Z-Source Inverter

Fang Zheng Peng, *Senior Member, IEEE*

***Abstract*—This paper presents an impedance-source (or impedance-fed) power converter (abbreviated as Z-source converter) and its control method for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. The Z-source converter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be obtained in the traditional voltage-source (or voltage-fed) and current-source (or current-fed) converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter (abbreviated as V-source converter) and current-source converter (abbreviated as I-source converter) and provides a novel power conversion concept. The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. To describe the operating principle and control, this paper focuses on an example: a Z-source inverter for dc-ac power conversion needed in fuel cell applications. Simulation and experimental results will be presented to demonstrate the new features.**

***Index Terms*—Converter, current-source inverter, inverter, voltage-source inverter, Z-Source inverter.**

I. INTRODUCTION

THERE EXIST two traditional converters: voltage-source (or voltage-fed) and current-source (or current-fed) converters (or inverters depending on power flow directions). Fig. 1 shows the traditional three-phase voltage-source converter (abbreviated as V-source converter) structure. A dc voltage source supported by a relatively large capacitor feeds the main converter circuit, a three-phase bridge. The dc voltage source can be a battery, fuel-cell stack, diode rectifier, and/or capacitor. Six switches are used in the main circuit; each is traditionally composed of a power transistor and an antiparallel (or freewheeling) diode to provide bidirectional current flow and unidirectional voltage blocking capability. The V-source converter is widely used. It, however, has the following conceptual and theoretical barriers and limitations.

- The ac output voltage is limited below and cannot exceed the dc-rail voltage or the dc-rail voltage has to be greater than the ac input voltage. Therefore, the V-source inverter is a buck (step-down) inverter for dc-to-ac power conversion and the V-source converter is a boost (step-up) rectifier (or boost converter) for ac-to-dc power conversion. For applications where over drive is desirable and the available dc voltage is limited, an additional dc-dc boost converter is needed to obtain a desired ac output. The additional power converter stage increases system cost and lowers efficiency.
- The upper and lower devices of each phase leg cannot be gated on simultaneously either by purpose or by EMI noise. Otherwise, a shoot-through would occur and destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noise's misgating-on is a major killer to the converter's reliability. Dead time to block both upper and lower devices has to be provided in the V-source converter, which causes waveform distortion, etc.
- An output *LC* filter is needed for providing a sinusoidal voltage compared with the current-source inverter, which causes additional power loss and control complexity.

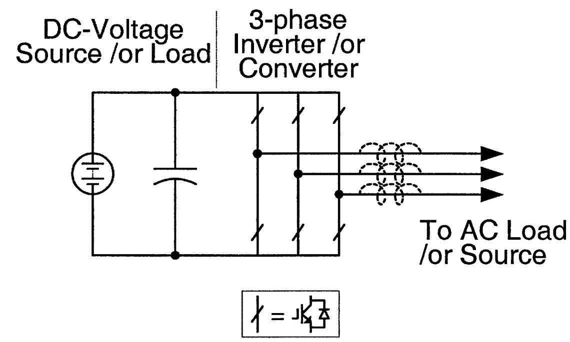

Fig. 1. Traditional V-source converter.

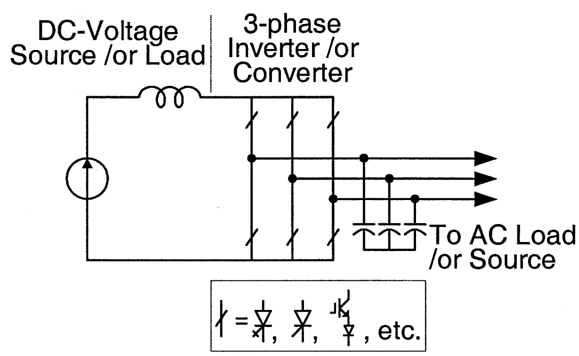

Fig. 2. Traditional I-source converter.

Fig. 2 shows the traditional three-phase current-source converter (abbreviated as I-source converter) structure. A dc current source feeds the main converter circuit, a three-phase bridge. The dc current source can be a relatively large dc inductor fed by a voltage source such as a battery, fuel-cell stack, diode rectifier, or thyristor converter. Six switches are

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The author is with the Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824-1226 USA, and also with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China (e-mail: fzpeng@egr.msu.edu).

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used in the main circuit, each is traditionally composed of a semiconductor switching device with reverse block capability such as a gate-turn-off thyristor (GTO) and SCR or a power transistor with a series diode to provide unidirectional current flow and bidirectional voltage blocking. However, the I-source converter has the following conceptual and theoretical barriers and limitations.

