Impedance-Source Networks for Electric Power Conversion Part I: A Topological Review

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***Abstract*—Impedance networks cover the entire of electric power conversion from dc (converter, rectifier), ac (inverter), to phase and frequency conversion (ac–ac) in a wide range of applications. Various converter topologies have been reported in the literature to overcome the limitations and problems of the traditional voltage source, current source as well as various classical buck–boost, unidirectional, and bidirectional converter topologies. Proper implementation of the impedance-source network with appropriate switching configurations and topologies reduces the number of power conversion stages in the system power chain, which may improve the reliability and performance of the power system. The first part of this paper provides a comprehensive review of the various impedance-source-networks-based power converters and discusses the main topologies from an application point of view. This review paper is the first of its kind with the aim of providing a "one-stop" information source and a selection guide on impedance-source networks for power conversion for researchers, designers, and application engineers. A comprehensive review of various modeling, control, and modulation techniques for the impedance-source converters/inverters will be presented in Part II.**

***Index Terms*—AC–AC power conversion, ac–dc power conversion, dc–ac power conversion, dc–dc power conversion, impedance-source network.**

I. Introduction

A. Overview

IMPEDANCE networks provide an efficient means of power conversion between source and load in a wide range of electric power conversion applications (dc–dc, dc–ac, ac–dc, ac–ac) [1], [2]. Various topologies and control methods using different impedance-source networks have been presented in the literature, e.g., for adjustable-speed drives [3], [4], uninterruptible power supply (UPS) [5], [6], distributed generation (fuel cell, photovoltaic (PV), wind, etc.) [7]–[14], battery or supercapacitor energy storage [15], [16], electric vehicles [17]–[19], distributed dc power systems [8], avionics [20], flywheel energy storage systems [21], electronic loads [22], dc circuit breaker [23] and others. A variety of converter topologies with buck, boost, buck–boost, unidirectional, bidirectional, isolated as well as nonisolated converters are possible by proper implementation of the impedance-source network with various switching devices, topologies, and configurations [44]–[141]. Fig. 1 shows the general configuration of an impedance-source network for electric power conversion, with possible switching configurations depending on application requirements.

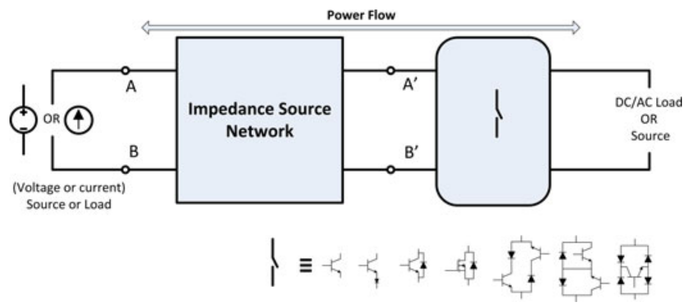

Fig. 1. General circuit configuration of impedance-source network for power conversion with different switching cells.

The basic impedance-source network can be generalized as a two-port network with a combination of two basic linear energy storage elements, i.e., L and C (dissipative components (R) are generally omitted). However, different configurations of the network are possible to improve the performance of the circuit by adding different nonlinear elements into the impedance network, e.g., diodes, switches, and/or a combination of both.

The impedance-source network was originally invented to overcome the limitations of the voltage-source inverter (VSI) and current-source inverter (CSI) topologies which are commonly used in electric power conversion [1]–[5]. The ac output voltage of the VSI is limited below the input voltage, i.e., the VSI is a buck type inverter which cannot serve the need of distributed generation and ac drives alone. It requires an additional dc–dc boost converter to obtain a desired ac output, which increases system cost and lowers efficiency. In addition, the switching devices are vulnerable to electromagnetic interference as misgating-on causes short-circuit across the inverter bridge and destroys the switching devices. The dead time introduced in such cases causes waveform distortion at the output. On the other hand, in the case of the CSI, the output voltage cannot be less than the input voltage. For applications where a wide voltage range is desirable, an additional dc–dc buck converter is needed. In addition, the upper and lower switches of

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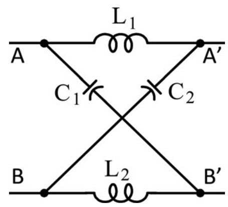


Fig. 2. Basic Z-Source impedance network.

the inverter 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.

To utilize the properties of the impedance-source network, different switching configurations are being adopted and modulated with different pulse width modulation (PWM) and control techniques to match various application requirements. Possible switch configurations range from simple-single switch topologies to very complex controlled multilevel and matrix configurations [28]–[43].

