An Improved Quasi-Z-Source DC-DC Converter with Continuous Input and Output Currents

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2023 IEEE 3rd International Conference on Smart Technologies for Power, Energy and Control (STPEC) | 979-8-3503-0473-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/STPEC59253.2023.10430784

***Abstract*—This article proposes an improved quasi-Z-source DC-DC converter (IqZSC) for a power conversion from low voltage sources (batteries, solar photovoltaic and fuel cells). It gives continuous input and output currents with less ripple due to presence of inductors at the input and output ports, unlike the basic quasi-Z-source converter (qZSC). Due to low ripple input current, it is a better choice for getting longer life span of the voltage sources. Also, it has common grounded output to eliminate measurement issues and electromagnetic interference (EMI) issues. As the IqZSC is developed from the qZSC by rearranging elements, it has equal number of elements as that of qZSC, and has two controlled switches which are operating at the same instant. Steady-state mathematical modelling of IqZSC is given and a comparative analysis is done by considering similar Z-source converters. Simulation studied are discussed to show the performance of the proposed converter.**

Keywords—Continuous current; DC-DC power conversion; low voltage energy sources; and Z-source converter

I. INTRODUCTION

In recent times, renewable energy sources (such as wind, solar photovoltaic (PV) cell, and fuel cell) are continuously gaining interest to meet the energy demand due to challenges associated with CO_2 reduction and exhausting fossil fuel resources. However, the fuel and solar PV cells have relatively low output voltage and variable in nature, and they cannot be used directly as DC bus for many applications [1]. Hence, a DC-DC converter is necessary for enhancing and controlling the low voltage levels of solar PV and fuel cells. Fig. 1 shows a role of a DC-DC converter in interfacing the low voltage sources (batteries, solar PV and fuels cells). The required features of a converter are high voltage gain, continuous input current, low device voltage/current stresses, good reliability and efficiency. Further, the converter is suggested to have continuous input current with low ripple for getting longer life of energy sources. Also, input and output terminals of the converter should connect to a common ground for eliminating measurement and electromagnetic interference (EMI) issues.

To fulfil the above requirements, many DC-DC converters are designed in terms of isolated and non-isolated configurations by researchers; based on series and parallel connection, voltage multipliers, switched capacitors, switched inductors, Z-source concept, coupled inductors, and transformers [2]-[4]. Although the isolated DC–DC converters can meet the above characteristics easily, they have leakage inductance issue which results in high-voltage spikes across semiconductor devices during switching transition, higher switching losses, and serious EMI issues [2]. Hence, a non-isolated converter is a better choice to eliminate the voltage spikes, and improve conversion efficiency. A conventional boost DC-DC converter (CBC) is a basic non-isolated converter. However, it is not a desirable one due to parasitic issues at switch-duty ratio extremities, which causes lower voltage gain and higher power loss of the CBC [2]. In addition, it demands a high-voltage-rated power semiconductor switch and suffers from large diode reverse recovery problem at higher duty-ratio. Although many other non-isolated converters are available [2]-[4], they are too complex and may increase the system's cost and size. Although the converters [2]-[4] have merits and demerits, they may be chosen based on the features, such as power flow directions, switching logics, and unstable/stable systems.

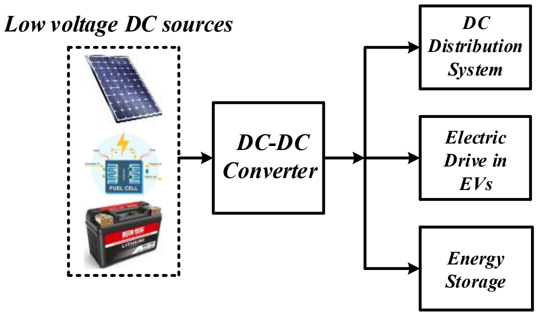

Fig. 1. Role of DC-DC converter in interfacing the low voltage sources.

