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Modified Diode Assisted Extended Boost Quasi Z-Source Inverter for PV Applications

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Abstract

The design, simulation and implementation of modified diode assisted extended boost q-ZSI (MDAEB q-ZSI) for photovoltaic application are proposed in this paper. It is the most efficient topology that provides a single stage conversion for PV systems by providing high input voltage gain, reduced number of components count, increased voltage boost property, reduced voltage ratings, reduced voltage stress across the switches and simplified control strategies. Its unique capability in single stage conversion with improved voltage gain is used for voltage buck and boost function. The operating modes and the steady state theoretical analysis of voltage boost, control methods and a system design guide for the proposed topology are investigated in this paper. A simulation model of the PV system based on MDAEB q-ZSI has been built in MATLAB/ SIMULINK. Performance parameters such as Total harmonic distortion (THD), voltage gain, voltage stress and boost factor are computed and compared with the conventional quasi z-source inverter. The prototype model for MDAEB q-ZSI is developed and the results are validated.

1. Introduction

In standalone PV systems, the power electronic converters play a vital role in the conversion of DC current of PV panels into AC to supply the load, with maximum efficiency and superior performance. The two stages of DC-DC-AC power conversion may result in usage of more circuit components, lower efficiency, higher cost and

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larger size in comparison to the single stage one [1]. The modified diode assisted extended boost quasi-Z-source inverter has a single power conversion stage which perfectly suits for interfacing of renewable energy sources.

The efficiency and the voltage gain of the conventional q-ZSI are limited and comparable with the traditional system of a voltage source inverter with the auxiliary step-up DC/DC converter in the input stage [2] [3]. The concept of extending the quasi ZSI gain without increasing the number of active switches has been reported in the literature [4] [5]. These new converter topologies are known as extended boost q-ZSI and can be generally classified as capacitor assisted, diode assisted topologies and hybrid topologies [5] [6]. In this paper, MDAEB q-ZSI with continuous input current [7] is presented, analyzed and compared for the simple boost control technique. Simulation studies of the proposed inverter configuration are carried out in MATLAB/SIMULINK. The capacitor voltage in the impedance network, voltage gain, boost factor, voltage stress and THD are calculated and compared with the quasi z-source inverter. Hardware of the modified diode-assisted QZSI is developed and the simulation results are verified.

2. Operating Modes and Steady State Analysis of MDAEB q-ZSI

The proposed topology of MDAEB q-ZSI is presented in **Figure 1**. The topology of MDAEB q-ZSI could be derived by the adding of one capacitor (*C3*), one inductor (L3) and two diodes (D2 and D3) to the conventional q-ZSI. The connection points of the capacitor C3 is interchanged to reduce its operating voltages. **Figure 2(a)** and **Figure 2(b)** show the equivalent circuits of the MDAEB q-ZSI for the shoot-through and the active states.

The extended boost q-ZSI has two operational modes at the dc side, non-shoot-through states and the shoot-through state [8] [9]. During the shoot through state the q-ZSI performs the voltage boost function. During the active state, the previously stored magnetic energy in turn provides the voltage boost at the load terminals. The unique LC impedance network provides the boosting function without disturbing the operation inverter [10]-[12].

2.1. Mode I (Shoot through Mode)

Let T = Operating period of the q-ZSI,
Ta = Active state,
Ts = Shoot through state,
Da = The duty cycle of an active state,
Ds = The duty cycles of shoot-through state,
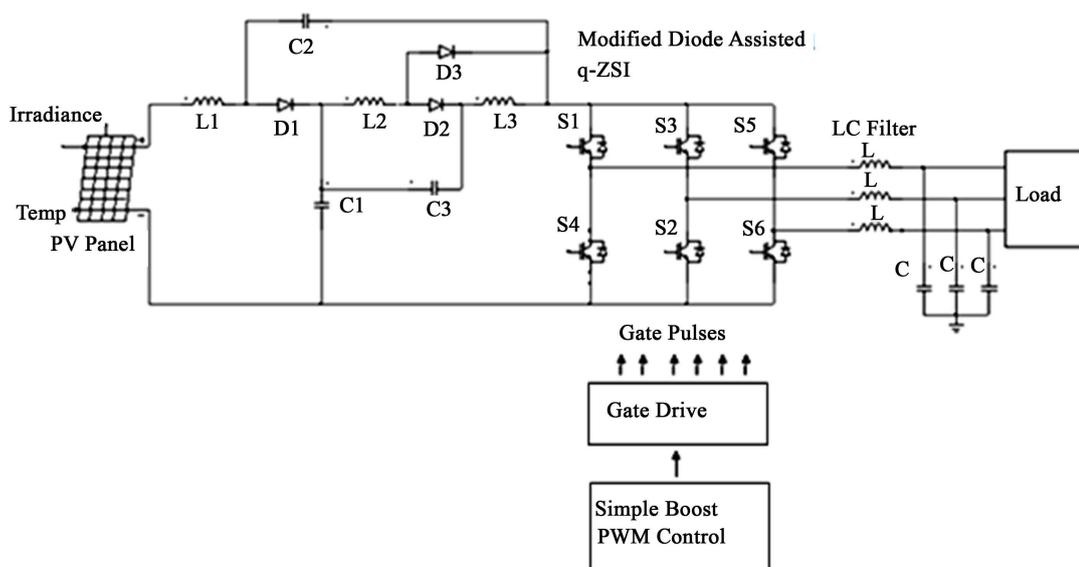
$$T = Ta + Ts \tag{1}$$

