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

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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 feed by limited output power such as photovoltaics and feul 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). PVs 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 beacuase of eliminating short circuit condition caused from turning on both switches of any inverter leg simul-

taneously. 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 tempreature 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.
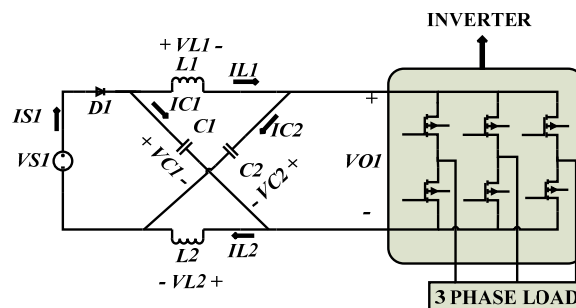
Fig. 1. Z-source inverter [2].

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] is 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 energythe 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 converters 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, L_1 and L_2, C_1 and C_2 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 D_1 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 D_1 is on and the inverter can work in eight active modes [2].

According to symmetry of ZSI the C1 and C_2, L_1 and L_2 have the same voltage and current waveforms respectively. The main relations of the converter are as follows [2]:

$$V_{C1}=V_{C2}=V_C \tag{1}$$

$$\frac{V_C}{V_{S1}} = \frac{1 - D_{st1}}{1 - 2 \times D_{st1}} \tag{2}$$

$$\frac{V_{O1}}{V_{S1}} = \frac{1}{1 - 2 \times D_{st1}} \tag{3}$$

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
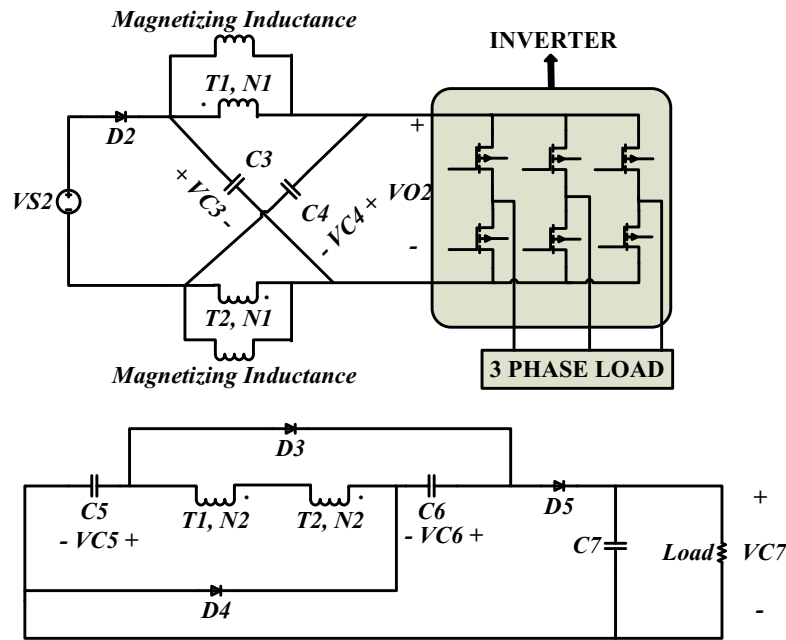
Fig. 2. The topology presented in [17].

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 V_{C7} 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 D_2 is off and C_3 and C_4 start to charge two magnetizing inductances of two transformers T_1 and T_2. In this state the voltage of C_3 and C_4 applies to primary windings of T_1 and T_2 and therefore, the voltage is transferred to two secondary windings. Two secondary windings voltage are added with the voltage of C_5 and C_6, turn on D_5 and start to charge C_7.

