A new soft-switching multi-input quasi-Z-source converter for hybrid sources systems

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Abstract
This study focuses on a zero voltage transition multi-input quasi-Z-source converter (qZSC). This topology can be used for input sources with different voltages and currents to provide a constant output voltage. In the proposed structure, several qZSCs are combined and the output filter of all stages is eliminated. Therefore, the overall number of circuit elements, cost, volume and weight are reduced in comparison with when they are in a separate operation. In this converter, the soft-switching conditions are provided for all stages by using only one auxiliary circuit. The employed technique provides zero-voltage zero-current switching (ZVZCS) and zero-voltage switching for main switches at turn-on and turn-off instants, respectively. The auxiliary switch turns on under zero-current switching and turns off under ZVZCS. Furthermore, the reverse recovery losses of diodes are reduced. The theoretical foundation of the proposed converter is presented and its performance is simulated by OrCAD software. The obtained results show 3.5% improvement in the efficiency at nominal loads, compared to its hard-switching counterpart. A dual-input prototype of the proposed structure is successfully built to support the validity of the theoretical analysis.

1 | INTRODUCTION

Recently, the fuel crisis, global warming and environmental pollution are major factors in shifting to renewable energy sources. Moreover, the Kyoto Protocol promotes us to use clean energies including fuel cell, photovoltaic (PV), wind energy, and so forth. The most important capability of PV and wind energy sources is to serve the energy demand, even in distant or out of grid places and in densely populated areas [1].

Renewable energy sources deliver various power in different environmental conditions such as different seasons and climates. Thereby, concurrent use of two or more energy sources is essential. In order to provide regulated voltage from several energy sources, different multi-input topologies have been proposed in recent years. In the multi-input converters (MICs), the number of passive elements and the current stress of semiconductors are reduced. High flexibility as well as better management in energy sources are other benefits of using MICs [2, 3].

The boost converter is used conventionally in the renewable energy section due to the continuous input current in continuous conducting mode (CCM), simple topology and step-up conversion ratio, while input inrush currents, instability in CCM, and vulnerable to the short circuit are its drawbacks. Moreover, from an experimental viewpoint, the efficiency of the converter drops significantly in high duty ratio, and this cannot provide high voltage gains.

In order to solve the mentioned problems, Z-source converters (ZSCs) are proposed in [4, 5]. The conventional ZSC, which is in X-shape with two identical capacitors and two identical inductors, was first proposed by Peng in 2002 [6]. This converter has a higher gain compared to the conventional boost converter. Furthermore, it has a lower input current ripple without using any extra filter. Higher reliability and buck-boost capability are other advantages of this converter. However, it has drawbacks including discontinuous input current, the high voltage stress on capacitors and disability of sharing the input and output grounds [7, 8].

Nowadays, the attention of the researchers is directed to the quasi-ZSC (qZSC). In this converter, the aforementioned problems of the ZSC are resolved while the benefits of the ZSC
are kept. So the qZSC is suitable for PV systems, distributed generations, hybrid electric vehicles and wind energy conversion systems, and so forth [9, 10]. However, switching losses of ZSC and qZSC are relatively high due to the high voltage and current stress of semiconductors [11].

Various soft-switching methods are proposed to reduce the switching losses and improve the efficiency of switching converters [12, 13]. Moreover, soft-switching techniques can be used to reduce electromagnetic interference (EMI) by decreasing $\frac{dv}{dt}$ and $\frac{di}{dt}$.

A zero-voltage transition (ZVT)-pulse width modulation (PWM) DC-DC boost converter with an active snubber cell is proposed in [14] to implement soft switching for all the switches without extra voltage stresses. The auxiliary circuit includes one switch, one inductor, two capacitors, and two extra diodes. Hence, the complexity of the whole system is increased and the power density is reduced.

A dual-input isolated full-bridge (FB) boost converter is presented in [15]. In this topology, each input voltage source is controlled by a separate controller. Also, the number of inputs can be expanded to $n$. Nevertheless, the converter suffers from hard switching.

In [16], a multi-input boost converter based on the switched-diode-capacitor cells is introduced. The main benefits of this converter are high voltage gain, simple control scheme, low component stresses and low input current ripple. However, this converter is limited to low-frequency operation due to hard switching, which leads to high switching losses.

The authors of [17] sought to provide a soft switching for all switches of an MIC. This method requires a lot of extra elements for each stage and several coupled inductors.

A soft-switching multi-input/multi-output bidirectional step-down converter is discussed in [18]. In this multiport topology, which is based on the switched resonator converter structure, all switches operate under ZCS conditions.

The authors in [19] introduced a two-stage multi-input dc/ac inverter. It consists of a multi-input ZCS converter and a standard multilevel inverter. However, this structure requires a high-frequency transformer.

A soft-switching MIC is investigated in [20]. An auxiliary circuit is employed to provide the ZVS conditions for all switches. Due to the series-connected input circuits, the common ground does not exist between stages.

In [21], a systematic topology by combining the FB and bidirectional DC-DC converters is proposed for deriving multipower converters (MPCs). The converter provides ZVS turn-on for all switches. These MPCs are suitable for isolation and bidirectional conversions. However, this topology suffers from turn-off losses.

A soft-switching three-phase quasi-Z-source (qZS) rectifier without any auxiliary circuit is presented in [22]. In this topology, the soft-switching conditions are achieved when the inductor current operates in the boundary conduction mode (BCM) or discontinuous conduction mode (DCM). Therefore, its control circuit design would be complex and the input current is discontinuous, which is not appropriate for the fuel cell and PV systems.

Reference [23] proposes a Z-source FB resonant DC-DC converter, which is only suitable for a single input power source. The topology needs to employ several switches and transformers when it is operated in the multi-input structure.

A soft-switched qZS inverter proposed in [24] needs two switches and a coupled inductor for a single stage. A soft-switching qZS DC-DC converter with a high voltage gain is suggested in [25]. Because of utilizing many elements in the mentioned converter, it is costly for MIC structures.

In [26, 27], soft-switching conditions are, respectively, provided for high step-up qZSC and qZS boost inverters. In these topologies, the ZVS conditions for the switches are attained by substituting a bidirectional flow switch with the traditional diode.

A soft-switching isolated qZSC based on FB is introduced in [28]. This converter does not require any auxiliary cells. However, it operates with four active switches in BCM, which complicates the structure and increases the cost.

A multi-input boost converter is also proposed in [3]. This topology provides soft-switching conditions with an auxiliary cell. However, it requires one auxiliary diode and a large output filter capacitor.

In [29], soft-switching conditions for qZSC is provided through the coupled inductors. It is noticeable that this method requires several coupled inductors in multi-input applications, which increases the size and cost of the converter. Based on the best knowledge of the authors, no soft-switching technique suitable for a multi-input qZSC has been introduced so far in the literature.

