A Five-Level Quasi Z-Source Based NPC Inverter for PV Applications

Chinmay Kumar Das
Dept. of Electrical Engineering
NIT Warangal
Warangal-506 004(T.S.), India
chinu92rocks@gmail.com

A. Kirubakaran, Senior Member IEEE
Dept. of Electrical Engineering
NIT Warangal
Warangal-506 004(T.S.), India
kiruba81@nitw.ac.in

V.T. Somasekhar
Dept. of Electrical Engineering
NIT Warangal
Warangal-506 004(T.S.), India
sekhar@nitw.ac.in

***Abstract*—Latterly, impedance source based multilevel inverters are becoming popular for emerging renewable power generations. This paper presents a Five-Level quasi Z-source (qZS) based neutral point clamped (NPC) for photovoltaic (PV) applications. This inverter circuit is formed by integrating a dual quasi Z-source with a T-type arm and a diode clamped arm. Compared to the existing impedance source based NPC type converters, the proposed topology has less number of switching devices and reduced voltage stress. The level shifted pulse width modulation (LS-PWM) with hybrid shoot-through technique is implemented to achieve high boost gain and reactive power capability. The performance of the proposed topology is examined through simulation results for input voltage changes and load changes.**

Keywords—Quasi Z-source, Five-Level Inverter, Neutral Point Clamped, Level Shifted PWM.

I. INTRODUCTION

Multilevel inverters (MLI) have attracted the researchers for decades for medium and high power applications. Many topologies [1] have been proposed both in three phase and single phase basis for DC/AC power conversion. The most common types of the MLIs are diode clamped MLI, flying capacitor based MLI and cascaded H-bridge MLI. MLI's are advantageous than any two-level voltage source inverters (VSI) on the basis of stepped voltage output, better THD, lesser filter requirement and low electromagnetic compatibility. However, it is always operated in buck mode and demands large dc-link voltage. In order to increase the output voltage, a boosting stage is necessitated between the source and the inverter [2]-[4]. The two-stage configurations became efficient for PV systems [4]-[5], they suffered from the problem of dead time control, bulky nature and the control complexity.

The above-stated problems were solved after the introduction of Z source inverter (ZSI) in 2003 [6]. This converter showed great potential for industrial drives and renewable energy sources. The major problem of shoot through was fixed through an impedance source which indeed was required for boosting of the input voltage. Investigation of ZSI inferred that it suffers from discontinuous input current. Therefore, quasi Z-source (qZS) network is proposed which reduced capacitor ratings and made the input current continuous [7]. Various MLI's have been proposed in recent years either Z source or quasi Z-source networks as front-end for single phase and three phase supply. Because these impedance sources based MLIs became easy solutions for emerging renewable power generations as they integrate both the benefits of impedance source and MLIs.

The ZSI offered boost and DC/AC conversion in the same topology but the limiting factor was it only give a three-level voltage i.e. 0 and $\pm V_{DC}$. Some topologies were proposed to eradicate this problem by integrating with existing multilevel inverter [8]-[12]. Integrating the advantage of NPC [8] was proposed which uses 2 impedance network as a front end to get five-level line voltages. In [9] an NPC based ZSI is proposed with a single DC source to give a similar output which reduced the component count to half the previous one. Wherein [10], [11] introduces the concept of partial and complete shoot through for a five-level NPC based ZSI. An alternative use of the LC network was proposed in [12] to form a T-source inverter (TSI) in order to have small leakage inductance. In [13] the combination of conventional Z-source with existing half bridge topology is proposed to increases the reliability of the system by controlling each dc source independently. However, owing to the issues of discontinuous input current in Z-source based MLIs, [14] and [15] proposes qZS based NPC type inverters for single-phase and three-phase supply respectively. The input current limitation was proposed in a configuration in [16] which reduced the stress across the capacitor. In [17] and [18] the composition of qZS based network with cascaded H-bridge was explored by integrating grid with PV. [17] Emphasizes on the complete 2ω ripple analysis of qZS based network and distributed MPPT of each cell but has a problem during partial shading of the PV module. [18] Eliminates the above problem by adding a battery to the existing configurations.

