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# Three Stage Cascaded Quasi-Z-Source Inverter System for Renewable Energy Applications

KEYWORDS: Quasi Z-source inverter, cascaded, shoot-through, photovoltaic

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**ABSTRACT** *This paper is devoted to a new topology derived from traditional ZSI called cascaded Quasi Z-source inverter (qZSI) for a single phase photovoltaic (PV) system. The cascaded is derived by adding one diode, one inductance, two capacitances to qZSI. Due to the cascaded structure and qZSI topology, the proposed system inherits all the advantage of impedance inverter which can realize buck/boost inversion and power conditioning in a single stage with improved reliability, lower component rating constant dc current from source and good power quality. In addition the cascaded solution reduces the shoot through duty cycle by 25% at the same voltage boost factor. Theoretical analysis of three stage qZSI in shoot through and non-shoot through operating modes are described. Simulation results are presented to validate the proposed system.*

## I. INTRODUCTION

The exhaustion of fossil fuel and its influence to the environment are getting serious day by day and the use of renewable-energy generating system is drawing more and more attention. As a renewable-energy source, photovoltaic (PV) energy has achieved global attention and grid-connected PV system has become one of the major uses of solar energy [1]. The worldwide-installed PV power capacity shows nearly an exponential increase due to improvements in solar energy technology and also decreasing cost. However, there are still two primary factors limiting the widespread application of PV power systems. The first is the cost of the solar module and their power conditioning system; the second is the variability of the output 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 [2]. To overcome this limitation, the conventional two-stage inverter topology applies a boost dc/dc converter to minimize the required KVA rating of the inverter, and boost the wide range input voltage to a constant desired output value. This leads to a higher component count low efficiency which opposes the goal of cost reduction [3].

As an alternative, the single stage Z-source inverter is proposed in [4] where it is explicitly shown that the Z- source inverter gains its voltage tuning flexibility by introducing a unique LC impedance network between its input source and inverter circuitry. Besides flexible gain tuning , the inserted impedance network is stated to have the advantage of protecting the inverter phases from short circuit damages even with no dead time delay inserted [5][6]. In addition power loss is reduced due to low number of switching devices. Therefore the single-stage inverter is an attractive solution for photovoltaic power generation systems due to its compactness, low cost, and reliability [7]. It is used for connecting PV to a single phase grid in [8], it is employed as an intermediary stage between PV and three phase grid in [9] and in [10] it is implemented for standalone operation of PV.

Different topologies of cascaded qZSIs have been recently proposed [11-15].In [16], the authors proposed a scalable cascaded Z-source inverter (ZSI) configuration for MIC application where the system reliability is highly enhanced compared with the cascaded H-bridge inverter, because the ZSI is immune to the shoot-through faults. Four new topologies have been derived from the original ZSI. Recently proposed quasi-Z-source inverters (qZSIs) have some new attractive advantages more suitable for application in PV systems [17]-[20]. This will make the PV system simpler and will reduce cost, because the new quasi-Z-source topology has some privileges compared to conventional Z-source inverter: i) Power ratings of required components is reduced ii) draws a constant current from the PV panel, thus there is no need for extra filtering capacitors; iii) reduces source stress. In addition to the above advantages, for the same component ratings and voltage and current stresses, the qZSI with the proposed cascaded qZS-network will ensure a higher voltage boost factor than with traditional the cascaded qZSI network. This paper deals with a detailed analysis of cascaded multi stage qZSI fed induction motor for photovoltaic system.

## II. QUASI Z-SOURCE INVERTER

Figures. 1 and 2 show the traditional voltage fed ZSI and voltage fed qZSI, respectively. the qZSI is an integrated boost-buck converter with a single power processing stage. If necessary, qZSI can boost the input voltage by introducing a special shoot-through switching state, which is the simultaneous conduction of both switches of the same phase leg of the inverter. This switching state is forbidden for the traditional voltage source inverters (VSI) because it causes the short circuit of the dc link capacitors 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.