In this study, a new soft-switching qZSC is proposed. This converter can be expanded to a multi-input structure. The main contributions of the work are summarised in the following. The converter does not have an output filter. The introduced topology can operate with one or more low-input voltage sources, for example, renewable energies that can deliver the power to the high-voltage dc bus, independently or simultaneously. A common load can be supplied with different current and voltage sources. In the proposed converter, soft switching for all semiconductor elements is provided simultaneously with only one auxiliary circuit. The main switches turn on under zero-voltage zero-current switching (ZVZCS) and turn off under ZVS, while the auxiliary switch turns on under ZCS and turns off under ZVZCS. Furthermore, all diodes turn off at ZCS and the reverse recovery problem is improved. Adding to this, the proposed structure keeps the advantages of conventional qZSCs and MICs such as less inrush current, higher reliability, higher voltage gain and high flexibility for better management in energy sources.

In Section 2, the theoretical foundation of the proposed multi-input qZSC is presented. Section 3 covers the design considerations. In Section 4, comparative analyses are presented, and the proposed converter is designed for a 200 W output power and simulated by OrCAD software. A prototype of the presented converter is built, and a comparison between experimental and theoretical results is carried out in Section 5. Finally, Section 6 covers the conclusion.
PROPOSED CONVERTER

Switching power supplies are precious for their small size, low cost, and high efficiency. However, they have a major drawback that causes switching ripples in their output voltage and current. This problem is solved by using the output filter. But it can increase the cost, size and losses of the converter. Regarding the structure of the qZSC, the proposed multi-input qZSC does not require any output filter. Based on the mentioned advantages of qZSC in the introduction, this converter is suitable for renewable energy sources and MICs. However, the switching losses of qZSCs are relatively high due to the high voltage and current stress of semiconductors. This study proposes a method to reduce these switching losses while maintaining the advantages of qZSCs and MIC. In the proposed method, one auxiliary circuit is used to implement the ZVT technique in qZSC. Figure 1(a) shows the proposed soft-switching filterless qZSC. In the proposed converter, soft switching is provided for all semiconductor devices and also the auxiliary switch.

The proposed topology can be expanded to a multi-input structure.

Figure 1(b) illustrates the suggested soft-switching multi-input qZSC. This structure includes an auxiliary circuit and several qZSC with a common load. As shown in Figure 1(b), only one auxiliary circuit is used to provide soft-switching conditions for all the stages. Also, the auxiliary switch turns on under ZCS and turns off under ZVZCS. In addition, the properties of multi-input structures such as the possibility of the operation in different voltages and currents are not limited by an appropriate switching pattern. The proposed switching pattern limits the operation of main switches to be turned on simultaneously. Each stage of this structure consists of the main power switch $S_\text{q}$, a diode $D_\text{q}$, two qZSC inductors $L_\text{q}$, two qZSC capacitors $C_{\text{q}}$, and a snubber capacitor $C_{\text{Sn}}$. The auxiliary circuit is depicted in the dashed box where $S_a$ is the auxiliary switch. Also, $C_{\text{r}1}$, $C_{\text{r}2}$, ..., $C_{\text{rn}}$ are resonant capacitors, and $L_r$ is a resonant inductor and load is shown by $R_{\text{Load}}$. Due to the similarity between the operation of multi-input and dual-input converters, the operation of the dual-input converter is investigated.

For the simplicity of the analysis, the following assumptions are considered in the steady-state operation and during a switching cycle. All capacitors and inductors of the main circuit are assumed large enough. Therefore, the inductor is modelled by a current source and the capacitor by a voltage source. Parallel capacitors $C_{\text{O}1}$ and $C_{\text{O}2}$ are modelled by a voltage source ($V_{\text{O}}$). All elements are assumed to be ideal and the converter operates in CCM.

Figure 2 shows the equivalent circuit of the proposed dual-input converter based on the aforementioned assumptions. It is noticeable that although the two main switches are turned on at the same time, they can be asynchronously turned off. Figure 3 shows the key waveforms of the theoretical analysis. The equivalent circuits of operating modes are illustrated in Figures 4 and 5. The operation modes of the proposed converter become different when the input currents are not equal.
It is assumed that before the first interval, all semiconductor devices except diode $D_1$ and $D_2$ are off.

**Interval 1 [$t_0-t_1$]:** The auxiliary switch $S_a$ is turned on at the beginning of this interval. A resonance begins between $L_r$, $C_{r1}$ and $C_{r2}$, and the current of $L_r$ is increased resonantly from zero. Therefore, ZCS conditions are achieved for $S_a$. When the current of $L_r$ reaches $2I$, this interval ends. In this interval, the current of $L_r$ and the voltages of $C_{r1}$ and $C_{r2}$ are as follows:

$$I_{Lr}(t) = \frac{V_f}{Z_1} \sin(\omega_1(t-t_0))$$  \hspace{1cm} (1)

$$V_{C1}(t) = -[V_f] \cos(\omega_1(t-t_0)) + 2V_O - V_{a1}$$  \hspace{1cm} (2)

$$V_{C2}(t) = -[V_f] \cos(\omega_1(t-t_0)) + 2V_O - V_{a2}$$  \hspace{1cm} (3)

where

$$Z_1 = \sqrt{\frac{L_r}{C_r}}, \quad \omega_1 = \frac{1}{\sqrt{L_rC_r}}, \quad C_r = C_{r1} + C_{r2}$$

$$V_f = \frac{C_{r2}}{C_r}V_2 + \frac{C_{r1}}{C_r}V_1 + V_o \quad I_{Lr}(t_0) = 0$$

$$V_1 = V_O - V_{a1} - V_{C1}(t_0), \quad V_2 = V_O - V_{a2} - V_{C2}(t_0)$$

$$2I = 2I_m + \left( \frac{D_1'}{1-D_1'} + \frac{D_2'}{1-D_2'} \right) I_m$$

$$V_{C1}(t_0) = -2V_O - V_{a1}, \quad V_{C2}(t_0) = -2V_O - V_{a2}$$

In the above equations, $D_1'$ and $D_2'$ are duty cycles of $S_1$ and $S_2$, respectively.

**Interval 2 [$t_1-t_2$]:** This interval begins by reaching $L_r$ current to $2I$. Thus, $D_1$ and $D_2$ turn off under ZCS conditions. In this interval, the snubber capacitors are discharged through resonance with $L_r$, $C_{r1}$ and $C_{r2}$. This interval lasts until the voltage of the main switches reaches zero. The following relations for the current of $L_r$ and the voltages of resonant and snubber capacitors can be given as follows:

$$I_{Lr}(t) = \frac{b}{Z_2} \times \sin(\omega_2(t-t_1)) + a \times (1-\cos(\omega_2(t-t_1))) + 2I$$  \hspace{1cm} (4)

$$V_{C1}(t) = Z_2 \frac{C_{r1}}{C_{r1}} a[\sin(\omega_2(t-t_1))] + V_{a1}(t_1)$$

$$-Z_2 \frac{C_{r1}}{C_{r1}} b[1-\cos(\omega_2(t-t_1))] - \frac{I}{C_{r1}} \left( \frac{C_{r1}}{C_{r1}} - 1 \right) (t-t_1)$$  \hspace{1cm} (5)

$$V_{C2}(t) = Z_2 \frac{C_{r2}}{C_{r2}} a[\sin(\omega_2(t-t_1))] + V_{a2}(t_1)$$

$$-Z_2 \frac{C_{r2}}{C_{r2}} b[1-\cos(\omega_2(t-t_1))] - \frac{I}{C_{r2}} \left( \frac{C_{r2}}{C_{r2}} - 1 \right) (t-t_1)$$  \hspace{1cm} (6)

