Design and Implementation of Step Up DC-DC Converter with a Cascaded Quasi-Z Source Network

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Abstract—This paper proposes a new topology of quasi-Z-source inverter (qZSI) which is used as step-up isolated dc/dc converter for residential fuel cell (FC) power systems. The proposed topology used is cascaded quasi Z source inverter and implemented using induction motor. The cascaded qZSI is derived by the adding of one diode, one inductor and two capacitors to the traditional qZSI. The proposed two-stage qZSI has all the advantages of conventional qZSI such as voltage boost and buck functions in a single stage, continuous input current, improved reliability and adds a feature such that it reduces the shoot-through duty cycle by over the 30% for the same voltage boost factor and component stresses of qZSI. The main focus of this paper is on the power conditioning units (PCUs) for residential power systems using two stage qZSI (cascaded qZSI), single phase isolation transformer, and a voltage doubler rectifier. Theoretical analysis of the two-stage qZSI in shoot-through and non-shoot-through operating modes is presented. The simulation and experimental results are also discussed and presented using Matlab.

Keywords—Quasi-Z-Source Inverter (qZSI), Cascaded qZSI, Fuel Cell (FC), Power Conditioning Unit (PCU), Voltage Doubler Rectifier (VDR), Voltage Source Inverter, Current Source Inverters

I. Introduction

The Z-source inverter (ZSI, Fig. 1a) is been introduced to overcome the problems of voltage source (VSI) and current source converters (CSI) by providing a new power conversion concept used for different renewable power applications such as fuel cells, solar panels and wind power generators, because of the unique capability of voltage boost and buck functions in a single stage [1-3]. ZSI 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 and hence three phase ZSI has nine switching states unlike VSI has eight states. The ninth switching state is forbidden for the traditional voltage source converters (VSI) because it causes the short circuit of the dc link capacitors. In the ZSI, the shoot-through states are used to boost the magnetic energy stored in the dc side inductors L1 and L2 without short-circuiting the dc capacitors C1 and C2 which boost the inverter output voltage during traditional operating states. If the input voltage is high enough the shoot-through states are eliminated and ZSI begins to operate as traditional VSI. The voltage-fed ZSI has a significant drawback such as discontinuous input current during the shoot-through mode. This problem is overcome by introducing quasi-Z-source inverter (qZSI) with continuous input current [4-6]. The voltage-fed qZSI features all the advantages of the ZSI and also ensures the continuous input current. This paper discusses the performance improvement method for the voltage-fed qZSI with continuous input current and improved reliability by the introduction of the two-stage quasi-Z-source (qZS) network, moreover the boost range is increased by cascading another stage at front end without increasing the number of switches. The 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 Fig. 1c. By the implementation of the proposed two-stage qZS-network the duty cycle of the shoot-through state could be sufficiently decreased to 30% for the same voltage boost factor and component stresses as compared to traditional qZSI.
II. CASCADED QUASI-Z-SOURCE NETWORK, EQUIVALENT CIRCUITS AND ITS OPERATION

This paper shows an implementation of cascaded qZSI for power conditioning unit. This means that low voltage from the energy source first passes through the front-end step-up dc/dc converter with galvanic isolation; afterward, the output dc voltage is inverted in the three-phase inverter and filtered to comply with the imposed standards and requirements (second dc/ac stage). The topology proposed with a cascaded qZS-network, a high-frequency step-up isolation transformer, and a voltage-doubler rectifier (VDR) performs the concept of dc/dc step-up converter suitable for PCUs.

A direct step-up dc/dc converter without input voltage pre-regulation is simpler in control and protection and provides high voltage gain when compared to traditional isolated full bridge converters. The varying voltage from the FC passes through the high-frequency inverter to the step-up isolation transformer. Due to rebooted voltage the isolation transformer has moderate turns ratio (1:7-1:8), which exerts a positive impact in terms of leakage inductance and efficiency[7]. This project is devoted to a new power circuit topology to be implemented in the front-end dc/dc converter such that the converter provides the following advantages as increased reliability, isolation transformer with reduced turns ratio, and reduced impact on the FC due to continuous input current for residential power generation.