In most of the literature, it is shown that the integration of impedance source with MLIs with the grid-connected PV system. However, in recent years development of inverter topologies with reactive power capability is becoming popular for PV applications. Therefore, in this paper, a five-level quasi Z-source based NPC inverter is proposed. The proposed topology combines the advantage of NPC structure with T-type arm and diode clamped arm in order to capacitate the provision of reactive power capability and also enhance the boosting factor. Modified level-shifted carrier waveform with hybrid shoot-through control is presented. Finally, the performance of the proposed topology is verified through simulation results for input voltage changes and load changes.

This work has received funding from Science and Engineering Research Board (SERB) under the project EMR/2016/007811.

978-1-7281-0653-3/19/$31.00 ©2019 IEEE

II. Converter and Control

A. *Proposed Five-Level qZS-NPC Inverter*

Fig. 1 depicts a five-level quasi Z-source neutral point clamped inverter (qZS-NPC) for PV applications. The two qZS networks are connected in such a manner that the two internal capacitors form a zero point structure for the neutral point clamped topology. 8 power semiconductor switches and 2 clamping diodes are used in order to provide a 3-level output. The load is connected between the midpoint of the clamping diode which is connected to neutral point through S_1, S_2 and the four switches of the diode clamped arm. The output level of the proposed converter is 0, (V_{DC}/2), V_{DC} in both positive and negative half. V_{DC} is the total dc-link voltage of the converter which is the sum of voltages across C_1, C_2, C_3, and C_4. Level shifting carrier wave modulation was applied to the converter to get the five-level output. The switching states of all the switches are described in Table I for each output level. One of the features of the converter is its ability to provide reactive power. This feature is incorporated in the proposed converter with slight changes in switching states.

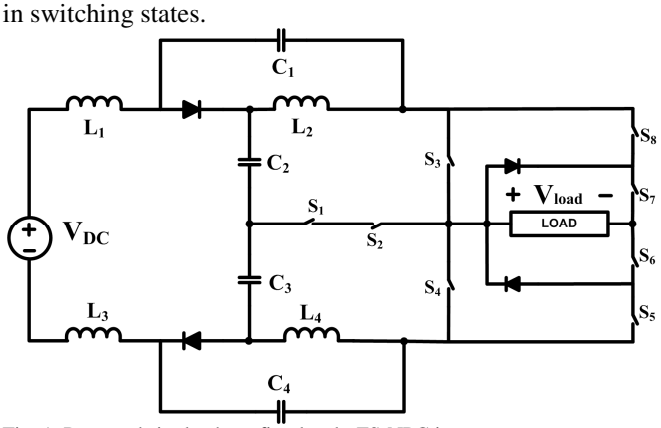

Fig. 1. Proposed single phase five-level qZS-NPC inverter.

TABLE I. Switching States

Output Levels	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	Switching States
V_{DC}	0	0	1	0	1	1	0	0	Active
V_{DC}/2	1	1	0	0	1	1	0	0	Active
0	1	1	0	0	0	1	1	0	Zero
-V_{DC}/2	1	1	0	0	0	0	1	1	Active
-V_{DC}	0	0	0	1	0	0	1	1	Active
0	0	1	1	0	0	0	0	0	Upper Shoot through
0	1	0	0	1	0	0	0	0	Lower Shoot through
0	0	0	1	1	0	0	0	0	Complete Shoot through

The working of the inverter contains 4 active states, 3 shoot through states and 1 zero state in order to boost the dc and obtain the level voltage. Fig. 2 illustrates the various stages of the working of the converter for unity power factor. The proposed topology is also capable to operate at leading and lagging power factor loads. The switching states are employed in such a way that whenever there is a lagging or leading load path will be provided for the energy stored in passive components can be released to source or freewheeled across itself.