$$V_{C1}(t) = -Z_2 \frac{C_{r1}}{C_{r1}} b[1-\cos(\omega_2(t-t_1))] + V_{C1}(t_1)$$

$$+ \frac{C_{r1}}{C_{r1}} a[\sin(\omega_2(t-t_1))] - \left( \frac{C_{r1}}{C_{r1}+C_{r1}} I \right) (t-t_1)$$  \hspace{1cm} (7)

$$V_{C2}(t) = -Z_2 \frac{C_{r2}}{C_{r2}} b[1-\cos(\omega_2(t-t_1))] + V_{C2}(t_1)$$

$$+ \frac{C_{r2}}{C_{r2}} a[\sin(\omega_2(t-t_1))] - \left( \frac{C_{r2}}{C_{r2}+C_{r2}} I \right) (t-t_1)$$  \hspace{1cm} (8)
FIGURE 4  Equivalent circuit models of the proposed converter for intervals 1, 2, 3, 4, 5 and 6

where

\[ a = I \left( \frac{C_1}{C_1} + \frac{C_2}{C_2} + 2 \right) \]

\[ b = \frac{C_1[V_{C1}(t_1) - V_{C1}(t)] + C_2[V_{C2}(t) - V_{C2}(t_1)]}{(C_1 + C_2)} \]

\[ C_1 = \frac{C_1 \times C_1}{C_1 + C_1}, \quad C_2 = \frac{C_2 \times C_2}{C_2 + C_2} \]

\[ V_{C1}(t_1) = 2V_O - V_{in1}, \quad V_{C2}(t_1) = 2V_O - V_{in2} \]

\[ Z_2 = \sqrt{\frac{I_r}{C_1 + C_2}}, \quad \omega_2 = \frac{1}{\sqrt{L_r(C_1 + C_2)}} \]

**Interval 3 [t_2-t_3]**: This interval starts by turning on the body diodes of \( S_1 \) and \( S_2 \) (\( D_{1B} \) and \( D_{2B} \)). Therefore, \( S_1 \) and \( S_2 \) can be turned on under zero voltage and zero current (ZVZC) conditions before turning off their body diodes. In this interval, resonance occurs between \( L_r, C_1 \) and \( C_2 \). The voltage of the resonant capacitors is initially increased to zero and the resonant inductor current reaches its maximum value \( I_{L,P} \). Then, this interval continues until the resonant inductor current is decreased to zero. In this interval, \( I_{L,P} \), \( I_{L,P} \), and resonant capacitors voltages are calculated as

\[ I_{L,P}(t) = I_{L,P}(t_2) \times (1 - \cos(\omega_1(t - t_2))) \]

\[ -\frac{|I|}{Z_1} \sin(\omega_1(t - t_2)) + I_{L,P}(t_2) \] (9)

\[ V_{C1}(t) = -|I| \times (1 - \cos(\omega_1(t - t_2))) \]

\[ -Z_1 I_{L,P}(t_2) \times \sin(\omega_1(t - t_2)) + V_{C1}(t_2) \] (10)
FIGURE 5  Equivalent circuit model of the proposed soft for intervals 7, 8, 9, 2.1, 2.2 and 2.3

\[ V_{G2}(t) = -[k] \times (1 - \cos(\omega_1(t - \tau_2))) \]
\[ -Z_1 I_{LR}(t_2) \times \sin(\omega_1(t - \tau_2)) + V_{G2}(t_2) \]
\[ I_{LR, P} = \pm \frac{1}{Z_1} \left( -2V_o + \frac{V_{in1}}{2} + \frac{V_{in2}}{2} \right) \]  

where

\[ k = \left( \left( \frac{V_{G1}(t_2) \times C_{\gamma}}{C_{\gamma}} \right) + \left( \frac{V_{G2}(t_2) \times C_{\gamma}}{C_{\gamma}} \right) \right) \]

**Interval 4 [\tau_1-\tau_4]:** This interval starts after the current of \( L_r \) reaches zero. Afterwards, the current of \( L_r \) is decreased and becomes negative. By changing the resonant inductor current flow, the current can be transmitted through the auxiliary switch body diode. Thus, the auxiliary switch \( S_d \) turns off under ZVZC conditions and its current is transmitted to \( D_{SB} \). The resonance between \( L_r, C_{\gamma 1} \) and \( C_{\gamma 2} \) continues through the switches \( S_1, S_2 \) and \( D_{SB} \) until the value of \( I_{LR} \) reaches zero. The key equations of this interval are identical to the previous interval.

**Interval 5 [\tau_4-\tau_5]:** At \( \tau_4 \), the body diode \( S_d \) turns off. This interval is similar to the switch-on time in the conventional qZSC, and qZSCs inductors are charged in this interval.

**Interval 6 [\tau_5-\tau_6]:** At the begging of this interval, \( S_2 \) is turned off. \( C_{\gamma 2} \) is charged linearly by the slop of \( L_2/C_T \). Thus, \( S_2 \) turns off under ZVS conditions. According to the circuit equivalent of this interval, \( C_{\gamma 1} \) is charged and \( C_{\gamma 2} \) is discharged. This interval continues until the value of \( V_{G2} \) reaches to \( 2V_o - V_{in2} \). In this interval, the voltages of \( C_{\gamma 2} \) and resonant capacitors are
described by

\[ V_{o1}(t) = -\frac{C_{r2}}{C_{r1} + C_{r2}} \left( \frac{I_2}{C_T} (t - t_b) \right) + V_{G1}(t_b) \] (13)

\[ V_{o2}(t) = \frac{C_{r1}}{C_{r1} + C_{r2}} \left( \frac{I_1}{C_T} (t - t_b) \right) + V_{G2}(t_b) \] (14)

\[ V_{G2}(t) = \frac{I_2}{C_T} (t - t_b) \] (15)

where

\[ C_T = C_{r2} + \frac{C_{r1} \times C_{r2}}{C_{r1} + C_{r2}} \]

**Interval 7 [t_b–t_1]:** By reaching the \( V_{o2} \) to \( 2V_o - V_{ia2} \), diode \( D_2 \) turns on at instant \( t_b \). The power of the second input is transferred to the output through \( D_2 \) while the inductors of the first input converter are still charging.

**Interval 8 [t_1–t_2]:** At \( t_1 \), \( S_1 \) is turned off and \( C_{r1} \) begins to charge linearly. Therefore, \( S_1 \) turns off under ZVS. Simultaneously, \( C_{r2} \) is charged and \( C_{r1} \) is discharged until \( V_{G2} \) reaches \( 2V_o - V_{ia1} \). The voltages across \( C_{r1}, C_{r2} \) and \( C_{r1} \) during this interval are:

\[ V_{o1}(t) = \frac{C_{r2}}{C_{r1} + C_{r2}} \left( \frac{I_1}{C_T} (t - t_b) \right) + V_{G1}(t_b) \] (16)

\[ V_{o2}(t) = \frac{C_{r1}}{C_{r1} + C_{r2}} \left( \frac{I_1}{C_T} (t - t_b) \right) + V_{G2}(t_b) \] (17)

\[ V_{G1}(t) = \frac{I_1}{C_T} (t - t_b) \] (18)

where

\[ C_T = C_{r1} + \frac{C_{r1} \times C_{r2}}{C_{r1} + C_{r2}} \]

**Interval 9 [t_1–t_2]:** When \( V_{o1} \) reaches \( 2V_o - V_{ia1} \), diode \( D_1 \) turns on at \( t_2 \). In this interval, the power of both inputs is transferred to the output and both stages operate as such the conventional goal ZSC in the switch-off time. This interval continues until \( S_2 \) is turned on again at the beginning of the next cycle.

