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A Switched Quasi-Z-Source Inverter with Continuous Input Currents

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***Abstract*—This paper proposes a modified Switched quasi-Z-Source Inverter (Sq-ZSI). The proposed Sq-ZSI achieves continuous input currents with a larger conversion ratio by replacing one diode of the Diode-assisted Switched Boost Inverter (DA-SBI) with a capacitor. Moreover, the voltage stress of the power switches in the proposed Sq-ZSI is lower and the voltage stress of the capacitors remains the same. The proposed topology is benchmarked with other Z-source inverters using active switches in terms of conversion ratio, voltage gain, and stresses on the power switches and capacitors. Simulation and experimental tests are provided to validate the analysis.**

***Index Terms*—Z-source inverter, impedance source inverter, quasi Z-source inverter, active switch, continuous input current, DC-AC inverter**

I. Introduction

Impedance source inverters (i.e., the Z-source inverter (ZSI) [1]) are being increasingly employed in power conversion applications, e.g., motor drives, distributed power systems, and hybrid electric vehicles due to their extraordinary performance in terms of high boost capability and efficiency [2]–[7]. The basic impedance source topologies, i.e., the traditional ZSI and quasi-ZSI (qZSI) [8] are exemplified in Fig. 1. Compared with the conventional voltage-source inverter, the impedance-source inverters can boost the voltage by adding the shoot-through state. This has become one attractive feature for ZSIs in single-stage conversion systems, which also avoids the use of the dead-time in the inverter.

In recent years, many attempts have been made to improve the performance of impedance source converters, e.g., to further extend the voltage gain range and to improve the control and design. Notably, the high boosting capability of the impedance-source inverters are possibly achievable by adding more passive components or active switches and properly arranging them. For instance, traditional switched-inductors (SL) or switched-capacitors (SC) can be added in the impedance networks [9]–[12]. In [9] and [10], the inductors in the ZSI/qZSI were replaced by SL impedance networks, and the resultant topologies can provide a higher boosting capability. Moreover, series-connected SL or SC cells were employed [11], [12], leading to both high conversion gains and low voltage stresses.

However, the extra passive components increase the overall system volume, weight, and cost. To address this, certain ZSI topologies with active switches have been proposed in the literature [13]–[16]. Fig. 2 shows a switched boost inverter (SBI) and a diode-assisted SBI (DA-SBI). Compared to the ZSI, the SBI has fewer passive components, but achieves the same boost capability with one active switch, as shown in Fig. 2(a). The improvement makes it more suitable for low-power applications [13]. However, it is clear that the capacitor voltage stress is very high due to the parallel connection with the dc input source. Moreover, the input current from the dc source is discontinuous because of the diode in the SBI. To address these drawbacks, a new family of quasi-switched boost inverters (qSBI) were proposed in [14]. By modifying the topology of the SBI, the capacitor voltage has decreased and a higher boost capability with continuous input currents can be obtained. Moreover, the SL and SC can be applied to the SBI for an even higher boost capability, as presented in [15], which can be cascaded in the impedance network by adding more inductors and diodes. In addition, the DA-SBI was proposed in [16]. There is no common ground between the dc source and the inverter, as shown in Fig. 2(b). The DA-SBI is considered as a modification of the SBI, and it features a high voltage gain and continuous input currents. Nevertheless, further efforts should be made to improve the performance of ZSI systems.

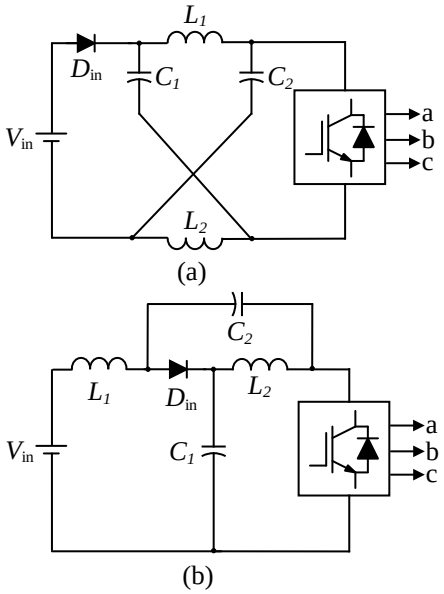

Fig. 1. Circuit schematics of impedance-source-fed three phase inverters: (a) Z-source inverter [1], and (b) quasi-Z-source inverter [8].