- The ac output voltage has to be greater than the original dc voltage that feeds the dc inductor or the dc voltage produced is always smaller than the ac input voltage. Therefore, the I-source inverter is a boost inverter for dc-to-ac power conversion and the I-source converter is a buck rectifier (or buck converter) for ac-to-dc power conversion. For applications where a wide voltage range is desirable, an additional dc–dc buck (or boost) converter is needed. The additional power conversion stage increases system cost and lowers efficiency.
- At least one of the upper devices and one of the lower devices have to be gated on and maintained on at any time. Otherwise, an open circuit of the dc inductor would occur and destroy the devices. The open-circuit problem by EMI noise's misgating-off is a major concern of the converter's reliability. Overlap time for safe current commutation is needed in the I-source converter, which also causes waveform distortion, etc.
- The main switches of the I-source converter have to block reverse voltage that requires a series diode to be used in combination with high-speed and high-performance transistors such as insulated gate bipolar transistors (IGBTs). This prevents the direct use of low-cost and high-performance IGBT modules and intelligent power modules (IPMs).

In addition, both the V-source converter and the I-source converter have the following common problems.

- They are either a boost or a buck converter and cannot be a buck–boost converter. That is, their obtainable output voltage range is limited to either greater or smaller than the input voltage.
- Their main circuits cannot be interchangeable. In other words, neither the V-source converter main circuit can be used for the I-source converter, nor vice versa.
- They are vulnerable to EMI noise in terms of reliability.

II. Z-Source Converter

To overcome the above problems of the traditional V-source and I-source converters, this paper presents an impedance-source (or impedance-fed) power converter (abbreviated as Z-source converter) and its control method for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. Fig. 3 shows the general Z-source converter structure proposed. It employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, load, or another converter, for providing unique features that cannot be observed in the traditional V- and I-source converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the above-mentioned conceptual

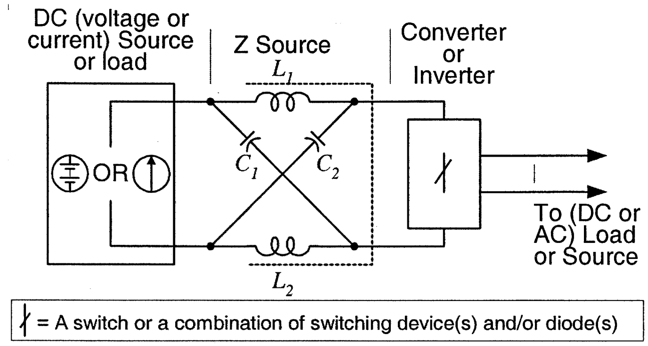

Fig. 3. General structure of the Z-source converter.

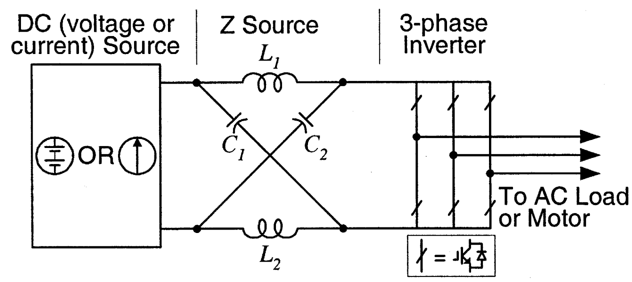

Fig. 4. Z-source converter structure using the antiparallel combination of switching device and diode.

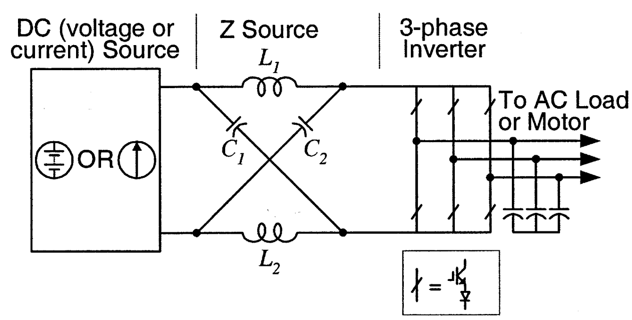

Fig. 5. Z-source converter structure using the series combination of switching device and diode.

and theoretical barriers and limitations of the traditional V-source converter and I-source converter and provides a novel power conversion concept.