### 2.2 Unequal input currents

By assuming \( I_{ia1} \) smaller than \( I_{ia2} \), only the second interval is substituted by the beneath intervals. Figure 5 illustrates the equivalent circuit of the following intervals.

**Interval 2.1 [t_1–t_2]:** This interval starts when the current of \( C_{r1} \) reaches \( I_1 \). As a result, diode \( D_1 \) turns off under ZC conditions, while \( D_2 \) remains on during this interval. \( C_{r1} \) begins to discharge through resonance with \( L_r, C_{r1} \) and \( C_{r2} \). This interval continues until the current of \( C_{r2} \) reaches \( I_2 \) and diode \( D_2 \) turns off. Therefore,

\[ V_{G1}(t) = -\left[ \frac{V_{C1}}{C_{r1}} \right] (1 - \cos(\omega_{21}(t - t_1))) + V_{G1}(t_1) \]

\[ + \left[ Z_{21} I_1 \frac{C_1}{C_{r1}} \left( \frac{1}{2} + \frac{C_1}{C_{r1}} \right) \right] \sin(\omega_{21}(t - t_1)) \] (19)

\[ - \left( \frac{1}{I_1} \right) \left( \frac{C_{r2}}{C_{r1} + C_{r2}} \right) \] (20)

\[ I_{L2}(t) = \frac{1}{Z_{21}} [V_1 \cos(\omega_{21}(t - t_1))] \]

\[ + \left[ I_1 \left( \frac{C_{r1}}{C_{r1} + C_{r2}} \right) + 2 \right] \times (1 - \cos(\omega_{21}(t - t_1))) + 2I_{L2} \] (21)

\[ V_{G2}(t) = -[V_1 \cos(\omega_{21}(t - t_1))] \]

\[ - \left[ Z_{21} I_1 \left( \frac{C_{r1}}{C_{r1} + C_{r2}} \right) + 2 \right] \sin(\omega_{21}(t - t_1)) + 2V_o - V_{ia2} \] (22)

where

\[ V_1 = V_{G1}(t_1) - V_{o1}(t_1), \quad V_2 = 2V_o + 2V_{ia2} - V_{o2}(t_1) \]

\[ I_1 = \frac{1}{Z_{21} I_{L2}} \]

**Interval 2.2 [t_2–t_3]:** When \( D_2 \) turns off, \( C_{r2} \) starts to discharge. In this interval, both snubber capacitors are discharged resonantly until \( C_{r1} \) is fully discharged. The important equations in this interval are as follows:

\[ I_{L2}(t) = -\left[ \frac{I_{L2}}{2} \right] \sin(\omega_{21}(t - t_{21})) + [a_1] (1 - \cos(\omega_2(t - t_{21}))) + 2I_{L2} \] (23)

\[ V_{o2}(t) = -\left[ \frac{C_{r1}}{C_{r2}} \right] \times (1 - \cos(\omega_2(t - t_{21}))) + V_{G2}(t_{21}) \]

\[ + \left[ \left( Z_{21} \frac{C_{r2}}{C_{r2}} \right) \times a_1 \right] \sin(\omega_2(t - t_{21})) - \left( \frac{I_2}{C_{r2} + C_{r2}} \right) (t - t_{21}) \] (24)
\[ V_{\text{G1}}(t) = -\left[ \frac{C_1}{C_{11}} \times h_1 \right] (1 - \cos(\omega_2(t - t_{21}))) + \left[ Z_2 \left( \frac{C_1}{C_{11}} \times a_1 \right) \sin(\omega_2(t - t_{21})) \right]
\]
\[ - \left( \frac{I_1}{C_{11}} \times \frac{C_1}{C_{11}} + 1 \right) (t - t_{21}) + V_{\text{G1}}(t_{21}) \]
\[ V_{\text{G1}}(t) = -\left[ \frac{C_1}{C_{11}} \times h_1 \right] (1 - \cos(\omega_2(t - t_{21}))) + V_{\text{G1}}(t_{21}) + \left[ Z_2 \left( \frac{C_1}{C_{11}} \times a_1 \right) \sin(\omega_2(t - t_{21})) \right]
\]
\[ - \left( \frac{I_1}{C_{11}} \times \frac{C_1}{C_{11}} + 1 \right) (t - t_{21}) + V_{\text{G1}}(t_{21}) \]  

where

\[ a_1 = \left( \frac{C_1}{C_{11}} + \frac{C_2}{C_{12}} \right) I_1 + \frac{C_2}{C_{12}} I_2 + 2 I_2 \]

\[ h_1 = \left( V_{\text{G1}}(t_{21}) - V_{\text{G1}}(t_{21}) \times \frac{C_1}{C_{11}} + C_2 \right) \]

\[ \left( V_{\text{G2}}(t_2) - V_{\text{G2}}(t_{21}) \times \frac{C_1}{C_{11}} + C_2 \right) \]

\[ C_1 = \frac{C_{11} \times C_{11}}{C_{11} + C_{11}}, \quad C_2 = \frac{C_{12} \times C_{12}}{C_{12} + C_{12}} \]

\[ Z_2 = \sqrt{\frac{L_{\gamma}}{C_1 + C_2}}, \quad \omega_2 = \frac{1}{\sqrt{L_{\gamma}(C_1 + C_2)}}, \quad I_2 = \frac{1}{1 - D_2} \]

**Interval 2.3 \([t_{21} - t_2] :** This interval starts after \(D_{1.8}\) turns on. Resonance occurs among \(L_{\gamma}, C_{11}, C_{12}\) and \(C_{22} .\) This interval continues until \(C_{12}\) fully discharges and the body diode of \(S_1\) turns on. At the end of this interval, interval 3 begins and all other intervals are similar to the previous state. The current of \(L_{\gamma}\) and voltages of \(C_{11}, C_{12}\) and \(C_{22}\) during this interval can be calculated as follows:

\[ I_{\gamma}(t) = \frac{1}{Z_{2.3}} \left[ V \sin(\omega_{2.3}(t - t_{22})) + I_{\gamma}(t_{22}) \right] \]

\[ + \left[ \frac{C_2}{C_{22}} I_2 + I_{\gamma}(t_{22}) \right] \times (1 - \cos(\omega_{2.3}(t - t_{22}))) \]

\[ V_{\text{G1}}(t) = -\left[ V \sin(\omega_{2.3}(t - t_{22})) + 2 V_{\gamma} - V_{\gamma 1} \right] \]

\[ - \left[ Z_{2.3} \left( \frac{C_2}{C_{22}} I_2 + I_{\gamma}(t_{22}) \right) \sin(\omega_{2.3}(t - t_{22})) \right] \]

**3 DESIGN CONSIDERATION**

The main circuits of the proposed structure consist of parallel traditional qZSC. As a result, the voltage gain and the elements design of main circuits are exactly similar to the conventional qZSC [30, 31], and it is more significant to focus on the design procedure of the auxiliary circuit. In the end, the theoretical analysis of efficiency improvement is presented.