Further, a power electronics converter based on Z-source concept was introduced for a simple and efficient power conversion [5]. The Z-source network consists of two capacitors and two inductors connected in X-shape, and placed after input voltage source to increase the voltage levels. Also, open and short circuit problems in the traditional current-source and voltage-source inverters can be eliminated by using Z-source network [5]. A Z-source DC-DC converter (ZSC) is discussed in [6], which has a voltage gain of $\frac{1}{(1-2D)}$, where D is a switch-duty ratio of the converter. Although the voltage gain is greater than that of CBC at low values of D, input and output voltages are not measured from common ground terminal. Also, it has a discontinuous input and output currents, which is undesirable for low voltage sources. A novel Z-source converter is also discussed in [7], which is slightly different from the ZSC [6]. Although it has continuous output current, it also has discontinuous input current and uncommon ground. In [8], a quasi-Z-source converter (qZSC) is presented. Although the qZSC has same voltage gain as that of the ZSC, it has a common ground and lower capacitor voltage stresses. Also, it has discontinuous output current and continuous input current. In [9], a common grounded Z-source DC-DC converter is discussed and it is obtained based on minor changes in the circuit configuration of the ZSC. Although it has common ground and high gain, it has discontinuous input and output currents.

Hence, to take care of the above issues, an improved quasi-Z-source DC-DC converter (IqZSC) is introduced in this article for a simple and efficient power conversion. It is developed by rearranging the elements of qZSC. Also, one of the three capacitors in the qZSC is replaced by a controlled switch without increasing the total number of elements. It has common ground, and continuous input and output currents with better voltage gain. As the IqZSC has continuous currents with less ripple content, it can take care of life span of the low voltage sources along with the enhancement of their voltage levels. Also, it can avoid the measurement and electromagnetic interference issues due to its common ground.

The arrangement of the article is as follows. Section II gives the operation of IqZSC along with the necessary mathematical relations. A comparative analysis is also given in section II. Simulation studies are described in section III. Section IV contains conclusion of the article.

II. Improved Quasi-Z-Source dc-dc Converter

Fig. 2 gives a schematic of an improved quasi-Z-source DC-DC converter (IqZSC). It can be noticed from Fig. 2 that the IqZSC has capacitors (C_1 and C_2), diodes (D_1 and D_2), inductors (L_1 and L_2), and switches (S_1 and S_2). The two switches will operate simultaneously. As it has two inductors at output and input ports, it gives continuous output and input currents with low ripple. Also, it has common grounded output to eliminate measurement and EMI issues. The operation and corresponding mathematical expressions of the IqZSC is discussed in the succeeding sections.

A. *Working of the IqZSC*

The working of the IqZSC is described in two operating intervals based on the switching states of S_1 and S_2. The operating intervals are considered as shoot-through interval ($0 < t < DT_s$) and non-shoot-through interval ($DT_s < t < T_s$), and the corresponding equivalent circuits are shown in Fig. 3.

$$\left.\begin{aligned} L_1\frac{di_{L1}}{dt} &= v_{in} + v_{C1} \\ L_2\frac{di_{L2}}{dt} &= -v_{C2} \\ C_1\frac{dv_{C1}}{dt} &= -i_{L1} \\ C_2\frac{dv_{C2}}{dt} &= i_{L2} - \frac{v_{C2}}{R} \end{aligned}\right\} \quad (1)$$

i. *During shoot-through interval*

During shoot-through interval, equivalent circuit of the IqZSC is given in Fig. 3(a). In this interval, S_1 and S_2 are ON, and D_1 and D_2 are reverse biased. The inductor L_1 starts charging and inductor L_2 starts discharging. Meanwhile, capacitors C_1 and C_2 start discharging. The necessary instantaneous equations are given in (1).