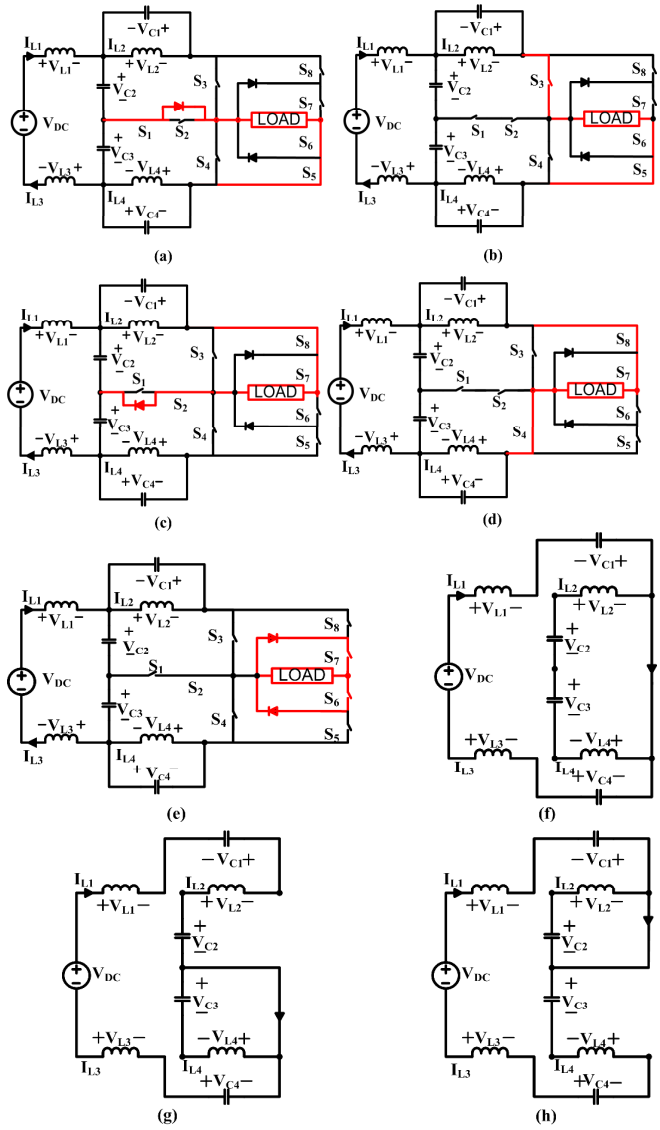

Fig. 2. Various modes of operation, (a)-(d) represents the active modes to get the level voltages, (e) represents the zero state, (f) complete shoot-through Mode, (g) Lower shoot-through mode and (h) Upper shoot-through mode.

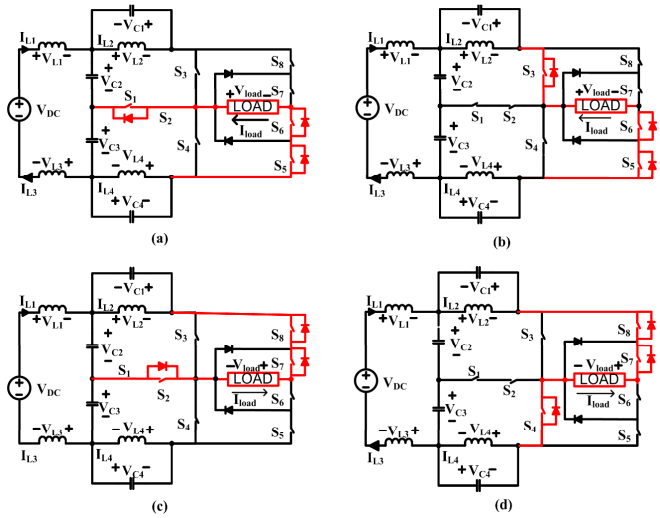

Fig. 3. (a) & (b) Working of the converter for positive output voltage and negative current, (c) & (d) Working of the converter for negative output voltage and positive current.

Fig. 3 describes the direction of current flow and corresponding output terminal voltage during the operation of proposed topology. It should be noted that current through the load from left to right is assumed to be in a positive direction and for positive voltage left side of load should be at higher potential.