$$Da + Ds = 1. \tag{2}$$

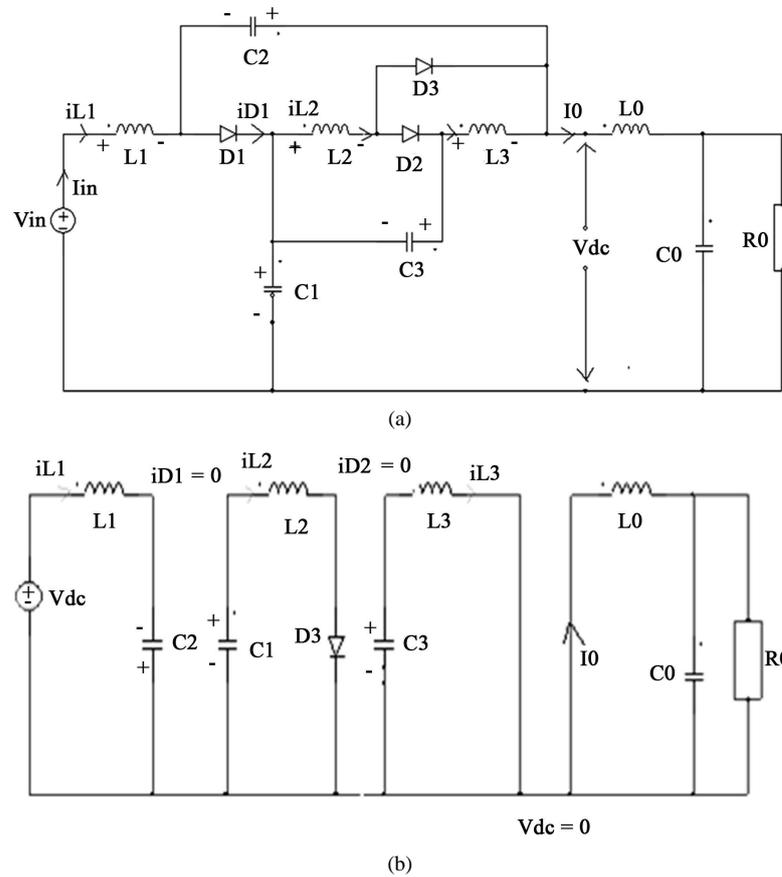**Figure 1.** Modified diode assisted extended boost q-ZSI based PV system.

Figure 2. Operating modes of MDAEB q-ZSI: (a) Mode-I; (b) Mode-II.

The equivalent circuit of the MDAEB q-ZSI during the shoot-through state is shown in **Figure 2(a)**. A unique LC impedance network is interfaced between the source and the inverter to achieve voltage boost and inversion in a single stage. During the shoot through state $D3$ is conducting and $D1$ and $D2$ diodes are in blocking state. All the inductors in the impedance network get charged up. Energy is transferred from the source to the inductor or the capacitor to the inductor when the capacitors are getting discharged.

The voltage across the inductors can be represented as

$$V_{L1} = V_{in} - V_{C1} \tag{3}$$

$$V_{L2} = V_{C1} \tag{4}$$

$$V_{L3} = V_{C3} + V_{C1}. \tag{5}$$

2.2. Mode II (Non-Shoot through Mode)

The equivalent circuit of the MDAEB q-ZSI during the active state is shown in **Figure 2(b)**. During the non shoot through state the diodes $D1$ and $D2$ are conducting and $D3$ is in blocking state. The inductors across the impedance network discharge and the capacitors get charged.

The voltage of the inductors can be represented as

$$V_{L1} = V_{in} - V_{C1} \tag{6}$$

$$V_{L2} = -V_{C3} \tag{7}$$

$$V_{L3} = -V_{C3} - V_{C2}. \tag{8}$$

Peak DC-link Voltage is

$$V_{dc} = V_{C1} + V_{C2} = \frac{V_{in}}{\left(Ds^2 - 3Ds + 1\right)} . \tag{9}$$