A. Modes of Operation

To regulate the varying input voltage, the front-end qZSI has two different operating modes: shoot-through and non-shoot through. In the non-shoot-through mode, the qZSI performs only the voltage buck function. This operation mode is typically used during light-load conditions, when the output voltage of an FC or a solar panel reaches its maximum. The inverter is controlled in the same manner as with the traditional VSI, utilizing only the active states when one and only one switch in each phase leg conducts. The transistors in the full-bridge configuration are controlled alternately in pairs (T1 and T4 or T2 and T3, Fig. 3) with 180°-phase-shifted control signals. In this operating mode, the duty cycle of inverter switches could never exceed 0.5. The equivalent circuit of the two-stage qZSI during non-shoot-through (active) states is shown in Fig. 4.1.

When the input voltage drops below some predefined value, the qZSI starts to operate in the shoot-through mode. In order to boost the input voltage during this mode, a special switching state—the shoot-through state—is implemented in the PWM inverter control. During the shoot-through states, the primary winding of the isolation transformer is shorted through all switches of both phase legs Fig. 4.2. Moreover, the shoot-through states are used to boost the magnetic energy stored in the dc-side inductors \( L_1, L_2, \) and \( L_3 \) without short circuiting the dc capacitors \( C_1 \) to \( C_4 \). This increase in the magnetic energy, in turn, provides the boost of the voltage seen on the inverter output during the active states. The equivalent circuit of the two-stage qZSI during the shoot-through state is shown in Fig. 4.3(b).

There are seven different shoot-through states: three shoot-through states via any one phase leg, three shoot-through states from combinations of any two phase legs, and one shoot-through state by all the three phase legs.
Fig. 6 Generation of PWM signals with shoot-through states during zero states.

III. CIRCUIT ANALYSIS OF THE CASCADED QZS-NETWORK

In the non-shoot-through mode, the inverter bridge viewed from the dc side is equivalent to a current source [Fig. 4]. From Fig. 5(a), for the active states, the voltages of the inductors can be represented as

\[ v_{L1} = V_{IN} - V_{C1} \] (1)
\[ v_{L2} = V_{C4} + V_{C2} = V_{C1} - V_{C3} \] (2)
\[ v_{L3} = -V_{C4} \] (3)

From the equivalent circuit of the two-stage qZSI during the shoot-through state [Fig. 5(b)], the voltages of the inductors can be represented as

\[ v_{L1} = V_{IN} + V_{C2} \] (4)
\[ v_{L2} = V_{C4} + V_{C1} \] (5)
\[ v_{L3} = V_{C3} \] (6)

Let us consider that the duty cycles of the shoot-through and non-shoot-through states are \( D_S \) and \( 1 - D_S \), correspondingly. At steady state, the average voltages of the inductors over one switching period are zero

\[ \bar{v}_{L1} = \frac{1}{T} \int_{0}^{T} v_{L1} dt = 0 \] (7)
\[ \bar{v}_{L2} = \frac{1}{T} \int_{0}^{T} v_{L2} dt = 0 \] (8)
\[ \bar{v}_{L3} = \frac{1}{T} \int_{0}^{T} v_{L3} dt = 0 \] (9)

From (1)–(9), we obtain

\[ \bar{v}_{L1} = D_S (V_{IN} + V_{C2}) + (1-D_S) (V_{IN} - V_{C1}) = 0 \] (10)
\[ \bar{v}_{L2} = D_S (V_{C4} + V_{C1}) + (1-D_S) (V_{C4} - V_{C2}) = 0 \] (11)
\[ \bar{v}_{L2} = D_S (V_{C4} + V_{C1}) + (1-D_S) (V_{C1} - V_{C3}) = 0 \] (12)
\[ \bar{v}_{L3} = D_S (V_{C3}) - (1-D_S) (V_{C4}) = 0 \] (13)

Solving (8), the voltages of capacitors \( C_1, \ldots, C_4 \) could be found as

\[ V_{C1} = V_{IN} \times \frac{[1-2D_S]}{[1-3D_S]} \] (14)
\[ V_{C2} = V_{IN} \times \frac{2D_S}{[1-3D_S]} \] (15)
\[ V_{C3} = V_{IN} \times \frac{[1-D_S]}{[1-3D_S]} \] (16)
\[ V_{C4} = V_{IN} \times \frac{D_S}{[1-3D_S]} \] (17)

