Improved Quasi Z-Source Inverter with Shoot-Through and Non-Shoot-Through Duty Ratios Prone Enhanced and Controllable Voltage Gain

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Abstract

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Abstract: The conventional quasi z-source inverters (QZSIs) are not capable of producing DC-side voltage gain through duty ratio control of switching pulses during non-shoot-through operation. This restricts freedom of control. In consequence, decoupled control between modulation index and duty ratio for producing DC-side voltage gain is not permitted. In this context, this paper proposes a novel active switched impedance network that contributes DC-side voltage gain through duty ratio control of the active switch during the non-shoot-through period. In effect, overall gain is improved. Also, variable DC-side gains are achieved at a fixed value of modulation index. Additionally, the shoot-through duty ratio based DC-side voltage gain is enhanced through the proposed active switched QZSI. The improved topology is analyzed. The simulation work is conducted in versatile operating conditions to highlight its diversified performances. The experiments also verify its operations under different conditions.

Index Terms- Improved quasi-Z-source inverter, non-shoot-through duty ratio, voltage gain, control freedom.

I. INTRODUCTION

There are various types of quasi-z-source inverters (QZSI) [1-3] that have been proposed by researchers in their recent works for practical usage. The topology is mainly used in converting low DC voltage directly into AC voltage in the applications of solar power conversion systems [4] and electrical vehicles. This is a single-stage power inverter with several advantages over a two-stage power conversion that consists of a cascaded connection of a boost converter and a voltage source inverter. The advantages are cited as both bucking and boosting of voltage conversion, pulse width modulation (PWM) of the power switch of the inverter bridge without dead time in the switching signal, reliable operation by sustaining shoot-through operation of the power switches, and no dead time-prone distortion or electromagnetic interference. The impedance network of QZSI provides DC-side voltage gain along with the prevention of short-circuit current at the DC source or DC bus. The improved non-isolated topologies for the last two decades are mentioned as extended boost [5, 6], enhanced boost [7-9], high boost or gain [10, 11], ultra-high gain [12], enhanced ultra-high gain [13], etc. All works emphasize the improvement of shoot-through-based voltage gain by reducing the range of the shoot-through duty ratio. This accomplishes the operation with a high range of modulation index (MI). There is a coupling between the relationship between shoot-through duty ratio and MI. The decoupling between the two control variables is not permissible in the above-mentioned topologies. The shoot-through state, zero state, and active state of PWM signals [14-18] are required to be chosen such that the required DC-side voltage-boosting action and power requirement at the AC-side are simultaneously fulfilled. The shoot-through state decides the voltage boost, whereas the MI decides the amplitude of the AC voltage. Here, the restriction of shoot-through span in PWM signals at high MI puts a limit on the voltage boost. Thus, high gain at a high modulation index cannot be achieved. On the contrary, the MI is lowered at higher voltage gain. This increases total harmonic distortion (THD). Thus, the QZSI (Fig. 1(a)) lacks control freedom [19]. In [20], an impedance network with two active switches for supporting independent control of shoot-through duty ratio and a modified three-phase inverter with one leg replaced by capacitors are suggested. But the dead-time is required for two legs of the switches on the inverter bridge.

In this context, a versatile active-switched QZSI is proposed, which primarily facilitates the flexibility of controlling DC-side voltage gain irrespective of the value of MI and also enhances shoot-through-based voltage gain. In addition, the separate duty ratio control during the non-shoot-through span provides extra DC-side voltage gain. The following distinguishable features of the suggested impedance network are mentioned:

i. The suggested QZSI provides DC-side voltage gain without shoot-through operation. This is not permitted for existing QZSIs.

ii. The duty ratio of the active switch (S7 in Fig. 1(b)) is different from the shoot-through duty ratio of inverter bridge switches, unlike conventional QZSIs.

iii. The ON time of the active switch (S7 in Fig. 1(b)) of the proposed impedance network is permitted to extend during the non-shoot-through period for flexibility of control.

iv. The adjustment of DC-side voltage gain can be decoupled from the adjustment of modulation ratio (or shoot-through duty ratio).

v. The shoot-through duty ratio-based DC-side voltage gain is also increased through the proposed active switched QZSI.
vi. A high boost in voltage is possible with joint controls of the duty ratios during shoot-through and non-shoot-through operations.