The boost factor of the input voltage is

$$B = \frac{V_{dc}}{V_{in}} = \frac{1}{\left(Ds^2 - 3Ds + 1\right)} . \tag{10}$$

3. Simulation Results

From the design considerations and specifications, the component parameters are calculated and it is presented in **Table 1**. MDAEB q-ZSI can be used for grid connected and standalone applications [13]-[16]. The simulation model of PV energy generation system with MDAEB q-ZSI for the boost factor B = 2 is shown in **Figure 3**. This is constructed in the MATLAB/SIMULINK environment. **Figure 4** shows the impedance network of MDAEB q-ZSI. The gating pattern of the pulse generation using the simple boost control technique is shown in **Figure 5**.
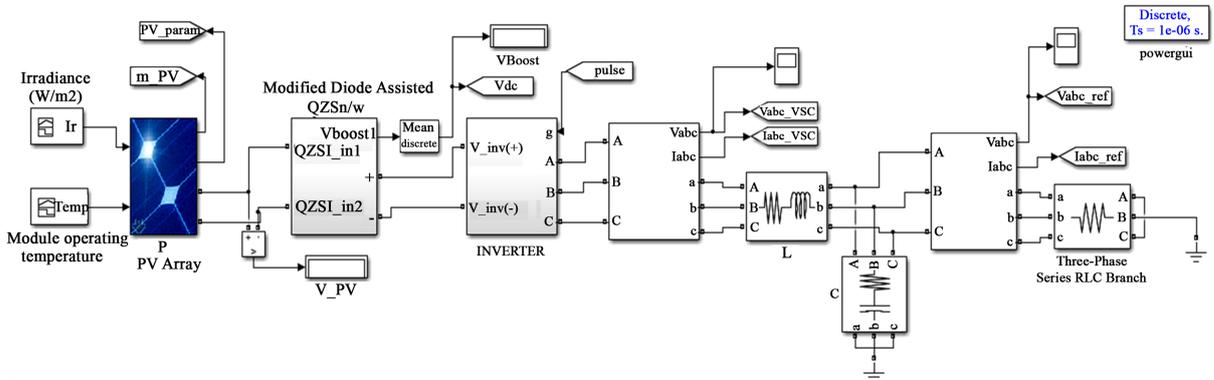
Figure 3. Matlab/Simulink circuit of PV based MDAEB q-ZSI.

Table 1. Simulation parameters.

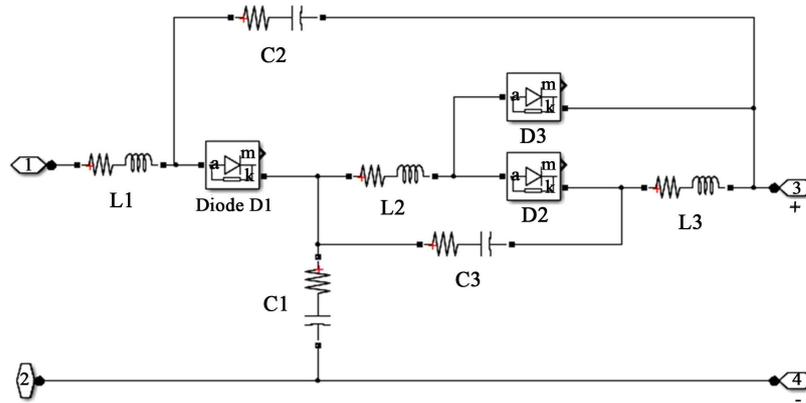| Parameters	Values
Input Voltage (PV Panle Vin)	21 V
PV Panel Power	100 Watts
Voc, Isc	21.24 V, 4.7 A
Vmpp, Impp	16.56 V, 4.3 A
Inductors L1, L2, L3 & rL	65 µH, 0.005 µH
Capacitors C1, C2, C3 & rC	185 µF, 0.0005 µF
Boost Factor (B)	2
Shoot through Duty Cycle Ds	0.178
Modulation Index (Ma)	0.822
Switching Frequency fs	10 kHz
Inverter Frequency	50 Hz
R Load	50 Ω
Filter Inductance & Capacitance	5 mH & 220 µF

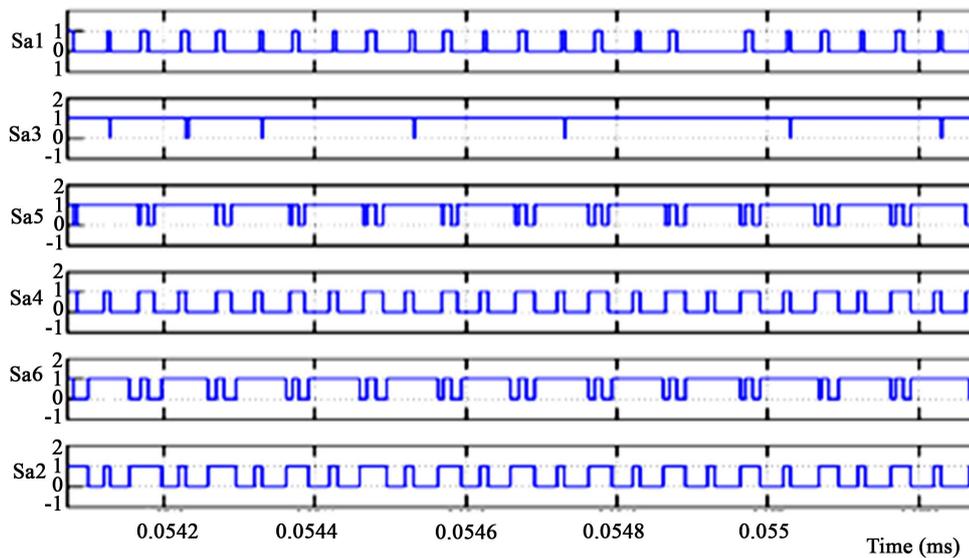**Figure 4.** Impedance Network of MDAEB q-ZSI.

Figure 5. Shoot through pulses.

3.1. PV Array Characteristics

Figure 6 shows the PV array characteristics. The characteristics are plotted for different insolation level at constant temperature.

3.2. Continuous Input Current

The proposed topology has continuous input current as shown in **Figure 7**.

3.3. DC-Link Voltage

The proposed topology operates normally producing the demanded boost of the input voltage for the boost factor. The simulation results of DC link voltage of MDAEB q-ZSI is shown in **Figure 8**.

From **Figure 8**, it is clear that for the input voltage of 21 V, MDAEB topology produce the boost voltage of 39 V.