ii. *During non-shoot-through interval*

Fig. 3(b) gives equivalent circuit of the IqZSC during non-shoot-through interval. In this interval, S_1 and S_2 are OFF, and D_1 and D_2 are forward biased. The stored energy in L_1 starts discharging and L_2 starts storing energy. Meanwhile, C_1 and C_2 start charging. The necessary instantaneous equations are given in (2).

$$\left.\begin{aligned} L_1\frac{di_{L1}}{dt} &= v_{in} - v_{C1} \\ L_2\frac{di_{L2}}{dt} &= v_{C1} - v_{C2} \\ C_1\frac{dv_{C1}}{dt} &= i_{L1} - i_{L2} \\ C_2\frac{dv_{C2}}{dt} &= i_{L2} - \frac{v_{C2}}{R} \end{aligned}\right\} \quad (2)$$

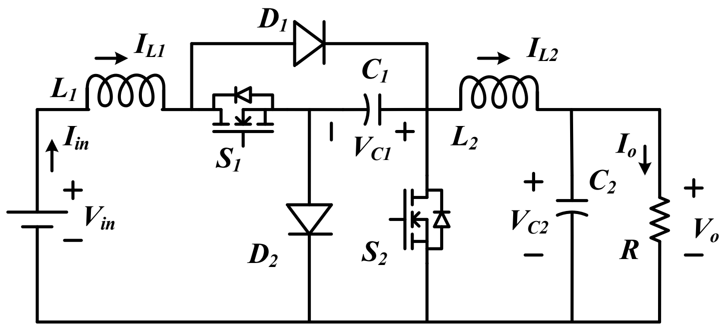

Fig. 2. An improved quasi-Z-source DC-DC converter (IqZSC).

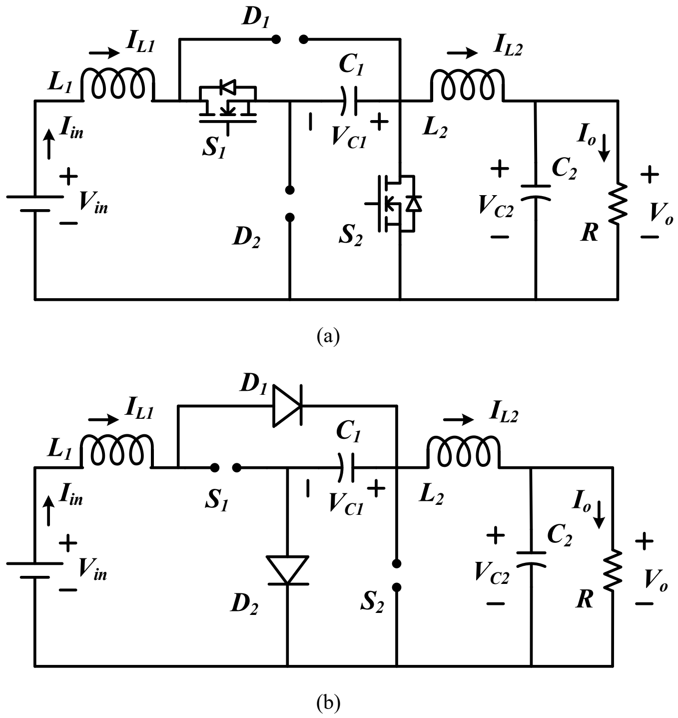

Fig. 3. Equivalent circuits of the IqZSC. (a) for $0 < t < DT_s$ interval and (b) for $DT_s < t < T_s$.

