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Quasi-Z-Source Inverter for Photovoltaic Energy Conversion System

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Abstract— **This paper represents the Quasi-Z-Source inverter for photovoltaic energy conversion system. Quasi-Z-Source Inverter (QZSI) is an enhancement to 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. 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. MATLAB / SIMULINK model of both the circuit topology (QZSI and ZSI) with different loading conditions are presented. Maximum Boost control technique is employed here. Theoretical analysis of voltage boost, control methods and a system design guide for the QZSI in PV systems are investigated in this paper. A comparative analysis between ZSI and QZSI is given in the end**

***Keywords**— Quasi-Z-Source inverter, Z-Source inverter, boosting ability, modulation index, photovoltaic (PV) system, maximum boost control .*

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 or 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 [1-3].

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 project 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. It is demonstrated from the theoretical analysis and simulation 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 [5-9].

II. CIRCUIT ANALYSIS OF THE QUASI-Z-SOURCE INVERTER

A. *Quasi-Z-Source Inverter Circuit*

Figs. 1a and 1b show the traditional voltage fed ZSI [4] 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. 2a and 2b. 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

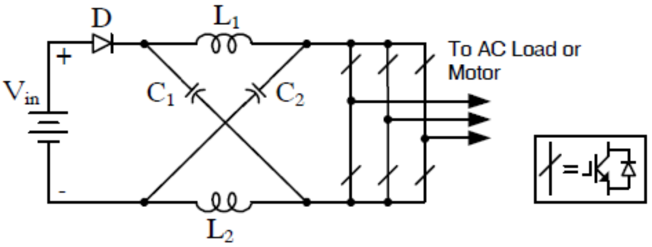


Figure 1a. Voltage fed Z-source inverter

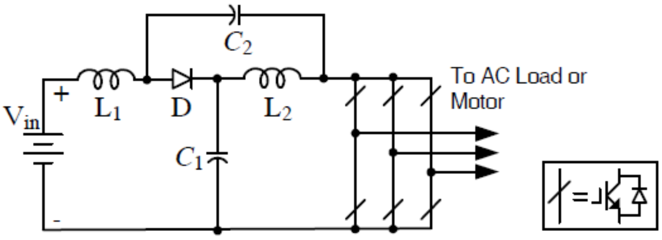


Figure 1b. Voltage fed Quasi-Z-source inverter

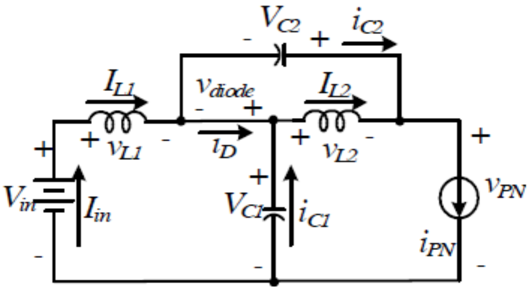


Figure 2a. Equivalent circuit of the QZSI in non-shoot-through states

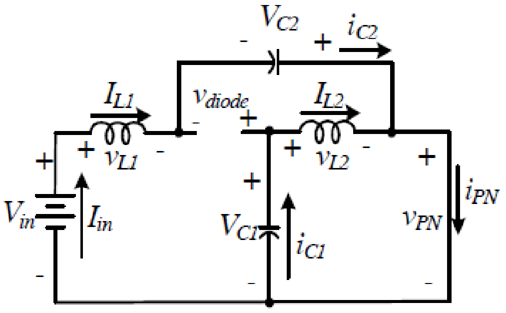


Figure 2b. Equivalent circuit of the QZSI in shoot-through states

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

All the voltages as well as the currents are defined in Figs 2a, 2b 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 T_1; thus one has T= To+$T_1$and the shoot-through duty ratio, D= To/T. From Fig.3.6 which is a representation of the inverter during the interval of the non-shoot through states T_1, one can get;

$$V_{L1}=V_{in}-V_{C1},V_{L2}=-V_{C1} \qquad (1)$$

And

$$V_{PN}=V_{C1}-V_{L2}=V_{C1}+V_{C2}.V_{diode}=0 \qquad (2)$$

Fig.4.5.which is a representation of the system during the interval of the shoot-through states To, one can get;

$$V_{L1}=V_{C2}+V_{in},V_{L2}=V_{C1} \qquad (3)$$

$$V_{PN}=0,V_{diode}=V_{C1}+V_{C2} \qquad (4)$$

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

$$V_{L1}=\bar{v}_{L1}=\frac{T_0(V_{L2}+V_{IN})+T_1(V_{IN}-V_{C1})}{T}=0$$

$$V_{L2}=\bar{V}_{L2}=\frac{V_{C1}T_0+(-V_{C2})T_1}{T}=0$$

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

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

$$\bar{V}_{pn}=V_{c1}+V_{C2}=\frac{T}{T_1-T_o}Vin=\frac{1}{1-2To/T}Vin=BVin \qquad (6)$$

