A New Configuration for Power Sharing of Two Z-Source Inverters

M. Ghani Varzaneh*, A. Rajaei* and M. Fakhraei

Abstract: This paper presents a new structure to provide the ability for power sharing of two Z-source inverters. According to the operation principles of Z-source inverters, only one input source supplies the circuit, which is a limitation particularly for the stand-alone systems fed by limited output power such as photovoltaics and fuel cells. Furthermore, if one source fails to supply, the load can't be supplied. This paper covers those via interconnection of impedance network of two Z-source inverters. The operating principles of the proposed topology for the stand-alone and power sharing conditions are described and the relations are derived. The topology is simulated, which the results verify the theoretical analysis and well performance of the system.

Keywords: Z-Source Inverter (ZSI), Power Sharing, DC-DC Converter, Photovoltaic System (PV).

1. Introduction
Nowadays; Replacing fossil fuels by renewable energy sources gathers much of interests in the recent decades. fuel cells [1].

One of the main types of renewable energy resources is photovoltaic (PV). PV's output voltage is limited and varies in a wide range, therefore employing step-up DC-DC converters between PV and inverter is inevitable. This extra power stage have some disadvantages related to efficiency, reliability and cost. Another configurations is employing impedance-source inverters [2]. Ref. [2] introduced a new circuit named Z-source inverter (Fig. 1). The circuit was built from an impedance network placed between the input DC source and the inverter and make the capability of step up the output voltage. An extra switching state called shoot-through state is applied which all the switches turned on. This configuration hadn't any extra transistors in its arrangement and only uses two inductors, two capacitors and a diode. The circuit has some advantages than switching DC-DC converters such as higher efficiency, lower cost and size and more reliability because of eliminating short circuit condition caused from turning on both switches of any inverter leg simultaneously. Afterwards, more efforts would do to improve Z-source inverters and could introduce better topologies [3-16].

Because of PV power dependency to several factors such as irradiation, panel temperature and etc., supplying a standalone load by PV systems [17]. To overcome the problem, the idea of using energy storage means such as batteries is a good way. Batteries can charge via the input or from the output if the output stage is bidirectional. In this system; batteries can discharge if the input can't handle the output power. Therefore; when it is necessary and if batteries has enough energy; the battery can act as a source in helping of the input source. In [18] by substituting one of the impedance networks capacitors with a battery a control system is proposed , to control the PV power, output power, and battery state of charge (SOC) at the same time., therefore, the cost and complexity of Z-source inverter is reduced.

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Fig. 1. Z-source inverter [2].
Ref. [19] studied load flow in a quasi Z-source inverter (qZSI) with a battery connected to one of the capacitors. Owing to presence of the battery, system can generate demand power. Proposed energy management secures the battery from over charging and over discharging. In [20-27], a PV system based on qZSI with energy storage is presented. The steady state relations are described in [20] and dynamic small-signal model of qZSI is extracted in [27]. The difference of the studies of [21] and [20] is the selection of the capacitor which is substituted with a battery. Ref. [21] has compared inductors current of proposed model with [20] in the various condition of input power, output power and SOC of battery in a table. Ref. [22] has established an enhanced frequency diving coordinated control strategy to optimize the dynamic power regulation and the battery current stress in short time scale in a hybrid ultracapacitor-battery system. Ref. [28] is similar to [22] in selection of a hybrid ultracapacitor-battery system but [28] use a Z-source inverter instead of a qZSI. In [23] a controller has been equipped with a harmonic compensator to control the battery current in the grid-connected mode and to regulate the microgrid voltage in the islanded mode in the presence of unbalanced and non-linear loads. Furthermore, the proposed controller adjusts the shoot-through duty cycle of the qZSI to regulate the PV voltage to its reference value provided through the maximum power point tracking algorithm. Ref. [24] has studied the operation of the system in presence of two batteries in parallel with two capacitors. Ref. [29] has considered the system which gets its power from wind energy that battery is in an auxiliary bidirectional circuit which gives and gets energy to a capacitor DC link of the rectifier. Ref. [30] is similar to [29] but [30] has connected output of the auxiliary bidirectional circuit to a capacitor of the Z-source inverter. Ref. [25] and [26] has used a hybrid battery-PV system in cascade multilevel inverters. Ref. [18-30] have focused on configuration with one input power while if two or several input power want to share their power with together through Z-source inverters, they can’t implement it with their topologies. In other words; sometimes various input DC sources with different voltage and power level want to supply one or several loads whose power is sum of input DC power sources via Z-source inverters (with considering 100 percent efficiency for the system). At this time, if there isn’t any way for sharing power, only some loads can be supplied. This paper has tried to solve it by make a connection between two traditional Z-source inverters.