The operation of the suggested inverter along with its modulation method are discussed in section II. Different mathematical analyses to characterize the behaviors of the proposed QZSI are provided in section III. The investigations and results of different studies are described in section IV. Section V concludes the findings.

Sub-mode 1 (Fig. 2(b)): \( S_1 \) \( S_6 \); ON/OFF; \( S_3 \); ON; \( D_3/ D_6 \); ON; \( D_2 \); OFF; \( D_1 \); ON; \( L_2 \), \( C_1 \), \( C_2 \) and \( C_3 \); Charging; \( L_1 \) and \( L_3 \); Discharging.

Sub-mode 2a (Fig. 2(c)): \( S_1 \) \( S_6 \); ON/OFF; \( S_7 \); OFF; \( D_3/ D_6 \); ON; \( D_2 \) and \( D_7 \); OFF; \( C_2 \) and \( C_3 \); Charging; \( L_1 \) and \( L_3 \); Discharging.

Sub-mode 2b (Fig. 2(d)): \( S_1 \) \( S_6 \); ON/OFF; \( S_7 \); OFF; \( D_3/ D_6 \); ON; \( D_1 \); OFF; \( D_6 \); ON; \( C_1 \) and \( C_2 \); Charging; \( L_1 \), \( L_2 \) and \( L_3 \); Discharging.

The operation in either sub-mode 2a (Fig. 2(c)) or sub-mode 2b (Fig. 2(d)) occurs on the basis of either non-conduction or conduction of diode ‘D’.

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**II. Operation of Proposed Active Switched QZSI**

The suggested active switched impedance network (Fig. 1) comprises inductors \((L_1, L_2, L_3)\), capacitors \((C_1, C_2, C_3)\), diodes \((D_1, D_2, D_3)\), and an independently controlled switch \((S_7)\). Here, different power switches are controlled as follows:

(i) Shoot-through duty ratio adjustments are made through the control of power switches in the inverter bridge,

(ii) The duty ratio switch ‘S’ is separately controlled from the inverter bridge switches. Thus, duty ratio control during the non-shoot-through stage is permitted.

In effect, variable DC-side voltage gains are obtained irrespective of the MI of the inverter bridge.

The switch ‘S’ [21-23] is considered to mitigate the abnormal profile of the DC-bus voltage \((V_{dc})\) for wide operation.

Next, the operation and modulation method of the suggested inverter are presented as follows:

**A. Shoot-through (ST) State (0-T_s)**

In this state- \( S_1 \) \( S_6 \); ON; \( D_2 \) and \( D_3 \); OFF; \( D_1 \); ON; \( L_1 \), \( L_2 \) and \( L_3 \); Charging; \( C_1 \); Charging and \( C_2 \), \( C_3 \); Discharging.

**B. Non-shoot-through (NST) State (T_s - T_o)**

There are three sub-modes as shown in Figs. 2(b)-2(d).

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**Fig. 1: Conventional and proposed QZSIs.**

**Fig. 2: Circuits during different operations.**
C. Operations During Different Sub-intervals

The total operating period (T_o) is divided into three spans as marked in the captions of Figs. 2(a), 2(b), and 2(c) or 2(d) as;

1) Time span (0-T_o): In this mode, the inductors ‘L_1 and L_3’ are charging through the shoot-through operation of inverter bridge switches. The other inductor ‘L_2’ is also separately charged from the DC supply voltage by closing the switch ‘S_7’. This is the shoot-through span.

