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Quasi-z-source inverter for photovoltaic power generation systems

Pravin P. Kalubarme
ME EPS Student/MSS's CET/Jalna/ India
* *pravinpkalubarme@gmail.com*
Prof. Santhosh Kompelli
Assistant Professor and Head of Electrical Engg Department/ MSS's CET/Jalna/India

Abstract
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. A prototype which provides three phase 50-Hz, 230Vrms ac has been built in laboratory. It is demonstrated from the theoretical analysis and MATLAB/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.

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.
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.
The new Z-Source Inverter (ZSI) advantageously utilizes the shoot through state to boost the dc bus voltage by gating on both upper and lower switches of a phase leg and produce a desired output voltage that is greater than the available dc bus voltage. In addition the reliability of the inverter is greatly improved because the shoot-through due to misgating can no longer destroy the circuit. Thus it provides a low-cost, reliable, and high efficiency single stage structure for buck and boost power conversion.
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 possesses continuous input current, reduced source stress, and lower component ratings when compared to the traditional ZSI.

Inverter

Inverter is a power electronic circuit that converts DC power to AC power of desired magnitude and frequency. The inverters find their applications in modern AC motor and uninterruptible power supplies.

Traditional Source Inverters

Traditional Source Inverters are Voltage Source Inverter and Current Source Inverter. The input of Voltage Source Inverter is a stiff DC voltage supply, which can be a battery or a controlled rectifier. Both single phase and three phase Voltage Source Inverters are used in industries. The switching device can be a conventional MOSFET, Thyristor, IGBT or a Power Transistor.

Voltage Source Inverter is the one in which the DC source has small or negligible impedance. In other words a Voltage Source Inverter has stiff DC source voltage at its input terminals. A Current-Fed Inverter or Current Source Inverter is fed with adjustable DC current source. In Current Source Inverter output current waves are not affected by the load.

Z-Source Inverter

It employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, load, or another converter, for providing unique features that cannot be observed in the traditional Voltage and Current source converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the above-mentioned conceptual and theoretical barriers and limitations of the traditional V-source converter and I-source converter and provides a novel power conversion concept.

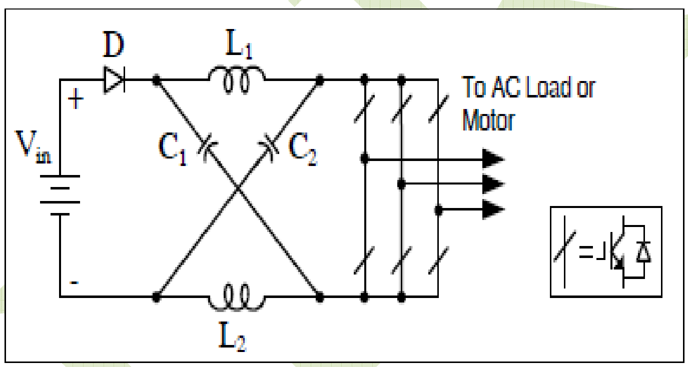

Fig. 2.2 Basic Circuit of Z-Source Inverter

In above fig.2.2, a two-port network that consists of a split-inductor L_1 and L_2 and capacitors $C_1$and C_2 connected in X shape is employed to provide an impedance source (Z-source) coupling the converter (or inverter) to the dc source, load, or another converter .The dc source/or load can be either a voltage or a current source/or load. Therefore, the dc source can be a battery, diode, rectifier, thyristor converter, fuel cell, an inductor, a capacitor, or a combination of those. Switches used in the converter can be a combination of switching devices and diodes such as the anti parallel combination, the series combination.

Quasi-Z-Source Inverter

The Quasi-Z-Source inverter circuit differs from that of conventional Z Source Inverter in LC impedance network interface between the source and inverter. Quasi-Z-source inverter acquires all the advantages of traditional Z-Source Inverter. Fig. 2.3 shows the basic topology of Quasi Z-source inverter. The Quasi Z-Source inverter extends several advantages over Z-Source inverter such as continuous input current, reduced component rating, and enhanced reliability. These advantages make the Quasi Z-source inverter suitable for power conditioning in renewable energy system. 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 Inverter (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 as shown in below Fig.2.3

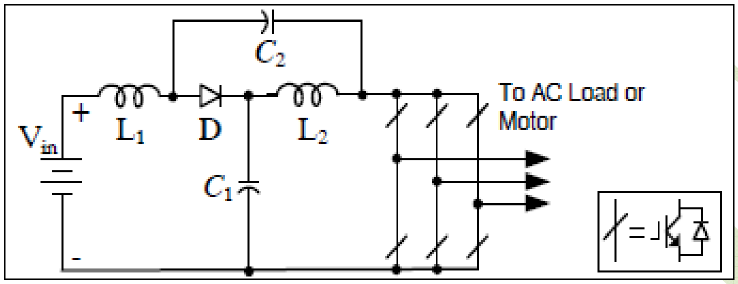

Fig 2.3 Basic Circuit of quasi-Z-Source Inverter

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.