The peak dc-link voltage across the inverter bridge is

\[ V_{dc} = V_{C1} + V_{C2} + V_{C3} + V_{C4} = V_{IN} \times \frac{1}{[1-3D_S]} \] (18)

The resulting boost factor \( B \) of the input voltage is

\[ B = \frac{V_{dc}}{V_{IN}} = \frac{1}{[1-3D_S]} \] (19)

For the desired input voltage boost factor \( B \), the duty cycle of the shoot-through state is calculated as

\[ D_S = \frac{1-B^4}{3} \] (20)

Higher stage qZS-networks can be designed by just multiple repeating of the parts \( D2-C3-L3-C4 \) [Fig. 1(b)]. For the \( n \)th stage qZS-network, the boost factor \( B \) of the input voltage is

\[ B_n = \frac{1}{[1-D_S (1+n)]} \] (21)

where \( n \) is the number of stages \( (n = 1 \text{ for traditional qZSIs, } n = 2 \text{ for two-stage qZSIs, etc.). The shoot-through duty cycle of the qZSI with two-stage qZS network and positive input voltage should never exceed the value defined by (21):} \]

\[ D_{s,max} < 1/3 \] (22)

IV. COMPARISON OF CASCADED QZSI WITH THE TRADITIONAL QZSI

A. Boost Performance Comparison

In contrast to the proposed two-stage qZS-network, the boost factor of the traditional topology based on two capacitors, two inductors, and one diode [single-stage qZS-network, Fig. 1(a)] is

\[ B = \frac{1}{[1-2D_S]} \] (23)

By comparing (19) and (21), the proposed two-stage qZS-network features a 33.3% smaller shoot-through duty cycle at the same boost factor of the input voltage than the traditional qZS network. It means that the time of the shoot-through states of the two-stage qZS could be decreased by 33.3% for one switching period. The shoot-through duty cycle of the qZSI with the cascaded and positive input voltage should never exceed one-third of the switching period as shown in (22), while in the traditional topology, it is, in theory, possible to use the shoot through duty cycle values up to one-half.

B. Comparison of Component Ratings

In Table I, the operating voltages of the inductors and capacitors during the shoot-through states are compared for the traditional and the two-stage qZS-networks. The average currents through the inductors in both configurations have the same value

\[ I_{L,av} = P/V_{IN} \] (24)

where \( P \) is the system power rating and \( V_{IN} \) is the input voltage. The maximum current through the inductors in both configurations occurs when the maximum shoot-through happens, which causes maximum ripple current. A 20% peak-to-peak current ripple through the inductors during maximum power operation was assumed for the comparison. During the shoot-through states, the voltages of inductors \( L1, L2, \) and \( L3 \) will have the same values and could be easily derived from (19). With the assumed peak-to-peak current ripple, the inductance for \( L1, L2, \) and \( L3 \) for the cascaded qZS-network can be calculated by
where \( f \) is the operating frequency of the qZS-network. In the case of the traditional qZS-network, the inductance under the same operating conditions is

\[
L_1 = L_2 = \frac{V_{\text{IN}} D_1}{0.2 \pi f L_{\text{LV}}} = \frac{V_{\text{IN}}^2}{0.2 \pi f^2 L_{\text{LV}}} \left(1 - D_1\right) \frac{1}{1 - 2D_1} \tag{25}
\]

(25)

As stated earlier, at the same boost factor, the two-stage qZS-network features a shoot-through duty cycle that is 33.3% lower. Finally, it means that, at the same operating conditions and target value of the dc-link voltage, the inductors in the two-stage configuration will have inductance values around 25% smaller than those of a traditional topology. Capacitors also play a very significant role in the qZS network, absorbing the current ripple and limiting the voltage ripple across the inverter bridge. The capacitance of capacitors \( C_1, C_2, C_3, \) and \( C_4 \) in the cascaded qZS-network should be

\[
C_1 = C_2 = C_3 = C_4 = \frac{0.2 \pi f D_1}{0.03 V_{\text{IN}}^2 * V_{\text{DC}} f} = \frac{0.015 V_{\text{IN}}^2}{0.015 V_{\text{DC}} f} \tag{27}
\]

(27)

Under the same operating conditions, the capacitance of capacitors \( C_1 \) and \( C_2 \) in a traditional qZS network is

\[
C_1 = \frac{0.2 \pi f D_1}{0.03 V_{\text{IN}}^2 * V_{\text{DC}} f} = \frac{0.015 V_{\text{IN}}^2}{0.015 V_{\text{DC}} f} \tag{28}
\]

(28)

For the same operating conditions and target value of the dc-link voltage, the capacitors in the two-stage configuration should have capacitance values that are 33.3% lower than those of a traditional topology. The average current through the diodes of the qZS-network equals the average current through the inductors in both of the compared topologies.