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 D_2 turns on. The voltage dropping to the primary windings are negative and so the diodes D_3 and D_4 turn on and capacitors C_5 and C_6 start to charge. At this time the diode D_5 is off and capacitor C_7 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 N_2/N_1, 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 C_7 is DC, so it is possible that C_1 is substituted with C_7. Fig. 3 shows the pro-
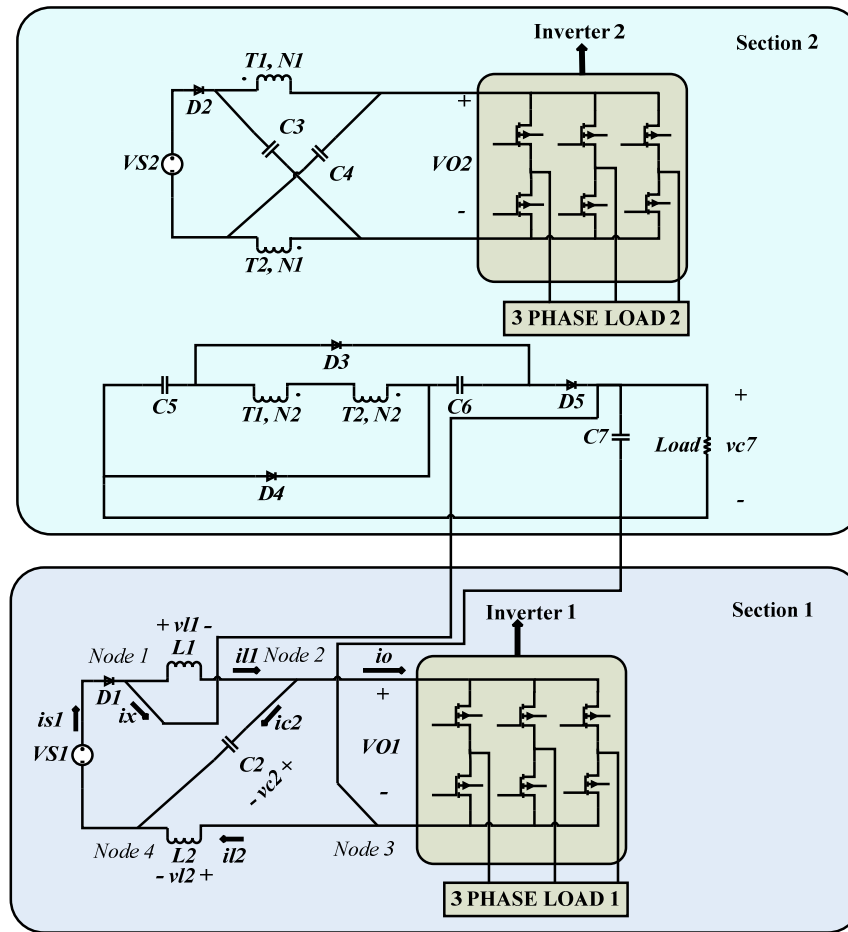
Fig. 3. The scheme of the proposed converter.

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 (Dst1). In other words; two control methods is available, the first; the values of duty cycle 2 (Dst2), V_{S2} and the transformers turn ratio determine the value of V_{C7} and then the value of V_{C7} and V_{S1} determines the value of D_{st1}, and the second; the value of V_{O1} and VS1 determine D_{st1} then the value of D_{st1} determines the value of V_{C7} and finally

the value of V_{S2} and V_{C7} determine the value of transformers turn ratio and D_{st2}. 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:

$$i_x = -i_{L1} \tag{7}$$

$$i_{C2} = i_{L1} - i_o \tag{8}$$

$$i_o = -i_x + i_{L2} \tag{9}$$

$$i_{C2} = -i_{L2} \tag{10}$$

$$i_{s1} = 0 \tag{11}$$

$$V_{L1} = V_{C7} \tag{12}$$

$$V_{L2} = V_{C2} \tag{13}$$

The relation between the instantaneous values of the converter variables in the non-shoot through state is as follow:

$$i_x = i_{s1} - i_{L1} \tag{14}$$

$$i_{C2} = i_{L1} - i_o \tag{15}$$

$$i_x = i_{L2} - i_o \tag{16}$$

$$i_{s1} = i_{C2} + i_{L2} \tag{17}$$

$$V_{L1} = V_{s1} - V_{C2} \tag{18}$$

$$V_{L2} = V_{s1} - V_{C7} \tag{19}$$

Applying the volt-second balance for L_1, and L_2 result in:

