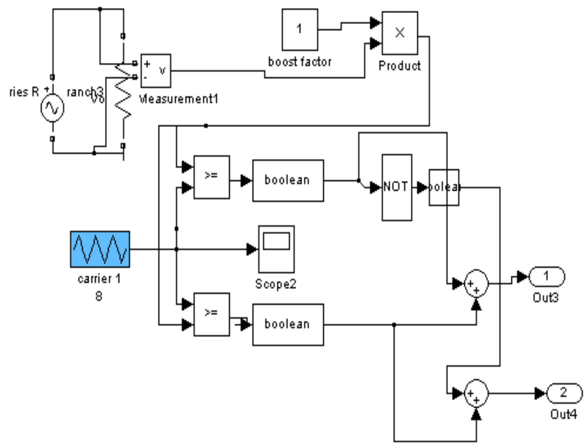

Fig. g. Pulse generator circuit of open loop qZSI

Case1- Output waveforms at Modulation index, M=0.85, Boost Factor, B=1

As per the theoretical calculation

DC voltage, VO=400 V

Output AC voltage (Phase voltage)

Vac=0.85*1*400/2=170 V

Output AC voltage (Line voltage),

Vac=170*1.73=294.1 V

The Output 3-phase AC Voltage

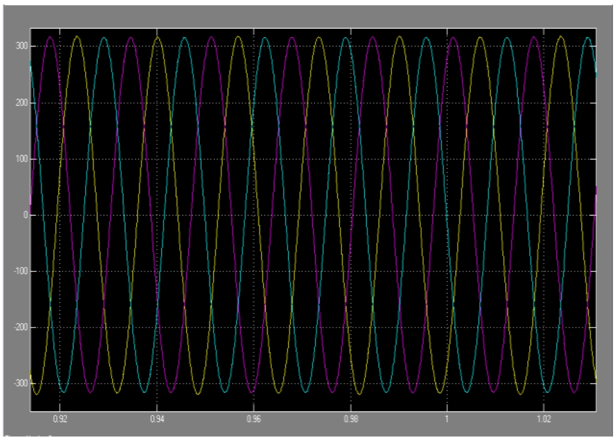

Fig. h. Output waveform for M=0.85 & B=1

By simulating the above circuit in fig. f. using MATlab simulink at modulation index, M=0.85 and B=1. output voltage waveform 316V is obtained. The magnitude of the output voltage by theoretical calculation is 294V which is nearly equal to simulation results.

Case 2- Output waveforms at Modulation index, M=1, Boost factor, B=1.366

As per the theoretical calculation,

DC voltage, VO=400 V

Output AC voltage (Phase voltage)

Vac=1*1.366*400/2=273.2V

Output AC voltage (Line voltage),

Vac=273.2*1.73=472.636V

The Output 3-phase AC Voltage

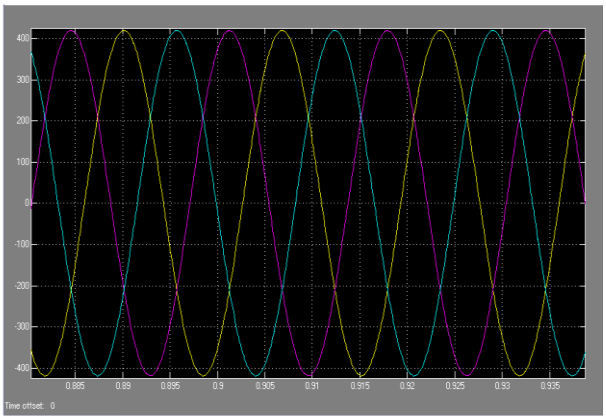

Fig. i. Output waveform for M=1 & B=1.366

By simulating the same circuit using MATlab simulink at modulation index, M=1, B=1.366, the output voltage of 421V is obtained. The magnitude of the output voltage by theoretical calculation is 273.2V which is nearly equal to simulation results and observed that the voltage is increased by increasing the modulation index, M and boost factor B.