In this context, a Switched quasi-Z-Source Inverter (Sq-ZSI) is proposed in this paper according to the DA-SBI. The

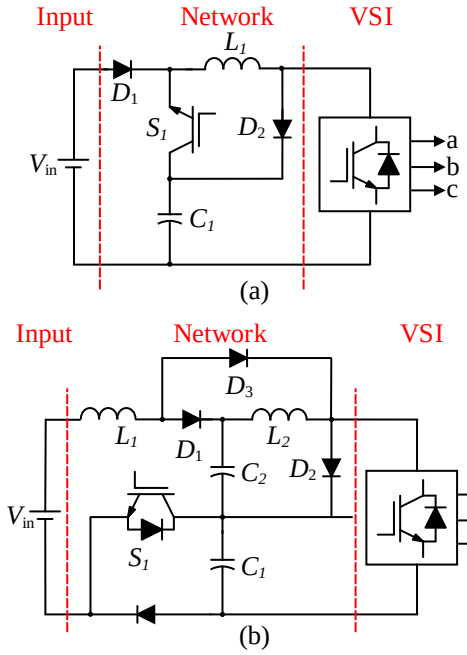

Fig. 2. Impedance-source networks with active power switches: (a) switched boost inverter (SBI), and (b) diode-assisted SBI (DA-SBI).

proposed topology can achieve continuous input dc currents and a higher boost capability, compared to the SBI and DA-SBI. The rest of this paper is organized as follows. In Section II, the operation principle of the proposed topology is presented. Moreover, comparisons with the conventional switched impedance networks are performed and benchmarking the results are also provided in Section II. Simulations and experimental tests are given in Section III, which verify the performance of the proposed topology in terms of continuous input dc currents and also high boost capability. Finally, the paper concludes in Section IV.

II. The Proposed Topology

A. Operation Principles

The proposed Sq-ZSI is shown in Fig. 3(a), which includes a quasi-Z-source network, an active switch (S_1), two diodes, and one extra capacitor. The operation principle of the proposed is similar to the prior-art ZSIs. That is, there are two operational modes: the shoot-through state and non-shoot-through state. The equivalent circuits of the Sq-ZSI in the shoot-through state and non-shoot-through state are shown in Figs. 3(b) and (c), respectively. In the following analysis, it is assumed that all capacitors (or inductors) in the topology are identical for simplicity.

In the shoot-through state (see Fig. 3(b)), the dc side is short circuited (e.g., dc-link voltage $V_{\rm dc} = 0$), the diodes D_1, D_2 and D_3 are reverse-biased and the active switch S_1 is turned ON. During this state, all the capacitors will charge the inductors. Then, it can be obtained that