B. *Steady-State voltage and current relations*

After applying volt-second balance principle to L_1, the obtained expression is given in (3).

$$V_{C1} = \frac{1}{1-2D}V_{in} \quad (3)$$

Table I. Comparison among the IqZSC and other similar ZSCs

	ZSC [6]	ZSC [7]	qZSC [8]	Common grounded ZSI [9]	IqZSC
Capacitors	3	3	3	3	2
Diodes	2	1	2	2	2
Inductors	2	3	2	2	2
Switches	1	1	1	1	2
Total elements	8	8	8	8	8
Gain ($\frac{V_o}{V_{in}}$)	$\frac{1}{1-2D}$	$\frac{(1-D)}{1-2D}$	$\frac{1}{1-2D}$	$\frac{2(1-D)}{1-2D}$	$\frac{(1-D)}{1-2D}$
Input current	Discontinuous	Discontinuous	Continuous	Discontinuous	Continuous
Output current	Discontinuous	Continuous	Discontinuous	Discontinuous	Continuous
Output terminal	Uncommon ground	Uncommon ground	Common ground	Common ground	Common ground

Similarly, for L_2, the obtained expression is given in (4).

$$V_{C2} = (1-D)V_{C1} = \frac{1-D}{1-2D}V_{in} \quad (4)$$

It can be understood from Fig. 3 that output voltage (V_o) of the IqZSC is same as V_{C2}.

$$V_o = V_{C2} = \frac{1-D}{1-2D}V_{in} \quad (5)$$

The voltage gain (G) of the IqZSC is given in (6).

$$G = \frac{V_o}{V_{in}} = \frac{1-D}{1-2D} \quad (6)$$

Further, after applying charge balance principle to C_1, the obtained expression is given in (7).

$$I_{L1} = \frac{1-D}{1-2D}I_{L2} = I_{in} \quad (7)$$

Similarly, for C_2, the obtained expression is given in (8).

$$I_{L2} = \frac{V_o}{R} = I_o \quad (8)$$

C. Design of passive elements

The minimum values of passive elements for continuous conduction mode of operation can be determined from the following inequalities.

$$\left.\begin{aligned} L_1 &\geq \frac{2D(1-D)T_sV_{in}}{(x_{L1}\%)(1-2D)I_{L1}} \\ L_2 &\geq \frac{D(1-D)T_sV_{in}}{(x_{L2}\%)(1-2D)I_{L2}} \\ C_1 &\geq \frac{D(1-2D)T_sI_{in}}{(x_{C1}\%)V_{in}} \\ C_2 &\geq \frac{(x_{L2}\%)T_sI_o}{(x_{C2}\%)8V_o} \end{aligned}\right\} \quad (9)$$

where $x_{V_{C1}}\%$ and $x_{V_{C2}}\%$ are percentage capacitor voltage ripples; $x_{I_{L1}}\%$ and $x_{I_{L2}}\%$ are percentage inductor current ripples; T_s is switching period; V_{in} and V_o are input and output voltages, and I_{in} and I_o are the input and output currents.

Further, inductor current ripple (ΔI_L) is determined as follows.

$$\Delta I_L = \int_0^{DT_s} \frac{di_L}{dt}dt \quad (10)$$

$$\left.\begin{aligned} \Delta I_{L1} &= \frac{V_{L1}}{L_1}DT_s \\ \Delta I_{L2} &= \frac{V_{L2}}{L_2}DT_s \end{aligned}\right\} \quad (11)$$

where V_{L_1} and V_{L_2} are inductor voltages during shoot-through mode (i.e., $0 < t < DT_s$ interval).

In a similar way, capacitor voltage ripple (ΔV_C) is determined as follows.

$$\Delta V_C = \int_0^{DT_s} \frac{dV_C}{dt}dt \quad (12)$$

$$\left.\begin{aligned} \Delta V_{C1} &= \frac{I_{C1}}{C_1}DT_s \\ \Delta V_{C2} &= \frac{I_{C2}}{C_2}DT_s \end{aligned}\right\} \quad (13)$$

where I_{C_1} and I_{C_2} are capacitor currents during shoot-through mode (i.e., $0 < t < DT_s$ interval).