Based on the active and shoot through stages of the converter following equations can be derived for its working. Equations (1)-(7) represent the active state whereas (8)-(13) represents shoot-through mode.

$$L_1\frac{di_{L1}}{dt}+L_3\frac{di_{L3}}{dt}=V_{in}-V_{C2}-V_{C3} \quad (1)$$

$$L_2\frac{di_{L2}}{dt}=-V_{C1} \quad (2)$$

$$L_4\frac{di_{L4}}{dt}=-V_{C4} \quad (3)$$

$$C_1\frac{dV_{C1}}{dt}=I_{L2}-I_{LOAD} \quad (4)$$

$$C_2\frac{dV_{C2}}{dt}=I_{L1}-I_{LOAD} \quad (5)$$

$$C_3\frac{dV_{C3}}{dt}=I_{L3}-I_{LOAD} \quad (6)$$

$$C_4\frac{dV_{C4}}{dt}=I_{L4}-I_{LOAD} \quad (7)$$

$$L_1\frac{di_{L1}}{dt}+L_3\frac{di_{L3}}{dt}=V_{in}+V_{C1}+V_{C4} \quad (8)$$

$$L_2\frac{di_{L2}}{dt}+L_4\frac{di_{L4}}{dt}=V_{C2}+V_{C3} \quad (9)$$

$$C_1\frac{dV_{C1}}{dt}=-I_{L1} \quad (10)$$

$$C_2\frac{dV_{C2}}{dt}=-I_{L2} \quad (11)$$

$$C_3\frac{dV_{C3}}{dt}=-I_{L4} \quad (12)$$

$$C_4\frac{dV_{C4}}{dt}=-I_{L3} \quad (13)$$

The boost factor (B) (14) and the output equation (15) of the converter remains the same as any qZSI [5], [6] where D is the shoot through duty cycle. Equations (16) & (17) represents the capacitor voltages.

$$B=\frac{1}{1-2D} \quad (14)$$

$$V_{out(RMS)}=\frac{MBV_{in}}{\sqrt{2}} \quad (15)$$

$$V_{C1}=V_{C4}=\frac{D}{1-2D}\frac{V_{in}}{2} \quad (16)$$

$$V_{C2}=V_{C3}=\frac{1-D}{1-2D}\frac{V_{in}}{2} \quad (17)$$

Based on the above given formulas and selecting the output voltage as 110 (RMS) volts, it can be found that D=0.28 and B=2.272.

B. Closed Loop Control Scheme

The main objective of the control scheme is to maintain the desired dc-link voltage. However, in these types of impedance source inverters, the dc-link voltage consists of active, zero and shoot through states which cause the dc-link varying from zero to peak value. The above-stated problem makes difficult to access the dc-link voltage [19] which can be solved by taking the capacitor voltage into account. The actual dc-link voltage is derived from sensing the capacitor voltage (V_{C2}) and by using the following expression $V_{DC}=V_{C2}/1-D$. This is compared with desired dc-link voltage and error is fed to the Proportional Integral (PI) regulator which gave the shoot through duty cycle as controlled output.

III. Modified Modulation Technique

Modulation is a key factor in working of any topologies. There are various kinds of modulation techniques presently available for multilevel inverters out of which these are broadly classified into 4 kinds: Level shift PWM techniques, Phase shift PWM techniques, Space Vector Modulation, and Hybrid modulation techniques. Fig. 4 gives the phase disposition level shifting PWM used for the proposed topology. Four high-frequency carrier waves and a sine reference wave utilized to develop the required switching logic in accordance with Table I. The logic for switches S_1-S_8 is given below was developed. The sine reference wave compared with carrier waves C1-C4 to give the respective pulsed output i.e. B, A, C and D. The waveform 'G' is just a 50Hz wave.

$$S_1=S_2=A\oplus B+C\oplus D\,,S_3=B,S_4=D\,,S_5=A\,,$$

$$S_6=G+\bar{C}G\,,S_7=\bar{A}G+\bar{G}\,,S_8=C \quad (18)$$

Shoot through insertion technique for proposed topology is a kind of hybrid technique. In this study, a simple boost shoot-through control scheme is used. During V_{DC} level S_3 and S_4 were shorted to obtain shoot through condition namely complete shoot through. During $+V_{DC}/2$ level S_1 and S_4 were shorted and S_2 and S_3 were shorted to obtain shoot through for the corresponding negative part namely lower shoot through and upper shoot through respectively. The equivalent circuit during the shoot through can be seen from Fig. 2.