In Fig. 3, a two-port network that consists of a split-inductor L_1 and L_2 and capacitors C_1 and C_2 connected in X shape is employed to provide an impedance source (Z-source) coupling the converter (or inverter) to the dc source, load, or another converter. The dc source/or load can be either a voltage or a current source/or load. Therefore, the dc source can be a battery, diode rectifier, thyristor converter, fuel cell, an inductor, a capacitor, or a combination of those. Switches used in the converter can be a combination of switching devices and diodes such as the antiparallel combination as shown in Fig. 1, the series combination as shown in Fig. 2, etc. As examples, Figs. 4 and 5 show two three-phase Z-source inverter configurations. The inductance L_1 and L_2 can be provided through a split inductor or two separate inductors.

The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. To describe the operating principle and control, this paper focuses on an application

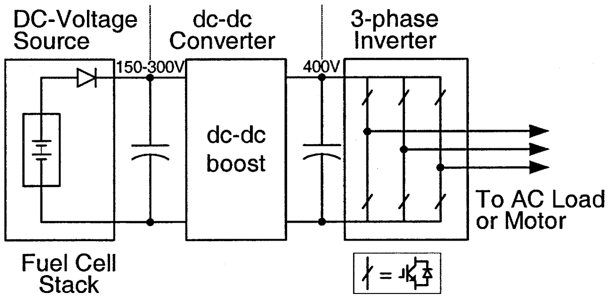

Fig. 6. Traditional two-stage power conversion for fuel-cell applications.

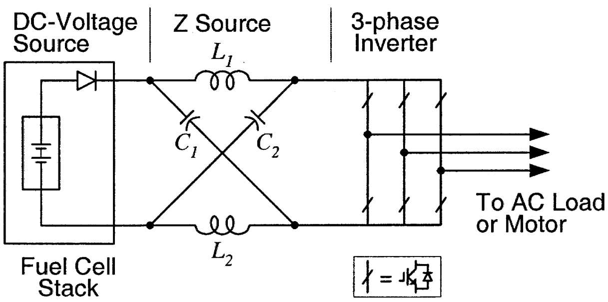

Fig. 7. Z-source inverter for fuel-cell applications.

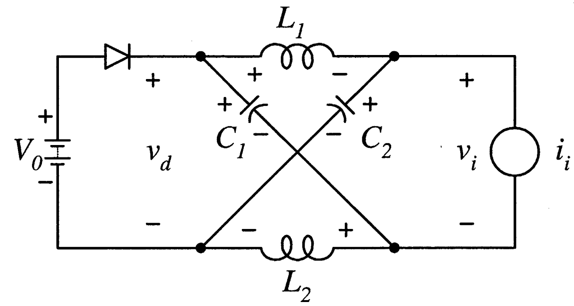

Fig. 8. Equivalent circuit of the Z-source inverter viewed from the dc link.

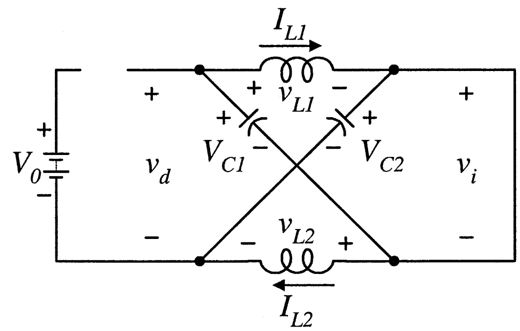

Fig. 9. Equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in the shoot-through zero state.

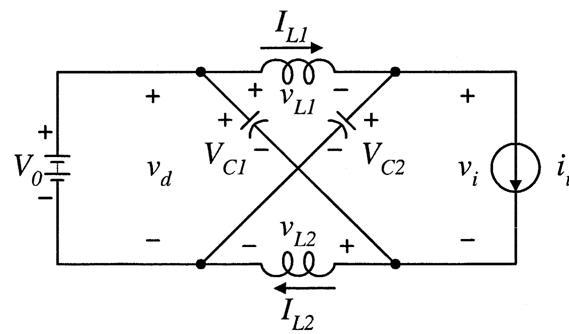

Fig. 10. Equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in one of the eight nonshoot-through switching states.

example of the Z-source converter: a Z-source inverter for dc-ac power conversion needed for fuel-cell applications.

Fig. 6 shows the traditional two-stage power conversion for fuel-cell applications. Because fuel cells usually produce a voltage that changes widely (2:1 ratio) depending on current drawn from the stacks. For fuel-cell vehicles and distributed power generation, a boost dc–dc converter is needed because the V-source inverter cannot produce an ac voltage that is greater than the dc voltage. Fig. 7 shows a Z-source inverter for such fuel-cell applications, which can directly produce an ac voltage greater and less than the fuel-cell voltage. The diode in series with the fuel cell in Figs. 6 and 7 is usually needed for preventing reverse current flow.