### Table I: Operating Voltages of the Inductors and Capacitors of the Traditional and Two-Stage QZS-Networks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Traditional qZS-network</th>
<th>Two-stage qZS-network</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{C1} )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-2D_3) )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-3D_3) )</td>
</tr>
<tr>
<td>( V_{C2} )</td>
<td>( V_{\text{IN}} \times (1-2D_3) )</td>
<td>( V_{\text{IN}} \times (2D_3)/(1-3D_3) )</td>
</tr>
<tr>
<td>( V_{C3} )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-2D_3) )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-3D_3) )</td>
</tr>
<tr>
<td>( V_{C4} )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-2D_3) )</td>
<td>( V_{\text{IN}} \times (1-D_3)/(1-3D_3) )</td>
</tr>
<tr>
<td>( V_{L1} )</td>
<td>( V_{\text{IN}} + V_{C2} )</td>
<td>( V_{\text{IN}} + V_{C2} )</td>
</tr>
<tr>
<td>( V_{L2} )</td>
<td>( V_{C1} )</td>
<td>( V_{C4} + V_{C1} )</td>
</tr>
<tr>
<td>( V_{L3} )</td>
<td>( V_{C3} )</td>
<td>( V_{C3} )</td>
</tr>
</tbody>
</table>

### Table II: Simulation Parameter

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( L_1, L_2 )</td>
<td>10( \mu )H</td>
</tr>
<tr>
<td>2</td>
<td>( C_2, C_4 )</td>
<td>10( \mu )F</td>
</tr>
<tr>
<td>3</td>
<td>( C_1 = C_3 )</td>
<td>220( \mu )F</td>
</tr>
<tr>
<td>4</td>
<td>( C_5 = C_6 )</td>
<td>20( \mu )F</td>
</tr>
<tr>
<td>5</td>
<td>Switching Frequency</td>
<td>1 kHz</td>
</tr>
<tr>
<td>6</td>
<td>Input voltage (Vin)</td>
<td>80v</td>
</tr>
<tr>
<td>7</td>
<td>Cascaded qzsi output (Vdc)</td>
<td>150v</td>
</tr>
<tr>
<td>8</td>
<td>Transformer ratings</td>
<td>100 VA, 10kHz</td>
</tr>
<tr>
<td>9</td>
<td>Transformer ratio</td>
<td>1:4</td>
</tr>
<tr>
<td>10</td>
<td>Voltage doubler output (Vout)</td>
<td>364v</td>
</tr>
<tr>
<td>11</td>
<td>Induction motor rating</td>
<td>1000VA, 500Vrms, 50Hz</td>
</tr>
<tr>
<td>12</td>
<td>Motor speed</td>
<td>1484 rpm</td>
</tr>
</tbody>
</table>

The PCU with cascaded qZSI is simulated using Matlab/Simulink R2009b and Simpower system in Mat lab
library shown in Fig.8 and Fig.9 and the parameters are shown in above Table II

Fig. 11. Single Phase Inverter Output

Fig. 12. Voltage Doubler Output

Fig. 13. Output three phase inverter (line voltages) $V_{ab}$, $V_{bc}$, $V_{ca}$

Fig. 14. Motor Speed

A. Closed Loop Simulation

On simulating the PCU, we can observe that the input voltage of 80V is been boosted to 150V as shown in fig.10. This shows the boost ratio is 1.8, consisting of small value of inductors and capacitors. Switching pulse is given by means of pulse generator with time period of 0.5T for each transistor and pulse width of 50%. Single phase inverter used here inverts the dc voltage of 150v from cascaded qZSI to ac voltage which is a square wave (fig.11). An isolation transformer with small step up ratio 1:2 is used here, due to losses in the transformer the output of transformer is not exactly twice. The VDR connected doubles the output from transformer exactly (fig.12) from 200V to 400V. The dc output obtained from VDR is again fed into a three phase inverter and induction motor, which can run the motor at a speed of 1484 rpm (fig.14). The Fig.13 shows the line voltage of three phase inverter which is around 347V. Thus the proposed step up dc-dc converter, which included cascaded qZSI, transformer and VDR can boost a low dc voltage to run a three phase induction motor.