### 3.1 Auxiliary circuit design

The auxiliary circuit is applied as an active snubber. Thus, the resonant inductor is selected to provide soft diodes turn-off, and snubber capacitors are designed to provide soft switching for the main switches, while the resonant capacitors are selected to provisionally store the energy.

#### 3.1.1 Resonant inductor

When the auxiliary switch turns on, an alternate current path is provided for the qZSC inductors, and these currents are diverted from the diodes into the auxiliary cell. The resonant inductor \(L_{\gamma}\) controls \(di/dt\) of the diodes. Therefore, the resonant inductor value can be obtained by determining the proper rate of diode current change. A good approximation is to allow the diode current reach zero within three times of the diode's
reverse recovery time [32].

\[ \frac{di}{dt} = \frac{I_1 + I_2}{3t_{rr}} \Rightarrow I_{tr} = \frac{2V_O - V_{sat} + V_{sat}}{\frac{di}{dt}} \]  

(32)

where \( t_{rr} \) is the reverse recovery time of the diode.

3.1.2  Snubber capacitors

The snubber capacitors are selected to control \( \frac{di}{dt} \) of the main switches. It delivers a substitute path for the \( \mu \)ZSC inductors currents when the main switches are turned off. The values of \( C_1 \) and \( C_2 \) can be designed as below [33]:

\[ C_1 \geq \frac{I_{sw1}t_1}{0.2V_{sat}}, \quad C_2 \geq \frac{I_{sw2}t_2}{0.2V_{sat}} \]  

(33)

where \( t_{1,2} \) are the switches current fall times, \( I_{sw1,2} \) are the switches currents before turning off, and \( V_{sat1,2} \) are the switches voltages after turning off.

3.1.3  Resonant capacitors

Since the snubber capacitors must be fully discharged in interval 2 to guarantee ZVS, the resonant capacitors should be larger than the snubber capacitors. The resonant capacitors and inductor determine the resonance time. Therefore, large resonant capacitors cause a long ZVT time, which increases conduction losses and the minimum duty cycle. On the other hand, small resonant capacitors induce a high voltage across the auxiliary switch. A widely adopted estimate is to select the resonant frequency 10 times greater than the switching frequency [34].

\[ T_{res} = 2\pi \sqrt{C_rL_r} = \frac{T_{sw}}{10} \]  

(34)

\( T_{sw} \) and \( T_{res} \) stand for the switching and resonance periods, respectively. Using Equations (32) and (34) yields,

\[ C_r = \left( \frac{T_{sw}}{20\pi} \right)^2 \frac{I_1 + I_2}{6t_{tr}\left(2V_O - \frac{V_{sat} + V_{sat}}{2}\right)} \]  

(35)

3.2  Semiconductor elements selection

The design of the semiconductor elements is based on its maximum voltage and current. The peak current and voltage stresses are obtained from the following relationships:

\[ I_{sa} = I_{Lx,p}, \quad I_{s1} = I_1 + \frac{|I_{Lx,p}|}{2}, \quad I_{s2} = I_2 + \frac{|I_{Lx,p}|}{2} \]  

(36)

\[ I_{D1} = I_1, \quad I_{D2} = I_2 + I_1 \]  

(37)

3.3  Efficiency improvement

The proposed soft-switching converter has lower switching losses, compared to its hard-switching counterpart. However, using the auxiliary circuit increases conduction losses. To calculate the total efficiency improvement, the switching losses and the conduction losses can be expressed as

\[ P_{loss,turn-off} = \frac{1}{2}C_1V_{sat1}^2f_{sw1} + \frac{1}{2}C_2V_{sat2}^2f_{sw} \]  

(40)

\[ P_{loss,turn-on} \approx \frac{1}{8}V_{sat1}I_{sat1}f_{sw1} + \frac{1}{8}V_{sat2}I_{sat2}f_{sw} \]  

(41)

\[ P_{loss,conduction} = \frac{I_{sw1,RMS}^2R_{sw1,ON} + I_{Lr,RMS}^2R_{Lr} + I_{C2,RMS}^2R_{C2}}{2} \]  

(42)

where \( V_{sat1,2} \) and \( I_{sat1,2} \) are the maximum voltage and current of the main switches. \( I_{sw1,2,RMS}, I_{Lr,RMS} \) and \( I_{C1,2,RMS} \) are the root mean square (RMS) current of the auxiliary switch, the resonant inductor and resonant capacitors, respectively. Therefore, the percentage of efficiency improvement is described by

\[ P_{improve} = P_{loss,turn-off} + P_{loss,turn-on} - P_{loss,conduction} \]  

(43)

As a result, the percentage of efficiency improvement can be calculated by \( P_{improve}/P_{out} \times 100 \).

3.4  Controller circuit

The controller block diagram of the proposed structure is depicted in Figure 6. The controller of this converter is similar to the traditional PWM controller [35]. Only two monostable and two Exclusive-OR (XOR) gates are added to the traditional controller to produce the gate signal of the auxiliary switch in a dual stage of the proposed structure. It should be noted that the main switches are simultaneously turned on. Hence, the two PWM controllers should be synchronised. Based on the circuit
4 | COMPARATIVE ANALYSES AND SIMULATION RESULTS

4.1 | Comparative analyses

In this part, the introduced topology is compared with other MICs. In Table 1, to make a fair comparison, all converters are considered as dual-input structures.

The proposed structure provides fully soft-switching conditions, high efficiency, continuous input current, common ground, simultaneous power delivery from the inputs.

According to Table 1, topologies proposed in [15, 16, 36, 37, 38] suffer from hard switching. Although soft switching for all switches is provided in [18], it requires a coupled inductor in each stage. In [20], the common ground does not exist between stages due to the series-connected input circuits; [39] has high input current ripple, and because of the hard-switching conditions in turn-off instants, its efficiency is decreased. Employing one auxiliary diode and a large output filter capacitor in [3] lead to more losses. In [40], the switches turn on under hard-switching conditions. In [41, 42] the leakage inductance of coupled windings increases the voltage stress of the switches and make unwanted resonances with parasitic capacitances, creating more electromagnetic emissions. Moreover, the proposed converter in [42] has discontinues input currents. In [43], soft-switching conditions are provided but the number of switches and diodes is high.

In addition to the advantages mentioned for the proposed structure, the efficiency increases with the elimination of switching losses and output filter. The elimination of the output filter results in 0.5% efficiency improvement, and the efficiency reaches 95.5% at the nominal load by providing soft switching for all switches. These results are given in Table 2.

4.2 | Simulation results

The proposed converter can operate in DCM and CCM. Based on the mentioned advantages of the qZSC in the introduction, the qZSC was proposed to resolve the problems of the ZSC such as discontinues input current. Therefore, the DCM operation of qZSC is not recommended for renewable energy sources, especially PVs. Also, employing DCM operation increases input filter values. In addition, the DCM operation requires a larger output capacitor and it is dependent on the load, which is not appropriate for our structure and application. One of the advantages of the DCM structure is to provide ZCS conditions for switches turn-on, whereas the proposed structure, in addition to providing ZVT, provides ZCS at switches turn-on instants. Therefore, the proposed method is analysed and designed in CCM operation.