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.

$$I_{L1}=I_{L2}=I_{in}=P/V_{in} \qquad (7)$$

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

$$I_{C1}=I_{C2}=I_{PN}-I_{L1} \qquad I_D=2L_1-I_{PN} \qquad (8)$$

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_{in} is the ac peak phase voltage; P is the system power rating.

(2) $m=\frac{T_1}{T_1-T_0}$ $\qquad n=\frac{To}{T_1-T_0}$ thus m>1; m-n=1;

(3) B= T/(T_1-T_0) 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}		$\hat{v}_{1n}$	
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}		$I_{PN}-I_{L1}$		$2I_{L1}-I_{PN}$	

(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 Method*

If the inverter is operated entirely in the non-shoot-through states (Fig. 2a) 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:

Thus when D = 0, $\hat{v}_{1n}$ is 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 *PN v*ˆ 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.

B. *Boost Control Methods*

All the boost control methods that have been explored for the traditional ZSI (i.e. simple boost, maximum boost, maximum constant boost) [5-7] can be utilized for QZSI control in the same manner. Generally speaking, the voltage gain of the QZSI is $G = \hat{v}_{1n} / 0.5\hat{v}_{PN} = MB$, 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.

Fig. 3 shows the voltage gain versus the modulation index of these three boost control methods. All have significantly higher gain than traditional PWM methods. Among these three boost control methods, the maximum boost control makes the most use of the conventional zero states, so it has the maximum *M* and the minimum voltage stress across the inverter bridge with the same voltage gain. However, it has the drawback of low-frequency ripples on the passive components of the QZSI, which requires a larger volume and weight and higher cost inductor and capacitor in the QZSI network.

The simple boost control has evenly spread shoot-through states, thus it doesn't involve low-frequency ripples associated with output frequency; but its voltage stress is the largest with a given G.

The maximum constant boost control [7] [8] [10] makes a compromise of the two mentioned boost control methods. 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. 4 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;

$$D=\frac{T_0}{T}=1-\sqrt{3}\frac{M}{2} \tag{9}$$

The boost factor is

$$B=\frac{1}{1-2D}=\frac{1}{\sqrt{3}M-1} \tag{10}$$

And the voltage gain equals

$$G=MB=\frac{M}{\sqrt{M}-1} \tag{11}$$

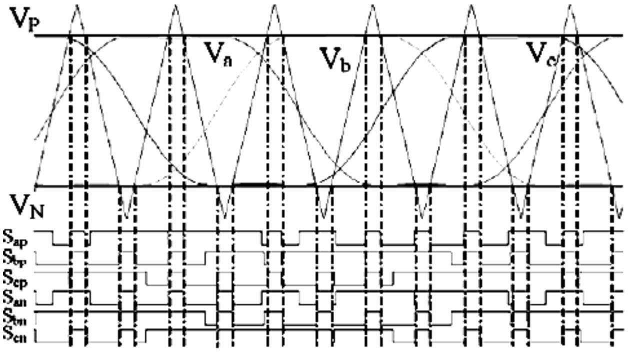


Figure 3. Sketch map of constant boost control for QZSI

The peak ac phase voltage can be calculated as

$$\hat{v}_{1n}=\frac{Vin}{2}G=\frac{MVin}{2\sqrt{3}M-2} \tag{12}$$

The above switching cycle describe the switching pattern of the leg devices which is suitable for shoot- through as well as non-shoot-through states. These are the pulsing pattern which are given to the phase leg devices like IGBTs or MOSFETs.

IV. QZSI DESIGN FOR PV POWER GENERATION SYSTEMS

A. Voltage and Current Rating for Switches

Fig. 5 shows the proposed QZSI in the PV power generation system. It connects the PV arrays and outputs three phase 50 Hz, 150 Vrms ac to resistive loads, which can be varied according to the modulation index (M) as well as boosting factor (B).