III. Equivalent Circuit, Operating Principle, and Control

The unique feature of the Z-source inverter is that the output ac voltage can be any value between zero and infinity regardless of the fuel-cell voltage. That is, the Z-source inverter is a buck–boost inverter that has a wide range of obtainable voltage. The traditional V- and I-source inverters cannot provide such feature.

To describe the operating principle and control of the Z-source inverter in Fig. 7, let us briefly examine the Z-source inverter structure. In Fig. 7, the three-phase Z-source inverter bridge has nine permissible switching states (vectors) unlike the traditional three-phase V-source inverter that has eight. The traditional three-phase V-source inverter has six active vectors when the dc voltage is impressed across the load and two zero vectors when the load terminals are shorted through either the lower or upper three devices, respectively. However, the three-phase Z-source inverter bridge has one extra zero state (or vector) when the load terminals are shorted through both the upper and lower devices of any one phase leg (i.e., both devices are gated on), any two phase legs, or all three phase legs. This shoot-through zero state (or vector) is forbidden in the traditional V-source inverter, because it would cause a shoot-through. We call this third zero state (vector) the shoot-through zero state (or vector), which can be generated by seven different ways: shoot-through via any one phase leg, combinations of any two phase legs, and all three phase legs. The Z-source network makes the shoot-through zero state possible. This shoot-through zero state provides the unique buck-boost feature to the inverter.

Fig. 8 shows the equivalent circuit of the Z-source inverter shown in Fig. 7 when viewed from the dc link. The inverter bridge is equivalent to a short circuit when the inverter bridge is in the shoot-through zero state, as shown in Fig. 9, whereas the inverter bridge becomes an equivalent current source as shown in Fig. 10 when in one of the six active states. Note that the inverter bridge can be also represented by a current source with

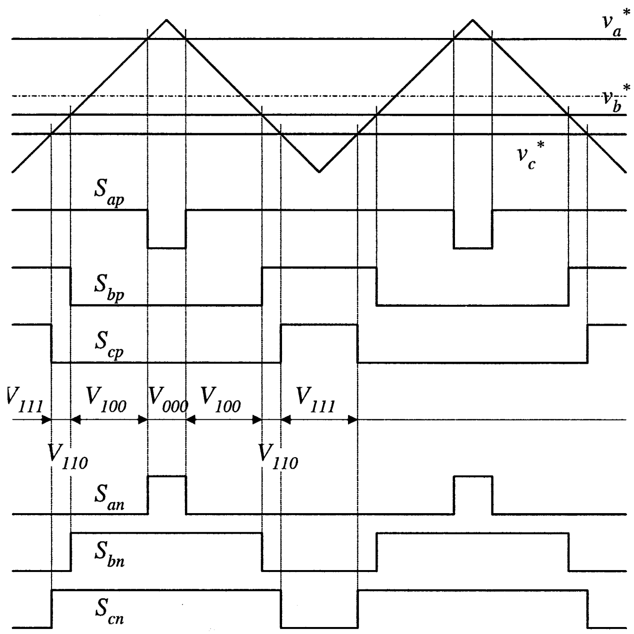

Fig. 11. Traditional carrier-based PWM control without shoot-through zero states, where the traditional zero states (vectors) V_{111} and V_{000} are generated every switching cycle and determined by the references.

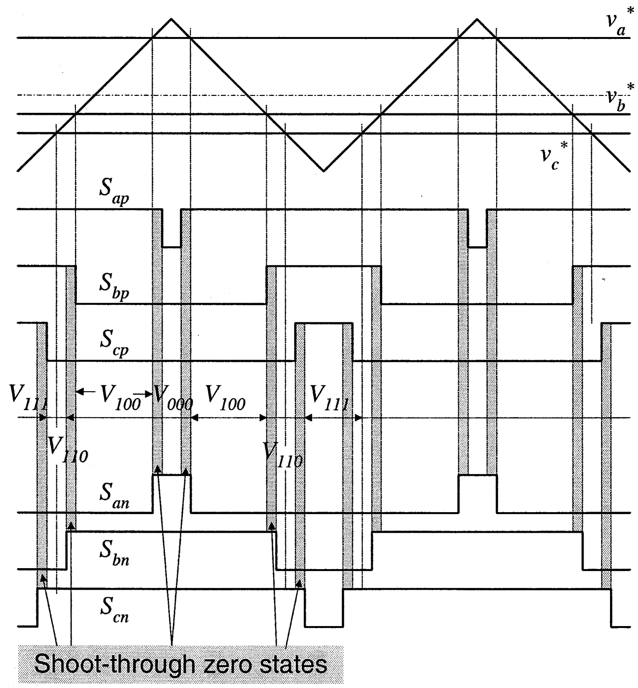

Fig. 12. Modified carrier-based PWM control with shoot-through zero states that are evenly distributed among the three phase legs, while the equivalent active vectors are unchanged.

zero value (i.e., an open circuit) when it is in one of the two traditional zero states. Therefore, Fig. 10 shows the equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in one of the eight nonshoot-through switching states.