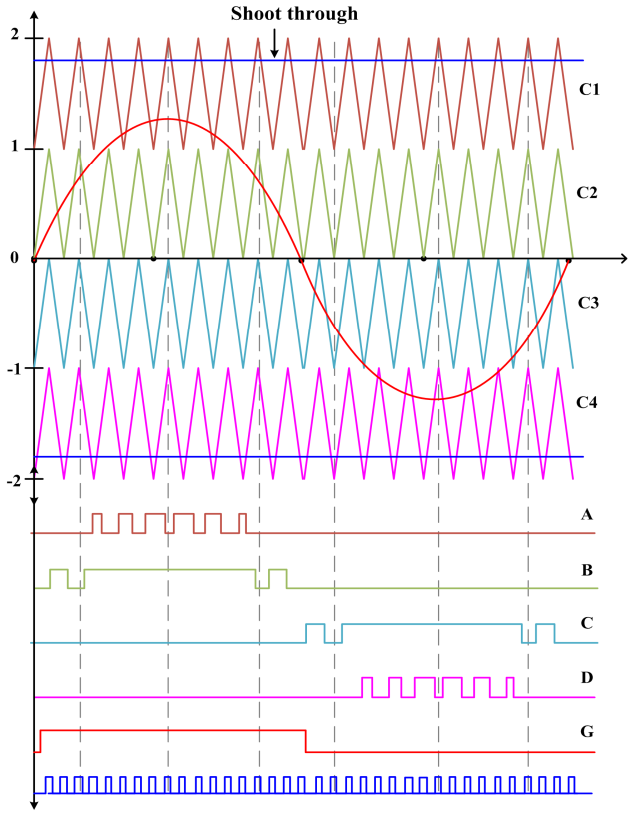

Fig. 4. Level shifting PWM technique.

IV. Simulation Results

The proposed five-level qZS-NPC inverter is studied for changes in input voltage and load through Matlab software. The proposed topology is tested for an input voltage of 100V, an output voltage of 110V (RMS) and a power rating of 500W. The parameters used for simulations are shown in Table II.

TABLE II. Simulation Parameters

Parameters	Values
Input Voltage	100 V
Inductors (L_1-L_4)	1mH
Capacitors (C_1-C_4)	1000µF
Switching Frequency	10 kHz
Output Voltage (RMS)	110 V
Output Power	500 W

Figs. 5 & 6 depicts the response of the five-level output voltage, inductor currents and capacitor voltages of the top qZS of the proposed topology under steady state condition. It is also tested for a power factor of 0.8 lagging and leading case and their responses are illustrated in Fig. 7. For good visibility of voltage and current, current is multiplied by a factor of 10 in all case. It can be noticed that the proposed topology can supply power for both leading and lagging load at the same time keeping the boost factor constant.

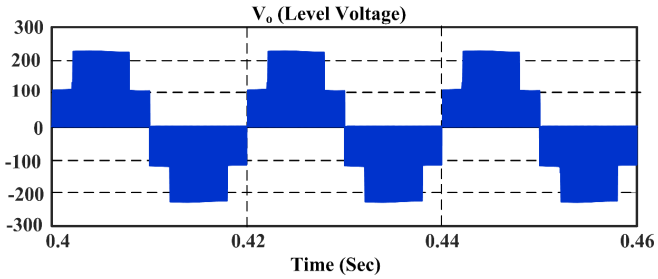

Fig. 5. Level output voltage of proposed converter.