Given an input PV voltage range, the maximum required voltage gain of the QZSI can be determined by;

$$G_{\max} = \frac{\hat{v}_{in}}{V_{in}/2} \approx 1.7 \qquad (13)$$

With maximum constant boost control method, the potential minimum modulation index *M* and maximum boost factor *B* can be determined by (4.10), (4.11)

$$M\min = \frac{G\max}{\sqrt{3}G\max - 1} \approx .875 \qquad (14)$$

$$B\max = \frac{1}{\sqrt{3}M - 1} \approx 1.94 \qquad (15)$$

The maximum voltage stress on the inverter bridge is predicted by $\hat{v}_{PN}$ = $B_{\max}$Vin ≈ 388V. As a result, 600 V IGBTs and a 600 V diode are chosen for the proposed QZSI. According to Table 4.1, the voltage ratings of capacitors C1 and C2 are approximately 300 V and 100 V. respectively. Furthermore, with a given system power rating, e.g. 10 kW, the maximum current flow through the inductor is

$$I_{in} = I_{L1} = I_{L2} = P/V_{in} = 50\text{ A} \qquad (16)$$

B. Inductor and Capacitor Selection

When the system is operating in boost conversion mode, the potential maximum interval of the shoot-though T_0, per switching cycle, can be calculated by

$$T_{o\_\max} = \frac{2 - \sqrt{3}M_{\min}}{fs} = 24\mu S \qquad (17)$$

The inductors in the QZSI network will limit the current ripple through the devices during boost conversion mode.

During shoot-though, the inductor current increases linearly. With the maximum constant boost control mode, the shoot-through interval, To, is evenly split into two intervals of half the duration. Choosing an acceptable peak to peak current ripple, r_c%, e.g. 20% in this application, the inductance can be calculated by;

$$L_1 = L_2 = \frac{V_L \Delta T}{\Delta I} = \frac{mVin}{I_{L\max} r_c\%}\frac{1}{2}To\max \approx 356\mu H \qquad (18)$$

Coupled inductors are used in this application in order to minimize the size and weight. With identical current flow, the flux is doubled for each inductor.

$$\varphi = 2Ni/\Re g = 2Ni \cdot AL \qquad (19)$$

Thus the inductance for each inductor is

$$L_1 = L_2 = N\phi/i = 2N^2/L \qquad (20)$$

The AMCC-250 core was selected, whose *AL* –Value (μ*H* / N^2) is 0.55 when the air gap- *lg* = 2 l *mm*. So using (4.19), each inductor is designed with 17 turns. The saturation current is approximately 65 A by referencing the appropriate tables on the datasheet for the AMCC-250 core.

The two capacitors are in series in the QZSI network when in the non-shoot-through states. These two capacitors absorb the current ripple and limit the voltage ripple on the inverter bridge so as to keep the output voltage sinusoidal. Assuming that the capacitance should be the same for each capacitor, the capacitance needed to limit the PN voltage ripple by *rv*%, e.g. 1%, can be calculated by;

$$\begin{aligned} C_1 = C2 &= 2\frac{Ic\Delta T}{\Delta V_{C1} + \Delta V_{C2}} \\ &= 2\frac{I_L}{B.Vin.r_v\%}\frac{1}{2}To\_\max \approx 310\mu F \end{aligned} \qquad (21)$$

V. SIMULATION RESULTS AND DISCUSSION

In this section the two models, created with the help of MATLAB/SIMULINK version 2010 for the purpose of DC to AC inversion from Photovoltaic generation system; Z-Source Inverter for Photovoltaic Energy Conversion System and Quasi-Z-Source Inverter for Photovoltaic energy conversion system. These two models are compared by its output waveform and THD analysis.

The simulations were done in MATLAB/SIMULINK with switching frequency f_{sw} = 8kHz.To simplify the simulation the PV array was simulated with PV panel voltage V_{dc} =12V. The impedance source network elements are; L_1 = L_2 = 500μH and C_1 = C_2 = 400μF. Filter inductor L_3 = L_4 =2 H and Filter Capacitor C_3 = 2 μF.

Both systems are further analyzed for different loading conditions like R and R-L loads. The resistive load is 5 kΩ and R-L load is 5 kΩ-5 H. Both the models are designed for single phase.

A. Z-Source Inverter for Photovoltaic energy conversion system

The Z-Source Inverter for Photovoltaic energy conversion system with R and R-L Load is described with the following circuit diagram.