All the traditional pulsewidth-modulation (PWM) schemes can be used to control the Z-source inverter and their theoretical input–output relationships still hold. Fig. 11 shows the traditional PWM switching sequence based on the triangular carrier method. In every switching cycle, the two nonshoot-through zero states are used along with two adjacent active states to synthesize the desired voltage. When the dc voltage is high enough to generate the desired ac voltage, the traditional PWM of Fig. 11 is used. While the dc voltage is not enough to directly generate a desired output voltage, a modified PWM with shoot-through zero states will be used as shown in Fig. 12 to boost voltage. It should be noted that each phase leg still switches on and off once per switching cycle. Without change the total zero-state time interval, shoot-through zero states are evenly allocated into each phase. That is, the active states are unchanged. However, the equivalent dc-link voltage to the inverter is boosted because of the shoot-through states. The detailed relationship will be analyzed in the next section. It is noticeable here that the equivalent switching frequency viewed from the Z-source network is six times the switching frequency of the main inverter, which greatly reduces the required inductance of the Z-source network.

IV. Circuit Analysis and Obtainable Output Voltage

Assuming that the inductors L_1 and L_2 and capacitors C_1 and C_2 have the same inductance (L) and capacitance (C), respectively, the Z-source network becomes symmetrical. From the symmetry and the equivalent circuits, we have

$$V_{C1} = V_{C2} = V_C \quad v_{L1} = v_{L2} = v_L. \tag{1}$$

Given that the inverter bridge is in the shoot-through zero state for an interval of T_0, during a switching cycle, T and from the equivalent circuit, Fig. 9, one has

$$v_L = V_C \quad v_d = 2V_C \quad v_i = 0. \tag{2}$$

Now consider that the inverter bridge is in one of the eight nonshoot-through states for an interval of T_1, during the switching cycle, T. From the equivalent circuit, Fig. 10, one has

$$v_L = V_0 - V_C \quad v_d = V_0 \quad v_i = V_C - v_L = 2V_C - V_0 \tag{3}$$

where V_0 is the dc source voltage and $T = T_0 + T_1$.

The average voltage of the inductors over one switching period (T) should be zero in steady state, from (2) and (3), thus, we have

$$V_L = \overline{v_L} = \frac{T_0 \cdot V_C + T_1 \cdot (V_0 - V_C)}{T} = 0 \tag{4}$$

or

$$\frac{V_C}{V_0} = \frac{T_1}{T_1 - T_0}. \tag{5}$$

Similarly, the average dc-link voltage across the inverter bridge can be found as follows:

$$V_i = \overline{v_i} = \frac{T_0 \cdot 0 + T_1 \cdot (2V_C - V_0)}{T} = \frac{T_1}{T_1 - T_0} V_0 = V_C. \tag{6}$$

The peak dc-link voltage across the inverter bridge is expressed in (3) and can be rewritten as

$$\hat{v}_i = V_C - v_L = 2V_c - V_0 = \frac{T}{T_1 - T_0}V_0 = B \cdot V_0 \quad (7)$$

where

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2\frac{T_0}{T}} \geq 1, \quad (8)$$

is the boost factor resulting from the shoot-through zero state. The peak dc-link voltage $\hat{v}_i$ is the equivalent dc-link voltage of the inverter. On the other side, the output peak phase voltage from the inverter can be expressed as

$$\hat{v}_{\text{ac}} = M \cdot \frac{\hat{v}_i}{2} \quad (9)$$

where M is the modulation index. Using (7), (9) can be further expressed as

$$\hat{v}_{\text{ac}} = M \cdot B \cdot \frac{V_0}{2}. \quad (10)$$

For the traditional V-source PWM inverter, we have the well-known relationship: $\hat{v}_{\text{ac}} = M \cdot V_0/2$. Equation (10) shows that the output voltage can be stepped up and down by choosing an appropriate buck–boost factor B_B,

$$B_B = M \cdot B = (0 \sim \infty). \quad (11)$$

From (1), (5) and (8), the capacitor voltage can expressed as

$$V_{C1} = V_{C2} = V_C = \frac{1 - \frac{T_0}{T}}{1 - 2\frac{T_0}{T}}V_0. \quad (12)$$

The buck–boost factor B_B is determined by the modulation index M and boost factor B. The boost factor B as expressed in (8) can be controlled by duty cycle (i.e., interval ratio) of the shoot-through zero state over the nonshoot-through states of the inverter PWM.