Block diagram of qZSI

Output of PV Array

The PV Array generates the DC voltage at its output side. This DC voltage is used as input to the quasi-Z-Source network.

Quasi-Z-Source Network

Quasi-Z-Source network is derived from the traditional Z-Source network. 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 qZSI has the unique advantages of lower component ratings and constant dc current from the source.

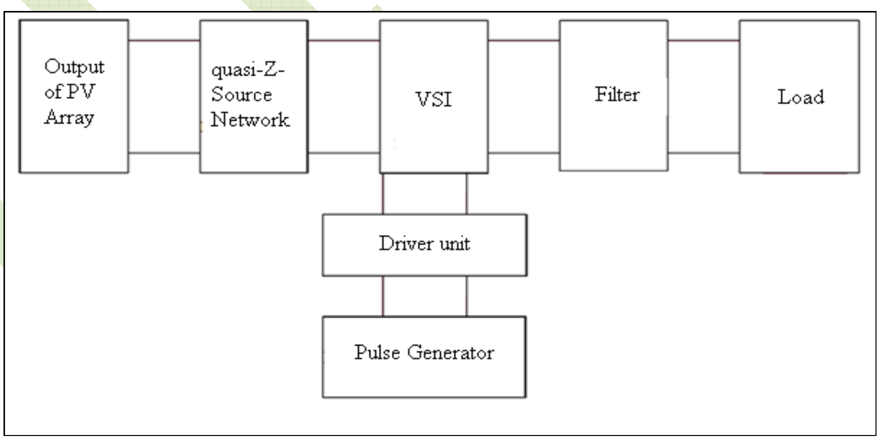

Fig 3.1 General Block Diagram of Quasi-Z-Source System

Voltage Source Inverter

Voltage Source Inverter is the one in which the DC source has small or negligible impedance. In other words a Voltage Source Inverter has stiff DC source voltage at its input terminals. A large capacitor is connected at the input terminals tends to make the input DC voltage constant. This capacitor also suppresses the harmonics fed back to the source. The Voltage Source Inverter is widely used.

Filters

It consists of a LC circuit to remove the ripple components raised during DC to AC conversion.

Pulse Generator and Driver Unit

To turn on the MOSFET it is necessary to inject the gate pulses to trigger on. These triggering pulses are generated by the pulse generator. These pulses are fed to each MOSFET which is to be turned on. In other words the driver unit directs the gate pulse to required MOSFET.

Circuit analysis

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 Fig.4.1 and Fig.4.2. 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, thequasi- Z-source network boosts the dc-link voltage. The major differences between the ZSI and qZSI are the qZSI draws a continuous constant dc current from the source.

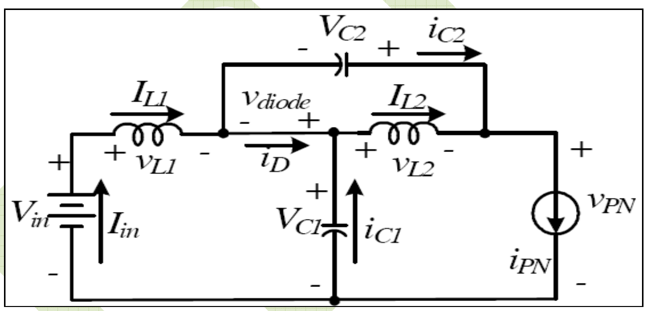

Fig. 4.1 Equivalent Circuit of the qZSI in Non Shoot-through States

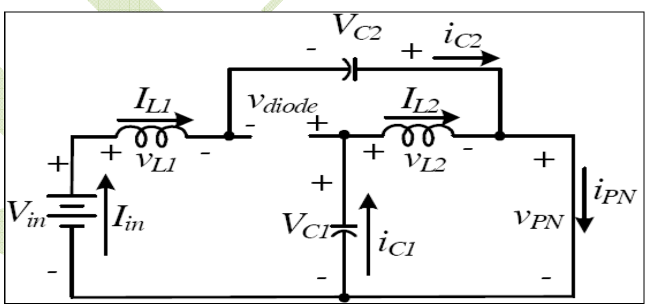

Fig. 4.2 Equivalent Circuit of the qZSI in Shoot-Through States

All the voltages as well as the currents are defined in Fig.4.1 and Fig.4.2 and the polarities are shown with arrows. Assuming that during one switching cycle T, the interval of the shoot through state is T_0; the interval of non-shoot-through states is T_1; thus one has T= T_0+$T_1$and the shoot-through duty ratio, D= T_0/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