$$V_{C7} \times D_{st1} + (V_{S1} - V_{C2}) \times (1 - D_{st1}) = 0$$
$$\Rightarrow v_{C2} = \frac{V_{S1}(1 - D_{st1}) + V_{C7} \times D_{st1}}{1 - D_{st1}} \tag{20}$$

$$V_{C2} \times D_{st1} + (V_{S1} - V_{C7}) \times (1 - D_{st1}) = 0$$
$$\Rightarrow V_{C2} = \frac{(V_{C7} - V_{S1}) \times (1 - D_{st1})}{D_{st1}} \tag{21}$$

Using Eq. (20) and Eq. (21), the relation between V_{S1} and V_{C7} can be calculated as:

$$V_{C7} = \frac{1 - D_{st1}}{1 - 2D_{st1}} V_{S1} \tag{22}$$

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} must be equal to

$\frac{1 - D_{st1}}{1 - 2D_{st1}} V_{S1}$.

By writing *kcl* in node 1, it can be shown:

$$i_{s1} = i_x + i_{L1} \tag{23}$$

Averaging Eq. (23), result in:

$$I_{S1} = I_X + I_{L1}^{AVG} \tag{24}$$

Similar approach for node 2, yields:

$$I_{L1}^{AVG} = I_O \tag{25}$$

i_o 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 is equal to $i_{l1} + i_{l2}$. Ignoring the inductors current ripple results: $i_o = I_{L1}^{AVG} + I_{L2}^{AVG}$. In non-shoot through state, i_o is equal with Inverter 1 current and if the average of Inverter 1 current in non-shoot through state is shown with $I_{inverter\ 1}^{AVG}$, it can be said:

$$I_O = I_{inverter\ 1}^{AVG} \times (1 - D_{st1}) + (I_{L1}^{AVG} + I_{L2}^{AVG}) \times D_{st1} \tag{26}$$

Using Eq. (25) and Eq. (26) dedicates:

$$I_{L1}^{AVG} = I_{inverter\ 1}^{AVG} \times (1 - D_{st1}) + (I_{L1}^{AVG} + I_{L2}^{AVG}) \times D_{st1} \tag{27}$$

By writing kcl in node 3, it can be exhibited:

$$i_o + i_x = i_{L2} \tag{28}$$

Averaging Eq. (28) results Eq. (29):

$$I_O + I_X = I_{L2}^{AVG} \tag{29}$$

The combination of Eq. (25) and Eq. (29) results Eq. (30):

$$I_X = I_{L2}^{AVG} - I_{L1}^{AVG} \tag{30}$$

Again for node 4, it can be deduced:

$$I_{S1} = I_{L2}^{AVG} \tag{31}$$

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 $I_{S1} = I_{L2}^{AVG}$ and so $P_{S1} = V_{S1}.I_{S1} = V_{S1}.I_{L2}^{AVG}$. Therefore; the $P_{Inverter\ 1} - P_{S1}$ is equal to P_{S2}. According to Eq. (22) it can be said that for CCM operation and establishing the switching method In accordance with what was said for the traditional Z-source inverters, the value of D_{st2} and the transformers turn ration must be determined to satisfy Eq. (22). Considering the relations governed the system, the following results are noticeable:

1-   If the value of D_{st2} is lower than the value required

to provide $V_{C7} = \frac{1-D_{st1}}{1-2D_{st1}}V_{S1}$,

a) the diode D5 will be off
b) the value of V_{C7} will be fixed to $\frac{1-D_{st1}}{1-2D_{st1}}V_{S1}$ by Section 1
c) the direction of power transfer will be from Section 1 to Section 2. The value of power transferred is equal to power of the load paralleled with C_7.