Note that the shoot-through zero state does not affect the PWM control of the inverter, because it equivalently produce the same zero voltage to the load terminal. The available shoot-through period is limited by the zero-state period that is determined by the modulation index.

V. Inductor and Capacitor Requirement of the Z-Source Network

For the traditional V-source inverter, the dc capacitor is the sole energy storage and filtering element to suppress voltage ripple and serve temporary storage. For the traditional I-source inverter, the dc inductor is the sole energy storage/filtering element to suppress current ripple and serve temporary storage. The Z-source network is a combination of two inductors and two capacitors. This combined circuit, the Z-source network is the energy storage/filtering element for the Z-source inverter. The Z-source network provides a second-order filter and is more effective to suppress voltage and current ripples than capacitor or inductor used alone in the traditional inverters. Therefore, the inductor and capacitor requirement should be smaller than the traditional inverters. Detailed design guide and formulas of the Z-source network will be presented in a near future paper. A brief discussion is given below in terms of physical sizes and requirements. When the two inductors (L_1 and L_2) are small and approach zero, the Z-source network reduces to two capacitors (C_1 and C_2) in parallel and becomes a traditional V-source. Therefore, a traditional V-source inverter's capacitor requirements and physical size is the worst case requirement for the Z-source network. Considering additional filtering and energy storage provided by the inductors, the Z-source network should require less capacitance and smaller size compared with the traditional V-source inverter. Similarly, when the two capacitors (C_1 and C_2) are small and approach zero, the Z-source network reduces to two inductors (L_1 and L_2) in series and becomes a traditional I-source. Therefore, a traditional I-source inverter's inductor requirements and physical size is the worst case requirement for the Z-source network. Considering additional filtering and energy storage by the capacitors, the Z-source network should require less inductance and smaller size compared with the traditional I-source inverter.

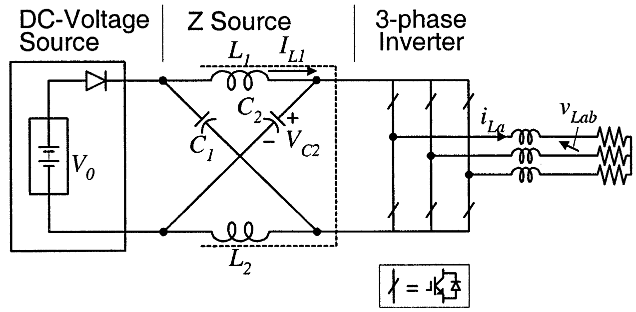

Fig. 13. Simulation and prototype system configuration.

VI. Simulation Results, Prototype, and Experimental Results

Simulations have been performed to confirm the above analysis. Fig. 13 shows the circuit configuration and Fig. 14 shows simulation waveforms when the fuel-cell stack voltage is $V_0 = 150$ V and the Z-source network parameters are $L_1 = L_2 = L = 160\ \mu$H and $C_1 = C_2 = C = 1,000\ \mu$F. The purpose of the system is to produce a three-phase 208-V rms power from the fuel-cell stack whose voltage changes 150∼340 V dc depending on load current. From the simulation waveforms of Fig. 14, it is clear that the capacitor voltage was boosted to $V_{C2} = 335$ V and the output line-to-line was 208 V rms or 294 V peak. In this case, the modulation index was set to $M = 0.642$, and the shoot-through duty cycle was set to $T_0/T = 0.358$, and switching frequency was 10 kHz. The shoot-through zero state was populated evenly among the three phase legs, achieving an equivalent switching frequency of 60 kHz viewed from the Z-source network. Therefore, the required dc inductance L is minimized. From the above analysis, we have the following theoretical calculations:

$$B = \frac{1}{1 - 2\frac{T_0}{T}} = 3.52 \quad (13)$$

$$V_{C1} = V_{C2} = V_C\frac{1 - \frac{T_0}{T}}{1 - 2\frac{T_0}{T}}V_0 = 2.26 \cdot 150 \text{ V} = 339\text{V} \quad (14)$$

$$\hat{v}_{\text{ac}} = M \cdot B \cdot \frac{V_0}{2} = 0.642 \cdot 3.52 \cdot \frac{150 \text{ V}}{2} = 169.5\text{V}. \quad (15)$$