3.4. Operating Voltages of the Capacitors in the Cascaded QZS Network

The theoretical and simulated results of the capacitor voltages across the impedance network for the proposed topology are compared in **Table 2**.
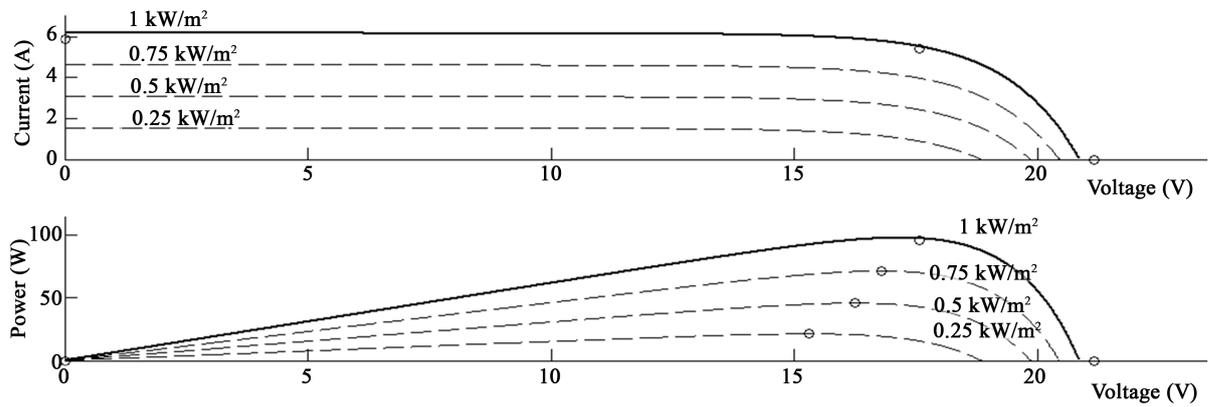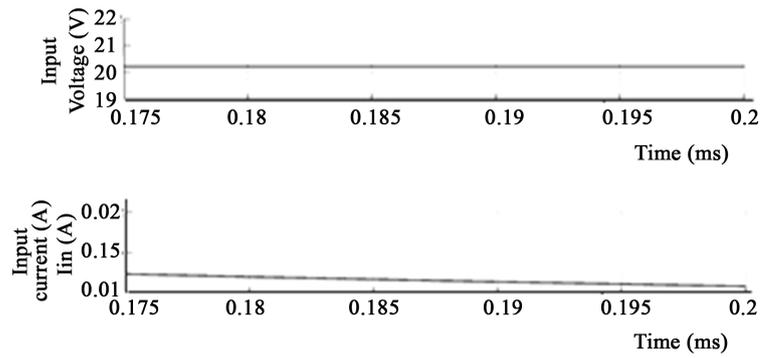
Figure 6. PV array characteristics.

Figure 7. Input voltage & current waveforms of MDAEB q-ZSI.
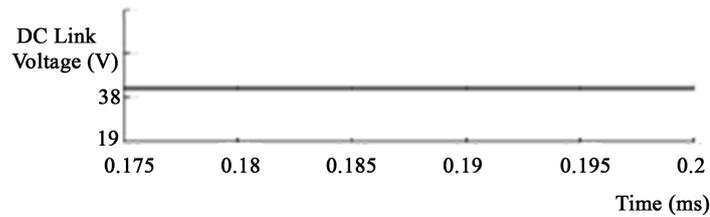

Figure 8. DC Link voltage of MDAEB q-ZSI.

Table 2. Operating voltages of capacitors in the impedance network.

Capacitor Voltage (V)	Formula	Theoretical Values (V)	Simulated Results (V)
V_{C1}	$\dfrac{V_{in}*(Ds^2-2Ds+1)}{(Ds^2-3Ds+1)}$	28	26
V_{C2}	$\dfrac{V_{in}*(2Ds-Ds^2)}{(Ds^2-3Ds+1)}$	14	13
V_{C3}	$\dfrac{V_{in}*(Ds-Ds^2)}{(Ds^2-3Ds+1)}$	6	5

From **Table 2** it is clear that the operating voltage of the capacitor C3 of MDAEB q-ZSI was reduced by more than five times by changing the interconnection points of the capacitors C3 as in **Figure 1**.

Figure 9 shows the operating voltages of the capacitors in the MDAEB q-ZSI.
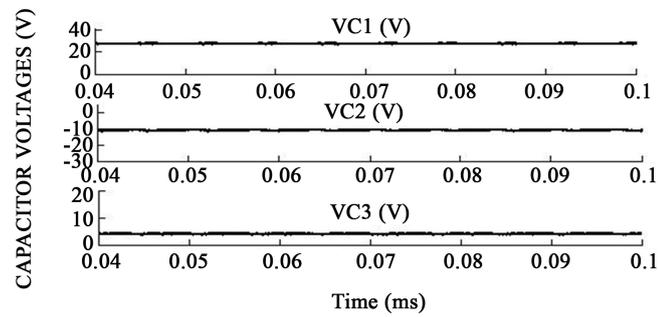
Figure 9. Capacitor voltages of MDAEB q-ZSI.

From **Figure 9** the average voltage across the capacitor C3 of MDAEB q-ZSI was reduced more than six times when compared to its basic diode assisted topology. **Figure 10** shows that the effect of modulation index on capacitor voltages of MDAEB q-ZSI.