Fig. 15 Closed loop circuit with disturbance

Fig. 16. input voltage for closed loop with disturbance

Fig. 17. output voltage for closed loop with disturbance
Fig. 18: Output current for closed loop with disturbance.

Simulation is done closed loop disturbance circuit separately (Fig. 15). The closed loop circuit consist of cascaded qZSI, isolation transformer, VDR with R load 100 ohms and PI Controller. Open loop circuit simulated without PI controller but for closed loop it is observed by giving disturbance voltage. The disturbance circuit consist of input voltage 50V in which disturbance is given after 2s time period and the disturbance voltage is 62V as shown in Fig. 16. The Fig. 17 shows that the disturbed voltage on closed loop is settled in closed loop circuit compensates the disturbed voltage. Thus the output voltage is been regulated for varying input voltage in closed loop circuit.

VI. EXPERIMENTAL VERIFICATIONS

The following calculations shows the theoretical output to be obtained at each stage of the whole system. Table III shows the comparison of theoretical value and simulation results obtained using Mat lab/simulink.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Theoretical value</th>
<th>Simulation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{dc}$</td>
<td>160V</td>
<td>145.9V</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>2V</td>
<td>1.825</td>
</tr>
<tr>
<td>$V_{oU}$</td>
<td>212.8V</td>
<td>195.5V</td>
</tr>
<tr>
<td>$V_{out}$</td>
<td>425.6V</td>
<td>363.8V</td>
</tr>
<tr>
<td>$V_{ph}$</td>
<td>200.63V</td>
<td>171.5V</td>
</tr>
<tr>
<td>$V_{pH}$</td>
<td>347.5V</td>
<td>360V</td>
</tr>
<tr>
<td>$C_1, C_2, C_4$</td>
<td>9.8µF</td>
<td>20 µF</td>
</tr>
<tr>
<td>$L_1, L_2, L_3$</td>
<td>7.7mH</td>
<td>10 µF</td>
</tr>
</tbody>
</table>

Here, Output of cascaded qZSI ($V_{dc}$) = 160V

$D_s = \frac{1}{3} \left( B_{max} \right)^{1/3} \approx 0.167$

Transformer ratio = 1:1.33.

Therefore, Transformer o/p ($V_{oU}$) = 212.8V

Voltage doubler rectifier o/p ($V_{out}$) = $V_{c1} + V_{c2} = 425.6V$

$V_s = \sqrt{2/3} \cdot V_d = 200.63V$.

$V_s = \sqrt{2/3} \cdot V_d = 347.5V$.

Given $P = 115w$, $V_{in} = 80v$, $f = 10kHz$. By Substituting the Values in eqn (27), $C_1 = C_2 = C_4 = 9.8µF$. By Substituting the Values in eqn (25), $L_1 = L_2 = L_3 = 7.7mH$.

VII. CONCLUSION

The paper focuses on PCUs using cascaded qZSI as a major part for residential power system which can be fed by a renewable energy source such as Fuel cells. The proposed cascaded qZS network inherits all the advantages of traditional solutions and reduced the shoot-through duty cycle by over 30% at the same voltage boost factor and component stresses as the conventional qZSI. By cascading or increasing the number of stages of qZS network the shoot through duty cycle can be further decreased. Voltage stress is lower when compared to ZSI. The turns number of the secondary winding of the isolation transformer could be reduced by turns ratio of 1 : 2 in the case of VDR instead of 1 : 10 of traditional full-bridge rectifiers due to the voltage doubling effect available with the VDR. The high-frequency step-up isolation transformer (1:2) provides the required voltage gain as well as input output galvanic isolation. The closed loop circuit is simulated using PI controller for an R load of 100 ohms. The proposed cascaded qZSI can be applied to almost all dc/ac, ac/dc, ac/ac, and dc/dc power conversion schemes. It can be used in demanding applications as power conditioners for FCs and solar panels. Thus the proposed circuit is implemented using induction motor and simulated using Mat lab/simulink.

REFERENCES