Ref. [17] has proposed a new topology (Fig. 2) which can be used to generate DC voltage as an additional output from a traditional Z-source inverter not requiring active semiconductor device. In this paper, the DC output voltage of the configuration in [17] is used as one of the capacitors in a conventional Z-source inverter. Therefore the ZSI is able to supply the AC load, even at insufficient power delivery conditions from main supply. With this idea, the problem of power sharing between two Z-source inverters is solved. In section 2, structure, operation principles and main relations of the proposed system is described and in section 3, the simulation results of the system are shown and compared with theoretical analysis.

This paper will address to explain more detail about the mentioned subject. In the next section, new model has been presented. In section 3 a case study has been introduced and evaluated. Section 4 has been dedicated to conclusion.

2. Proposed Structure and Operating Principles

The conventional Z-source inverter is shown in Fig. 1 [2]. In Fig. 1, because of symmetry, L1 and L2, C1 and C2 should be equal. It is supposed that the circuit works in CCM. So the circuit has two modes: the shoot through mode and the non-shoot through mode. The inverter can make shoot through time via turning on both switches in one, two or three legs simultaneously. In this mode both inductors start charging through the capacitors and the diode D1 turns off because difference of sum of the capacitors voltage and input DC voltage make turn it off. Because in this inverter turning both switches of any leg is possible, so this inverter have higher reliability than the traditional inverters. Another mode is non-shoot through. When the shoot through mode finishes, the non-shoot through mode will starts. In this mode the diode D1 is on and the inverter can work in eight active modes [2].

According to symmetry of ZSI the C1 and C2, L1 and L2 have the same voltage and current waveforms respectively. The main relations of the converter are as follows [2]:

\[ V_{C1} = V_{C2} = V_C \] (1)

\[ \frac{V_C}{V_{S1}} = \frac{1 - D_{st1}}{1 - 2 \times D_{st1}} \] (2)

\[ \frac{V_{O1}}{V_{S1}} = \frac{1}{1 - 2 \times D_{st1}} \] (3)

In Eq. (1)-(3): a) Dst1 represents duty cycle of the circuit shown in Fig. 1 and is defined as ratio of the shoot through time to the switching period, b) with ignoring the capacitors voltage ripple, the average of capacitors voltage have been considered instead of the instantaneous values of them, c) VO1 represents the non-shoot through value of the inverter DC link.

As was mentioned; this paper wants to share power between Z-source inverters which have different input voltage and power level. This principle will be implemented.
through substituting one of two capacitors of a Z-source inverter with a DC voltage prepared from another Z-source inverter. The way that builds the necessary DC voltage has been explained in [17]. The proposed topology in [17], is shown in Fig. 2.

In Fig. 2 leakage inductances of the transformers is ignored as it does not affect the performance of the system. The converter of Fig. 2 can work in two modes: CCM and DCM. Because different modes only have different equations and constraints, so in this paper that only the value of VC7 is important, various modes isn't important and it is supposed the converter of Fig. 2 works in CCM.

The topology of Fig. 2 also works in two sub-interval. The first is related to the shoot through state. At this interval D2 is off and C3 and C4 start to charge two magnetizing inductances of two transformers T1 and T2. In this state the voltage of C3 and C4 applies to primary windings of T1 and T2 and therefore, the voltage is transferred to two secondary windings. Two secondary windings voltage are added with the voltage of C5 and C6, turn on D5 and start to charge C7.

The non-shoot through state starts when shoot through finishes via the inverter as was explained for the Z-source inverter. at this state the diode D2 turns on. The voltage dropping to the primary windings are negative and so the diodes D3 and D4 turn on and capacitors C5 and C6 start to charge. At this time the diode D3 is off and capacitor C7 supplies the load. The main steady state equations of the topology shown in Fig. 2, are as follows [17]:

\[
V_{C3} = V_{C4} = \frac{1 - D_{st2}}{1 - 2 \times D_{st2}} \times V_{S2} \tag{4}
\]

\[
V_{C5} = V_{C6} = \frac{2n \times k \times D_{st2}}{1 - 2 \times D_{st2}} \times V_{S2} \tag{5}
\]

\[
V_{C7} = \frac{1 + D_{st2}}{1 - 2 \times D_{st2}} \times 2n \times k \times V_{S2} \tag{6}
\]

In Eq. (4)-(6): a) D_{st2} represents duty cycle of the circuit shown in Fig. 2 and is defined as ratio of the shoot through time to the switching period, b) with ignoring the capacitors voltage ripple, the average of capacitors voltage have been considered instead of the instantaneous values of them, c) n is the transformers turn ratio and is defined N2/N1, d) k is the transformers coupling coefficient.