From **Figure 10** it is clear that the average value of voltage across the capacitor C3 of MDAEB q-ZSI was reduced with the increasing modulation index.

3.5. Output Voltage and Current Waveforms

The simulation results of the output line voltage, load voltage and load current waveforms of MDAEB q-ZSI for the simple boost modulation technique without filter are shown in **Figures 11-13**.

The simulation results of line voltage, load voltage and load current waveforms of MDAEB q-ZSI for Simple Boost technique with filter are shown in **Figures 14-16**. Filtered three phase output line voltage is shown in **Figure 17**.

4. Performance Characteristics of MDAEB Q-ZSI

Performance parameters of the MDAEB q-ZSI are analyzed for various modulation indices for the given boost factor. They are Total Harmonic Distortion, inductor current ripple of q-ZSI, capacitor voltage ripple, voltage gain and voltage stress, boost factor.

4.1. Total Harmonic Distortion (THD)

Total Harmonic Distortion of MDAEB q-ZSI is analyzed and compared with the conventional quasi ZSI for the simple boost modulation technique.THD is calculated for various modulation index values and the effect of the modulation indices on THD and the comparison is shown in **Figure 18**.

From **Figure 18** THD increase with the decrease in the modulation index and the MDAEB q-ZSI has reduced THD, when compared to the quasi ZSI.

4.2. Voltage Gain (G)

Voltage Gain, G is calculated for the simple boost modulation technique. In **Figure 19** the voltage gain G is compared with different values of modulation indices for the simple boost modulation technique.

Voltage gain, G is given by,

$$G = M * B \qquad (13)$$

where M = Modulation Index,

B = Boost Factor.

From **Figure 19** it is clear that when compared with the conventional quasi ZSI, the proposed topology have increased voltage gain for the same value of the modulation index (Ma).

4.3. Boost Factor (B)

The boost factor is calculated for the simple boost modulation technique. In **Figure 20**, the boost factor B is compared with different values of the shoot through duty cycle Ds. Boost factor is given by
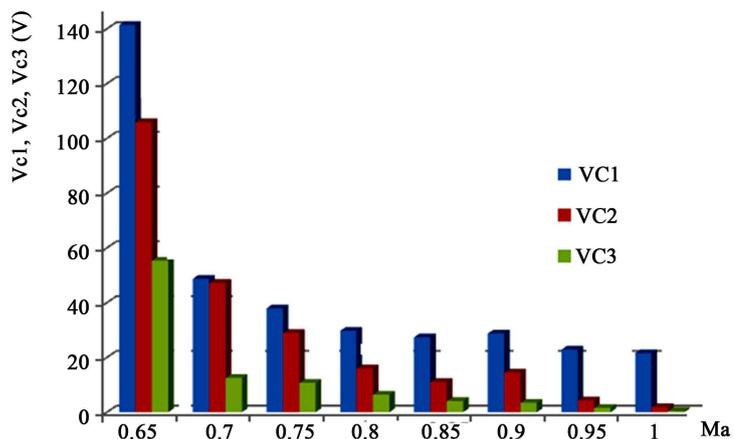
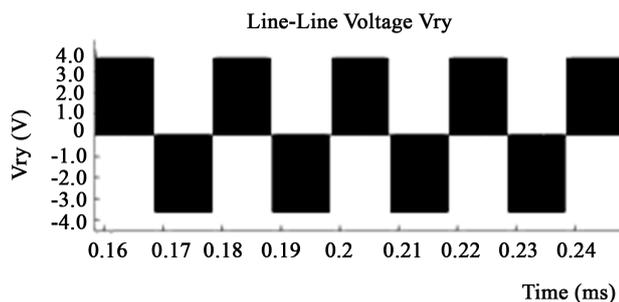**Figure 10.** Effect of modulation index on capacitor voltage of MDAEB q-ZSI.
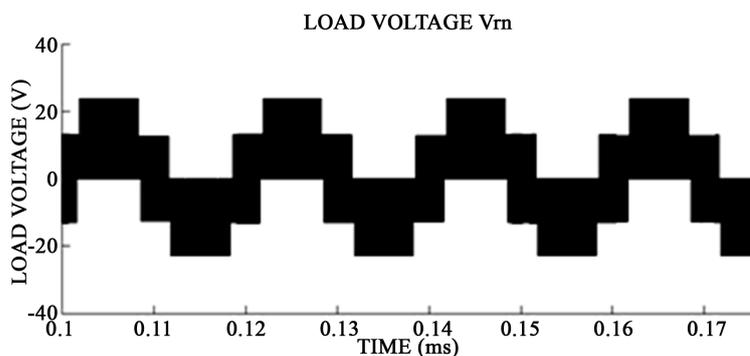

Figure 11. Line voltage waveform for MDAEB q-ZSI.

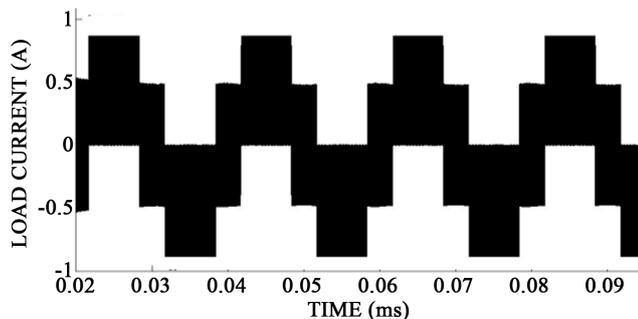
Figure 12. Load voltage waveform.