2-   If the value of V_{C7} is equal to $\frac{1-D_{st1}}{1-2D_{st1}}V_{S1}$, the power can flow from Section 2 to Section 1 according to Eq. (24), Eq. (27), Eq. (30) and Eq. (31). In other words, the load paralleled with C_7 will be handle from V_{S2} and the load of Section 1 will handle by V_{S1} and V_{S2}. It can be said that in this mode, depending on the values of V_{S1} and V_{S2}, D_{st1} and D_{st2} are adjusted so that $V_{C7} = V_{C2}$. So the controller

gets the signals V_{S1} and V_{S2} as the inputs and according to the desirable value of V_{O1}, D_{st1} and D_{st2} are prepared. This operation mode is the main operation mode.

3-   If the value of V_{C7} is higher than $\frac{1-D_{st1}}{1-2D_{st1}}V_{S1}$, the power of the load paralleled with C_7 and the load is in the output of Inverter 1 will be handle by V_{S2}. In this condition I_{L2}^{AVG} is equal to zero. The value of V_{O1} can be calculate as follow:

$$\Rightarrow vl1^{non-shoot\ through} = \frac{-VC7}{1-D_{st1}} \tag{32}$$

$$V_{O1} = V_{C7} - vl1^{non-shoot\ through}$$

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

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.

name	value
Inductors L_1, L_2	300 μH
Capacitors C_2, C_3, C_4, C_5, C_6	1000 μF
Capacitors C_7	3000 μF
V_{S1}	75 V
V_{S2}	25 V
D_{st1}	0.34
D_{st2}	0.30
$I_{inverter\ 1}^{AVG}$	23.06 A
$Load$	10 Ω
Turns ratio (n)	1
Coupling coefficient (k)	0.99
IGBTs forward voltage (Part number: STGW38IH130D)	1.5 V
Diodes forward voltage (Part number: SFA1608)	0.38
Inductance leakage of transformers windings	10 μH
resistance of transformers windings	0.1 Ω

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 $\frac{1-D_{st1}}{1-2D_{st1}}V_{S1}$. 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:
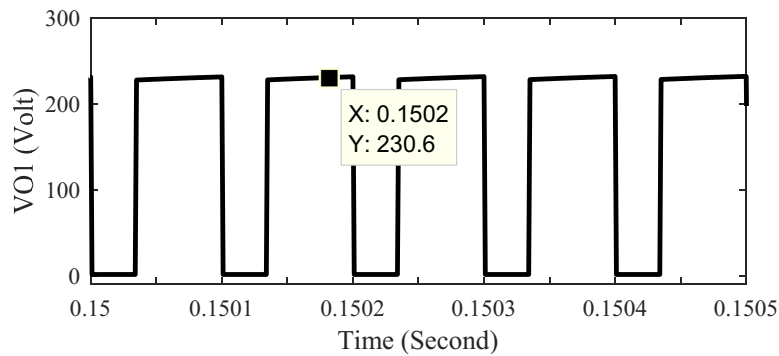