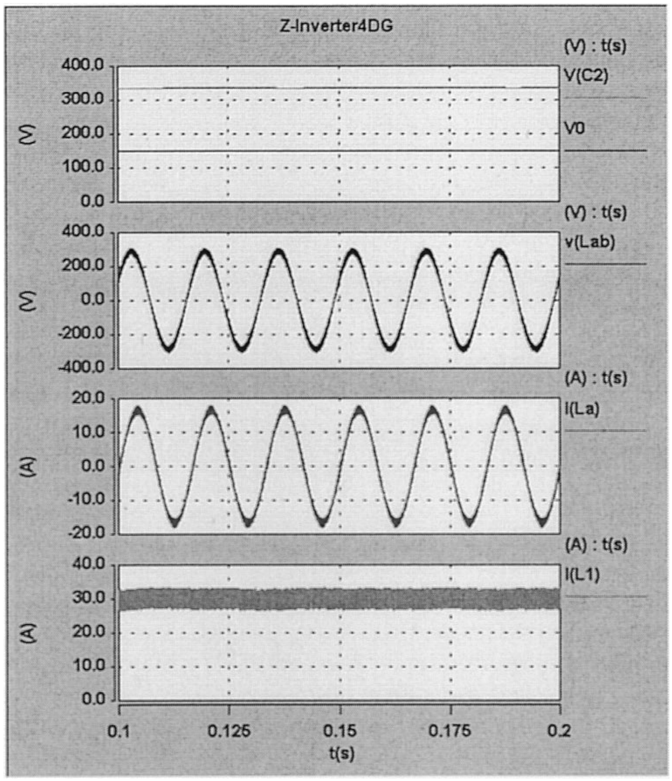

Fig. 14. Simulation waveforms when the fuel-cell voltage $V_0 = 150$ V, inverter modulation index $M = 0.642$, and shoot-through duty cycle $T_0/T = 0.358$.

Equation (15) is the phase peak voltage, which implies that the line-to-line voltage is 208 V rms or 294 V peak. The above theoretical values are quite consistent with the simulation results. The simulation proved the Z-source inverter concept.

A prototype as shown in Fig. 13 has been constructed. The same parameters as the simulation were used. Figs. 15 and 16 show experimental results. When the fuel-cell voltage is low, as shown in Fig. 15, the shoot-through state was used to boost the voltage in order to maintain the desired output voltage. The waveforms are consistent with the simulation results. When the fuel-cell voltage is high enough to produce the desired output voltage, the shoot-through state was not used, as shown in Fig. 16, where the traditional PWM control without shoot-through was used. By controlling the shoot-through state duty cycle T_0/T or the boost factor B, the desired output voltage can be obtained regardless of the fuel cell voltage.

VII. Conclusions

This paper has presented an impedance-source power converter for implementing dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. The Z-source converter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source, thus providing unique features that cannot be observed in the traditional voltage-source and current-source converters where a capacitor and inductor are used, respectively. The Z-source converter overcomes the conceptual and theoretical barriers and limitations of the traditional voltage-source converter and current-source converter and provides a novel power conversion concept. The Z-source concept can be applied to almost all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion.

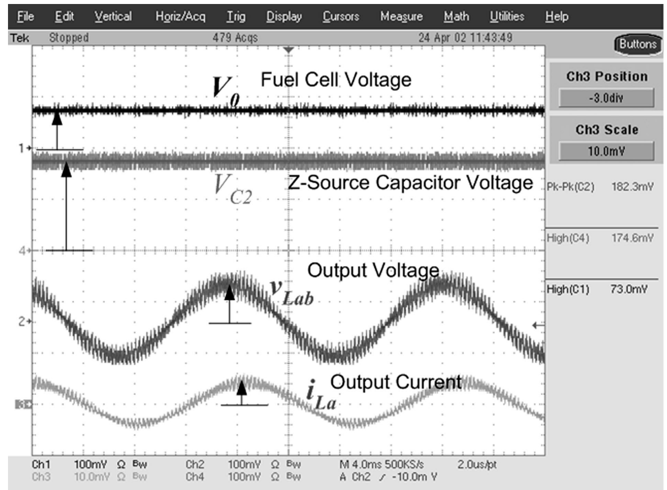

Fig. 15. Experimental waveforms when the fuel-cell voltage is low, inverter modulation index $M = 0.642$, and shoot-through period ratio $T_0/T = 0.358$ (V_0 and V_{C2} : 200V/div, V_{Lab} : 2*200V/div, i_{La}: 50 A/div, and time: 4 ms/div).