D. Comparison among the IqZSC with other similar Z-source converters

A comparison among the IqZSC and other similar Z-source DC-DC converters [7]-[10] is given in Table I. The comparison is in terms of voltage gain, number of elements, nature of input and output currents, and nature of output terminal with respect to input terminal. It can be observed from Table 1 that the IqZSC and other ZSCs have equal total number of elements. However, the IqZSC has two capacitors and two controlled switches in comparison to other ZSCs. Further, it has continuous input and output currents, and common ground.

III. Validation

The steady-state behaviour of IqZSC is validated in PowerSim software. The operating specifications for verifying the performance of IqZSC are; input voltage $V_{in} = 24$ V, output power $P_o = 500$ W, output voltage $V_o = 48$ V, switching frequency $f_S = 20$ kHZ, and allowable ripples, $x_{I_{L1}} = x_{I_{L1}} = 20\%$ and $x_{V_{C1}} = x_{V_{C2}} = 1\%$. The values of energy storage elements are; $L_1 = 385$ μH, $L_2 = 385$ μH, $C_1 = 330$ μF and $C_2 = 22$ μF. Fig. 4 shows simulation studies of IqZSC at $D = 33.33\%$. Fig. 4(a) shows output voltage $V_o = 48$ V, output current $I_o = 10.41$ A and input current $I_{in} = 20.81$ A for $V_{in} = 24$ V. It is understood from Fig. 4(b) that capacitor voltages $V_{C1} = 72$ V and $V_{C2} = 48$ V along with the drive voltage for switches V_{GS} and input voltage V_{in}. Fig. 4(c) shows mean inductor currents $I_{L1} = 20.81$ A and $I_{L2} = 10.41$ A. It can be understood from Figs. 4(d) and 4(e) that voltage across semiconductor devices (S_1, S_2, D_1 and D_2); $V_{S1} = 72$ V, $V_{S2} = 72$ V, $V_{D1} = -72$ V and $V_{D2} = -72$ V along with V_{GS} and V_{in}. Figs. 4(f) and 4(g) shows peak current through the semiconductor devices (S_1, S_2, D_1 and D_2); $I_{S1} = 22.86$ A, $I_{S2} = 13.48$ A, $I_{D1} = 22.87$ A and $I_{D2} = 13.49$ A. It can be observed from Fig. 4(h)