Fig. 4. Inverter 1 DC link voltage
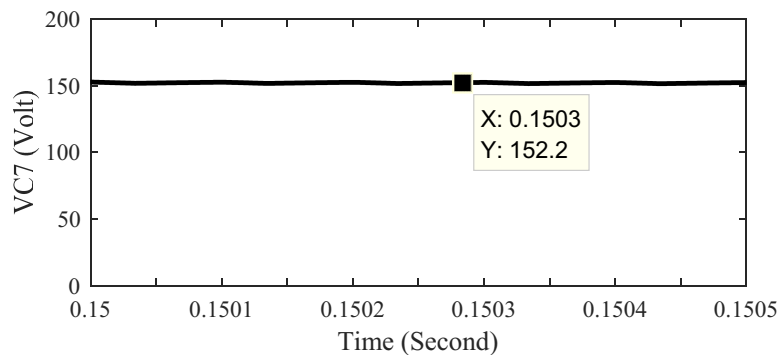
Fig. 5. The output of auxiliary circuit of Section 2
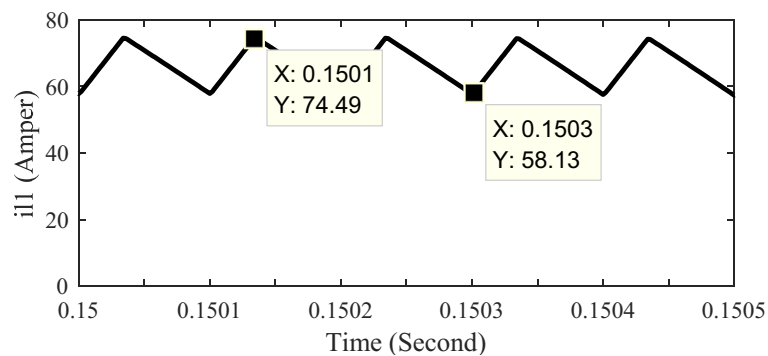
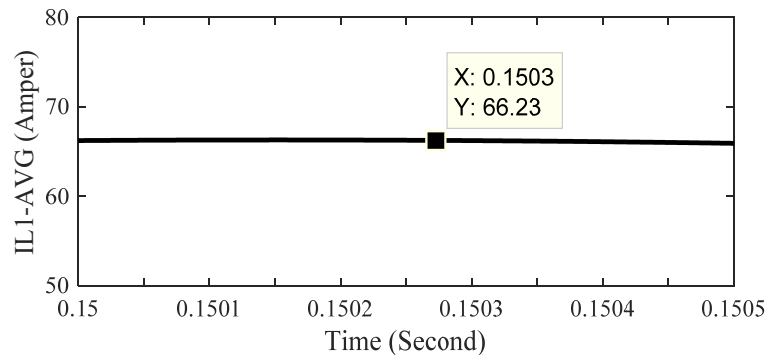**Fig. 6.** The instantaneous current of L1
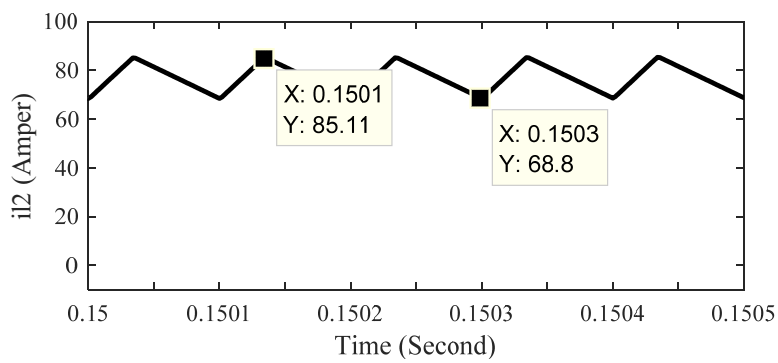
Fig. 7. The average value of L_1 current

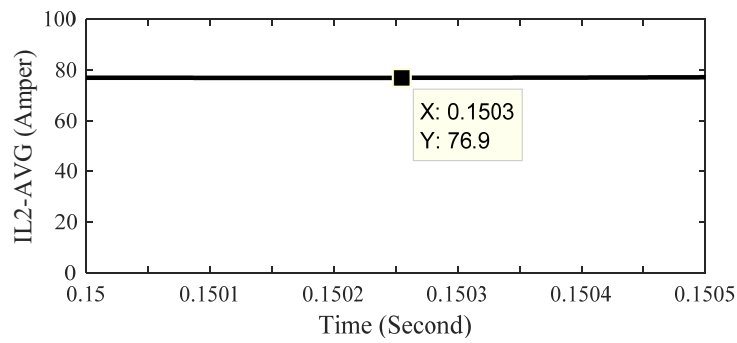**Fig. 8.** The instantaneous current of L_2