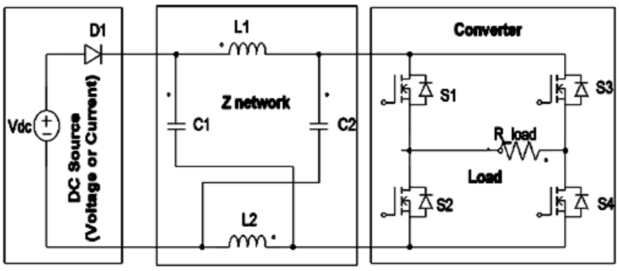


Figure 4a. Circuit Diagram of Z-Source Inverter with R load

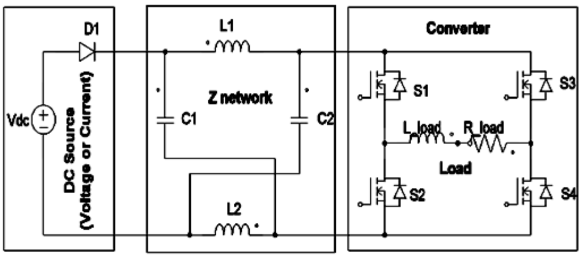


Figure 4b. Circuit Diagram of Z-Source Inverter with R-L load

For simplicity the two loading conditions; R load and R-L load, the simulation diagram is shown only for R load. The results are given further for both loading conditions.

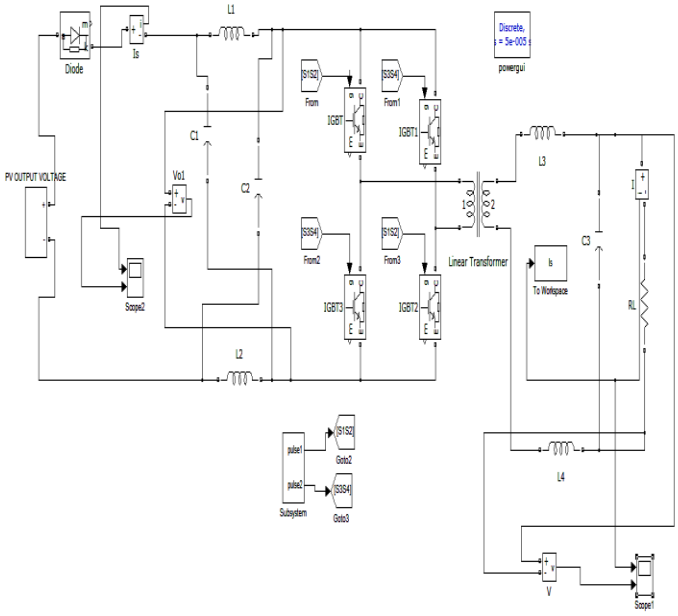
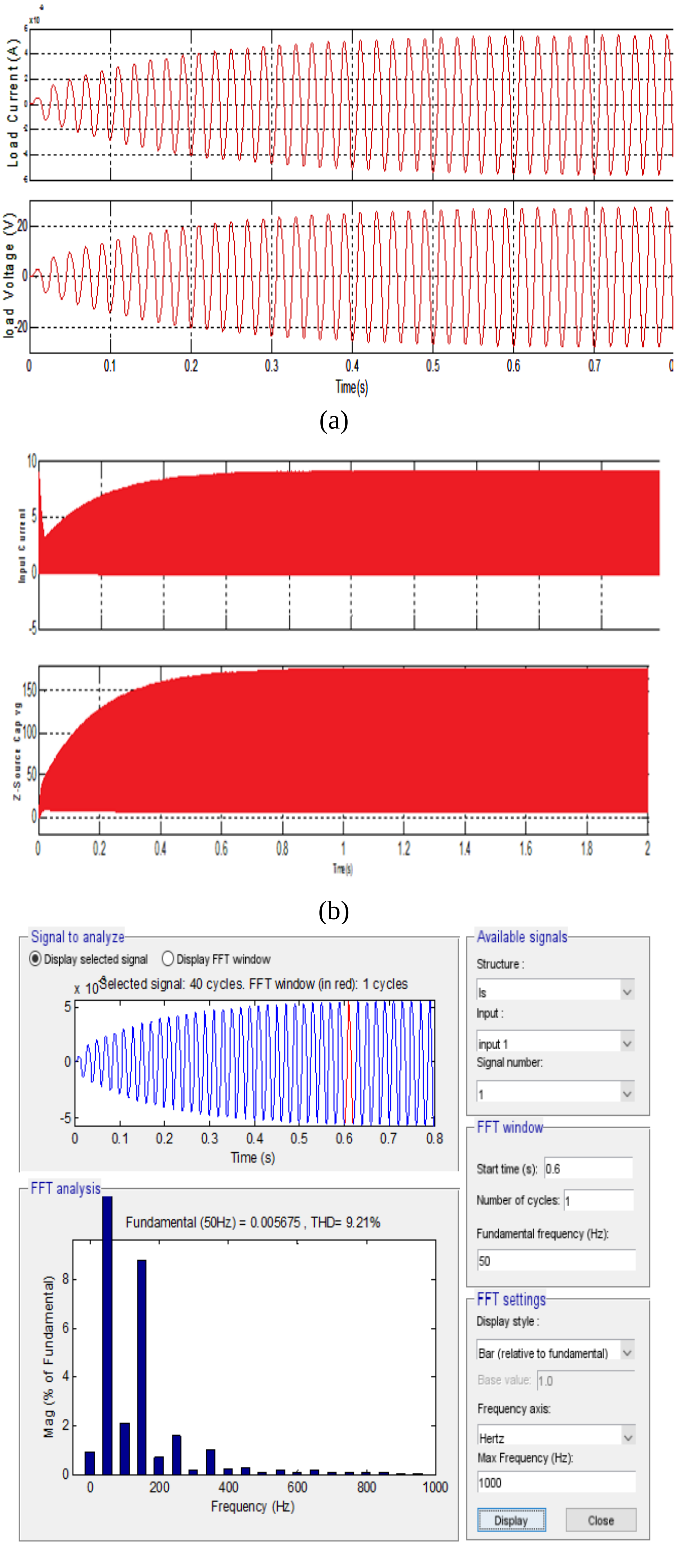