The proposed ZVT dual-input qZSC converter in CCM is simulated by OrCAD for the output power of 200 W, output voltage of 100 V, input voltages of $V_{in1} = 25$ V and $V_{in2} = 50$ V. The proposed converter is designed based on Section 3, and the values of the circuit elements are summarised in Table 3. The simulation waveforms of the proposed converter are depicted in Figures 7–9.

The introduced ZVT technique also provides soft switching in DCM operation for all semiconductor elements. The simulated voltage and current waveforms of the soft-switching qZSC in DCM operation are depicted in Figure 10. The DCM operation has an extra mode compared to CCM. In this mode the inductor’s current becomes zero, the diode is reverse biased and the load is supplied through the output capacitors. As shown in Figure 10, the soft-switching conditions in DCM are provided for all semiconductors.

5 | EXPERIMENTAL RESULTS

In order to verify the accuracy of the proposed dual-input converter, a prototype of the simulated converter is built with 200 W power. All semiconductors are selected as IRFP460 switches and BYV32 diodes. The photograph of the implemented prototype is shown in Figure 11. The experimental waveforms obtained from the implemented prototype are depicted in Figures 12–14.

According to Figures 12(a) and (b), the voltages across the main switches $S_1$ and $S_2$ are reduced to zero before turn-on instants and then their currents are increased smoothly. Moreover, the rate of voltage rising is slow after turning the
| Topology                        | [3] | [15] | [16] | [17] | [20] | [36] | [37] | [38] | [39] | [40] | [41] | [42] | [43] | Proposed |
|--------------------------------|-----|------|------|------|------|------|------|------|------|------|------|------|------|----------|
| No. switches                   | 3   | 8    | 2    | 4    | 3    | 3    | 2    | 2    | 3    | 2    | 2    | 3    | 6    | 3        |
| No. diodes                     | 3   | 8    | 4    | 4    | 1    | 3    | 3    | 2    | 8    | 8    | 4    | 5    | 4    | 2        |
| No. inductors/coupled          | 3/- | 2/-  | 2/-  | 3/-  | 3/-  | 2/-  | 2/-  | 2/-  | -/-  | 2/-  | 2/-  | 1/-  | 2/-  | 2/-  | 5/-    |
| No. capacitors                 | 5   | 2    | 6    | 2    | 3    | 3    | 4    | 2    | 8    | 6    | 5    | 4    | 6    | 6        |
| Soft switching of main switch  | ✓   | ✗    | ✓    | ✓    | ✓    | ✗    | ✓    | ✗    | ✓    | ✗    | ✗    | ✓    | ✓    | ✓        |
| ON                             | ✓   | ✗    | ✓    | ✓    | ✓    | ✗    | ✓    | ✗    | ✓    | ✗    | ✗    | ✓    | ✓    | ✓        |
| OFF                            | ✓   | ✗    | ✓    | ✓    | ✓    | ✗    | ✓    | ✗    | ✓    | ✗    | ✗    | ✓    | ✓    | ✓        |
| Soft switching of auxiliary     | ✓   | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓        |
| switch                         | ✓   | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓        |
| ON                             | ✓   | ✗    | ✓    | ✓    | ✓    | ✗    | ✓    | ✗    | ✓    | ✗    | ✗    | ✓    | ✓    | ✓        |
| OFF                            | ✓   | ✗    | ✓    | ✓    | ✓    | ✗    | ✓    | ✗    | ✓    | ✗    | ✗    | ✓    | ✓    | ✓        |
| Output extra filter            | ✓   | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓        |
| Common ground                  | ✓   | ✗    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓        |
| Continuous input current       | ✓   | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓    | ✓        |
| $V_{in}(V)/V_{out}(V)$          | 50,100/200 | 30,60/400 | 33,50/400 | 175,300/100 | 12,12/30 | 10,10/177 | 25,20/100 | 20,30/95 | 48,28/300 | 30,40/400 | 45,40/410 | 36,42/200 | 20-40,60/760 | 25,50/100 |
| $P_{out}(W)/f_{SW}(kHz)$        | 400/100 | 2000/50 | 160/30 | 1000/70 | 1000/40 | 83/25 | 500/15 | 60/25 | 200/50 | 800/50 | 280/50 | 200/50 | 500/100 | 200/100  |
| Inductor values (µH)            | 1000*2.5/22*2/240/2400 | 900*2/22*2/240 | 1000*147,260,36,22,1.5/1500,250 | 1000*2/- | 3000*2/- | 1500*2/- | 1000*2/- | 3000*2/- | 120*2/- | 250*2/300 | 3.1/120,1920 | 2*40/N/A | 200*4,5/- |
| Capacitor values (µF)           | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 | 0.015*2/0.015*2 |

**Note:**
- ✓ = Having each attribute. ✗ = not having each attribute. - = not having auxiliary switch or capacitors or inductor. *number = Show the number of required parameter. N/A = not available.
| Efficiency | Common ground | Fully soft-switched | Voltage gain | Current stress on the main semiconductors | Voltage stress on the main semiconductors | Components of auxiliary circuit | Components of main circuit | Converter |
|------------|---------------|---------------------|--------------|------------------------------------------|------------------------------------------|----------------------------------|---------------------------|-----------|
| 95.5       | Yes           | Yes                 | \( \frac{V_o}{V_{in}} = \frac{1-D'_{i}}{1-2D'} \) | \( I_S = I + \frac{|I_{S_i}|}{I} \) | \( V_{S_i} = 2V_o - V_{in} \) | Zero diode | Two diodes | Dual-input soft-switching qZSC converter (qZSC) without output filters (proposed converter) |
| 92         | Yes           | No                  | \( \frac{V_o}{V_{in}} = \frac{1-D'_i}{1-2D'} \) | \( I_S = I \) | \( V_{S_i} = 2V_o - V_{in} \) | ✓ | Two diodes | Dual Input qZSC without Output Filters |
| ≈95.5      | Yes           | Yes                 | \( \frac{V_o}{V_{in}} = \frac{1-D'_i}{1-2D'} \) | \( I_S = I + |I_{S_i}| \) | \( V_{S_i} = 2V_o - V_{in} \) | Zero Diode | One diode | Soft-switching qZSC without output filters (proposed converter) |
| ≈92        | Yes           | No                  | \( \frac{V_o}{V_{in}} = \frac{1-D'_i}{1-2D'} \) | \( I_S = I \) | \( V_{S_i} = 2V_o - V_{in} \) | ✓ | One diode | qZSC without output filters |
| 91.5       | Yes           | No                  | \( \frac{V_o}{V_{in}} = \frac{1-D'_i}{1-2D'} \) | \( I_S = 2I_{in} - I \) | \( V_{S_i} = 2V_o - V_{in} \) | ✓ | One diode | Conventional qZSC |

Note: \( I_i = (1/D)I_{in} \), \( D \) is the Duty Cycle and \( i \) is the number of stages.
main switches off. Therefore, the main switches turn on under ZVZCS and turn off under ZVS.

