DESIGN AND ANALYSIS OF A MULTI-LEVEL QUASI Z SOURCE BASED NPC INVERTER

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***Abstract*— A Z-network plus switched-capacitor based DC-DC boost converter (ZSCBC) is proposed. The integration of the Z-network with a switched capacitor is responsible for yielding a high-voltage gain and that too at lower duty ratios compared to the conventional quasi-Z-source dc–dc converter (QZSC). Since the proposed converter contains Z or impedance network, the operating duty ratio is less than 0.5, such as in QZSC, and retains its advantages, such as common ground and low-voltage stress on Z-network capacitors. Unlike QZSC, the switch and all the diode voltage stresses in the proposed converter are low even at high-voltage gains. A detailed steady-state analysis is presented to identify the salient features of the proposed Z-network-based boost converter and thereafter compared with other Z-source-based configurations. The small-signal analysis is established, and a single-loop voltage mode controller is designed. A 48–250-V, 130-W prototype is built to demonstrate the effectiveness of the ZSCBC.**

***Keywords*— Z-network plus switched-capacitor based DC-DC boost converter (ZSCBC), quasi-Z-source dc–dc converter (QZSC), Z-network capacitors, a single-loop voltage mode.**

1. INTRODUCTION

In recent years, due to the crisis in global fossil fuel energy, more attention is being paid in integrating renewable energy sources. In case of photovoltaic (PV) power generation, the dc grid is one of the options for integration as well as power management. The PV panels have fluctuating and a very low output voltage, and to make them self-sufficient, a number of intermediate cascading step-up power conversion structures are required. A multistage conversion is required, where a basic dc–dc boost converter (BBC) boosts the low voltage of PV panels to a high voltage, which is further used as a dc-link voltage of the inverter. Though this multistage power electronic conversion is able to serve the purpose, the number of intermediate converters required is more. More number of converters not only increases the number of components but also decreases the overall efficiency, which leads to reduced reliability. Theoretically, BBC can realize very high voltage gain, but the duty ratio is limited due to nonidealities of the devices, passive components, and efficiency considerations. Therefore, BBC is not a suitable option as front-end converter in the inverter dc-link voltage regulation. In such applications, the Z-source inverter (ZSI) is a viable option. It not only performs single-stage power conversion. (Boosting plus dc–ac conversion) but also effectively eliminates the limitations of the conventional voltage-source and current-source inverters. In [4], a family of quasi-ZSI (QZSI) inverters is presented with the voltage gain similar to conventional ZSI. A QZSI with the continuous input current is reported, which surpasses the limitation of ZSI, whereas another QZSI with discontinuous input current is reported in the literature to reduce the voltage stress across Z-source capacitors. A number of converters based on ZSI that offer single-stage conversion and short-circuit immunity of inverter legs along with different modulation techniques to improve voltage gain, reduce inductor current ripple, and achieve various performance indices are discussed. The impact of modulation strategies on reliability and harmonics of impedance source inverters is discussed. The effect of modulation strategies on voltage/current stresses