Figure 5. SIMULINK model of Z-Source Inverter for Photovoltaic energy conversion system



(a)

(b)

Signal to analyze

● Display selected signal ○ Display FFT window

Selected signal: 40 cycles. FFT window (in red): 1 cycles

FFT analysis

Fundamental (50Hz) = 0.005675 , THD= 9.21%

Available signals

Structure : Is

Input : input 1

Signal number: 1

FFT window

Start time (s): 0.6

Number of cycles: 1

Fundamental frequency (Hz): 50

FFT settings

Display style : Bar (relative to fundamental)

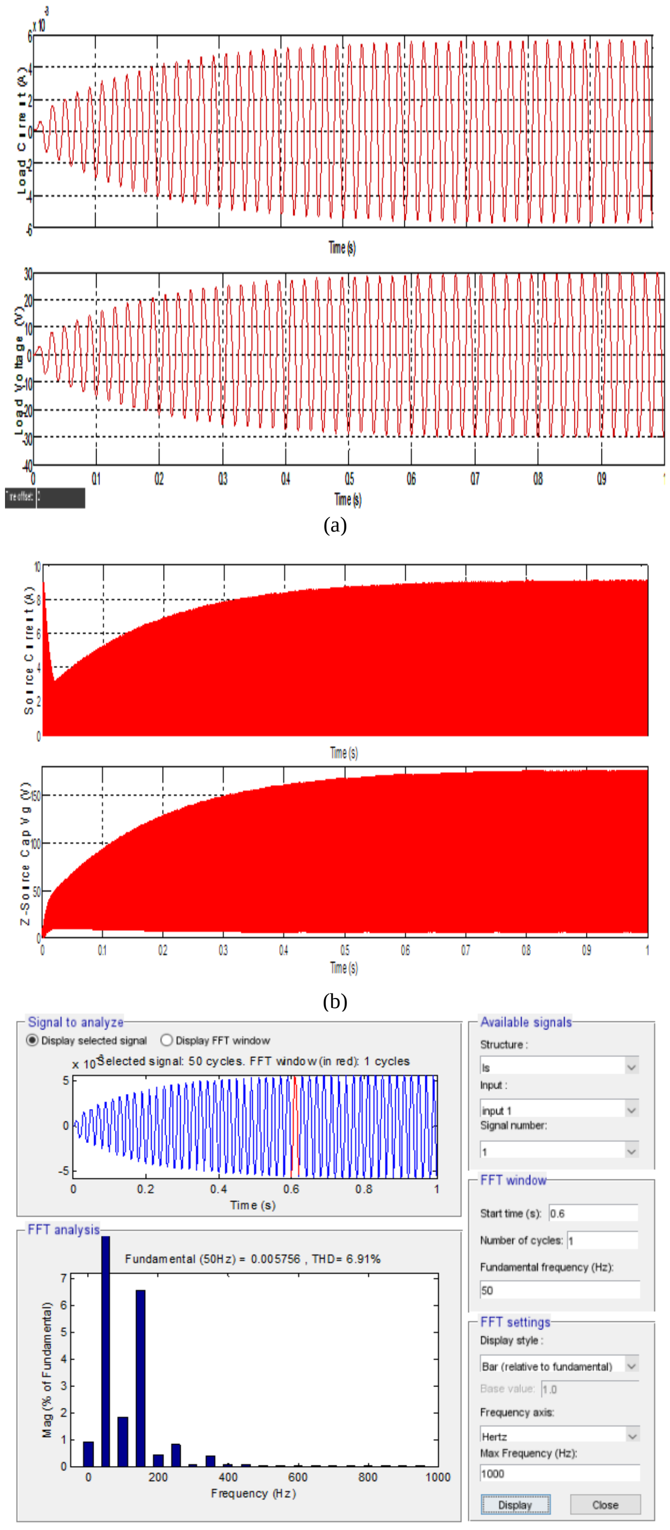
Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