The impedance-source converter overcomes the aforementioned conceptual and theoretical barriers and limitations of the classical VSI and CSI and provides a novel power-conversion concept. The major advantage of this topology is that it can operate as V-source or an I-source depending on the application and needs, and the output voltage can be varied from 0 to ∞. Since the publication of the first impedance-source network, called a "*Z-source network*," in year 2002 [1], many modified topologies with improved modulation and control strategies have been proposed and published to improve the performance in various applications [2]–[25]. Fig. 2 shows the basic Z-source impedance network, which consists of inductors L_1 and L_2 and capacitors C_1 and C_2 connected at both ends (Z-shape) which acts as a buffer between load and source (voltage source or current source).

B. Operating Principle of the Impedance-Source Converter

The concept of the impedance-source network can be applied to any dc-to-dc, ac-to-ac, ac-to-dc, and dc-to-ac power conversions. The dc source and/or load can be either a voltage or current source and/or a load. A Z-source impedance network is used as an example to briefly illustrate the operating principle and control of the impedance-source network. Fig. 3 shows the circuit diagram of the Z-source converter and its equivalent circuit during active and shoot-through states. During the shoot-through state, the output terminals of the impedance network A′ and B′ are short-circuited by a switch or combination of switches which will, in turn, cause diode D in the network to reverse-bias. Energy stored in the inductor and capacitor during this shoot-through state is transferred to the load during the next active state, in which the diode D is returned to conduction. The switching circuit viewed from the dc side during the active state is equivalent to a current source as shown in Fig. 3(a). Averaging of these two switching states results in an expression to compute the peak dc-link voltage $\hat{v}_{A',B'}$, across terminals A′ and B′, in terms of its input voltage $V_{\rm in}$ as $\hat{v}_{A',B'} = \frac{1}{1-\beta d_{\rm ST}} V_{\rm in} = BV_{\rm in}$, where $d_{\rm ST}$ is the fractional shoot-through time assumed in a switching period, and $\beta \geq 2$ is a factor determined by the impedance network chosen, e.g., for Z-source inverter and quasi-Z-source inverter (ZSI and qZSI), $\beta = 2$. Equating the denominator of the boost factor (B) to zero then results in the permissible range of $d_{\rm ST}$ as $0 \leq d_{\rm ST} < \frac{1}{\beta}$, whose upper limit corresponds to an infinite gain.

A three-phase voltage-fed ZSI, as shown in Fig. 4, is used as an example to briefly illustrate the operating principle as described previously. The three-phase ZSI bridge has nine permissible switching states (six active states, two zero states, and one shoot-through state), unlike the traditional three-phase VSI which has eight (six active states, two zero states). During zero states, the upper three or lower three switches of the inverter bridge are turned on simultaneously, thus shorting the output terminals of the inverter and producing zero voltage across the load. During one of the six active states, the dc voltage is impressed across the load, positively or negatively. However, during shoot-through states, the load terminals are shorted through both the upper and lower devices of any one-phase leg, any two-phase legs, and all three-phase legs [1] producing zero voltage across the load. This shoot-through state has the same effect, i.e., producing zero voltage across the load as the traditional zero states; however, these shoot-through states can boost the output voltage. The shoot-through state is forbidden in the traditional VSI, because it would cause a short circuit across the dc link and damage the converter. The Z-source network and the shoot-through zero state provide a unique buck–boost capability for the inverter by varying the shoot-through time period and modulation index M of the inverter. Theoretically, the output voltage of the inverter ($\hat{v}_{\rm ac} = MB/2 = M[1 - 2d_{\rm ST}]^{-1} V_{\rm in}/2$) can be set to any value between 0 and ∞. However, some practical aspects and performance of the converter need to be considered for large voltage buck or boost operation, e.g., to avoid exceeding device limitations.

All the traditional PWM schemes can be used to control the impedance-source converter, and their theoretical input–output relationships still hold true. However, in addition to all states in the traditional modulation techniques, a new state called a "shoot-through state" is introduced and embedded in the modulation strategy for the impedance network-based power converter without violating the volt–sec balance in the operating principle. With the unique feature of these shoot-through states, several new PWM methods modified from sine PWMs and space vector modulation [28]–[43] are developed to control the output voltage. In addition, there are various control methods applied for various applications which will be discussed in Part II in detail.