The non-shoot-through time span is sub-divided as,

2) Time span (T_{sh} - T_{c7}): In this time interval, the inductors ‘L_1 and L_3’ are discharging. The charging powers of capacitors and load powers are supplied like basic QZSI. But the charging process of the inductor ‘L_2’ still takes place, as given in Fig. 2(b). Thus, the ON-state time span of the switch ‘S_7’ is greater than the shoot-through time span of inverter switches. The operational flexibility of the proposed boosting network provides enhanced voltage gain beyond shoot-through duty ratio-prone voltage gain. This also gives control freedom due to the decoupling of the duty ratio of the switch ‘S_7’ from modulation index of the inverter bridge. As a result, DC-side voltage gain is independently controlled by controlling the duty ratio of the switch ‘S_7’, irrespective of the value of the modulation index.

3) Time span (T_{c7} - T_o): In this time duration, all inductors ‘L_1, L_2, and L_3’ are discharging. At this time, the circuit in either Fig. 2(c) or Fig. 2(d) is active depending on either non-conduction or conduction of diode ‘D_2’, respectively. Therefore, different voltage gains are achieved on the basis of the circuit in this time span during the non-shoot-through span.

The PWM signals for the upper switches of the inverter bridge, shoot-through pulse, and pulse for switching of ‘S_7’ are shown in Fig. 3. The various duty cycles of the PWM signals are mentioned as D_{sh}=0.25 (M=0.75), and D_{c7}=0.6.

III. VOLTAGE BOOST PERFORMANCE

In the suggested QZSI (Fig. 1(b)), two types of DC-side voltage gain arise in consideration of the circuits in Figs. 2(c) and 2(d) under non-shoot-through operation. These are presented as follows:

A. DC-bus Voltage from the modes in Figs. 2(a)-2(c)

The Volt-sec equations for the inductors ‘L_1 and L_2’ together in switching period (T_o) are mathematically written:

\[ \int_{0}^{T_o} (V_{L1} + V_{L2}) \, dt = 0 \]  

(1)

The equation in (2) is expressed from (1) as,

\[ (V_{in} + V_{C3})D_{sh} + (V_{in} - V_{C3})(D_{c7} - D_{sh}) + V_{in}D_{c7} \]

\[ + (V_{in} + V_{C1} - V_{C2})(1 - D_{c7}) = 0 \]  

(2)

Here, shoot-through duty ratio and duty ratio of active switch (s7) are symbolized as ‘D_{sh}' and ‘D_{c7}', respectively. In case of the inductor ‘L_3’ as,

\[ D_{sh}V_{c2} + (1 - D_{sh})(-V_{C3}) = 0 \]  

(3)

From (3), it is given in below,

\[ V_{C3} = \frac{D_{sh}}{1 - D_{sh}} V_{c2} \]  

(4)

From (2) and (4), the capacitor is derived as given below,

\[ V_{c2} = \frac{(1 + D_{c7})(1 - D_{sh})}{(1 - 2D_{sh})}V_{in} \]

\[ + \frac{(1 - D_{c7})(1 - D_{sh})}{(1 - 2D_{sh})}V_{C1} \]  

(5)

The peak value of DC-bus voltage is calculated from (6) using (4) and (5),

\[ \hat{V}_{dc} = V_{c2} + V_{C3} = B_{p1} V_{in} \]  

(6)

In (6), boosting factor is denoted as ‘B_{p1}'. The gain of conventional QZSI is,

\[ B \overset{c}{=} \frac{1}{1 - 2D_{sh}} \]  

(7)

D. Pulse Width Modulation (PWM) Logic

The simple boost control (SBC) PWM [16] technique for the proposed QZSI is applied.

![Fig. 3: Pulses for switching of upper leg switches and S7, and ST state.](image)

![Fig. 4: B_{p1} vs. D_{sh} using (4)-(6) and V_{c2}=V_{in}.](image)
The plots in Fig. 4 present the enhancement of shoot-through-based voltage gain is achieved for the proposed case in comparison to conventional gain.