$$V_{\rm L1\text{-}S} = V_{\rm C_1} + V_{\rm C_3} + V_{\rm in} \tag{1}$$

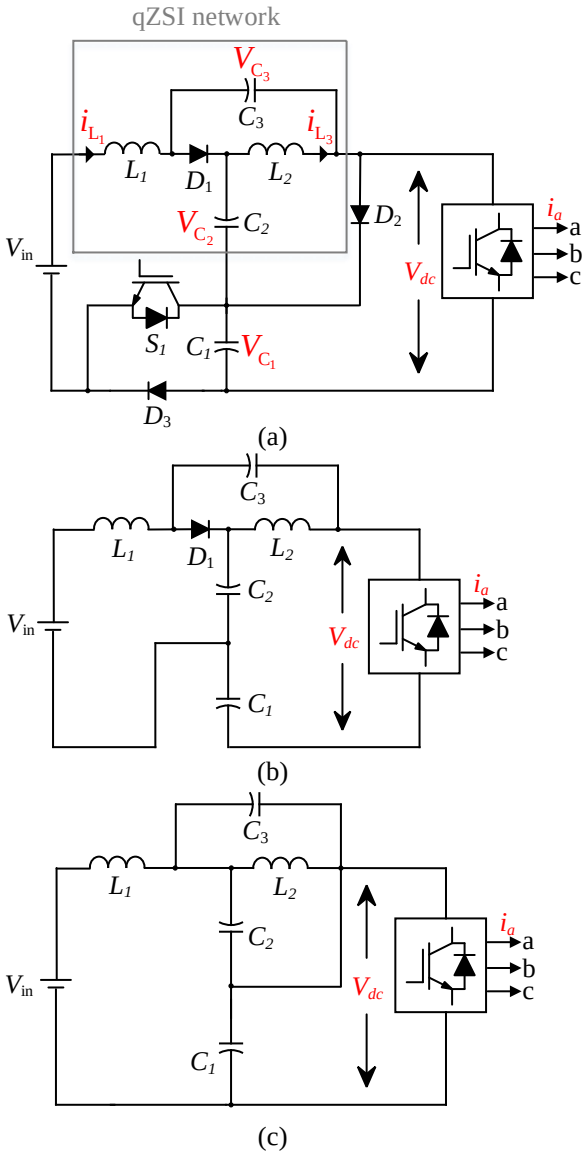

Fig. 3. Schematics of the proposed switched qZSI: (a) circuit diagram, (b) equivalent circuit during the shoot-through state, and (c) equivalent circuit during the non-shoot-through state.

$$V_{\rm L2\text{-}S} = V_{\rm C_1} - V_{\rm C_2} \tag{2}$$

in which $V_{\rm L1\text{-}S}$ and $V_{\rm L2\text{-}S}$ are the voltages across the inductor L_1 and L_2, respectively, $V_{\rm C_1}$, $V_{\rm C_2}$, and $V_{\rm C_3}$ are the corresponding voltages across the capacitor C_1, C_2, and C_3, and $V_{\rm in}$ is the dc-source voltage.

In the non-shoot-through state (see Fig. 3(c)), all three diodes are in ON state, the active switch S_1 is turned OFF and the inductors release the stored energy to the ac load (inverter). It is known that during one cycle, the inductor average voltage should be zero, and then applying the volt-second balance principle to all the inductors leads to

$$DV_{\rm L1\text{-}S} + (1-D)\,V_{\rm L1\text{-}N} = 0 \tag{3}$$

$$DV_{\rm L2\text{-}S} + (1-D)\,V_{\rm L2\text{-}N} = 0 \tag{4}$$

where $V_{\text{L1-N}}$ and $V_{\text{L2-N}}$ represent the inductor voltages on L_1 and L_2, respectively, during the non-shoot-through state, and D is the duty cycle. Furthermore, according to Fig.4(c), the following can be obtained by applying the Kirchhoff's voltage law:

$$V_{\text{L1-N}} = V_{\text{in}} + V_{\text{C}_3} - V_{\text{dc}}^{\text{p}} \tag{5}$$

$$V_{\text{L2-N}} = -V_{\text{C}_2} = -V_{\text{C}_3} \tag{6}$$

in which V_{dc}^{p} is the peak dc-link voltage. Subsequently, the capacitor voltages can be expressed as

$$V_{\text{C}_1} = \frac{1}{1-3D} V_{\text{in}} \tag{7}$$

$$V_{\text{C}_2} = V_{\text{C}_3} = \frac{D}{1-3D} V_{\text{in}} \tag{8}$$

Furthermore, the peak dc-link voltage V_{dc}^{p} and boost factor B can be obtained as

$$V_{\text{dc}}^{\text{p}} = \frac{1}{1-3D} V_{\text{in}} = B \cdot V_{\text{in}} \tag{9}$$

with

$$B = \frac{1}{1-3D} \tag{10}$$

is the boost factor. Consequently, the voltage gain G in respect to the modulation index M can be expressed as

$$G = MB = \frac{M}{3M-2} \tag{11}$$

B. Comparison with Prior-art ZSI Topologies

According to the above analysis, it is known that the proposed Sq-ZSI can achieve a higher boosting capability. The performance of the proposed Sq-ZSI is compared with the ZSI, SBI, and DA-SBI, as shown in Table I. Figs. 4 and 5 benchmark the boost capability of the four selected topologies. In Fig. 4, the relationship between the duty cycle D and the boost factor B for these topologies is presented. It is observed that the boost factor of the proposed Sq-ZSI is much higher than the benchmarked topologies within a wide range of shoot-through duty ratios (i.e., 0-0.3). Moreover, Fig. 5 compares the voltage gains of the selected topologies in respect to the modulation index. It can be seen in Fig. 5 that the voltage gain of the proposed Sq-ZSI is higher than that of the selected topologies for the same modulation index. It is noted that the modulation index has an important impact on the power quality. To obtain the same voltage output, the proposed Sq-ZSI has a higher M compared with other topologies, as it is shown in Fig. 5.