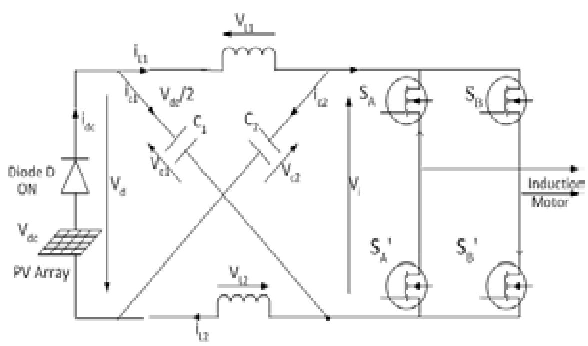


**Figure. 1. Z-source inverter circuit**

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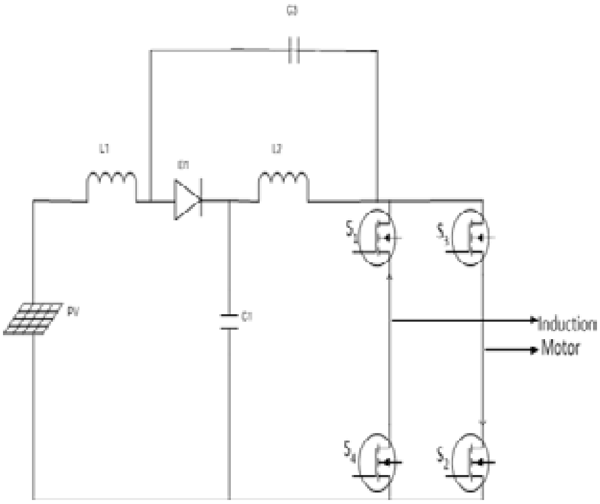



Figure. 2. Quasi-Z--source inverter circuit

## III. MULTI STAGE CASCADED QUASI Z -SOURCE INVERTER

The cascaded (two-stage) qZS-network is derived by the adding of one diode (D2), one inductor (L3), and two capacitors (C3 and C4) to the traditional qZSI, as shown in Figure. 3. The cascaded three stage qZS-network is derived by the adding of two diodes, two inductors and three capacitors to the traditional qZSI, as shown in Figure. 4. To regulate the varying input voltage, the cascaded qZSI is operated in two modes: shoot-through and non shoot-through modes. When the output voltage of solar reaches maximum ,the inverter operates in non shoot- through mode and hence only buck operation is performed. On the other hand when the output voltage of solar is reduced below a predefined level, qZSI enters into a non shoot-through state performing boost/buck operation depends on the modulation index and shoot through duty cycle. The impedance network which is connected in between the input and the inverter bridge also protects the circuit from shoot through faults thereby increasing the reliability of the system. In addition the cascaded qZS- network enables the duty cycle of the shoot-

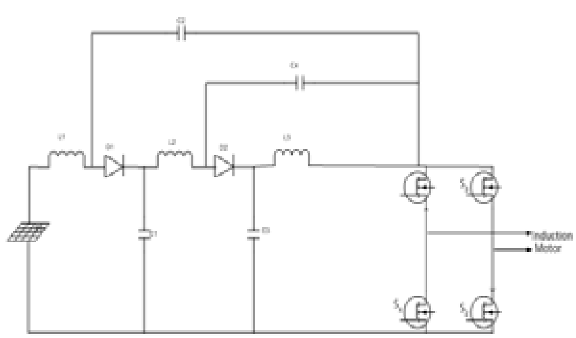



Figure. 3. Two Stage Cascaded Quasi-Z--source inverter circuit

through state be sufficiently decreased at the same voltage boost factor and component stresses than those of the traditional qZSI. Due to the decreased shoot-through duty cycle, the values of the inductors and capacitors of the qZS-network could also be decreased.