Figures 12(c) and (d) show that the voltages across diodes start rising after the current completely falls to zero. As a result, diodes turn off at ZCS and the reverse recovery problem can be improved.

In Figure 13(a), the current of the auxiliary switch rises and falls linearly. In addition, its voltage remains zero after turn-off instant. Accordingly, the auxiliary switch turns off under ZVZCS and turns on under ZCS conditions.

Figure 13(b) shows the voltage and current waveforms of the output load. In this figure, the ripple of both the voltage and current is less than 7%, which confirms the satisfactory performance of the proposed structure.
In order to demonstrate the independent operation of input sources, the prototype is implemented in two separate conditions. In each condition, the duty cycle of one switch is zero and another converter operates at the nominal current. As shown in Figure 14(a), the soft-switching conditions is provided for $S_1$ and $D_1$ when the duty cycle of $S_2$ is kept zero. Also, according to Figure 15(b), the soft switching is achieved for $S_2$ and $D_2$ when the duty cycle of $S_1$ is kept zero.

When the inputs voltages are equal, the switching of the main switches is simultaneous and the current circulation between qZSCs in the multi-input structure does not occur. But according to the key waveforms, circuit models and theatrical analyses of the proposed converter (in Section 2), when the inputs voltages are different due to the different duty cycle values of main switches, the current circulation between qZSCs occurs at turn-off instants. This happens in modes 6 and 8. In mode 6, at turn-off instants of the $S_2$, the current of the lower stage is transferred to the upper stage. The current circulation continues until the voltage of the $S_2$ reaches the maximum value and $D_2$ turns on. This transferred current is observed in the current waveform of $S_1$ (Figure 12(a)). Similarly, in mode 8, the current of the upper stage is transferred to the lower stage until the voltage of the $S_1$ reaches the maximum value. This transferred current is observed in the current waveform of $D_2$ (Figure 12(d)).

The experimental results validate simulation and theoretical analysis. There is some oscillation in the waveforms due to the resonance between parasitic inductors and capacitors, acquisition noises, or measurement tool adjustment that poses some changes in simulation and theoretical results. Figure 13(a) is similar to the simulation results, except a resonance during the turn-off instance, which is due to the resonance between the resonant inductor and the auxiliary switch capacitor.

To illustrate the advantages of this work, the simulation and experimental results of the proposed converter and the study [40] are compared. The structure and the experimental results of the study [40] are shown in Figure 15. In this topology, the ZVT technique is provided with one auxiliary circuit. This structure employs diode-capacitor multiplier at the output and does not need any extra output filter. This converter can provide ZVS conditions for all switches at turn-off instant (Figures 15(c) and (d)). However, this topology suffers from turn-on switching losses. The article [40] did not examine the possibility of independent operation of the input sources and the reverse recovery problem of the diodes. So we simulated the study [40] by OrCAD for the output power of 800 W, the output voltage of 400 V, input voltages of $V_{in1} = 30$ V and $V_{in2} = 40$ V. The simulation results are illustrated in Figure 16. As shown in Figure 16(a), the diodes have the reverse recovery problem. Based on Figures 16(b) and (c), when one of the inputs currents is zero ($I_{in2} = 0$), the switch is still turned off under ZVS conditions, but half of the capacitors do not charge and the output voltage is reduced by half. The experimental results of the proposed converter show that the main switches turn on under ZVZCS and turn off under ZVS (Figures 12(a) and (b)), and the problem of reverse recovery of diodes in the proposed topology has been solved (Figures 12(c) and (d)). Also, when one of the input currents is zero, the soft switching is still provided for the semiconductor elements (Figure 14), and the output voltage is fully supplied.

Efficiency comparison between the proposed dual-input converter and its hard-switching counterpart is obtained through simulation with the OrCAD software, and it is shown in Figure 17. The efficiency of the proposed dual-input converter is shown by a solid line, while the efficiency of its hard switching counterpart is shown by a dotted line.

6 | CONCLUSION

In this study, a new ZVS method is proposed for a multi-input qZSC. In this technique, a ZVT cell with one active switch, respectively, provides ZVZCS and ZCS conditions for all stages of main switches turning-on and turning-off. Moreover, ZCS turn-on and ZVZCS turn-off is achieved for the auxiliary switch. Therefore, turn-on capacitive losses of the main switches are totally eliminated. In addition, EMI noises and
FIGURE 12 Experimental voltage and current waveforms of (a) main switch $S_1$, (b) main switch $S_2$, (c) diode $D_1$, (d) diode $D_2$

FIGURE 13 Experimental voltage and current waveforms of the auxiliary switch $S_a$, (b) output load

FIGURE 14 Experimental voltage and current waveforms of (a) main switch $S_1$ (when $I_{in2} = 0$), (b) diode $D_1$ (when $I_{in2} = 0$), (c) main switch $S_2$ (when $I_{in1} = 0$), (d) diode $D_2$ (when $I_{in1} = 0$)
reverse recovery losses of diodes are reduced. The proposed converter has the ability to transfer energy from different input sources to the output load simultaneously and individually. Furthermore, the proposed idea can be easily extended to include more qZSC. The introduced structure is a suitable candidate for renewable energy applications due to its advantages in reduced devices, simple configuration, and so forth. The theoretical analysis and design considerations of the converter are described in this study. Also, the experimental results of a 200 W laboratory prototype verify the integrity of the presented analysis.
RESULTS