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

Fig.3.7.which is a representation of the system during the interval of the shoot-through statesT_0, one can get;

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

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

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

$V_{L1}=\bar{v}_{L1}=\frac{T_0(V_{C2}+V_{in})+T_1(V_{in}-V_{C1})}{T}=0 \qquad V_{L2}=\bar{V}_{L2}=\frac{(V_{C1})T_0+(-V_{C2})T_1}{T}=0$

Thus,

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

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

$\bar{V}_{PN}=V_{C1}+V_{C2}=\frac{T}{T_1-T_0}V_{in}=\frac{1}{1-2\frac{T_0}{T}}V_{in}=BV_{in}$ (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.

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

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

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

In summary, the voltage and current stress of the qZSI are shown in Table 3.1. The stress on the ZSI is shown as well for comparison, where

(1) M is the modulation index; $\hat{v}_{\ln}$ is the ac peak phase voltage; P is the system power rating.

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

(3) B=$\frac{T}{T_1-T_0}$ thus m+n=B, 1<m<B

From Table 4.1. 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 4.1 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_2in 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.

QZSI Design for PV Power Generation System

Inductor and Capacitor Selection

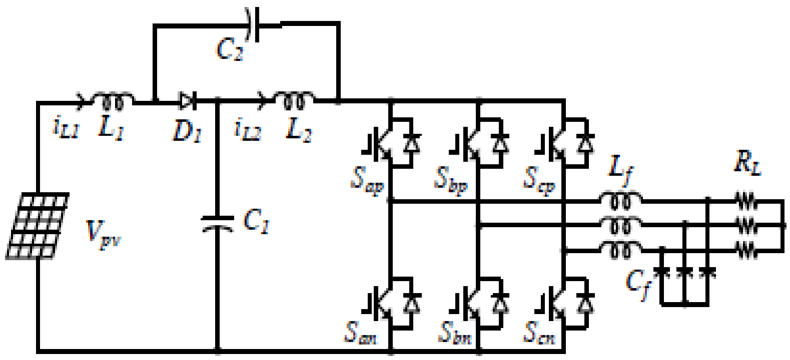

Fig.4.1 qZSI in the PV Power Generation System

Fig.4.1. shows the proposed qZSI in the PV power generation system. It connects the PV arrays and outputs three phase 50 Hz, 230 V_{rms} AC to resistive loads. A three-phase LC Filter connected in Y is set right after the inverter bridge to get 50-Hz sinusoidal AC outputs. In the proposed PV power generation system, the frequency of the carrier *f c* is 10 kHz, and the shoot-though frequency *f s* as seen by the qZSI network is doubled to 20 kHz. 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

$$T_{0\_max}=\frac{2-\sqrt{3}M_{min}}{f_s}=24\mu s \tag{9}$$

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, T_0, 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

$$L_1=L_2=\frac{V_L \Delta T}{\Delta i}=\frac{mV_{in}}{I_{L\ max} r_{c\%}}\frac{1}{2}T_{0\_max}=356\mu H \tag{10}$$

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

$$C_1=C_2=\frac{I_C \Delta T}{\Delta(V_{C1}+V_{C2})}=2\frac{I_L}{BVI_{in} r_{v\%}}\frac{1}{2}T_{0\_max}=310\ mF \tag{11}$$