(c)

Figure 6. Various simulation outcomes for Z-Source Inverter for Photovoltaic energy conversion system for R load
(a) Output voltage and current waveform (b) Source current and Z-Source Capacitor voltage (c) THD analysis with FFT method for R load



(a)

(b)

Signal to analyze

● Display selected signal ○ Display FFT window

Selected signal: 50 cycles. FFT window (in red): 1 cycles

FFT analysis

Fundamental (50Hz) = 0.005756 , THD= 6.91%

Available signals

Structure : Is

Input : input 1

Signal number: 1

FFT window

Start time (s): 0.6

Number of cycles: 1

Fundamental frequency (Hz): 50

FFT settings

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

(c)

Figure 7. Various simulation outcomes of Z-Source Inverter for Photovoltaic energy conversion system for R-L load
(a) Output voltage and current waveform (b) Source current and Z-Source Capacitor voltage (c) THD analysis with FFT method for R-L load

B. Quasi-Z-Source Inverter for Photovoltaic energy conversion system

The Z-Source Inverter for Photovoltaic energy conversion system with R and R-L Load is described with the following circuit diagram.

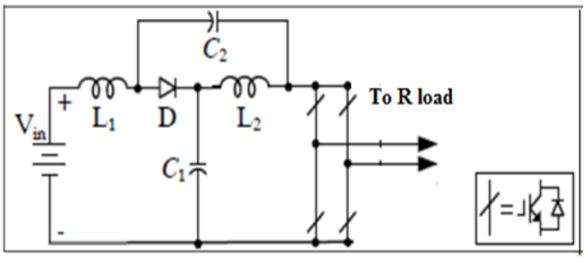


Figure 8a. Circuit Diagram of Quasi-Z-Source Inverter with R load

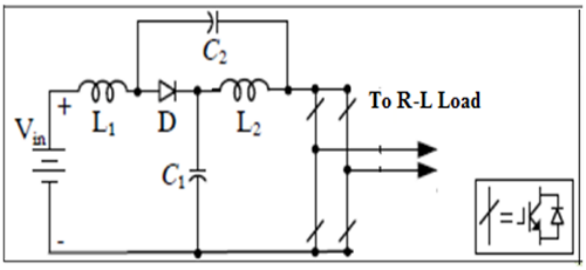


Figure 8b Circuit Diagram of Quasi-Z-Source Inverter with R-L load

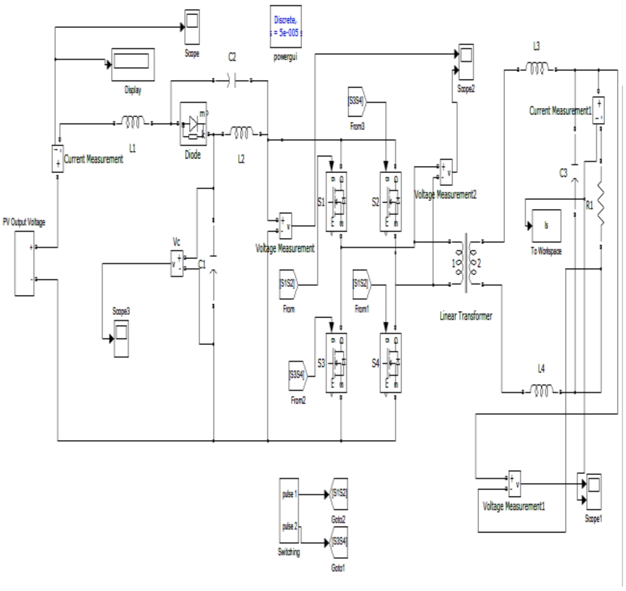
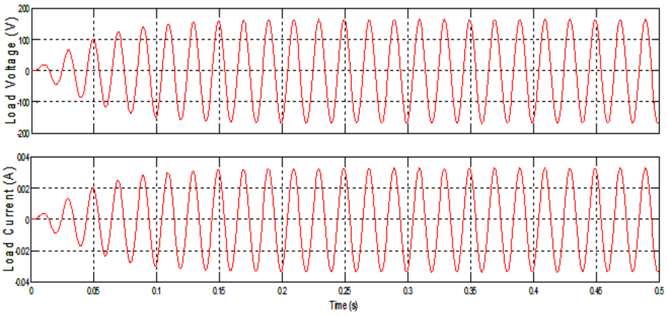
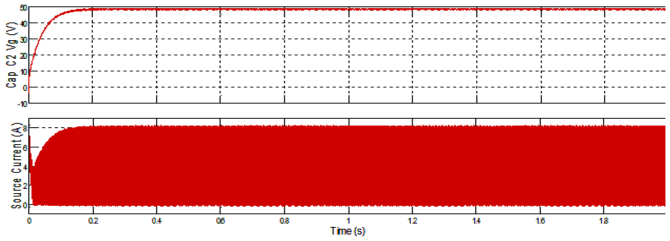