and power loss is also described. In, the inductors of ZSI are replaced with switched-inductor (SL) cells to increase the voltage gain. Though this replacement increases gain, it is achieved at the cost of reduced duty cycle range and increased voltage stress on the devices. In, SL-based QZSI (SLQZSI) is introduced, where one of the inductors of QZSI is replaced by SL cell to achieve a voltage gain higher than that of QZSI. In, two SLQZSI configurations are introduced in which both the inductors of QZSI are replaced with SL cells. This modification yielded a higher voltage gain that is same as that of the SL-based ZSI (SLZSI) [9]. Though the gain of SLQZSI is higher than ZSI, it still possesses the limitations of SLZSI. Recently, the concept of boosting through the Z-network has been extended to dc–dc power conversion. The inductor of BBC is replaced by a Z-network to realize a high voltage gain Z-source dc–dc converter (ZSC). A quasi ZSC (QZSC) is presented with a slight modification in converter of, i.e., replacement of Z-network with quasi Z-network and output diode with an inductor to reduce the output voltage ripple. However, this resulted in reduced voltage gain. The steady-state analysis of ZSC in continuous-current mode (CCM) is explained. A QZSC is presented in which has voltage gain same as in ZSC but with lower voltage stress on Z-network capacitors. Furthermore, it has a common ground between its input and output terminals. A Three-Z-network boost converter which is basically an SL-based quadratic boost converter. However, the devices suffer from higher voltage stress. A common grounded ZSC presented in Fig. 1(b) had voltage gain higher than ZSC with lower voltage stress on its components, but its voltage gain is comparatively lower than other reported converters and has discontinuous input current, which is a major limitation. The impedance-network boost converter presented has identical behaviour as that of SLQZSC, and that is why, it inherits all the limitations of the topology reported in. To realize higher voltage, gain dc–dc converters, Z-networks are integrated with switched capacitors (SCs), and a number of solutions on this aspect are available in the literature. The voltage gain of ZSC is further increased by cascading an SC cell in [21]. However, it has the limitation of discontinuous input current, limited voltage gains, and the absence of common ground between its input and output terminals. A QZSC with voltage-lift cell presented has increased voltage gain by compromising on the duty ratio range along with the increased voltage stress across the devices. Two new configurations of QZSC with single SC branches but the voltage gain is very low and none of them has a common ground. A QZSC with switched capacitor presented, as shown in Fig. 1(d), has voltage gain nearly twice that of the converter reported, but this gain is not sufficiently high. A QZSC with hybrid SC/SL arrangement, which has a high voltage gain, but with higher number of passive components and no common ground. A QZSC with a hybrid SL arrangement is which has very high voltage gain but a lower duty ratio range and higher voltage stress across devices. A switched capacitor based Z-source dc-dc converter (SCZSC) [27] shown in Fig. 1(e) is a combination of Fig. 1(b)and Fig. 1(d) [24], providing higher voltage gain and retaining all the properties of the converter but it suffers from the limitation of discontinuous input current. In most of the converters reported in the literature, there are some major limitations that need the utmost attention that is:

1) Low voltage gain
2) High voltage stress across devices
3) Low duty ratio range
4) No common ground between input and output terminals.

The above-stated limitations sparked an idea to address them by integrating the Z-network with switched capacitors in a new way, to come up with the proposed converter and motivated to evolve Z-network plus SC-based dc–dc boost converter (ZSCBC). In this article, a new ZSCBC is presented. ZSCBC shown in Fig. 1(f) is a combination of quasi-Z-network and switched capacitors, and it offers higher voltage gain than all the reported converters and has a common ground. ZSCBC retains all the advantages of SOQZSC. Moreover, the device voltage stress in ZSCBC is also same despite of different arrangement of components in the circuits.

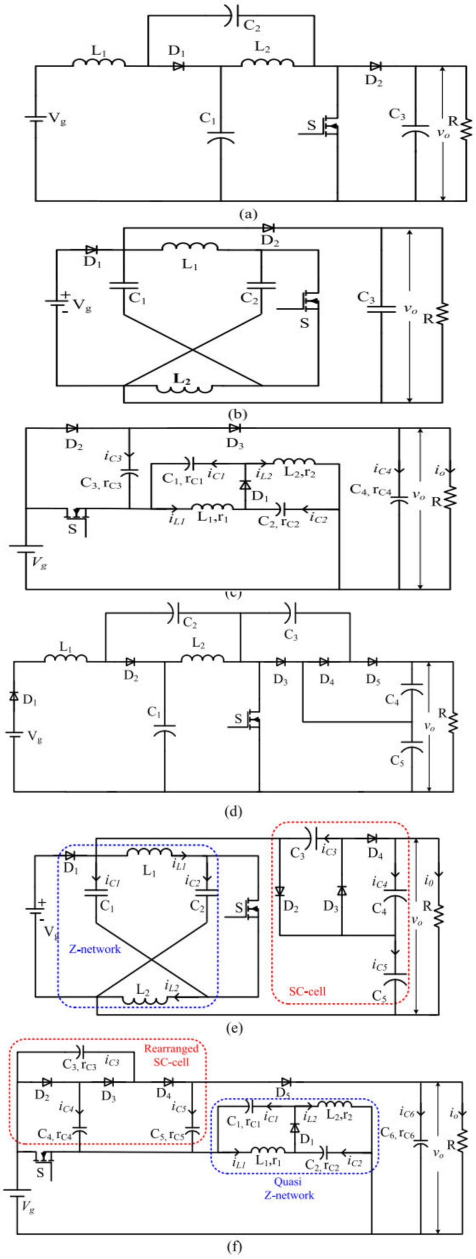


Fig. 1. (a) QZSC based. (b) Common ground. (c) SOQZSC. (d) QZSC with a switched capacitor. (e) SCZSC. (f) Proposed ZSCBC.

2. PROPOSED FIVE-LEVEL QZS- INVERTER

Therefore, in this paper, a five-level quasi-Z-source-based NPC inverter is proposed. The proposed topology combines the advantage of ZSI and diode clamped arm in order to capacitate the provision of reactive power capability and also enhance the boosting factor. A modified level-shifted carrier waveform with hybrid shoot-through control is presented.

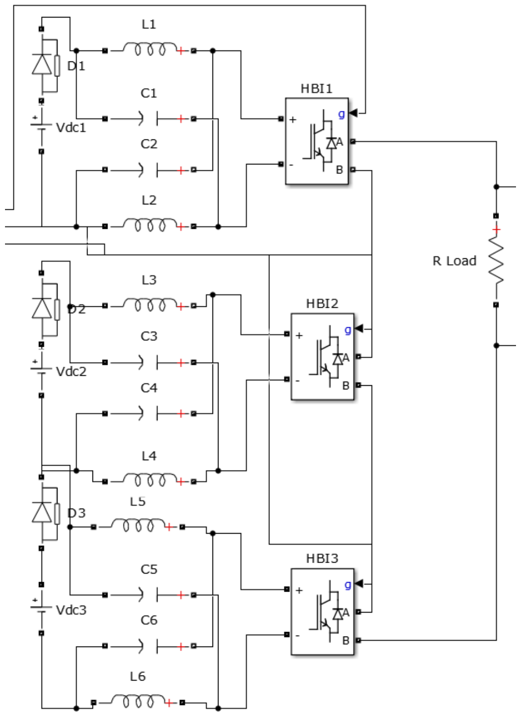


Fig. 2 depicts a five-level quasi-Z-source neutral point clamped inverter (qZS-NPC) for PV applications.

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 the neutral point through S1, S2, and the four switches of the diode clamped arm. The output level of the proposed converter is 0, (VDC/2), VDC in both positive and negative half. VDC is the total dc-link voltage of the converter which is the sum of voltages across C1, C2, C3, and C4. Level-shifting carrier wave modulation was applied to the converter to get the five-level output. The switching states of all the switches 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.

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.

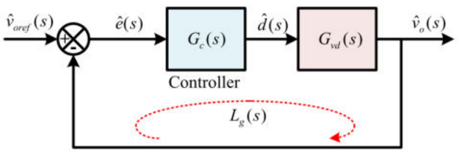


Fig3. Block diagram of the closed-loop controlled system.

The above-stated problem makes it 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 (VC2) and by using the following expression. This is compared with desired dc-link voltage and the error is fed to the Proportional Integral (PI) regulator which gave the shoot-through duty cycle as controlled output.

3. MODIFIED MODULATION TECHNIQUE

Modulation is a key factor in the 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. The phase disposition level shifting PWM is used for the proposed topology. Four high-frequency carrier waves and a sine reference wave were utilized to develop the required switching logic. The logic for switches S1- S8 is given below and was developed. The sine reference wave was compared with carrier waves C1-C4 to give the respective pulsed output i.e. B, A, C, and D.