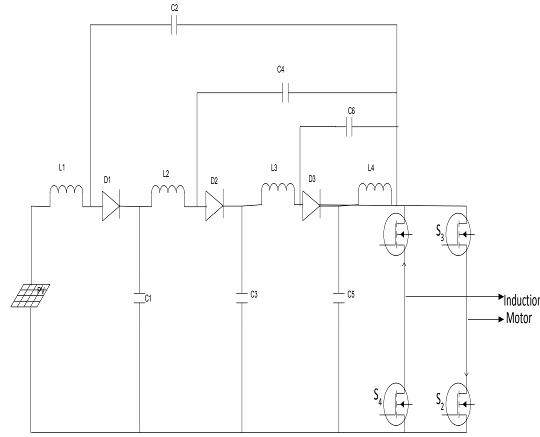
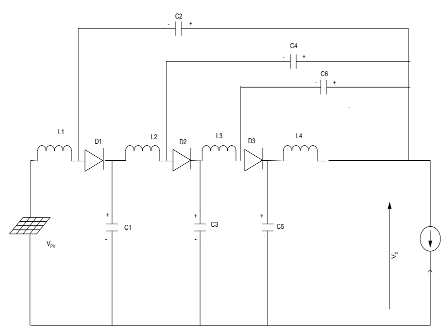


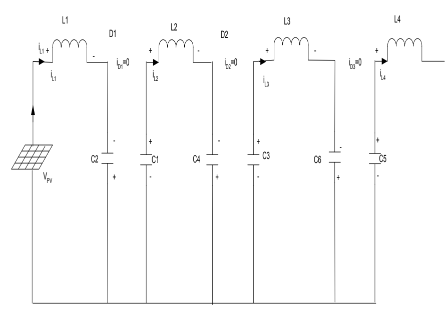

Figure. 4. Three Stage Cascaded Quasi-Z--source inverter circuit

## IV. CIRCUIT ANALYSIS OF THE CASCADED THREE STAGE QUASI -SOURCE INVERTER

When the inverter is in nonshoot-through active or null state, the resulting equivalent circuit is shown in Figure. 5a, with diodes conducting, and the inverter bridge and its load replaced by a current source, whose value is nonzero for active state and zero for null state.




(a)




(b)

Figure. 5 Equivalent circuits of three stage cascaded qZSI (a )non shoot-through (b) shoot-through states

The inductor voltages for the active state can be given as

$$V_{L1} = V_{P} - V_{C1} \quad (1)$$

$$V_{L2} = V_{C1} - V_{C3} = V_{C4} - V_{C2} \quad (2)$$

$$V_{L3} = V_{C3} - V_{c5} = V_{C6} - V_{C4} \quad (3)$$

$$V_{L4} = -V_{C6} \quad (4)$$

Assuming now that the inverter enters to its shoot-through state, the redrawn equivalent circuit is shown in Figure. 5b where the diodes are reverse biased, and the inverter bridge is short through. Using this equivalent circuit the second set of state equation is derived as:

$$V_{L1} = V_{PV} + V_{C2} \tag{5}$$

$$V_{L2} = V_{C4} + V_{C1} \tag{6}$$

$$V_{L3} = V_{C6} + V_{C3} \tag{7}$$

$$V_{L4} = V_{C5} \tag{8}$$

Averaging the inductor voltage over a switching period and equating it to zero, give rise to set of equations in terms of input voltage $V_{PV}$.

$$V_{l1} = \int_{t}^{t+1} V_{L1} dt = 0$$

$$V_{l2} = \int_{t}^{t+1} V_{L2} dt = 0$$

$$V_{l3} = \int_{t}^{t+1} V_{L3} dt = 0$$

$$V_{l4} = \int_{t}^{t+1} V_{L4} dt = 0 \tag{9}$$

From equations (1)-(9) we obtain

$$\begin{cases} V_{L1} = D(V_{C2} + V_{PV}) + (1-D)(V_{PV} - V_{C1}) = 0 \\ V_{L2} = D(V_{C4} + V_{C1}) + (1-D)(V_{C1} - V_{C3}) = 0 \\ V_{L3} = D(V_{C6} + V_{C3}) + (1-D)(V_{C3} - V_{C5}) = 0 \\ V_{L4} = DV_{C5} - (1-D)V_{C6} = 0 \end{cases} \tag{10}$$