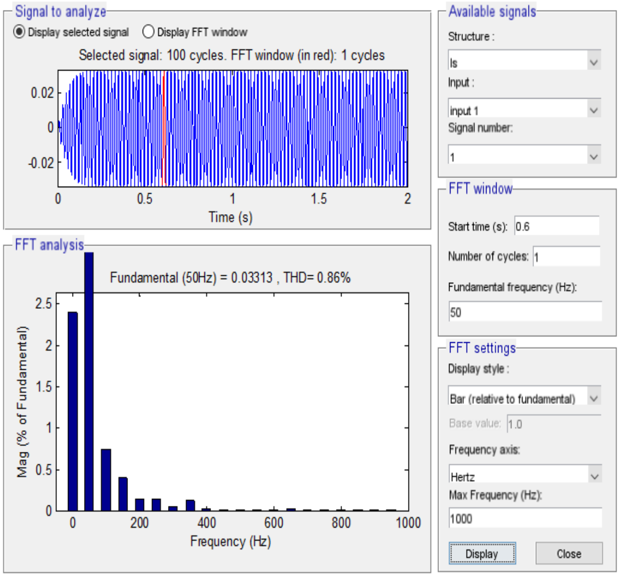
Figure 9. SIMULINK model of Quasi-Z-Source Inverter for Photovoltaic energy conversion system



(a)



(b)



● Display selected signal ○ Display FFT window

Selected signal: 100 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 0.03313 , THD= 0.86%

Structure : Is

Input : input 1

Signal number: 1

Start time (s): 0.6

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

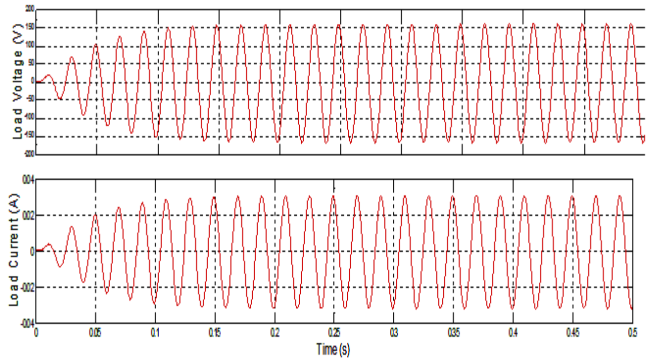
Base value: 1.0

Frequency axis: Hertz

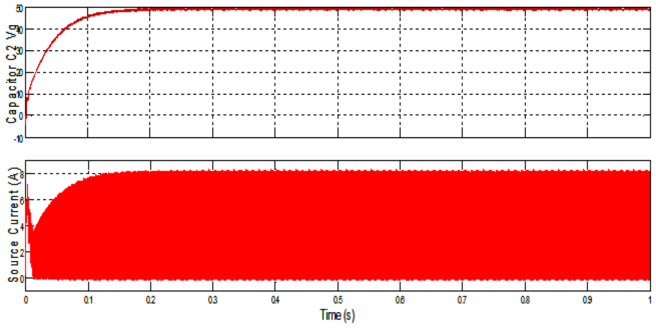
Max Frequency (Hz): 1000

(c)