**B. DC-bus Voltage from the modes in Figs. 2(a), 2(b), 2(d)**

In the inductor ‘L2’ the mathematical expression is written,

\[ D_{sh}V_{in} + (1 - D_{sh})(V_{in} - V_{c2}) = 0 \]  \hspace{1cm} (8)

From (4) and (8), the following equations are derived,

\[ V_{c2} = \left( \frac{1}{1 - D_{sh}} \right) V_{in}, \quad V_{c3} = \left( \frac{D_{sh}}{1 - D_{sh}} \right) \left( \frac{1}{1 - D_{sh}} \right) V_{in} \]  \hspace{1cm} (9)

Therefore, the peak of DC-bus voltage is,

\[ \hat{V}_{dc} = \left( \frac{1}{1 - D_{sh}} \right) \left( \frac{1}{1 - D_{sh}} \right) V_{in} = B_p V_{in} \]  \hspace{1cm} (10)

In (10), the ‘B_p’ indicates boosting gain. In (4) to (6) and (10), the duty ratios and MI varies as, \(0 < D_{sh} < 0.5, 0 < D_{s7} < 1\) and \(0 < M < 1\).

The plots in Fig. 5 reveal that the boosting gain is varying with the variations of the duty ratio \(D_{s7}\) of the active switch ‘S7’. Here, the gain due to the variation increases at a particular value of shoot-through duty ration \(D_{sh}\). Thus, it indicates decoupled duty ratio control of ‘S7’ from shoot-through duty ratio is permissible using the proposed QZSI to obtain variable DC-side voltage gain.

**IV. STUDIES AND RESULTS**

The parameters in the different studies are mentioned in Table 1. The performance of the proposed QZSI under diversified working conditions is tested. Both simulation and experimental studies for verification of the performances are discussed as follows:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductors ((L_a, L_b, L_c))</td>
<td>0.5 mH</td>
</tr>
<tr>
<td>Capacitors ((C_a, C_b))</td>
<td>220 μF</td>
</tr>
<tr>
<td>Filter inductor ((L_f))</td>
<td>1 mH</td>
</tr>
<tr>
<td>Filter capacitor ((C_f))</td>
<td>50 μF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10 kHz</td>
</tr>
</tbody>
</table>

\[ \begin{align*}
V_{in} &= 0 \text{ to } 72 \text{ V} \\
V_{out} &= 288 \text{ V}
\end{align*} \]

A. Verification in simulation platform

The following case studies are presented as,

1. **Operation with variable shoot-through duty ratios:**

The working of the suggested QZSI is tested under the different shoot-through duty ratios as \(D_{sh} = 0.2\) (\(M = 0.8\)) and \(D_{sh} = 0.4\) (\(M = 0.6\)). The results are shown in Figs. 6 (a) and 6 (b) respectively. Here, the duty ratio of the active switch ‘S7’ is fixed at the value of 0.6, i.e., \(D_{s7} = 0.6\).

![Fig. 6: Responses under different shoot-through duty ratios.](image-url)
peaks of the output AC voltage \(V_{oa}\) in the two cases closely match the calculated values of 96 V and 216 V respectively. The responses in Fig. 6 agree with the calculated values.

![Capacitors and input voltages](Image 58x605 to 188x692)

![Output voltage](Image 112x277 to 243x366)

ii. Operation with variable duty ratios of the switch ‘S’ at fixed MI or shoot-through duty ratio:

Then, the operation of the suggested QZSI is tested under the different duty ratios of the controlled switch, as \(D_{S1}=0.5\) and \(D_{S2}=0.6\). The responses are given in Figs. 7 (a) and 7 (b) respectively. In the operations, the shoot-through duty ratio is fixed at the value of 0.1, i.e., \(D_{sh}=0.1\) (M=0.9). With the input voltage \(V_{in}\) of 72 V, the capacitor voltage \(V_{c1}\) is found as 72 V. The two capacitor voltages of impedance network \(V_{c2}, V_{c3}\) alter from 162 V (according to (5)) to 180 V (according to (9)) and from 18 V (according to (4)) to 20 V (according to (9)) respectively due to the step up of duty ratio of ‘S’ from 0.5 to 0.6. The peak value of DC-bus voltage increases from 180 V (according to (6)) to 200 V (according to (10)). The responses in Fig. 7 agree with the calculated values. In Figs. 7 (a) and 7 (b), the amplitudes of AC-side voltage \(V_{oa}\) are equal to the calculated values of 81 V and 90 V, respectively.