Case 3- Output waveforms at Modulation index, M=0.85, Boost Factor, B=2.118

As per the theoretical calculation,

DC voltage [1], VO=400 V

Output AC voltage (Phase voltage)

Vac=0.85*2.118*400/2=360.06V

Output AC voltage (Line voltage),

Vac=360.06*1.73=622.90V

The Output 3-phase AC Voltage

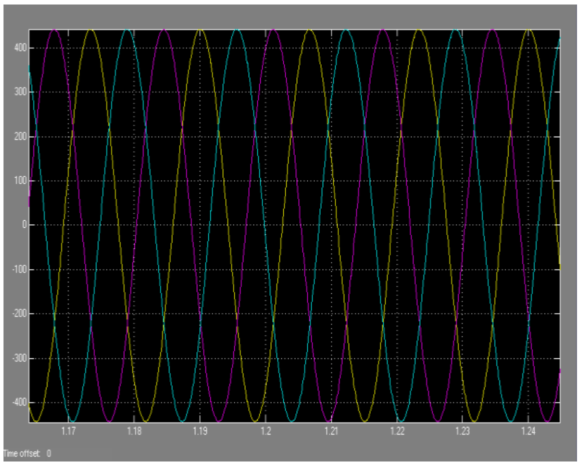

Fig. j. Output waveform for M=0.85 & B=2.118

By simulating the same circuit in fig. f. using MATlab simulink at modulation index, M=0.85 and B=2.118., the output voltage of 440V is obtained. The magnitude of the output voltage by theoretical calculation is 360.06V which is nearly equal to simulation results.

EXPERIMENTAL RESULTS

Fig. k. Prototype of qZSI for PV system

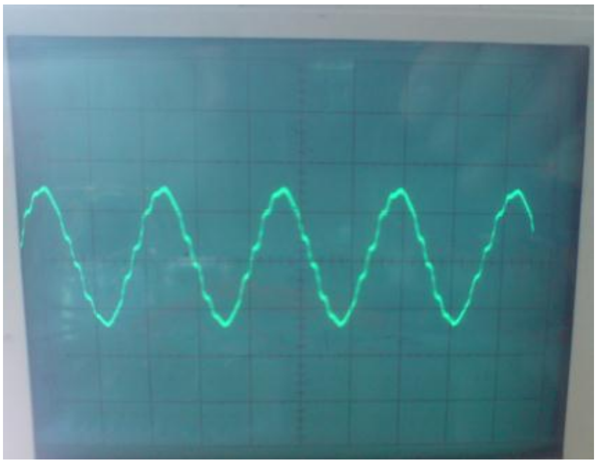

Fig. l. Output waveform of the prototype

The proposed prototype for qZSI is fabricated and tested. The hardware implementation of the microcontroller based qZSI system used for photovoltaic power generation system is as shown in fig.k. The output waveform is shown in fig. l.

A solar cell is connected at the input of an inverter which produces a voltage of 18V DC. This voltage is given to the inverter. The inverter produces a constant ripple free 24V output.

By observing the results above, it can be seen that the implementation of quasi Z-source inverter for PV generation is verified experimentally. Also, it can be seen that the output voltage of quasi Z-source inverter can be varied over a wide range. That is, the output voltage of quasi Z-source inverter may be either greater than or less than the input voltage.

V. ADVANTAGES

The qZSI inherits all the advantages of the ZSI which can be interchangeable.The power conditioning in a single stage with improved reliability. Unique advantage of qZSI is lower component rating and constant dc current from source. The qZSI has continuous input current, reduced source stress. The quasi Z-source inverter (qZSI) is suitable for residential PV system.

VI. CONCLUSION AND FUTURE WORK

In this paper a quasi-Z-source inverter with a new topology is presented, which is derived from the traditional ZSI. The proposed 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, the proposed qZSI has advantages of continuous input current, reduced source stress, and lower component ratings when compared to the traditional ZSI. Theoretical analysis, control method, and system design guide are presented in this paper. Both simulation and experimental results show that with a voltage range of 1:2 at the PV input, the qZSI can provide single phase 50 Hz, 230 Vllrms ac voltage, which verifies the theoretical analysis.

A grid-connected PV power generation system is one of the most promising applications of renewable energy sources. The proposed qZSI based PV power generation system is intended as a grid connected system and transfers the maximum power from the PV array to the grid by maximum power point tracking technology. In that case, the efficiency would be improved and the cost would be reduced with the proposed one stage power conversion system. For the high power application we can use IGBT's in place of MOSFET. SPWM can be replaced by SVPWM. DSP processor can be used instead of microcontroller.

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