C. Status of Impedance-Source Topologies and Applications

Z-source-related research has grown rapidly since it was first proposed in 2002; the numbersof modifications and new Z-source topologies have grown exponentially. Fig. 5 shows the number of publications over the last ten years (a total of 1113 as of Sept. 2013) and a summary of the Z-source converter categories and Z-source network topologies that can be found in the recent literature. According to the conversion functionality,

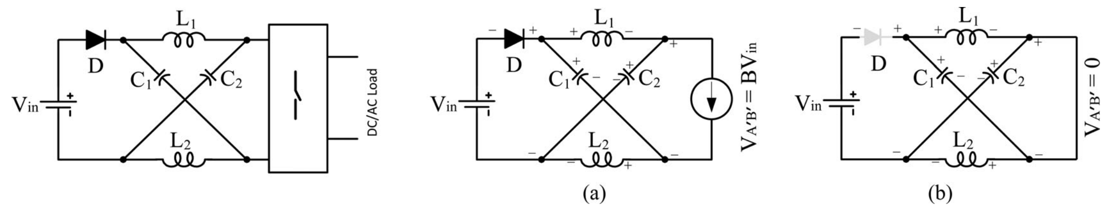


Fig. 3. Voltage-fed Z-source converter illustrating its equivalent circuit during (a) active state and (b) shoot-through state.

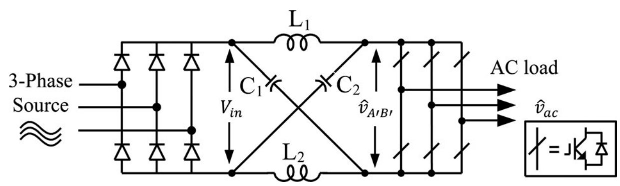


Fig. 4. Voltage-fed ZSI—an example of a ZSI.

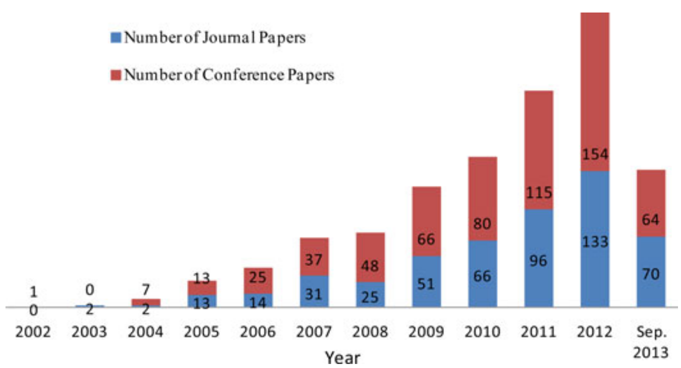


Fig. 5. Numbers of publications (total 1113 as of Sept. 2013).

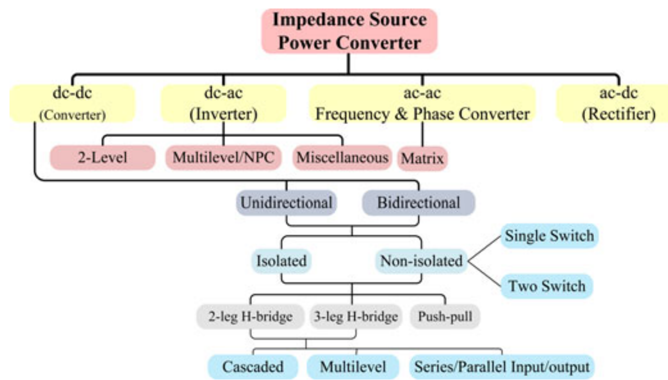


Fig. 6. Categorization of impedance-source network-based power converters.

it can be divided into four main categories: dc–dc converters, dc–ac inverters, ac–ac converters, and ac–dc rectifiers. A further breakdown leads to two-level and multilevel [59]–[71], ac–ac and matrix converters [72]–[83], and nonisolated and isolated dc–dc converters [44]–[58]. From the Z-source network topology standpoint, it can be voltage-fed or current-fed. Further, impedance networks can be divided based on the magnetics used in the impedance-source network, i.e., nontransformer based [91]–[117] and transformer or coupled inductor based [118]–[134].

The Z-source concept has opened up a new research area in power electronics. The previous description only provides a brief summary of the major Z-source network topologies. There are many modifications and variations on the previous Z-source topologies. Each topology has its own unique features and applications to which it is best suited. There is no one-size-fits-all solution. It is expected that new Z-source topologies will continuously be put forth to meet and improve converter performance in different applications. Renewable energy generation, such as PV and wind power, and motor drives are prospective applications of Z-source converters because of the unique voltage buck–boost ability with minimum component count and potential low cost. New power electronic devices, such as silicon carbide (SiC) and gallium nitride (GaN) devices, will definitely improve the performance of Z-source converters [24], [25]. Their high switching frequency, low loss, and high temperature capacity will contribute to small Z-source passive components, high efficiency of the converter, and high power density. Currently, Z-source converters are still advancing in topologies and applications.