The innovation of this paper is making connection between the topologies of Fig. 1 and Fig. 2. This idea is useful when the inputs voltage level of the topologies are different and the topology wants to connect to each other for sharing power and supply their inverters separately. This paper substitutes one of the capacitors of the topology of Fig. 1 with the DC output of the topology of Fig. 2. Because the voltage of capacitor C7 is DC, so it is possible that C1 is substituted with C7. Fig. 3 shows the pro-
posed converter.
By the interconnection, section 2 prepares a DC voltage that is used in section 1. Because of existence of diode \( D_5 \), the section 2 hasn’t any loading effect on section 1 from voltage viewpoint. But the current of section 2 will change when the interconnection is applied. So the voltage gain of each converter won’t be changed owing to the interconnection. For analyzing the proposed converter of Fig. 3, it should be said that the converter operation is similar to traditional Z-source inverters. The difference between the converter and Z-source inverters is presence of two independent input sources: one is \( V_{S1} \) and the second is \( V_{C7} \) which is independent from duty cycle 1 (\( D_{s1} \)). In other words; two control methods is available, the first; the values of duty cycle 2 (\( D_{s2} \)), \( V_{S2} \) and the transformers turn ratio determine the value of \( V_{C7} \) and then the value of \( V_{S2} \) and \( V_{C7} \) determine the value of transformers turn ratio and \( D_{s2} \). The circuit is analyzed in CCM and so two state are considered: the shoot through state and the non-shoot through state. The relation between the instantaneous values of the converter variables in shoot through state is as follow:

\[
i_x = -i_{L1}
\]

(7)

\[
i_{c2} = i_{L1} - i_o
\]

(8)

\[
i_o = -i_x + i_{L2}
\]

(9)

\[
i_{c2} = -i_{L2}
\]

(10)
\[\begin{align*}
    i_{s1} &= 0 \\
    V_{L1} &= V_{C7} \\
    V_{L2} &= V_{C2} \\
    \text{The relation between the instantaneous values of the converter variables in the non-shoot through state is as follow:} \\
    i_x &= i_{s1} - i_{L1} \\
    i_c2 &= i_{L1} - i_o \\
    i_x &= i_{L2} - i_o \\
    i_{s1} &= i_{c2} + i_{L2} \\
    V_{L1} &= V_{s1} - V_{C2} \\
    V_{L2} &= V_{s1} - V_{C7} \\
    \text{Applying the volt-second balance for } L_1, \text{ and } L_2 \text{ result in:} \\
    V_{C7} \times D_{st1} + (V_{s1} - V_{C2}) \times (1 - D_{st1}) &= 0 \\
    \Rightarrow v_{C2} &= \frac{V_{s1}(1 - D_{st1}) + V_{C7} \times D_{st1}}{1 - D_{st1}} \\
    V_{C2} \times D_{st1} + (V_{s1} - V_{C7}) \times (1 - D_{st1}) &= 0 \\
    \Rightarrow v_{C2} &= \frac{(V_{C7} - V_{s1}) \times (1 - D_{st1})}{D_{st1}} \\
    \text{Using Eq. (20) and Eq. (21), the relation between } V_{s1} \text{ and } V_{C7} \text{ can be calculated as:} \\
    V_{C7} &= \frac{1 - D_{st1}}{1 - 2D_{st1}} V_{s1} \\
    \text{Equation (22) indicates that if Section 1 of Fig. 3 wants to operate as a Z-source inverter which is sharing power with another Z-source inverter, } V_{C7} \text{ must be equal to } \\
    \frac{1 - D_{st1}}{1 - 2D_{st1}} V_{s1}. \\
    \text{By writing } kcl \text{ in node 1, it can be shown:} \\
    i_{s1} &= i_x + i_{L1} \\
    \text{Averaging Eq. (23), result in:} \\
    I_{s1} &= I_x + I_{AVG}^{L1} \\
    \text{Similar approach for node 2, yields:} \\
    I_{AVG}^{L1} &= I_o \\
    \text{i}_o \text{ similar to other variables has two state, shoot through and non-shoot through. In shoot through state, Inverter 1 is short circuit and } i_o \text{ is equal to } i_{L1}^1 + i_{L2}^1. \text{ Ignoring the inductors current ripple results: } i_o = I_{AVG}^{L1} + I_{AVG}^{L2}. \text{ In non-shoot through state, } i_o \text{ is equal with Inverter 1 current and if the average of Inverter 1 current in non-shoot through state is shown with } I_{AVG}^{inverter 1}, \text{ it can be said:} \\
    I_o &= I_{AVG}^{inverter 1} \times (1 - D_{st1}) + (I_{AVG}^{L1} + I_{AVG}^{L2}) \times D_{st1} \\
    \text{Using Eq. (25) and Eq. (26) dedicates:} \\
    I_{AVG}^{L1} &= I_{AVG}^{inverter 1} \times (1 - D_{st1}) + (I_{AVG}^{L1} + I_{AVG}^{L2}) \times D_{st1} \\
    \text{By writing } kcl \text{ in node 3, it can be exhibited:} \\
    i_o + i_x &= i_{L2} \\
    \text{Averaging Eq. (28) results Eq. (29):} \\
    I_o + I_x &= I_{AVG}^{L2} \\
    \text{The combination of Eq. (25) and Eq. (29) results Eq. (30):} \\
    I_x &= I_{AVG}^{L2} - I_{AVG}^{L1} \\
    \text{Again for node 4, it can be deduced:} \\
    I_{s1} &= I_{AVG}^{L2} \frac{1 - D_{st1}}{1 - 2D_{st1}} V_{s1}.
\end{align*}\]
The proposed converter has ability of using in hybrid renewable energies (for example). In other words; because the converter can get two sources separately so the subject of power sharing is existence. According to relation (31), source 1 supply the converter by and so