Where D=T0/T is the shoot through duty ratio and capacitor voltages are obtained by solving equation (10)

A. Peak DC link voltage during non-shoot through

$$\hat{V}_i = \frac{V_{PV}}{1 - 4\frac{T_0}{T}} = BV_{PV} \tag{11}$$

B..Shoot through duty ratio:

For a given boost factor B, shoot through duty cycle can be calculated as

$$D = \frac{1 - \frac{1}{B}}{4} \tag{12}$$

It is clear from the analysis that the cascaded three stage qZSI system characterizes 25% reduction in the shoot-through duty ratio for the the same voltage boost factor than their counterparts thereby improving the performance of the inverter.

## V. SIMULATION RESULTS

To validate the accuracy of given analytical relationship of the proposed system, a MATLAB Simulink model of Solar Cell Powered cascaded three stage quasi Z-Source inverter fed induction motor is presented as in Figure. 5. The output of single phase inverter is applied to the induction motor. The induction motor is represented by its equivalent circuit The simulation system is set up with the following parameters: L1=L2=L3=10mH;L4=100mH;C1=220µF;C2=10µF;C3=C5=5000µF; C4=C6=1µF; solar voltage $V_{PV}$=25V; switching frequency=10KHZ;and shoot through duty ratio $T_0$/T=0.12;boost factor=2.

Solar output voltage of 25V and DC link voltage of 50V is shown in Figure. 6. When the input voltage is low, the inverter operates in shoot-through mode with $T_0$/T=0.125.There is a significant reduction in shoot-through ratio and it is observed that due to three stage cascaded solution the shoot through ratio will never exceed one fourth of the switching period. The capacitor voltages are shown in Figures 7 and 8 respectively. The output volage and current waveforms for boost operation is shown in Figure. 9.The output current is sinusoidal, therefore it easily synchronizes with the grid voltage. When the input voltage is sufficiently large, then shoot-through is not required and hence the inverter operates in non shoot-through mode as traditional inverter as shown in Figure. 10. Output voltage, DC link voltage and output waveforms are shown in Figure 11 for an input voltage of VPV=40V .It is observed from Figure 12 that to achieve the same output in two stage cascaded, the shoot through required is $T_0$/T=0.2.Speed response of the system is shown in Figure 13.The rotor speed increases and settles down at 1500rpm.It is found from the Figure. 14 that the shoot-through ratio of single stage at same voltage boost factor is very high compared to three stage qZSI system. This is a favourable advantage for photovoltaic applications.