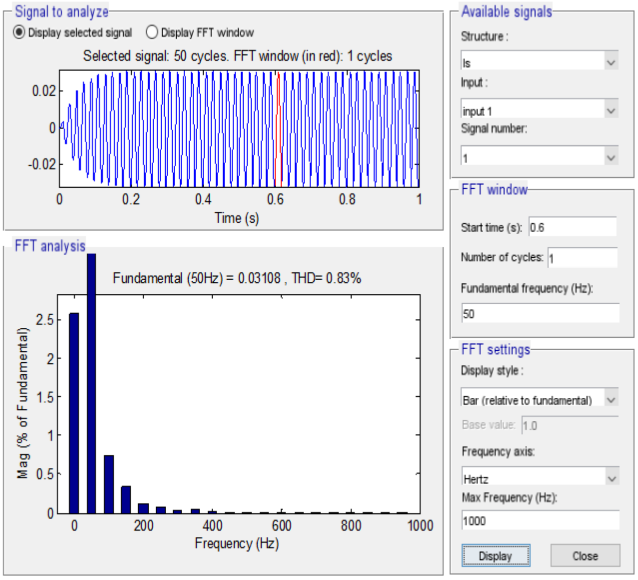
Figure 10. Various simulation outcomes of QZSI for Photovoltaic energy conversion system for R load
(a) Output voltage and current waveform (b) Quasi-Z-network capacitor (C_2) Voltage and Source Current (c) THD analysis with FFT method for R load



(a)



.(b)



● Display selected signal ○ Display FFT window

Selected signal: 50 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 0.03108 , THD= 0.83%

Structure : Is

Input : input 1

Signal number: 1

Start time (s): 0.6

Number of cycles: 1

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 1000

(c)

Figure 11. Various simulation outcomes of QZSI for Photovoltaic energy conversion system for R-L load
(a) Output voltage and current waveform (b) Quasi-Z-network capacitor (C_2) Voltage and Source Current (c) THD analysis with FFT method for R-L load

C. *Performance comparison of various topology*

Table 2 Comparison table for both ZSI and QZSI system with resistive loading

S.No.	Output parameter	Z-Source inverter	Quasi-Z-Source inverter
1	Output Voltage	20 V (rms)	115 V (rms)
2	Output Current	4 mA(rms)	0.032 A (rms)
3	THD	9.21%	0.86%
4	Impdence-source capacitor vg	177	49 V
5	Source current	9 A	8 A

Following comments can be given from the **Table 2:**

- QZSI has high boosting ability than ZSI.
- QZSI has higher output current.
- THD is excellent in QZSI.
- Less Voltage Stress on Impedance-Source capacitor in QZSI.
- Less Source current hence less losses in switching devices in QZSI.

Table 3 Comparison table for both ZSI and QZSI system with R-L loading

S.No.	Output parameter	Z-Source inverter	Quasi-Z-Source inverter
1	Output Voltage	21.2 V (rms)	113 V (rms)
2	Output Current	3.7 mA(rms)	0.021 A (rms)
3	THD	6.91%	0.83%
4	Impdence-source capacitor vg	178	49 V
5	Source current	8.5 A	8.2 A

Following comments can be given from the **Table 3:**

- QZSI has high boosting ability than ZSI.
- QZSI has higher output current.
- THD is excellent in QZSI.
- Less Voltage Stress on Impedance-Source capacitor in QZSI.
- Less Source current hence less losses in switching devices in QZSI.

VI. CONCLUSION

This paper presents a Quasi-Z-source inverter for Photovoltaic energy conversion system, 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.

With the help of **Table 2** and **Table 3** we can conclude that Quasi-Z-Source Inverter based topology for photovoltaic energy conversion system has following advantageous conclusion remarks;

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- Boosting ability of QZSI is high for the same modulation index and circuit component as compared to ZSI based system. Since it boosts input PV voltage 12V to 115 V in case of R load which results very good feature of this QZSI topology.
- Total Harmonics distortion is very low 0.86% & 0.83% for R and R-L loading simultaneously for QZSI system, given in comparison **Table 2** and **Table 3** which is under the acceptable limit of THD according to IEEE standards. This is an excellent merit over the basic ZSI topology. It is universally demanded that supply voltage and currents should be of pure sinusoidal in modern power quality concepts.
- The impedance source capacitor voltage stress is very low (49V) as compared to the ZSI topology, this causes increase of capacitor size and rating. Higher the value of voltage stress higher will be the size and rating of capacitor.
- Source current drawn by the QZSI circuit is less than ZSI for R and R-L loading simultaneously, given in comparison **Table 2** and **Table 3** that causes less switching losses and lower ratings of components.

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