A. PWM (Pulse Width Modulation)

Pulse-width modulation (PWM), or pulse-duration modulation (PDM), is a method of reducing the average power delivered by an electrical signal, by effectively chopping it up into discrete parts. The average value of voltage (and current) fed to the load is controlled by turning the switch between supply and load on and off at a fast rate. The longer the switch is on compared to the off periods, the higher the total power supplied to the load.

PWM Control Methods Various Sinusoidal Pulse Width Modulation (SPWM) schemes can be applied to the ZSI and their input-output relationship is still hold. Minor modifications in SPWM techniques can provide shoot-through pulses for ZSI.

B. Different PWM methods used to control ZSI are as follows:

a) Simple Boost Control (SBC) with triangular carrier PWM

b) SBC with sine carrier PWM

c) Maximum boost control and Maximum boost control with third harmonic injection

SBC with Triangular Carrier PWM In this technique, firing pulses are generated by comparing three sinusoidal reference signals and two constant voltage envelopes with the triangular carrier wave. The sinusoidal reference signals are phase displaced by 120 degrees and the amplitude of two envelopes is equal to the peak amplitude of reference signals. When the magnitude of the triangular carrier wave is greater than or equal to the positive envelope (or) lower than or equal to the negative envelope, shoot-through pulses are generated and they control the shoot-through duty ratio. The reference sinusoidal voltage signals along with the triangular carrier wave and two constant DC voltages are shown in Figure- 9a. The pulses produced using this method are shown in Figure-9b. For a complete switching period TS, T0 are the zero state time periods and D0 is the shoot-through duty ratio:

$$(D_0)=\frac{T_0}{T_s}$$

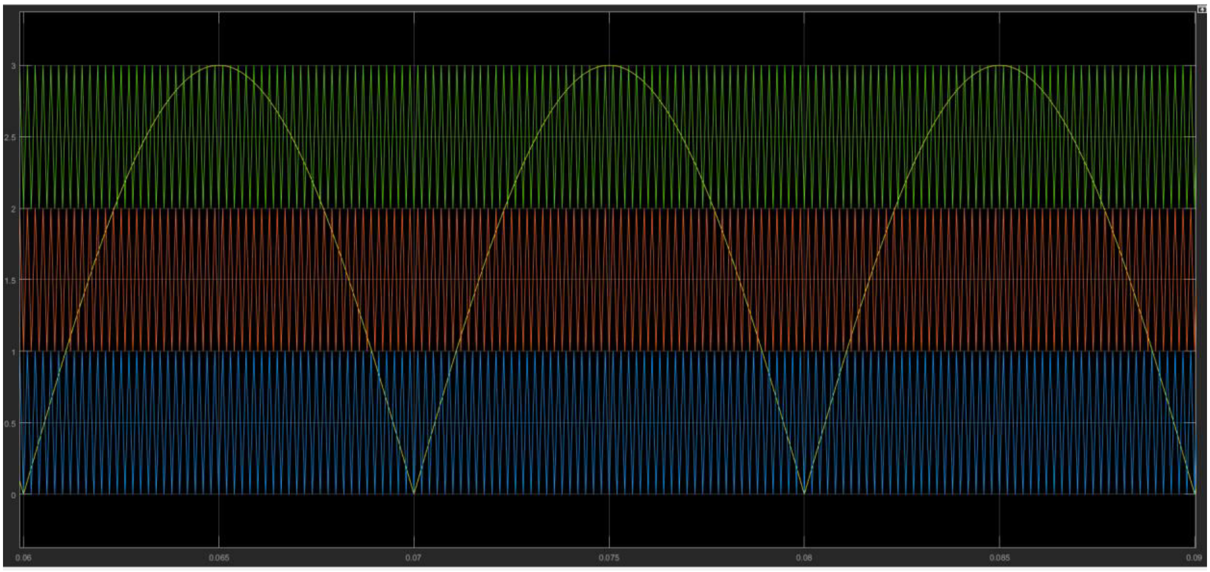


Figure4. Sinusoidal Pulse Width Modulation (SPWM)

PWM Control Methods Various Sinusoidal Pulse Width Modulation (SPWM) schemes can be applied to the ZSI.