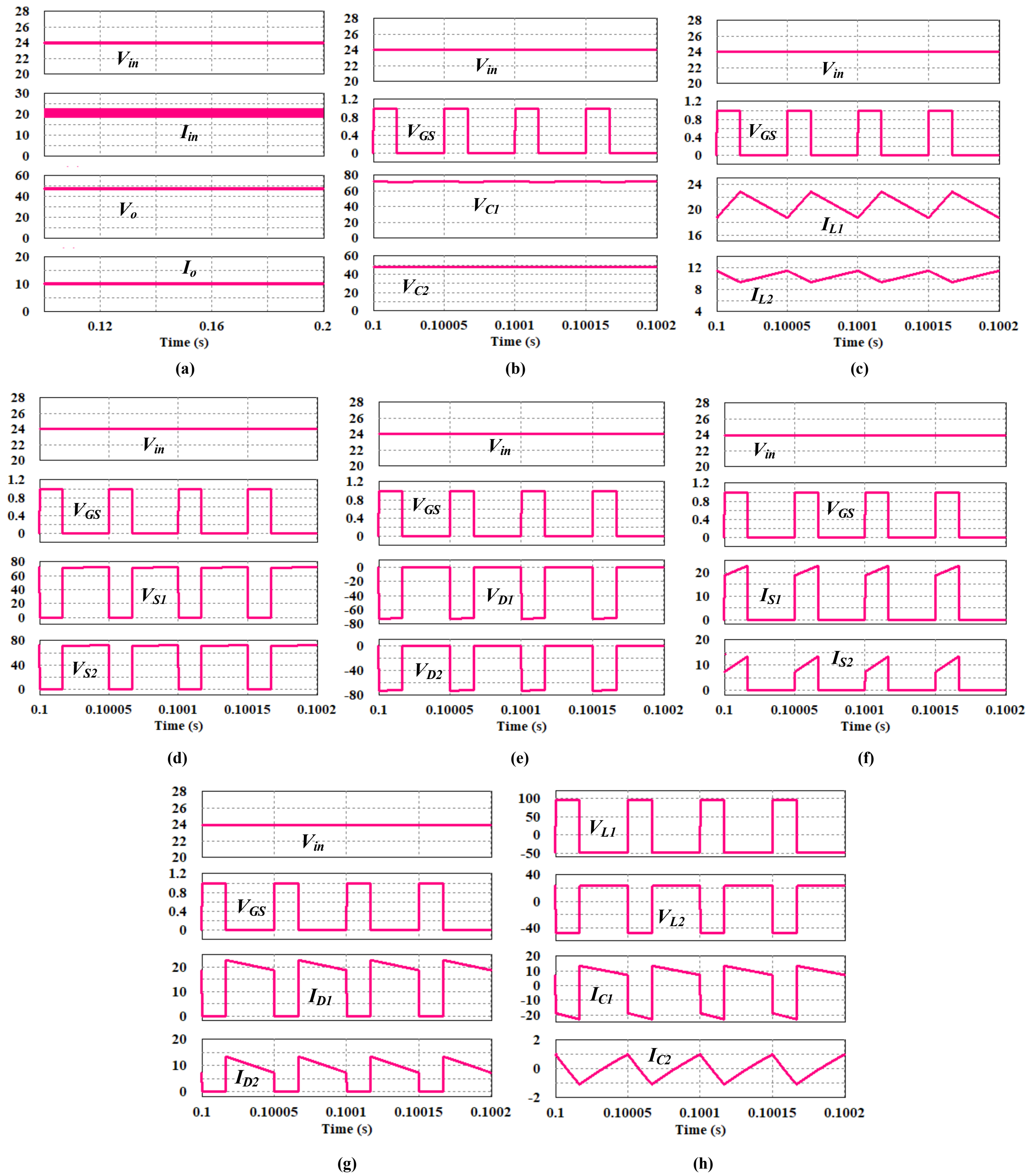

Fig. 4. Steady-state simulation studies of the IqZSC. (a) V_o, I_o, I_{in}, and V_{in}; (b) V_{C1}, V_{C2}, V_{GS}, and V_{in}; (c) I_{L1}, I_{L2}, V_{GS}, and V_{in}; (d) V_{S1}, V_{S2}, V_{GS}, and V_{in}; (e) V_{D1}, V_{D2}, V_{GS}, and V_{in}; (f) I_{S1}, I_{S2}, V_{GS}, and V_{in}; (g) I_{D1}, I_{D2}, V_{GS}, and V_{in}; and (h) I_{C1}, I_{C2}, V_{L1}, and V_{L2}. **[Y-axis has voltage/current values, having units "V" or "A"]**

that peak inductor voltages $V_{L1} = 95.87$ V and $V_{L2} = -48.27$ V, and peak capacitor currents $I_{C1} = -22.82$ A and $I_{C2} = 1.01$ A.

IV. Conclusion

An improved quasi-Z-source DC-DC converter (IqZSC) is introduced for power conversion from low voltage sources. Steady-state mathematical modelling of the IqZSC is discussed, and a comparison is also made by considering a few similar Z-source converters. It is understood from the comparison that the IqZSC and other ZSCs have equal total number of elements. Further, the IqZSC has continuous input and output currents, and common ground in comparison to other ZSCs. The steady-state performance of IqZSC is tested through simulation studies by considering a 500 W system. From the simulation studies, it is verified that the IqZSC has continuous currents. Also, the obtained output voltage from simulation studies is in-line with the theoretical discussion. Further, current and voltage stresses of the elements in the IqZSC are studied.

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