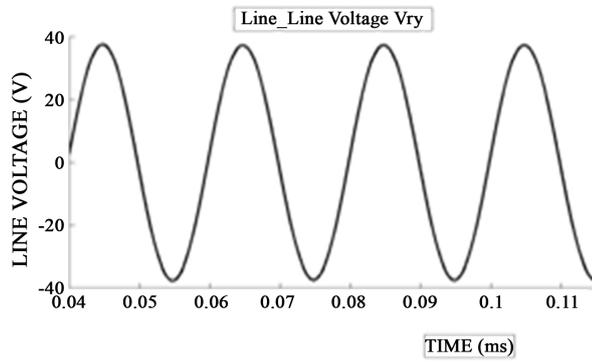**Figure 13.** Load current waveform for MDAEB q-ZSI.

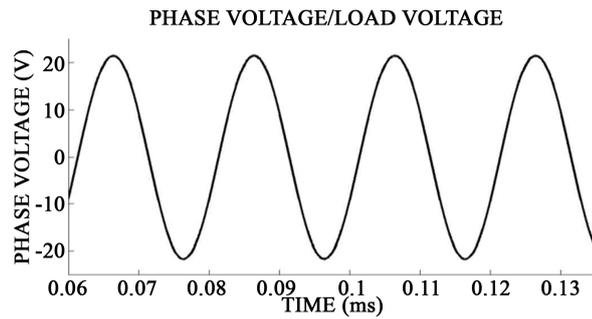**Figure 14.** Filtered output line voltage waveform.
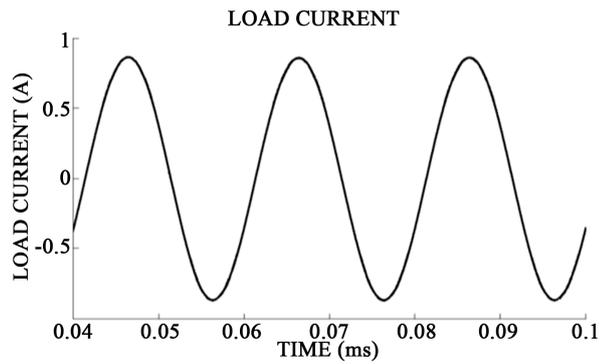

Figure 15. Filtered output load voltage waveform.

Figure 16. Filtered output load current waveform.
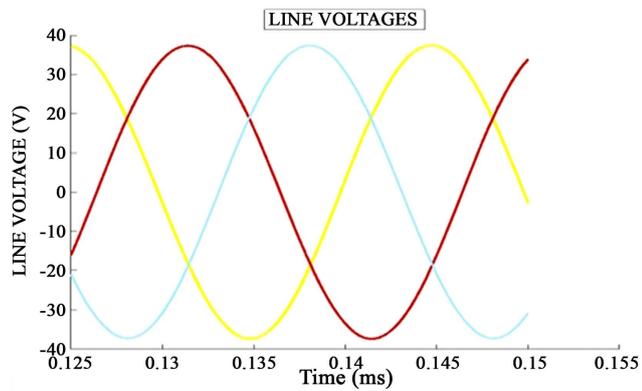

Figure 17. Filtered output line voltage waveform.
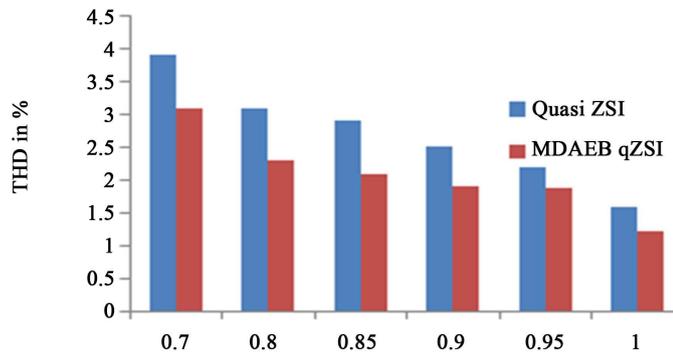
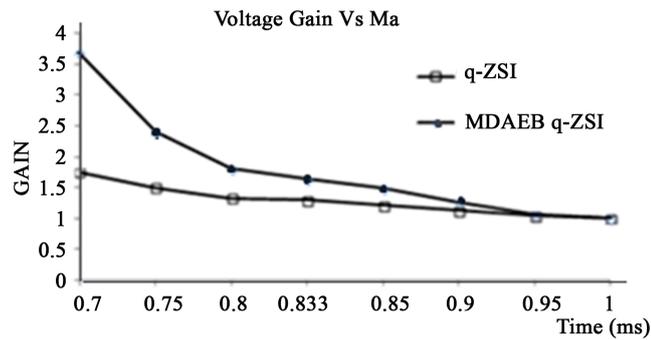Figure 18. Effect of modulation index on THD.
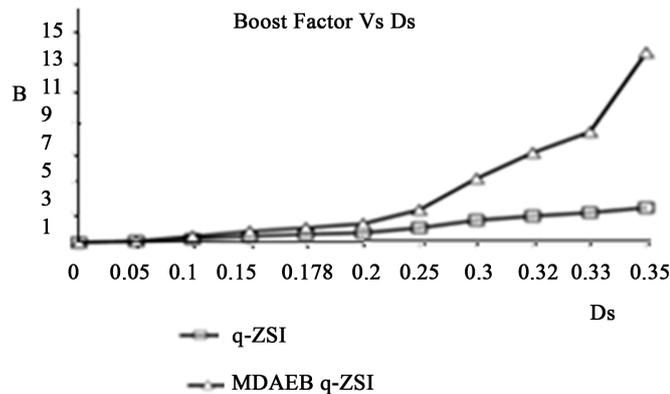

Figure 19. Comparison of voltage gain.