Results

Case- Output waveforms at Boost Factor, B=1

➢ **As per the theoretical calculation**

DC voltage, V_{in}=400 V

Output AC voltage (Phase voltage) V_{ac}=0.935*1*400/2=187V

Output AC voltage (Line voltage) V_{ac}=187*1.73=324 V

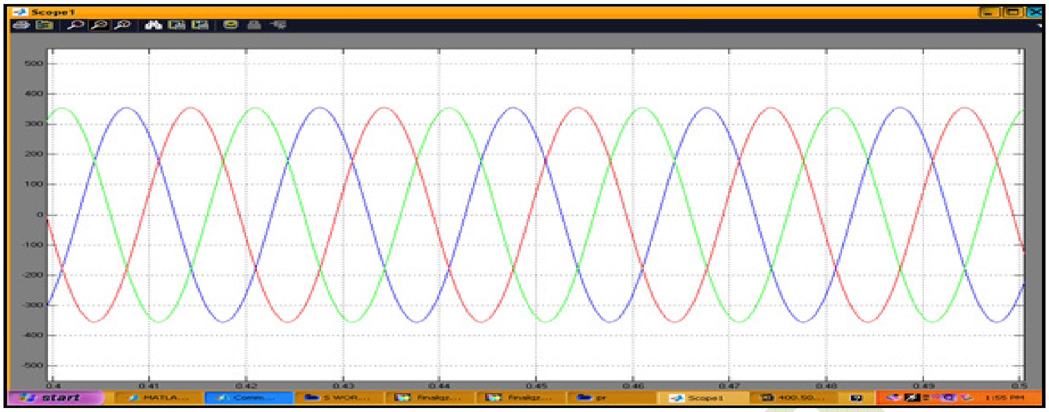

Fig.5.1 Simulation results for Buck conversion mode(B=1)

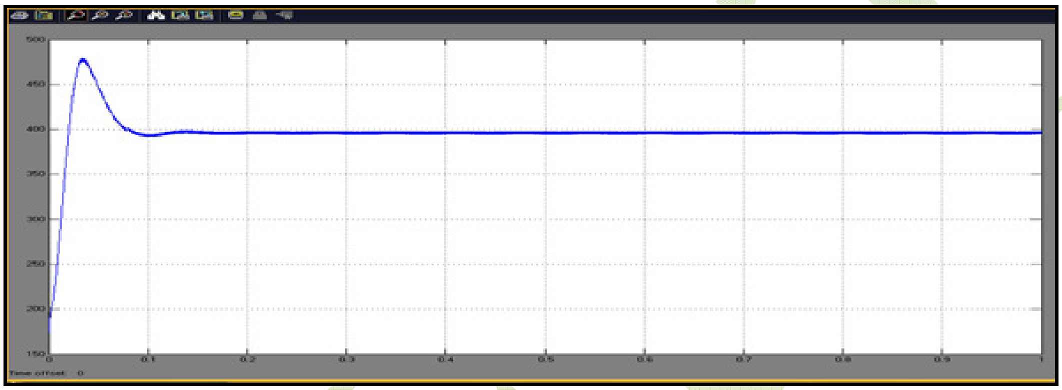

Fig.5.2 Simulation result of Voltage across capacitor C1

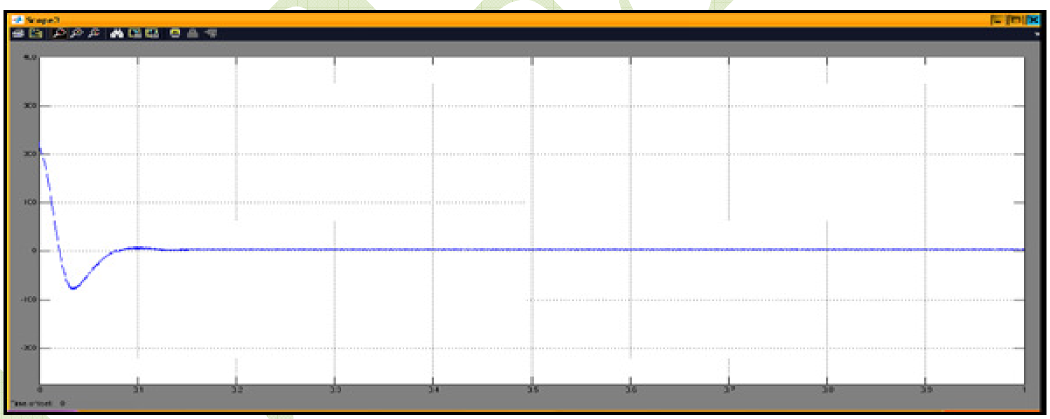

Fig.5.3 Simulation result of Voltage across capacitor C2

Comment: By simulating the circuit 4.1 using MATLAB/ SIMULINK at modulation index M=0.85 and boost factor B=1. We got the output voltage 355 V. The magnitude of the output voltage by theoretical calculation is 324V which is nearly equal to simulation results. As input voltage of 400 V is bucked to 355V so this is Buck Conversion Mode.

Conclusion

This project has presented quasi-Z-Source Inverter with a new topology, 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 project. Simulation results show that with a voltage range of 1:2 at the PV input (from 200V to 400 V), the qZSI can provide three phase 50Hz, 230 V_{rms} ac voltage, which verifies the theoretical analysis.

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