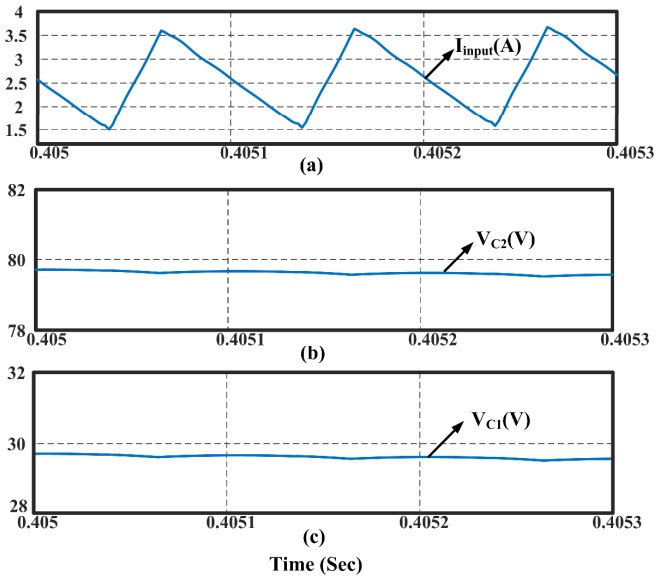

Fig. 6. Response of qZS network (a) Input Current, (b) & (c) Voltage across C2 and C1 respectively.

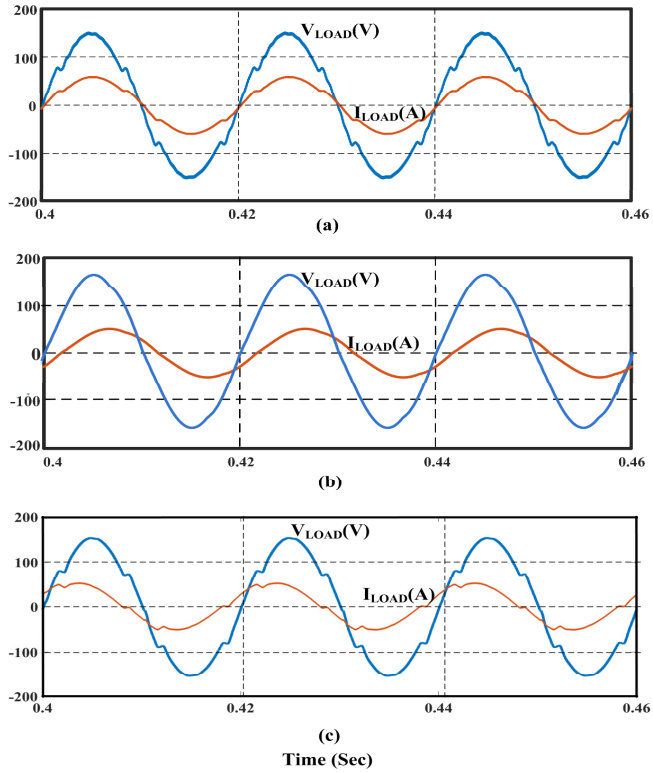

Fig. 7. Output voltage and current waveforms for (a) R Load, (b) RL Load, and (c) RC Load.

Further the closed loop performance was observed for both load change and an input voltage change. Fig. 8 depicts the response of shoot-through duty cycle, dc-link voltage, output voltage and their corresponding load current for a step change input voltages. It is observed that the dc-link voltage is maintained constant as 220V by adjusting the shoot through duty cycle for input changes from 100V to 120V.