In addition to the advantage of a high boost capability, as demonstrated above, the proposed Sq-ZSI can achieve lower voltage stresses on the power switches. The switch voltage stress γ_s can be defined as:

$$\gamma_s = \frac{V_s}{G V_{\text{dc}}^{\text{p}}} \tag{12}$$

where V_s is the voltage on the switches and G, V_{dc}^{p} are as defined previously. Fig. 6 shows that the power switch stresses of the proposed Sq-ZSI are lower than other topologies in a wide voltage gain range. Moreover, comparison of capacitor voltage stresses can be seen in Table I. Although the proposed Sq-ZSI has a higher boost factor, the same capacitor voltage stress compared to the SBI and DA-SBI is achieved.

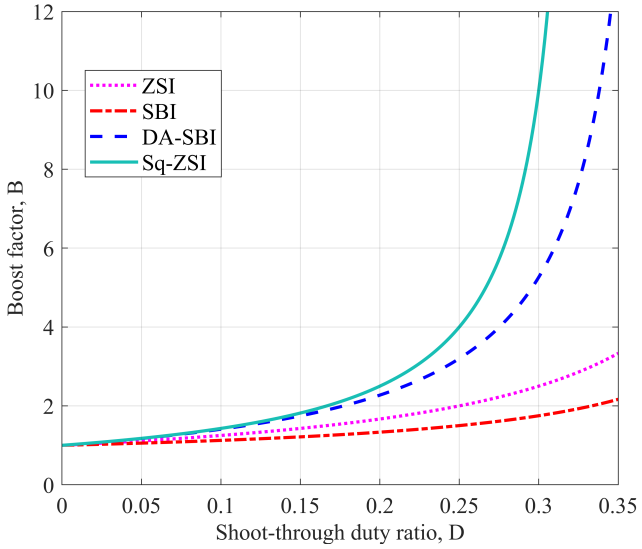

Fig. 4. Comparison of the boost factor versus the shoot through duty ratio D among the selected topologies.

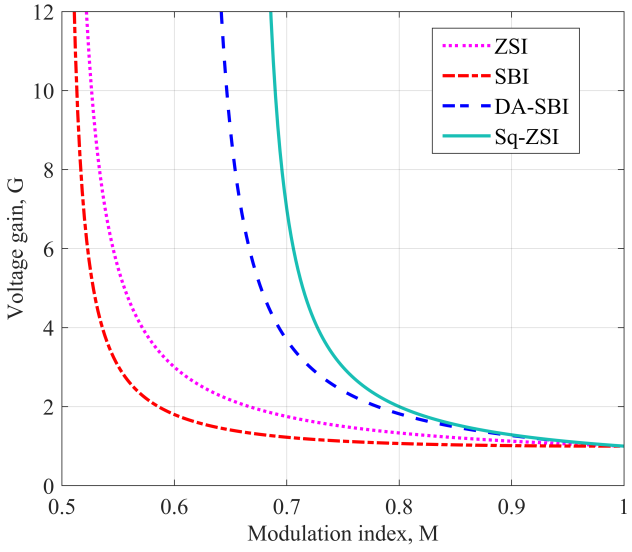

Fig. 5. Comparison of the voltage gain versus the modulation index M among the selected topologies.

III. Simulation and Experimental Results

Simulations and experimental tests are conducted to verify the performance of the proposed impedance source network. The system parameters used in the simulation and experimental prototype are given in Table II. The modulation index M and duty ratio D are chosen as 0.83 and 0.25 in the initial state for simulations and experimental tests.

TABLE I
BENCHMARKING OF SELECTED IMPEDANCE SOURCE INVERTERS.