Figs. 6 and 7 reveal that the DC-side voltage gain is achieved with the adjustments of shoot-through and non-shoot-through duty ratios.

![Inductors currents and scaled (1:15) DC-bus voltage](Image 329x354 to 457x440)

![Capacitors and input voltages](Image 383x248 to 512x334)

![Output voltage](Image 380x442)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 468x376 to 567x440)

![Capacitors and input voltages](Image 470x593 to 567x659)

![Output voltage](Image 495x452)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 503x564 to 567x683)

![Capacitors and input voltages](Image 518x717)

![Output voltage](Image 528x729)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 540x81)

![Capacitors and input voltages](Image 546x85)

![Output voltage](Image 557x85)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 563x96)

![Capacitors and input voltages](Image 565x96)

![Output voltage](Image 570x96)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 574x108)

![Capacitors and input voltages](Image 577x108)

![Output voltage](Image 581x108)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 583x119)

![Capacitors and input voltages](Image 588x119)

![Output voltage](Image 591x119)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 595x131)

![Capacitors and input voltages](Image 598x131)

![Output voltage](Image 602x131)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 604x142)

![Capacitors and input voltages](Image 608x142)

![Output voltage](Image 610x142)

![Inductors currents and scaled (1:15) DC-bus voltage](Image 612x142)

![Capacitors and input voltages](Image 615x142)

![Output voltage](Image 617x142)

iii. Voltage boosts without shoot-through operation (M=1):

The operation of the proposed active-switched QZSI at M=1 with \(D_{sh}=0.5\) is performed, and the results of various variables are shown in Fig. 8(a). The responses obtained agree with the expected values. This case study discloses its DC-side voltage-boosting capability without shoot-through state \(D_{sh}=0\).

At M=1, the different DC-bus voltage in Fig. 8(b) is achieved by changing \(D_{S1}=0.6\) from \(D_{S2}=0.5\) in Fig. 8(a). Thus, variable stepped-up DC-bus voltages are obtained at M=1 with the proposed boost inverter.

![Inductors currents and scaled (1:15) DC-bus voltage](Image 614x154)

![Capacitors and input voltages](Image 617x154)

![Output voltage](Image 620x154)
B. Experimental Studies

The performances of the proposed QZSI under versatile operations are experimentally tested. The power switches (MOSFET: 2sk3878) are used to fabricate the proposed QZSI. The PWM signals produced by the controller (NUCLEO-G474RE development board) are applied to trigger the power switches via the driver (TLP 250).

The recorded responses using a digital storage oscilloscope are presented in Figs. 9-11. Fig. 9 presents the different waveforms when the boost inverter is controlled by SBCPWM signals having ‘M=0.8’ and ‘D_{sh}=0.6’, respectively.

![Waveforms](image)

The operation under different test conditions from Fig. 9 is performed. Here, ‘M=0.9’ and ‘D_{sh}=0.5’ are used. The responses of various variables under the test condition are shown in Fig. 10.

![Waveforms](image)

Fig. 11 shows the different waveforms when the boost inverter is controlled by SBCPWM signals having ‘M=1.0’ and ‘D_{sh}=0.5’, respectively. Here, the shoot-through state is absent, and the DC-bus voltage shows a flat profile.

![Waveforms](image)
V. CONCLUSIONS

An improved quasi-z-source network has been introduced in this paper. The merits of the suggested inverter are mentioned as follows: (i) the DC-side voltage gain is achieved through combined duty ratio controls during shoot-through and non-shoot-through operations; (ii) enhanced voltage gain is achieved through non-shoot-through duty ratio control; (iii) the non-shoot-through duty ratio is decoupled from modulation index for getting variable DC-side voltage gain at a fixed value of modulation index; (iv) operation at M = 1 with variable voltage gain is permitted; (v) In addition to control freedom, the shoot-through-prone DC-side voltage gain is augmented through the suggested active switched qZSI. The diverse features declare the proposed boost inverter a superior option over the existing QZSIs.

REFERENCES