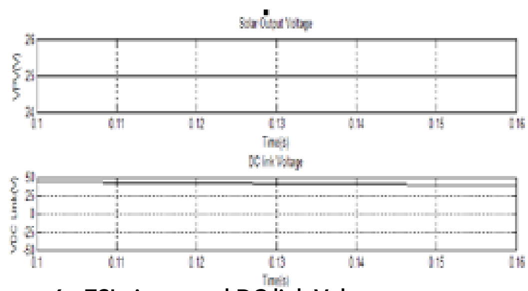



**Figure.6 qZSI input and DC link Voltage**

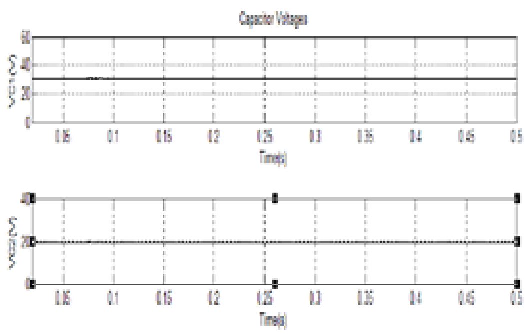



**Figure.7 Capacitor voltages($V_{C1}$&$V_{C2}$)**

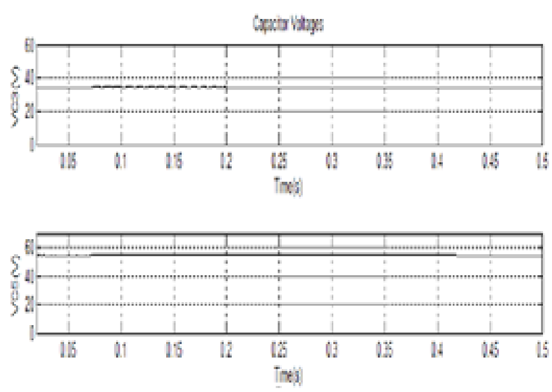



**Figure.8 Capacitor voltages($V_{C3}$&$V_{C5}$)**

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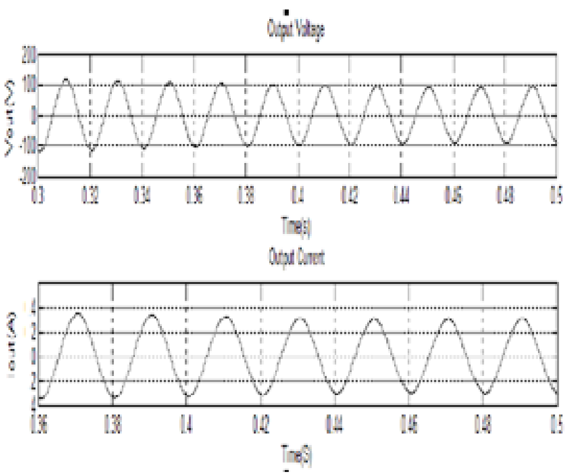


Figure. 9 Inverter output voltage and current waveforms: $V_{PV}$=25V; $T_0$/T=0.125

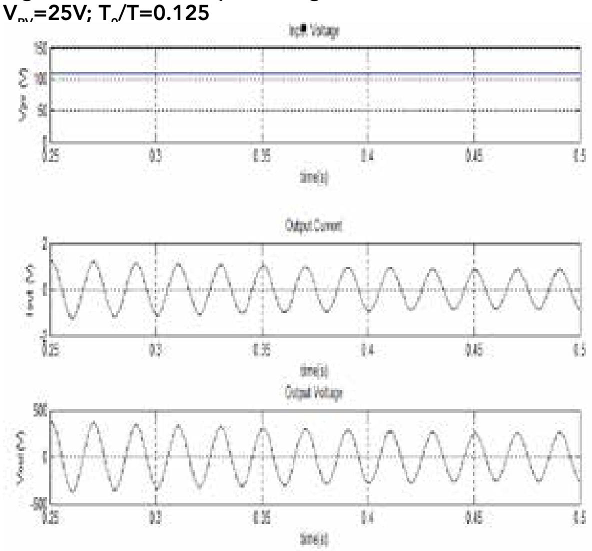


Figure. 10 Inverter output voltage and current waveforms: $V_{PV}$=110V; $T_0$/T=0

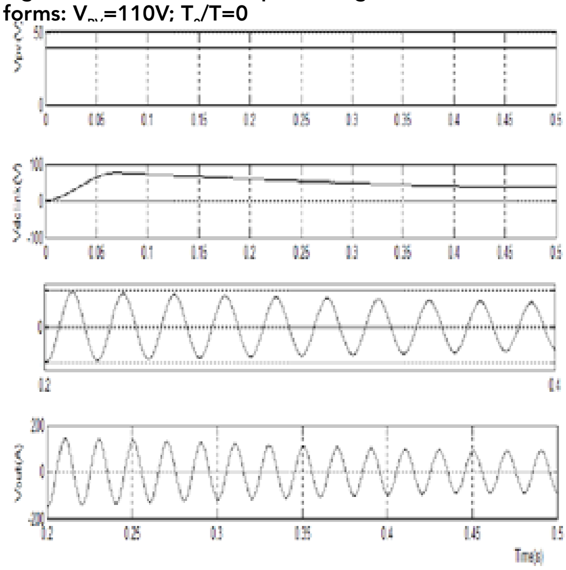

Figure. 11 Solar output voltage, DC link voltage, output current and voltage waveforms: $V_{PV}$=40V;To/T=0.125