The shoot-through duty ratio (D0), boost factor (B), and voltage gain (G) with triangular carrier wave are given by,

$$D_0 = 1 - M$$

$$B = \frac{1}{2M - 1}$$

$$G = \frac{M}{2M - 1}$$

Where, M is the Modulation Index

C. Level Shifting PWM

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 VDC level S3 and S4 ere shorted to obtain shoot through condition namely complete shoot through. During +VDC/2 level S1 and S4 were shorted and S2 and S3 were shorted to obtain shoot through for the corresponding negative part namely lower shoot through and upper shoot through respectively.

D. DYNAMIC ANALYSIS AND CONTROLLER DESIGN

The steady-state analysis of the proposed converter. The equivalent circuits are now transformed into mathematical models for a better understanding of the behavior of the proposed converter during dynamic conditions. The state-space modeling provides an easy means of analysis of switching circuits, such as the proposed converter. The inductor currents and capacitor voltages are considered as state variables in this state-space model formulation. Using KVL/KCL equations, first, a set of first-order differential equations are obtained and thereafter transformed into state-space.

4. SIMULATION RESULTS

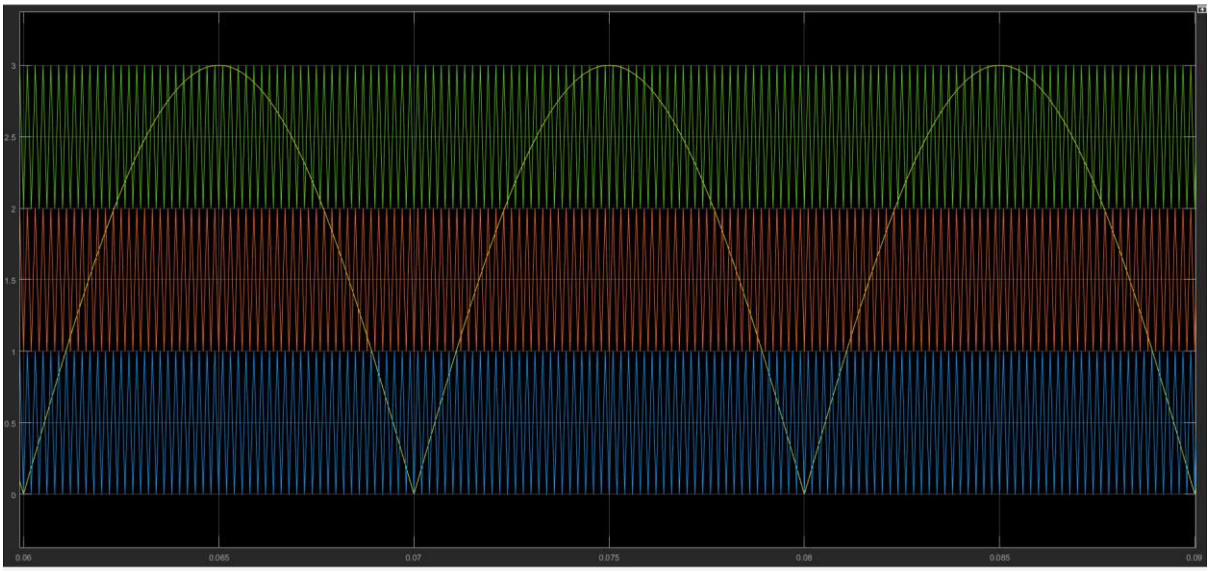


Fig5Level Shifting PWM for the 5 level output

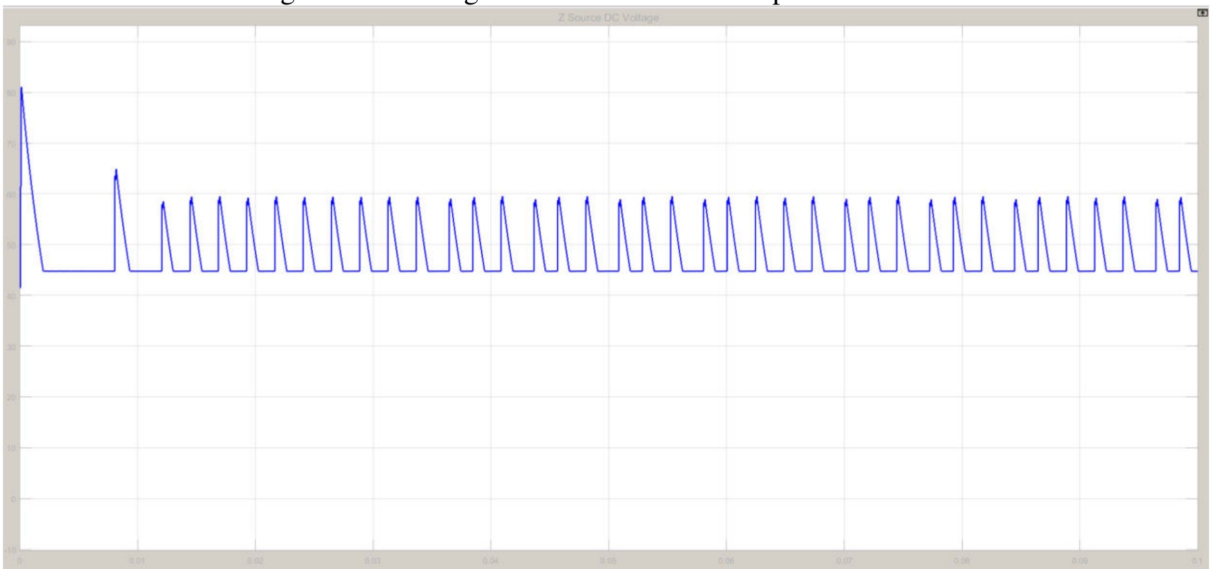


Fig6. Z source Voltage output

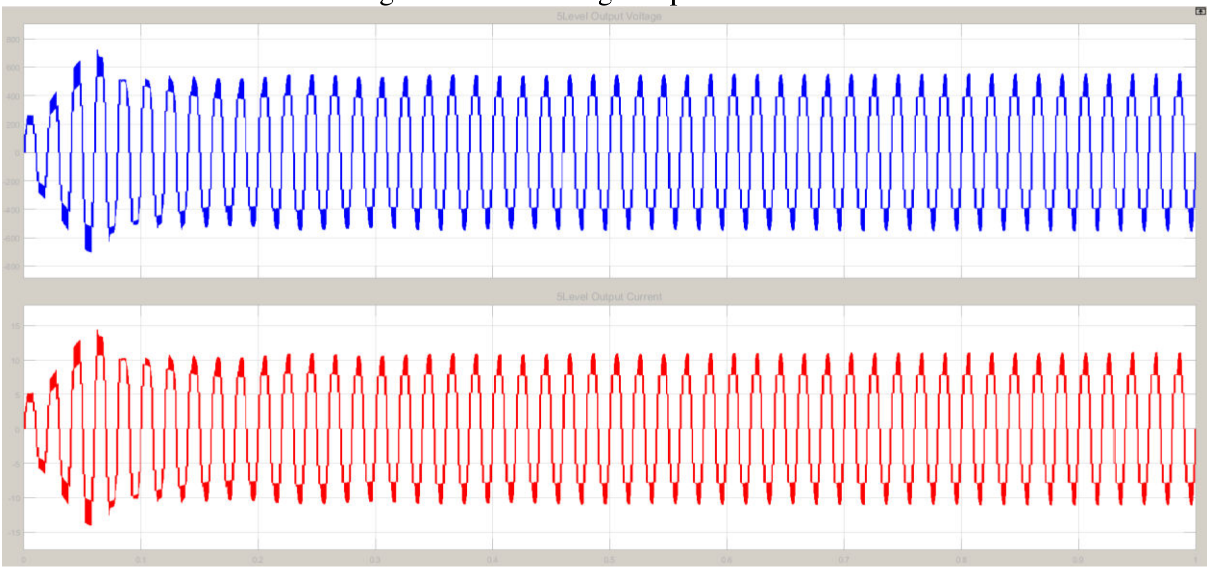
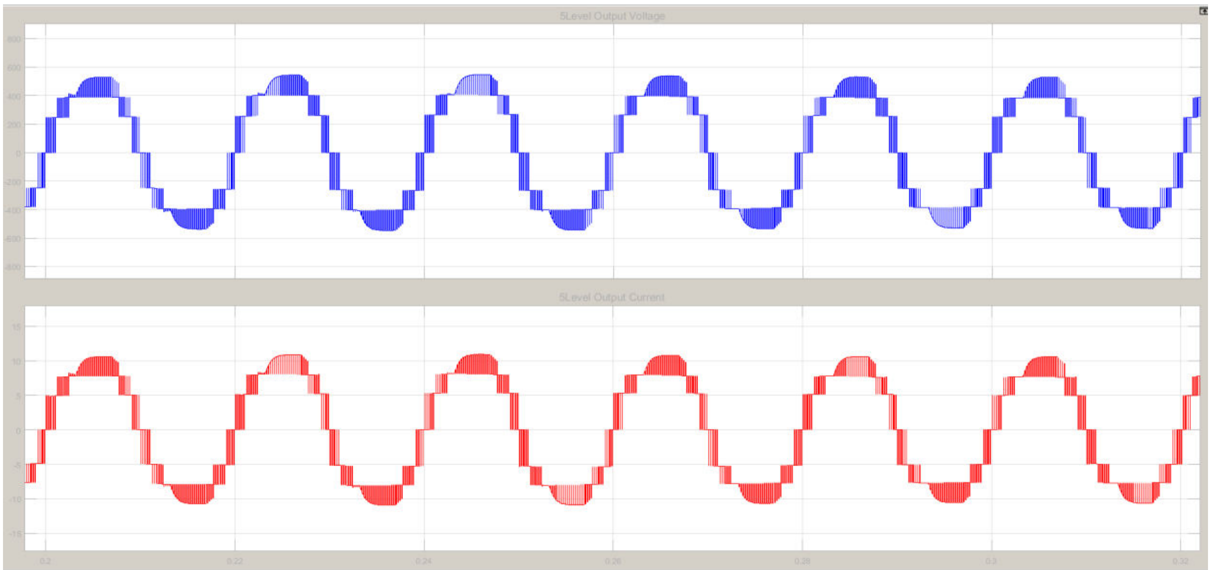


Fig7. Z source Inverter Voltage and Current Outputs



Fi8. Zoomed View of the 5Level Voltage and Current waveforms.

Conclusion

A new single-phase five-level quasi Z-source inverter is presented. The proposed topology has inherent features of both a high boosting factor and reactive power capability. A ZSCBC was proposed in this article, exhibiting voltage gain higher than QZSC while keeping the main advantages of QZSC intact, such as low Z-network capacitor voltage stress, common ground, and wider duty ratio range. The steady-state analysis of the ZSCBC and its comparison with other reported topologies 1–7 revealed that:

1) The voltage stress of the switch and all the diodes are equal irrespective of their physical location;

2) Lower switch and diode stress even at a high-voltage gain; and

3) Voltage gain enhancement through the addition of a diode–capacitor network.

Unlike the proposed converter, topologies 1–6 are unable to incorporate the voltage-gain enhancement feature. 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 their 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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