Impedance-Source Inverters		ZSI [1]	SBI [1]	DA-SBI [16]	Proposed Sq-ZSI
Boost Factor	B	$\frac{1}{1-2D}$	$\frac{1-D}{1-3D}$	$\frac{1}{D^2-3D+1}$	$\frac{1}{1-3D}$
Voltage Gain	G	$\frac{M}{2M-1}$	$\frac{M^2}{2M-1}$	$\frac{M}{M^2+M-1}$	$\frac{M}{3M-2}$
Power Switch Voltage Stress	$\frac{V_s}{GV_{dc}^p}$	$2-\frac{1}{G}$	$\frac{1}{G-\sqrt{G^2-G}}$	$\frac{2G}{1-G+\sqrt{5G^2-2G+1}}$	$\frac{3G-1}{2G}$
Capacitor Voltage Stress	V_{C_1}	/	BV_{in}	BV_{in}	BV_{in}
	V_{C_2}	/	/	BDV_{in}	BDV_{in}
	V_{C_3}	/	/	/	BDV_{in}

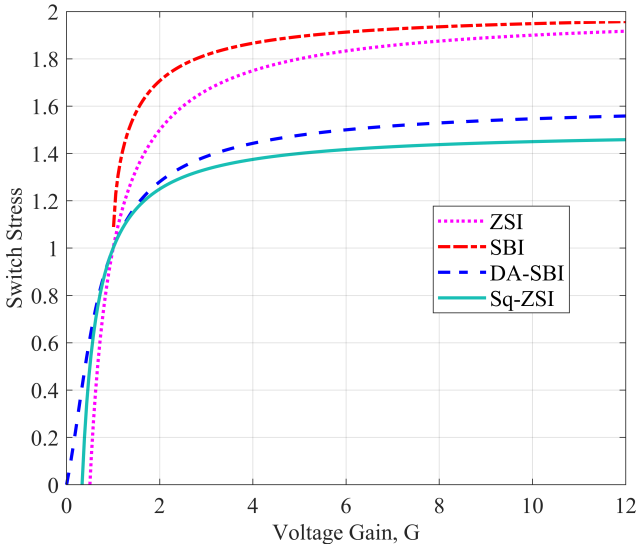

Fig. 6. Switch stress among the selected topologies with various voltage gains.

TABLE II
PARAMETERS OF THE SQ-ZSI.

Parameter	Symbol	Value
DC input voltage	V_{in}	25 V
Sq-ZSI inductance	L_1, L_2	640 μH
Sq-ZSI capacitor	C_1, C_2, C_3	100 μF
Load inductance	L_f	3 mH
Load resistance	R_f	40 Ω
Switching frequency	f_s	10 kHz