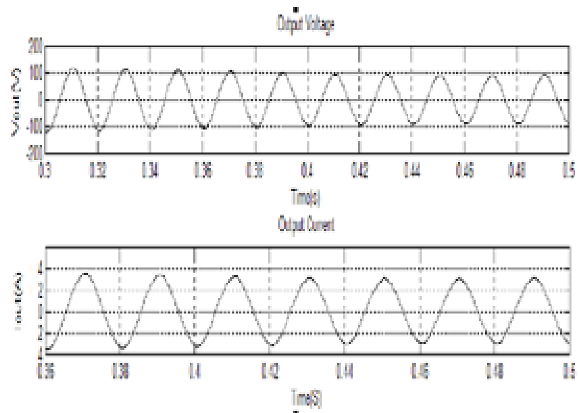


Figure 12 Inverter output voltage and current waveforms:$V_{PV}$=25V; $T_0$/T=0.2 in cascaded two stage qZSI

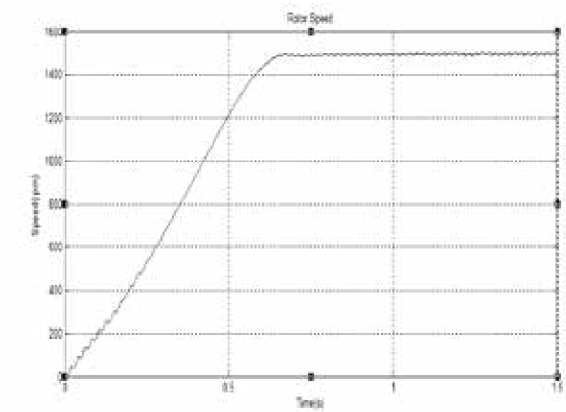


Figure. 13. Speed response of the system

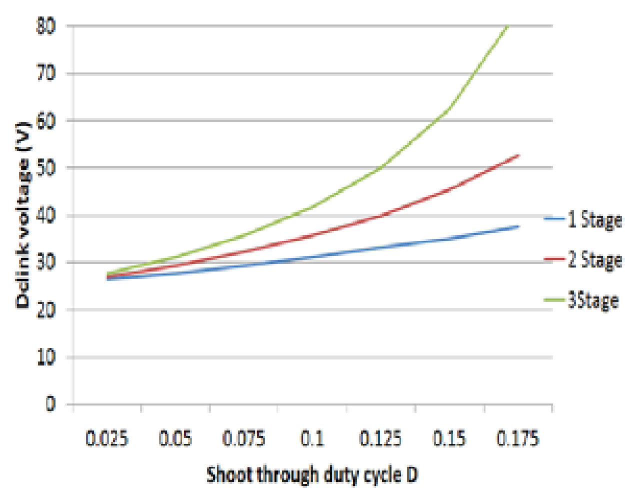


Figure. 14 Comparison of cascaded qZSI system

## VI. CONCLUSION

In this paper cascaded three stage qZSI system fed induction motor for photovoltaic application is presented. Detailed analysis reveals that the proposed system inherits all the advantages of traditional qZSI as continous input current, low inrush current, low component ratings , less source stress voltage and boost/buck operation in single stage In addition the cascaded structure reduces the shoot through duty ratio by over 25% at same voltage boost factor as traditional qZSI. The cascaded structure also enhances the reliability of the system through shoot-through capability of qZSI. It is seen that small ratings of passive components are adequate to compensate the unpredictable solar input; thereby efficiency mitigation of induction motor can be avoided. Operational analysis and mathematical calculations prove that cascaded structure is more suitable for photovoltaic applications. The disadvantage of the system is that the passive component counts and their summarized values will be increased. Analytical models are verified using Matlab Simulink and the results are presented. The simulation results are in line with the predictions.

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