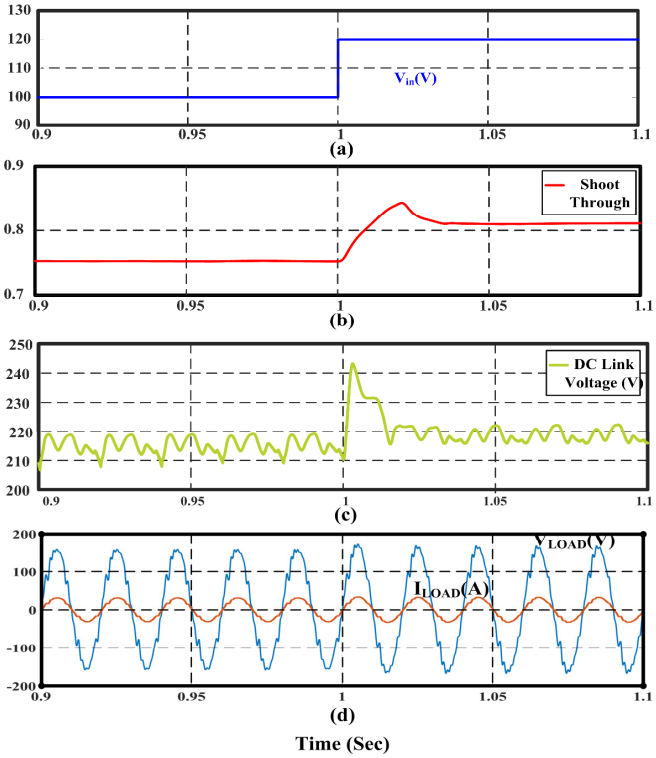

Fig. 8. Response of (a) DC-link voltage, (b) Shoot through duty cycle, and (c) Output voltage and load current for step change in input voltage.

Similarly, Fig. 9 depicts the response of dc-link voltage, shoot-through duty cycle, output voltage and their corresponding load current for a step change in load. It can be seen that the output voltage is maintained constant during the load changes at time t = 1 Sec. This shows that the developed controller is well regulated the dc-link voltage and the output voltage by adjusting the shoot-through duty cycle for the changes in input voltage as well as load changes.

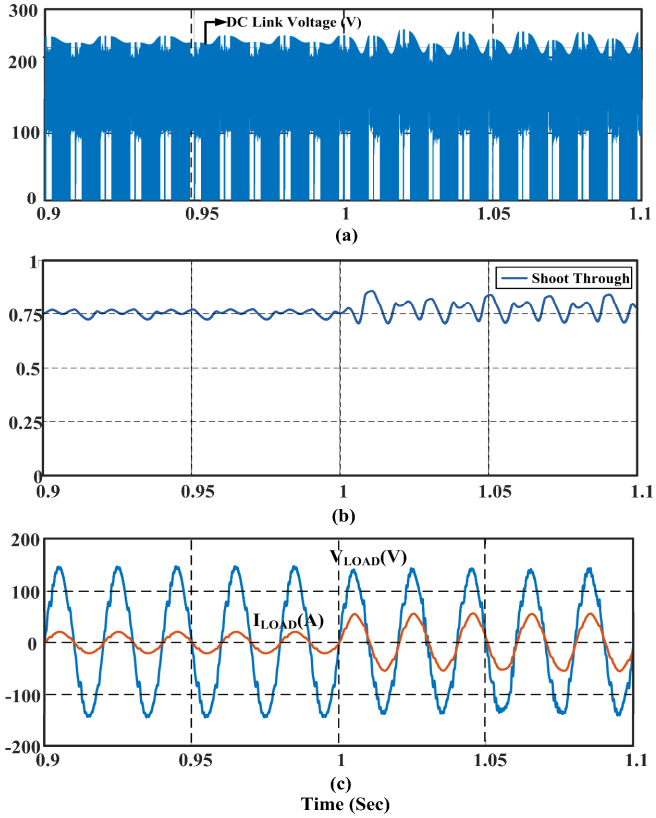

Fig. 9. Response of (a) DC-link voltage, (b) Shoot through duty cycle, and (c) Output voltage and current for step change in load.

V. Conclusion

A new single phase five-level quasi Z-source based Neutral Point Clamped inverter is presented for PV applications. The proposed topology has inherent features of both high boosting factor and reactive power capability. Modified hybrid shoot-though control with level-shifted carrier waves is presented to realize the five-level output waveforms. Steady state equations are also derived for its working in active and shoot through states. Finally, the effectiveness of the proposed topology is confirmed through Matlab software during step changes in input voltage and change in load.

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