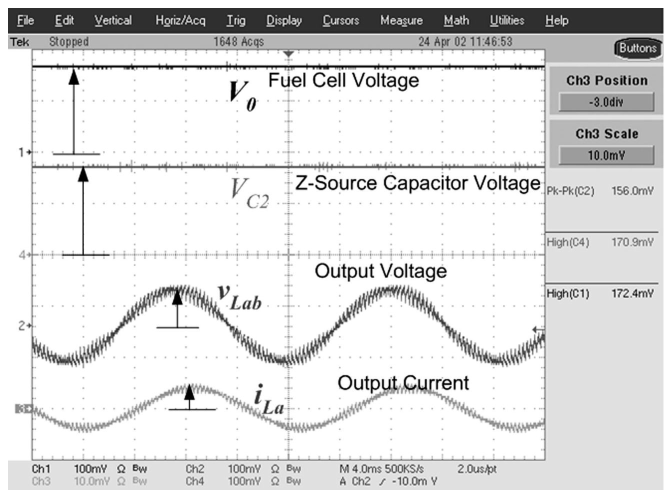

Fig. 16. Experimental waveforms when the fuel-cell voltage is high. Inverter modulation index $M = 1.0$, and without using the shoot-through state or shoot-through period ratio $T_0/T = 0$.

This paper focused on an example—a Z-source inverter for fuel-cell applications. Through the example, the paper described the operating principle, analyzed the circuit characteristics, and demonstrated its concept and superiority. Analytical, simulation, and experimental results have been presented. The Z-source inverter can boost–buck voltage, minimize component count, increase efficiency, and reduce cost.

It should be noted again that the Z-source concept can be applied to the entire spectrum of power conversion. Based on the concept, it is apparent that many Z-source conversion circuits can be derived. As another example, the Z-source concept can be easily applied to adjustable-speed drive (ASD) systems as shown in Fig. 17. The Z-source rectifier/inverter system can produce an output voltage greater than the ac input voltage by controlling the boost factor, which is impossible for the traditional

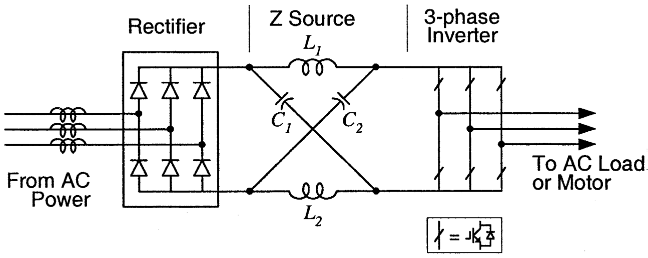

Fig. 17. Z-source rectifier/inverter system for adjustable-speed drives.

ASD systems. Due to the page limit, detailed analysis and description of the system and other Z-source conversion circuits will be presented in future papers.

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Fang Zheng Peng (M'92–SM'96) received the B.S. degree from Wuhan University, Wuhan, China, in 1983, and the M.S. and Ph.D. degrees from Nagaoka University of Technology, Nagaoka, Japan, in 1987 and 1990, respectively, all in electrical engineering.

From 1990 to 1992, he was a Research Scientist with Toyo Electric Manufacturing Company, Ltd., engaged in research and development of active power filters, flexible ac transmission systems (FACTS) applications, and motor drives. From 1992 to 1994, he was a Research Assistant Professor with Tokyo Institute of Technology, where he initiated a multilevel inverter program for FACTS applications and a speed-sensorless vector control project. From 1994 to 2000, he was with Oak Ridge National Laboratory (ORNL) and, from 1994 to 1997, he was a Research Assistant Professor at the University of Tennessee, Knoxville. He was a Staff Member and Lead (Principal) Scientist of the Power Electronics and Electric Machinery Research Center at ORNL from 1997 to 2000. In 2000, he joined Michigan State University, East Lansing, as an Associate Professor in the Department of Electrical and Computer Engineering. He is also currently a specially invited Adjunct Professor at Zhejiang University, Hangzhou, China. He is the holder of ten patents.

Dr. Peng has received numerous awards, including the 1996 First Prize Paper Award and the 1995 Second Prize Paper Award from the Industrial Power Converter Committee at the IEEE Industry Applications Society Annual Meeting; the 1996 Advanced Technology Award of the Inventors Clubs of America, Inc., the International Hall of Fame; the 1991 First Prize Paper Award from the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS; the 1990 Best Paper Award from the *Transactions of the Institute of Electrical Engineers of Japan*; and the Promotion Award of the Electrical Academy. He has been an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS since 1997 and Chair of the Technical Committee for Rectifiers and Inverters of the IEEE Power Electronics Society.