1. Eskandarian, N., Harchegani, A.T., Kazemi, S.S.: A novel structure for high step-up DC-DC converter with flexibility under the variable loads for EV solar charging system. Int. Trans. Electr. Energy Syst. 30, e12375 (2020)
2. Hema Chander, A., Sahu, L.K., Ghosh, S.: Stand-alone multiple input photovoltaic inverter for maximum power extraction and voltage regulation under mismatched atmospheric conditions. IET Renewable Power Gener. 14(9), 1584–1595 (2020)
3. Torki Harchegani, A., Mahdavi, M.: A new soft switching dual input inverter for renewable energy systems. J. Power Electron. 17(5), 1127–1136 (2017)
4. Rostami, S., Abbasi, V., Blaabjerg, F.: Implementation of a common grounded Z-source DC–DC converter with improved operation factors. IET Power Electron. 12, 9, 2245–2255 (2019)
5. Deng, W. et al.: Series Z-source and nine-switch dual-output inverter stage two-stage matrix converter. IET Power Electron. 10(2), 143–150 (2017)
6. Peng, E.Z.: Z-source inverter. IEEE Trans. Ind. Appl. 39(2), 504–510 (2003)
7. Babaei, E., Shokati Asl, E.: Steady-state analysis of high-voltage gain multiple series Z-source inverter. IET Power Electron. 10(12), 1518–1528 (2017)
8. Zakipour, A., Shokri Kojori, S., Tavakoli Bina, M.: Closed-loop control of the grid-connected Z-source inverter using hyper-plane MIMO sliding mode. IET Power Electron. 10(15), 2229–2241 (2017)
9. Pires, V.F., Foiot, D., Cordeiro, A.: Three-phase qZ-source inverter with fault tolerant capability. IET Power Electron. 10(14), 1852–1858 (2017)
10. Liu, J., Wu, J., Qiu, J., Zeng, J.: Switched Z-Source/Quasi-Z-Source DC–DC Converters With Reduced Passive Components for Photovoltaic Systems. IEEE Access 7, 40893–40903 (2019)
11. Gadalla, B., et al.: Analysis of loss distribution of conventional boost, Z-source and Y-source converters for wide power and voltage range. Trans. Environ. Electr. Eng. 2(1), 1–9 (2017)
12. Esteki, M., et al.: Family of soft-switching pulse-width modulation converters using coupled passive snubber. IET Power Electron. 10(7), 792–800 (2017)
13. Ashghar, A.: Ultra high step-down ZVS synchronous buck converter with low switch voltage stress. IET Power Electron. 13(10), 2039–2048 (2020)
14. Ting, N.S., Aksoy, I., Sahin, Y.: ZVT-PWM DC–DC boost converter with active snubber cell. IET Power Electron. 10(2), 251–260 (2017)
15. Zhang, Z., et al.: Dual-input isolated full-bridge boost dc–dc converter based on the distributed transformers. IET Power Electron. 5(7), 1074–1083 (2012)
16. Hou, S., et al.: Multi-input step-up converters based on the switched-diocecapacitor voltage accumulator. IEEE Trans. Power Electron. 31(1), 381–393 (2016)
17. Lam, J., Jain, P.K.: An asymmetrical PWM (APWM) controlled multi-input isolated resonant converter with zero voltage switching (ZVS) for hybrid renewable energy systems. In: 2014 IEEE 36th International Telecommunications Energy Conference (INTELEC), Vancouver, BC, pp. 1–6 (2014). https://doi.org/10.1109/INTELEC.2014.6972220
18. Jabbari, M., Dorcheh, M.S.: Resonant multi-input/multi-output/bidirectional ZCS step-down DC–DC converter with systematic synthesis for point-to-point power routing. IEEE Trans. Power Electron. 33(7), 6024–6032 (2018)
19. Reddi, N.K., et al.: An Isolated multi-input ZCS DC–DC front-end converter based multilevel inverter for the integration of renewable energy sources. IEEE Trans. Ind. Appl. 54(1), 494–504 (2018)
20. Wu, R., et al.: Newly designed ZVS multi-input converter. IEEE Trans. Ind. Electron. 58(2), 555–566 (2011)
21. Wu, H., et al.: Multiport converters based on integration of full-bridge and bidirectional DC–DC topologies for renewable generation systems. IEEE Trans. Ind. Electron. 61(2), 856–869 (2014)
22. Zhang, Q., et al.: A Novel modulation for soft-switching three-phase quasi-Z-source rectifier without auxiliary circuit. IEEE Trans. Ind. Electron. 65(6), 5157–5166 (2018)
23. Dong, X., et al.: Z-source resonant soft-switching converter for flexible DC power distribution application. In: 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, pp. 1–5 (2016). https://doi.org/10.1109/PESGM.2016.7741561
24. Battiston, A., et al.: Soft-switched quasi-Z-source inverter-fed permanent magnet synchronous machine for hybrid/electric vehicle applications. EPE J. 27(2), 85–96 (2017)
25. Rezvanyardom, M., Mirzaei, A., Heidari, S.: Fully soft switching non-isolated quasi Z-source DC-DC converter with high voltage gain. IEEE J. Emerging Sel. Top. Power Electron. (2020). doi:10.1109/JESTPE.2020.2970151
26. Poorali, B., Adib, E.: Soft-switched high step-up quasi-Z-source DC–DC converter. IEEE Trans. Ind. Electron. 67, 4547–4555 (2019)
27. Xia, K., et al.: Quasi-Z-source boost inverter with soft-switching. In: 2016 19th International Conference on Electrical Machines and Systems (ICEMS), Chiba, Japan, pp. 1–6 (2016). https://ieeexplore.ieee.org/document/7837395
28. Husey, O., et al.: Galvanically isolated quasi-Z-source DC–DC converter with a novel ZVS and ZCS technique. IEEE Trans. Ind. Electron. 62(12), 7547–7556 (2015)
29. Karimi, M., Mahdavi, M., Torki Harchegani, A.: A new soft switching qZSC converter by using coupled inductor. Electr. Power Compon. Syst. 46(3), 270–277 (2018)
30. Yang, L., et al.: A quasi-Z-source DC–DC converter. In: 2014 IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, pp. 941–947 (2014). https://doi.org/10.1109/ECCE.2014.6953800
31. Tajikuchi, T., Koizumi, H.: Quasi-Z-source dc–dc converter with voltage-lift technique. In: IECON 2013–39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, pp. 393 (2013). https://doi.org/10.1109/IECON.2013.6699302
32. Pressman, A.I.: Switching Power Supply Design, 2nd ed., pp. 425–428. McGraw-Hill, New York (1998)
33. Noon, J.P.: A 250 kHz, 500 W power factor correction circuit employing zero voltage transitions. In: Unitrode Power Supply Design Seminar Manual SEM1000, Unitrode Corp, Waltham, MA, pp. 1.1–1.15 (1994)
34. Rezvanyardom, M., Adib, E., Farzanehfard, H.: New interleaved zero-current switching pulse-width modulation boost converter with one auxiliary switch. IET Power Electron. 4(9), 978–983 (2011)
35. Di Napoli, A., et al.: Control strategy for multiple input DC-DC power converters devoted to hybrid vehicle propulsion systems. In: ISIE 2002. Proceedings of the 2002 IEEE International Symposium on Industrial Electronics, 2002, L'Aquila, Italy, vol. 3, pp. 1036–1041 (2002). https://doi.org/10.1109/ISIE.2002.1025887
36. Varesi, K., et al.: A high-voltage gain nonisolated noncoupled inductor based multi-input DC-DC topology with reduced number of components.
for renewable energy systems. Int. J. Circuit Theory Appl. 46, 505–518 (2018)

37. Dehimi, A., et al.: A new multi-input step-up DC–DC converter for hybrid energy systems. Electr. Power Syst. Res. 149, 111–124 (2017)

38. Baraei, M.R., et al.: Non-isolated multi-input–single-output DC/DC converter for photovoltaic power generation systems. IET Power Electron. 7, 2806–2816 (2014)

39. Honarjoo, B., et al.: Non-isolated high step-up three-port converter with single magnetic element for photovoltaic systems. IET Power Electron. 11(13), 2151–2160 (2018)

40. Zhu, B., et al.: A dual-input high step-up DC/DC converter with ZVT auxiliary circuit. IEEE Trans. Energy Convers. 34(1), 161–169 (2019)

41. Mohseni, P., et al.: Ultra-high step-up two-input DC–DC converter with lower switching losses. IET Power Electron. 12, 2201–2213 (2019)

42. Faraji, R., Adib, E., Farzanehfard, H.: Soft-switched non-isolated high step-up multi-port DC–DC converter for hybrid energy system with minimum number of switches. Int. J. Electr. Power Energy Syst. 106, 511–519 (2019)

43. Deng, J., Wang, H., Shang, M.: A ZVS three-port DC/DC converter for high-voltage bus-based photovoltaic systems. IEEE Trans. Power Electron. 34, 10688–10699 (2019)

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