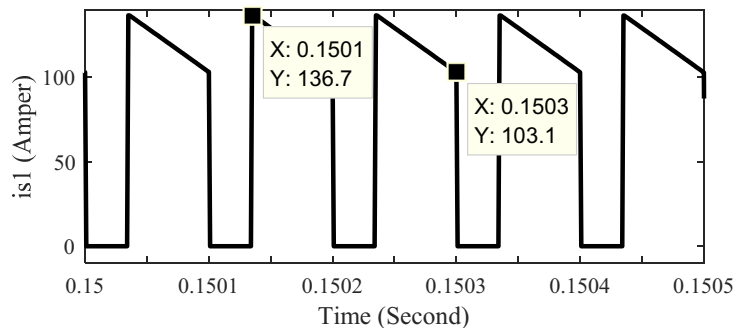**Fig. 9.** The average value of L_2 current

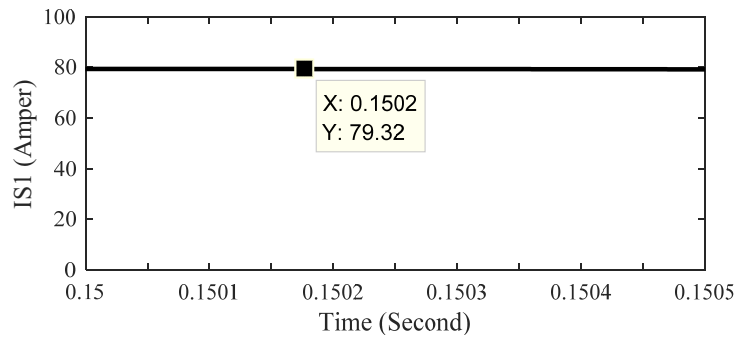**Fig. 10.** The instantaneous value of i_{S1}
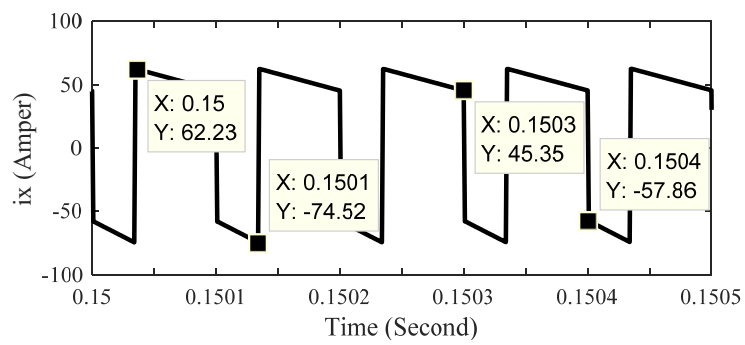
Fig. 11. The average value of i$_{S1}$

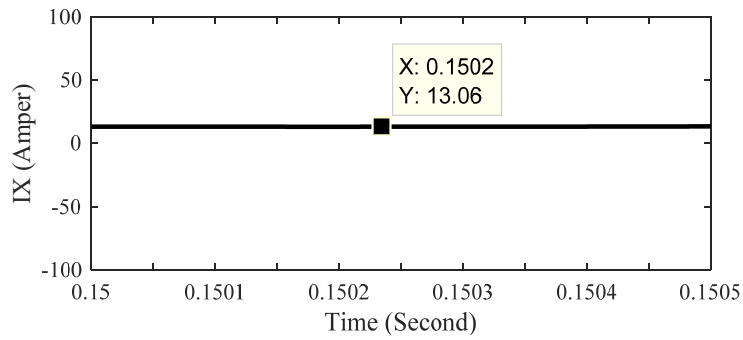**Fig. 12.** The instantaneous value of transferred current