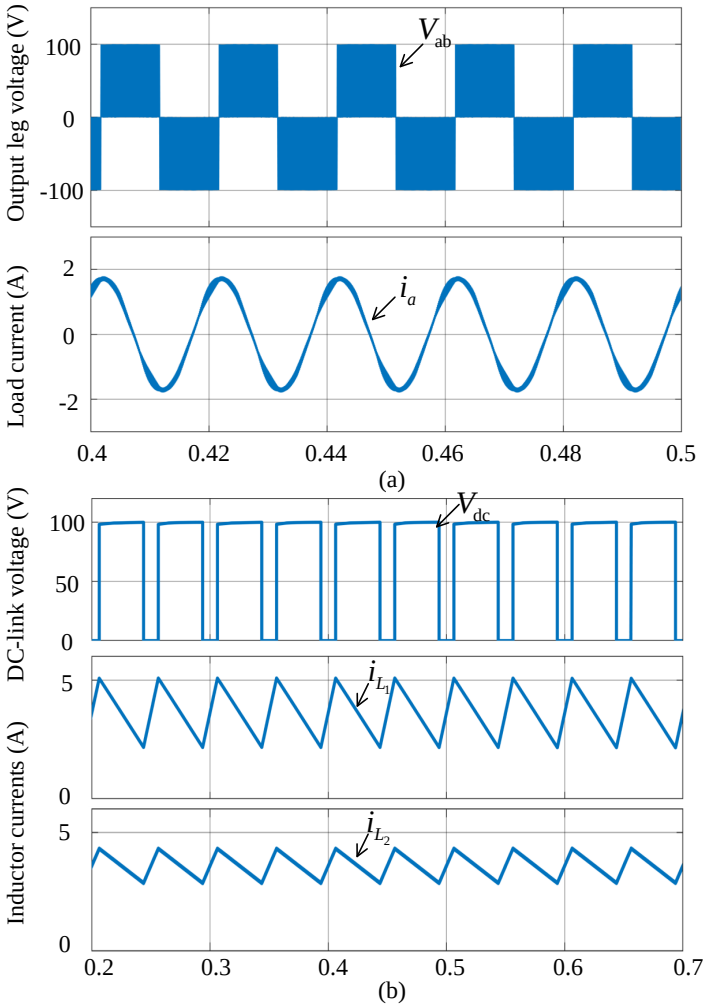

Fig. 7. Simulation results of the proposed Sq-ZSI: (a) the output leg voltage and load current in the Sq-ZSI, and (b) the dc-link voltage and inductor currents in the Sq-ZSI.

A. Simulation Results

Simulations are carried out in the PLECS and Matlab/Simulink with an open-loop control. According to (10), the boost factor can be calculated as B = 4, and thus the dc-link voltage should be boosted to 100 V (the peak). Simulation results are presented in Figs. 7 and 8. As shown in Fig. 7(a), the boosted voltage matches well with the calculated value and the load current is about 1.8 A (the peak). Additionally, all the inductor currents increase during the shoot-through state, as shown in Fig. 7(b), achieving continuous dc currents, as

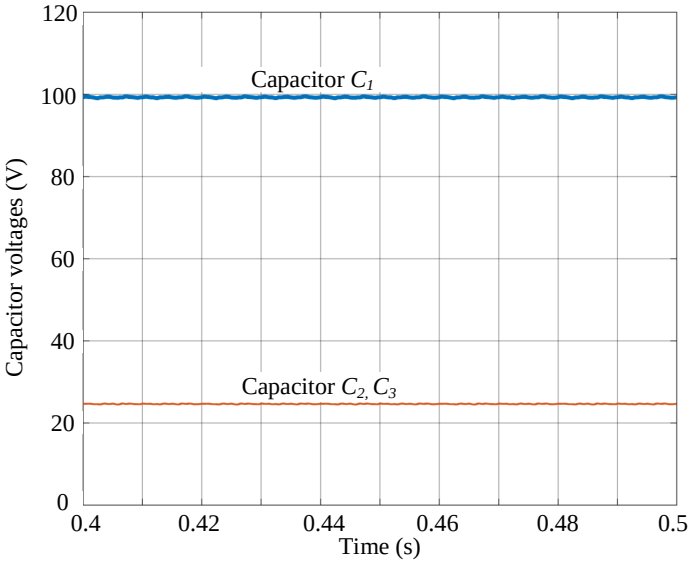

Fig. 8. Simulation results (capacitor voltages) of the Sq-ZSI.

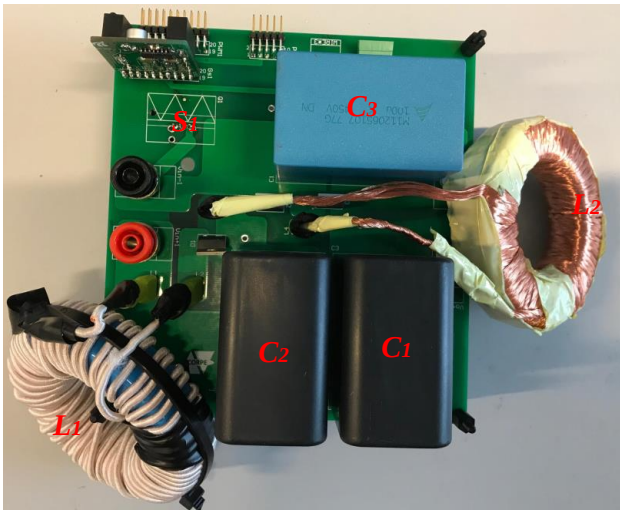

Fig. 9. Photo of the experimental setup of the proposed Sq-ZSI.