The resistance of transformers windings 0.1 \( \Omega \) Therefore; the power of the load paralleled with \( C_7 \) and the load in the output of Inverter 1 will be handle by \( V_S2 \).

In this condition \( I_{AVG} \) is equal to zero. The value of \( V_{O1} \) can be calculate as follow:

\[
V_{O1} = V_{C7} - v I_{non\text{-}shoot} \overline{V}
\]

\[
= V_{C7}(1 + \frac{D_{st1}}{1 - D_{st1}}) \tag{33}
\]

4- The configuration of Fig. 3 is very useful if the load paralleled with \( C_7 \) and the load in the output of Inverter 1 are non-sensitive to voltage. In other words; if one of the parts of Fig. 3 (Section 1 or Section 2) is off, another part can supply all loads in different voltage level. For example if \( V_{S2} \) interrupts and \( V_{S1} \) can supply the loads are paralleled with \( C_7 \) and in the output of the Inverter 1, the Z-source inverter in Section 1 will supply its inverter in special relation said for the converter of Fig. 1 and will supply the load paralleled with \( C_7 \), in value \( \frac{1 - D_{st1}}{1 - 2D_{st1}} V_{S1} \).

Table 1. The simulation parameters.

<table>
<thead>
<tr>
<th>name</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductors ( L_1, L_2 )</td>
<td>300 ( \mu H )</td>
</tr>
<tr>
<td>Capacitors ( C_2, C_3, C_4, C_5, C_6 )</td>
<td>1000 ( \mu F )</td>
</tr>
<tr>
<td>Capacitors ( C_7 )</td>
<td>3000 ( \mu F )</td>
</tr>
<tr>
<td>( V_{S1} )</td>
<td>75 ( V )</td>
</tr>
<tr>
<td>( V_{S2} )</td>
<td>25 ( V )</td>
</tr>
<tr>
<td>( D_{st1} )</td>
<td>0.34</td>
</tr>
<tr>
<td>( D_{st2} )</td>
<td>0.30</td>
</tr>
<tr>
<td>( I_{AVG}^{Inverter} )</td>
<td>23.06 ( A )</td>
</tr>
<tr>
<td>Load</td>
<td>10 ( \Omega )</td>
</tr>
<tr>
<td>Turns ratio (( n ))</td>
<td>1</td>
</tr>
<tr>
<td>Coupling coefficient (( k ))</td>
<td>0.99</td>
</tr>
<tr>
<td>IGBTs forward voltage (Part number: STGW38I130D)</td>
<td>1.5 ( V )</td>
</tr>
<tr>
<td>Diodes forward voltage (Part number: SFA1608)</td>
<td>0.38</td>
</tr>
<tr>
<td>Inductance leakage of transformers windings</td>
<td>10 ( \mu H )</td>
</tr>
<tr>
<td>resistance of transformers windings</td>
<td>0.1 ( \Omega )</td>
</tr>
</tbody>
</table>
3. Simulation Results

In order to evaluate the performance of the system and the theoretical analysis, the system is simulated. The simulation parameters of the system are accordance of actual experimental situation and shown in Fig. 3 are shown in Table 1:

It can be seen that according to Eq. (7) and above values, \( V_{C7} \) is equal to \( \frac{1 - \delta_{21}}{1 - \delta_{20}} V_{31} \). So the converter is in sharing power mode which was explained in result 2 in this page. The figures extracted from the simulation are as below:

- Fig. 4. Inverter 1 DC link voltage
- Fig. 5. The output of auxiliary circuit of Section 2
- Fig. 6. The instantaneous current of L1
Fig. 7. The average value of $L_1$ current

Fig. 8. The instantaneous current of $L_2$

Fig. 9. The average value of $L_2$ current

Fig. 10. The instantaneous value of $i_{S1}$
Fig. 11. The average value of $i_{S1}$

Fig. 12. The instantaneous value of transferred current

Fig. 13. The average value of transferred current

Fig. 14. The value of capacitor $C_2$ voltage
Now; for evaluation of the simulation results match with the equation, the values shown in the figures are checked via the equations.

By extraction the values $I_{S1}$, $I_{L_{2}}^{AVG}$ and $I_X$, it is possible that (24) is checked:

\[ I_{S1} = I_K + I_{L_{2}}^{AVG} \Rightarrow 79.32 \equiv -13.06 + 66.23 \] \hspace{1cm} (34)

Again it is possible that Eq. (27) is checked by the values:

\[ I_{L_{1}}^{AVG} = I_{inverter_1} \times (1 - D_{st1}) + (I_{L_{1}}^{AVG} + I_{L_{2}}^{AVG}) \times D_{st1} \]
\[ \Rightarrow 66.23 \equiv 23.06 \times (1 - 0.34) + (66.23 + 76.9) \times 0.34 \] \hspace{1cm} (35)

For Eq. (30):

\[ I_K = I_{L_{2}}^{AVG} - I_{L_{1}}^{AVG} \Rightarrow 13.06 \equiv 76.9 - 66.23 \] \hspace{1cm} (36)

For Eq. (31):

\[ I_{S1} = I_{L_{2}}^{AVG} \Rightarrow 79.32 \equiv 76.9 \] \hspace{1cm} (37)

For Eq. (6):

\[ V_{C7} = \frac{1 + D_{st2}}{1 - 2 \times D_{st2}} \times 2n \times k \times V_{S2} \]
\[ \Rightarrow 152.2 \equiv \frac{1 + 0.3}{1 - 2 \times 0.3} \times 2 \times 25 \] \hspace{1cm} (38)

The difference between the both side of Eq. (37) is related to voltage drop in non-ideal circuit elements. Finally; the Eq. (3) is checked:

\[ \frac{V_{O1}}{V_{S2}} = \frac{1}{1 - 2 \times D_{st1}} \Rightarrow \frac{230.6}{75} = \frac{1}{1 - 2 \times 0.34} \] \hspace{1cm} (39)

Fig. 15 shows the power flow scheme in the proposed topology. In this figure, the demand of Inverter 2 is generated only by source 2 ($V_{s2}$) and the demands of Load and Inverter 1 are generated by source 1 ($V_{s1}$) and source 2 ($V_{s2}$) in the sharing mode.

It is clear that the proposed model and the equations work very good and the simulation verifies them. But in this configuration, the average current values of $L_1$ and $L_2$ aren’t the same.
4. Conclusion

This paper presented a new structure which is able to share power between two Z-source inverters by providing an interconnection between impedance networks. This configuration is useful when several inputs with different voltage and power want to share power. In this topology the inductors haven’t the same average current. Switching method of the converter is described which determines $D_{m1}$ and $D_{m2}$ according to the two different input voltage values and the desirable value of output voltage. All efforts for controlling the converter is in the direction of Equalization of the capacitors of Z-sources. By providing this condition, the power shares between two sources. The relation between the duty cycles and the operation modes were evaluated and explained and verified by simulations.

References


M. Ghani Varzaneh was born in Isfahan, Iran in 1988. He received his B.Sc. and M.Sc in electrical engineering from University of Isfahan and Islamic Azad University in 2012 and 2014 respectively. His interests are power electronics converters design, simulation, control and manufacturing. He is currently a PhD student in power electronics field at Shiraz University of Technology.

A. H. Rajaei (IEEE M’12) was born in Jahrom, Iran. He received the M.Sc. and the Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2009 and 2013, respectively. He is currently an Assistant Professor with the Shiraz University of Technology, Shiraz, Iran. His main research interests include renewable energy resources, power converters, electric vehicles, and motor drive systems.

M. Fakhraei was born Bushehr, Iran, in 1989. He received the B.S degree from Azad University, Bushehr, Iran, in 2011, and the M.S degree from Shiraz University of Technology, Shiraz, Iran, in 2016, all in electronic engineering. His research interests include power converters design, z-source converters and multilevel converters.