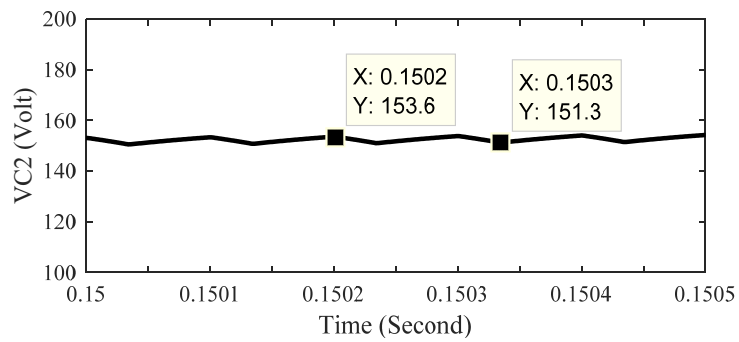**Fig. 13.** The average value of transferred current

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_{L2}^{AVG} and I_X, it is possible that (24) is checked:

$$I_{S1} = I_X + I_{L1}^{AVG} \quad \Rightarrow \quad 79.32 \cong -13.06 + 66.23 \qquad (34)$$

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

$$I_{L1}^{AVG} = I_{inverter\ 1}^{AVG} \times (1 - D_{st1}) + (I_{L1}^{AVG} + I_{L2}^{AVG}) \times D_{st1}$$

$$\Rightarrow 66.23 \cong 23.06 \times (1 - 0.34) + (66.23 + 76.9) \times 0.34 \quad (35)$$

For Eq. (30):

$$I_X = I_{L2}^{AVG} - I_{L1}^{AVG} \quad \Rightarrow 13.06 \cong 76.9 - 66.23 \qquad (36)$$

For Eq. (31):

$$I_{S1} = I_{L2}^{AVG} \quad \Rightarrow 79.32 \cong 76.9 \qquad (37)$$

For Eq. (6):

$$V_{C7} = \frac{1 + D_{st2}}{1 - 2 \times D_{st2}} \times 2n \times k \times V_{S2}$$

$$\Rightarrow 152.2 \cong \frac{1 + 0.3}{1 - 2 \times 0.3} \times 2 \times 25 \qquad (38)$$

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:

$$\frac{V_{O1}}{V_{S2}} = \frac{1}{1 - 2 \times D_{st1}} \Rightarrow \frac{230.6}{75} = \frac{1}{1 - 2 \times 0.34} \qquad (39)$$

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.
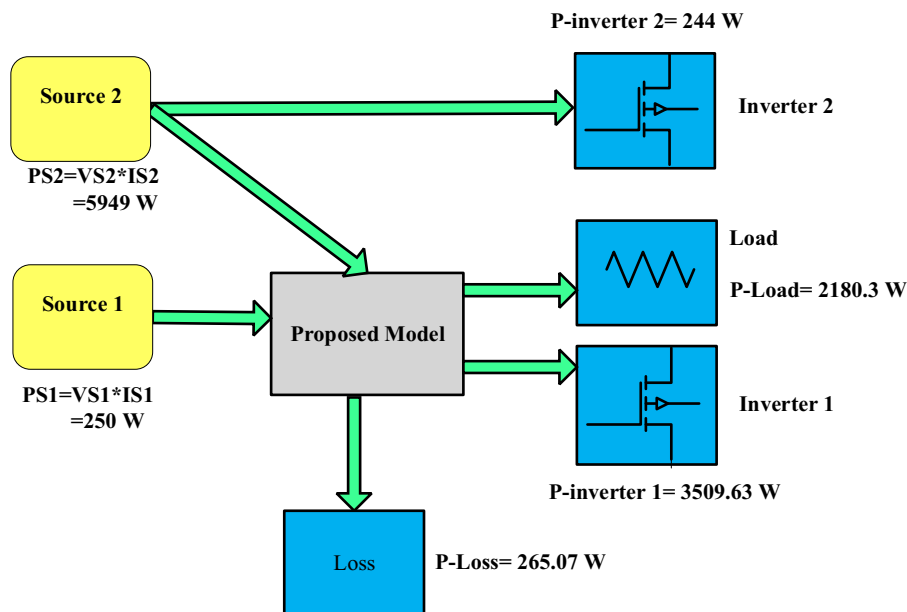

Fig. 15. The scheme of power flow through the proposed system.

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_{st1} and D_{st2} 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.

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