Figure 20. Boost factor comparison.

$$B = \frac{1}{\left(Ds^2 - 3Ds + 1\right)} \tag{14}$$

From **Figure 20**, the proposed topology have increased boost factor of the input voltage for the same value of the shoot through duty cycle Ds when compared with the conventional q-ZSI.

4.4. Voltage Stress

Voltage stress is compared with voltage gain for the simple boost modulation technique. Voltage stress is calculated from the voltage gain G. **Figure 21** shows the variation of voltage stress/DC voltage with voltage gain (G) for MDAEB q-ZSI and the traditional quasi ZSI.

Voltage stress across the devices is given by

$$V_S \left(2 * G - 1\right) * V_{IN}. \tag{15}$$

From **Figure 21** it is clear that the simple boost PWM control technique gives better voltage gain and reduced voltage stress for the MDAEB q-ZSI than the conventional quasi ZSI.

From the simulation results it is observed that MDAEB q-ZSI gives higher RMS value of the output voltage, higher voltage gain, increased boost factor, reduced voltage stress and reduced THD when compared with the traditional quasi ZSI for the simple boost modulation technique. It provides reduced operating voltages of the capacitor C3. MDAEB q-ZSI is the preferred topology for the photovoltaic applications when compared to the conventional q-ZSI.

5. Experimental Results

In order to verify the theoretical assumptions the laboratory setup for MDAEB q-ZSI was assembled. The experimental setup for the PV connected MDAEB q-ZSI was shown in **Figure 22**.

The shoot through pulses and the gate pulses during the switching sequence of the three phase inverter are shown in **Figure 23** and **Figure 24**. The shoot through duty cycle is 0.178 and the modulation index is 0.822.

The boost voltage and the load voltage of the MDAEB q-ZSI are shown in **Figure 25** and **Figure 26**. For the input voltage of 21 V, the proposed topology produces the boost voltage of 42 V for the boost factor B = 2.

From the hardware results it is shown that modified diode assisted extended boost q-ZSI have continuous input current, high dc link voltage ,high demanded boost ,reduced voltage stress, increased voltage gain and increased load voltage.
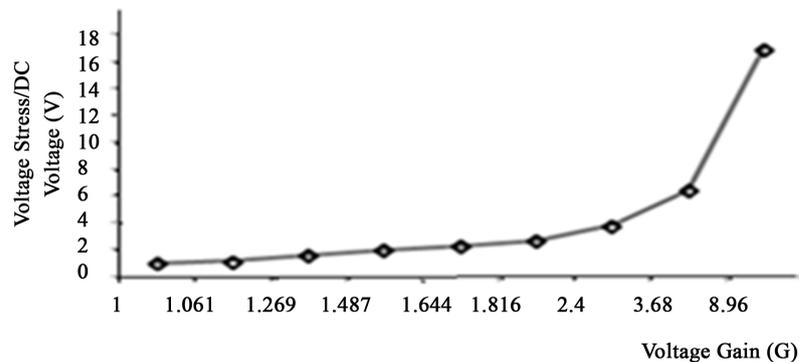

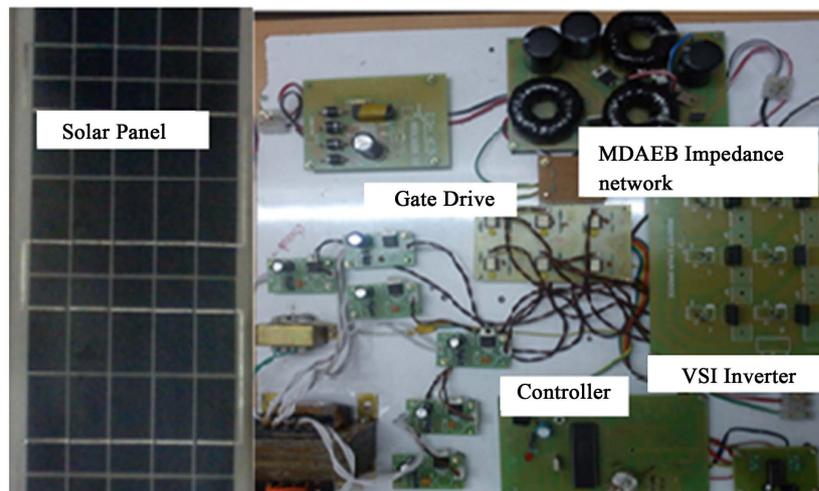**Figure 21.** Effect of voltage gain on voltage stress.
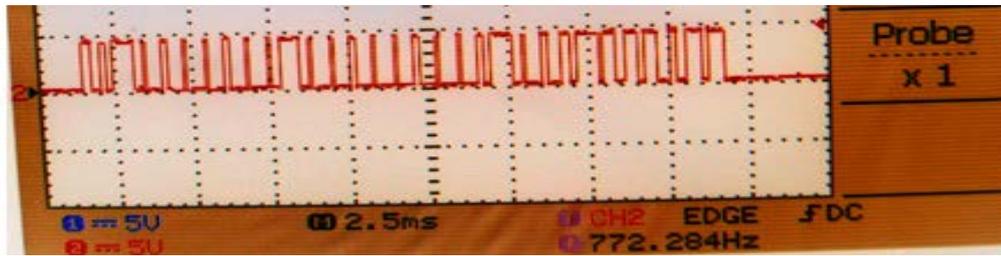

Figure 22. Experimental setup.