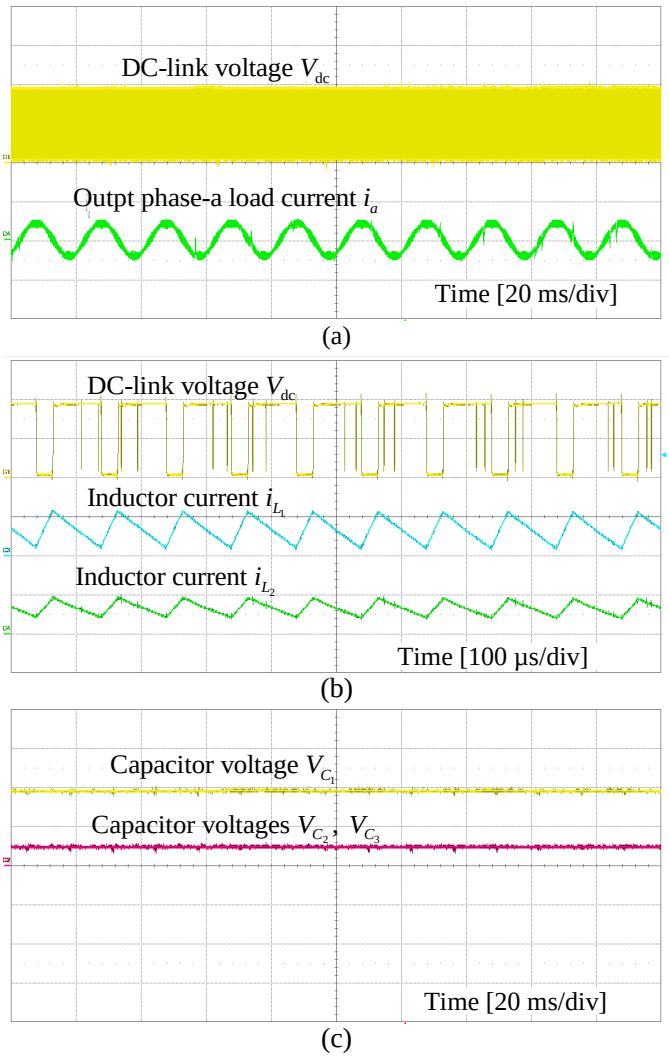

Fig. 10. Experimental results of the proposed Sq-ZSI: (a) dc-link voltage V_{dc} [50 V/div] and output phase-a current i_a [2 A/div], (b) dc-link voltage V_{dc} [50 V/div] and inductor currents i_{L_1}, i_{L_2} [5 A/div], and (c) capacitor voltage V_{C_1}, V_{C_2}, V_{C_3} [100 V/div].

discussed in Section II. It is observed in Fig. 8 that the capacitor voltages V_{C_1}, V_{C_2}, and V_{C_3} are boosted to 100 V, 25 V, and 25 V, and thus the peak dc-link voltage V_{dc} is 100 V, which demonstrates the effectiveness of the proposed topology.

B. Experimental Results

To verify the performance of the proposed topology, the experimental setup is built and the photo of the setup is shown in Fig. 9. The parameters of the setup are the same as in the simulations. The Pulse-Width Modulation (PWM) is achieved in a digital signal processor (DSP) TMS320F28335, where the open-loop control is also implemented.

The experimental results are shown in Fig. 10. In Fig. 10(a), the dc-link voltage is boosted to 97 V and the load current is about 1.6 A. Compared with the simulation results (i.e., Fig. 7(a)), the boost factor is slightly lower considering the parasitic effect in the circuits (capacitors and inductors). In Fig. 10(b), it is seen that the inductor currents also increase linearly in the shoot-through state, meaning that the proposed topology can ensure continuously drawing currents from the input source. Additionally, Fig. 10(c) shows the capacitor voltages. It can be observed that the capacitor voltages V_{C_1}, V_{C_2} and V_{C_3} are boosted to 97 V and 23 V ($V_{C_2} = V_{C_3}$), which are in agreement with the theoretical analysis. In all, the above simulations and experimental tests have verified the effectiveness of the proposed topology in terms of high boosting capability, continuous input current and lower voltage stresses on the capacitor and power switches.