Figure 23. The shoot through pulses.
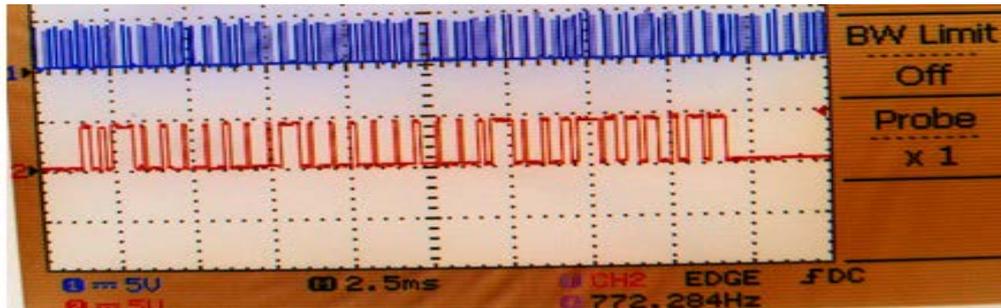

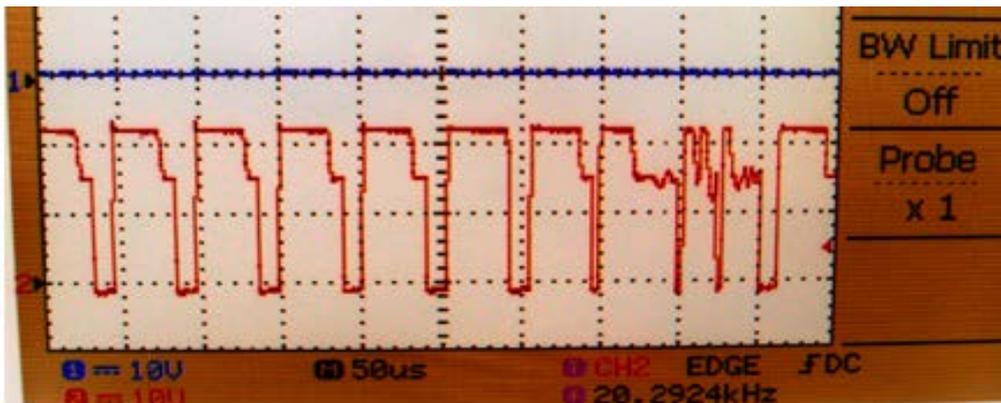**Figure 24.** Gate pulses.

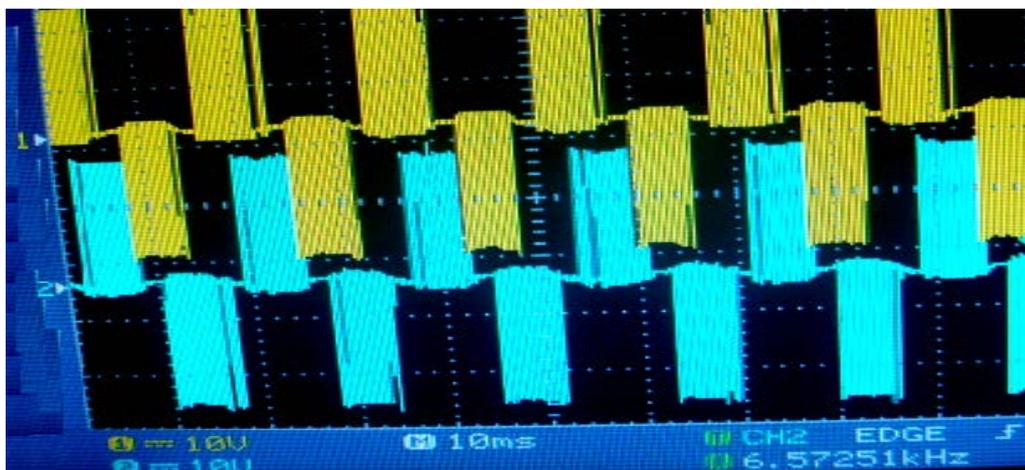**Figure 25.** Boost voltage.

Figure 26. Output line-line voltage.

6. Conclusion

In this paper, the topology of modified diode assisted extended boost quasi ZSI for PV applications has been discussed and compared with the conventional q-ZSI. The detailed steady state operation of the proposed topology is analyzed and simulated. Simulation results validate the theoretical analysis. From the results, it is observed that the voltage stress across the impedance network is reduced and the operating voltages of the capacitors are reduced by five times; reduced THD, higher boost factor and better spectral quality of the output are obtained compared to QZSI configuration. Therefore, the proposed topology of extended QZSI is suited for PV applications.

Acknowledgements

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