IV. Conclusion

In this paper, a Switched quasi-Z-Source Inverter (Sq-ZSI) was proposed. Compared with the Switched Boost Inverter (SBI) and Diode-Assisted SBI (DA-SBI), the boost capability

of the proposed Sq-ZSI is enhanced and the current from the dc source in the proposed topology can be continuous. Moreover, the voltage stresses of the power switches are lower than the SBI, DA-SBI, and Sq-ZSI, while, the stress of the capacitor remains the same. Simulations and experimental results have demonstrated that the proposed topology has a superior performance in terms of good boost capability and a continuous input current.

REFERENCES

[1] F. Z. Peng, "Z-source inverter," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 504–510, Mar. 2003.

[2] Y. Yang, K. A. Kim, F. Blaabjerg, and A. Sangwongwanich, *Advances in Grid-Connected Photovoltaic Power Conversion Systems*. Woodhead Publishing, 2018.

[3] A. Chub, D. Vinnikov, E. Liivik, and T. Jalakas, "Multiphase quasi-Z-source DC-DC converters for residential distributed generation systems," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 8361–8371, Oct. 2018.

[4] C. Qin, C. Zhang, A. Chen, X. Xing, and G. Zhang, "A space vector modulation scheme of the quasi-Z-source three-level T-type inverter for common-mode voltage reduction," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 8340–8350, Oct. 2018.

[5] W. Liang, Y. Liu, B. Ge, and X. Wang, "DC -link voltage balance control strategy based on multidimensional modulation technique for quasi-Z-source cascaded multilevel inverter photovoltaic power system," *IEEE Trans. Ind. Informat.*, vol. 14, no. 11, pp. 4905–4915, Nov. 2018.

[6] J. Yuan, Y. Yang, Y. Shen, W. Liu, F. Blaabjerg, and P. Liu, "An embedded enhanced-boost Z-source inverter topology with fault-tolerant capabilities," in *Proc. IEEE IECON*, Oct. 2018, pp. 3712–3717.

[7] W. Liu, J. Yuan, Y. Yang, and T. Kerekes, "Modeling and control of single-phase quasi-Z-source inverters," in *Proc. IEEE IECON*, Oct. 2018, pp. 3737–3742.

[8] J. Anderson and F. Z. Peng, "Four quasi-Z-source inverters," in *Proc. IEEE PESC*, Jun. 2008, pp. 2743–2749.

[9] M. Zhu, K. Yu, and F. L. Luo, "Switched inductor Z-source inverter," *IEEE Trans. Power Electron.*, vol. 25, no. 8, pp. 2150–2158, Aug. 2010.

[10] M. Nguyen, Y. Lim, and G. Cho, "Switched-inductor quasi-Z-source inverter," *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3183–3191, Nov. 2011.

[11] D. Li, P. C. Loh, M. Zhu, F. Gao, and F. Blaabjerg, "Generalized multicell switched-inductor and switched-capacitor Z-source inverters," *IEEE Trans. Power Electron.*, vol. 28, no. 2, pp. 837–848, Feb. 2013.

[12] J. Yuan, Y. Yang, P. Liu, Y. Shen, Z. Qiu, and F. Blaabjerg, "An embedded enhanced-boost Z-source inverter," in *Proc. IEEE PEAC*, Nov. 2018, pp. 1–6.

[13] A. Ravindranath, S. K. Mishra, and A. Joshi, "Analysis and PWM control of switched boost inverter," *IEEE Trans. Ind. Electron.*, vol. 60, no. 12, pp. 5593–5602, Dec. 2013.

[14] M. Nguyen, T. Le, S. Park, and Y. Lim, "A class of quasi-switched boost inverters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 3, pp. 1526–1536, Mar. 2015.

[15] A. Ho, T. Chun, and H. Kim, "Extended boost active-switched-capacitor/switched-inductor quasi-Z-source inverters," *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5681–5690, Oct. 2015.

[16] M. Hasan Babayi Nozadian, E. Babaei, S. H. Hosseini, and E. Shokati Asl, "Steady-state analysis and design considerations of high voltage gain switched Z-source inverter with continuous input current," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5342–5350, Jul. 2017.