This paper provides a comprehensive survey on the topic of impedance-source network-based power converters/inverters and is organized as follows: Section II categorizes the available impedance-source power converters/inverters based on conversion functionality and further subcategorizes them into different switching configurations. Section III describes different impedance-source network topologies segregated as transformer/coupled inductor or nontransformer. Finally, Section IV provides a comparison of different impedance network-based converters and a conclusion.

II. Categories of Impedance-Source Converter Based on Conversion Functionality

Fig. 6 shows a broad categorization of the impedance network-based power converters using different switching configurations as shown in Fig. 7. Proper amalgamation of these different topologies with impedance-source networks gives a wide range of unique power converter topologies ranging from medium voltage and power to high voltage and power. In addition, using these switching configurations, both unidirectional/bidirectional as well as isolated/nonisolated converters, can be implemented for dc–dc, dc–ac, ac–dc, and ac–ac systems to satisfy the needs of numerous power applications.

A. DC–DC Converter Topologies

Various isolated/nonisolated dc–dc converters are proposed in the literature with different control and modulation techniques.

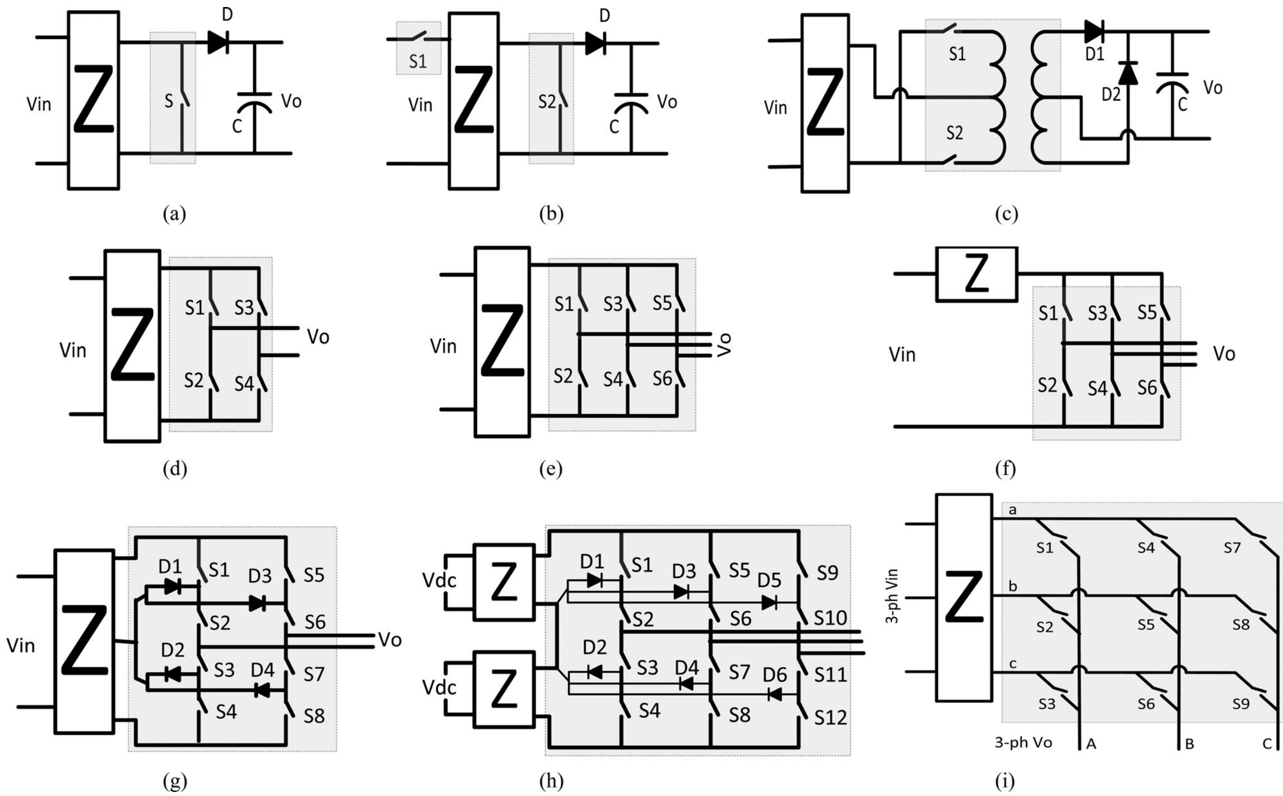


Fig. 7. Possible switching configurations (a)–(c) for dc–dc converter; (d)–(i) using multiple diodes and switches (in unidirectional and/or bidirectional configurations) for dc–dc, dc–ac, ac–dc, and ac–ac converter (Z→impedance-source network).

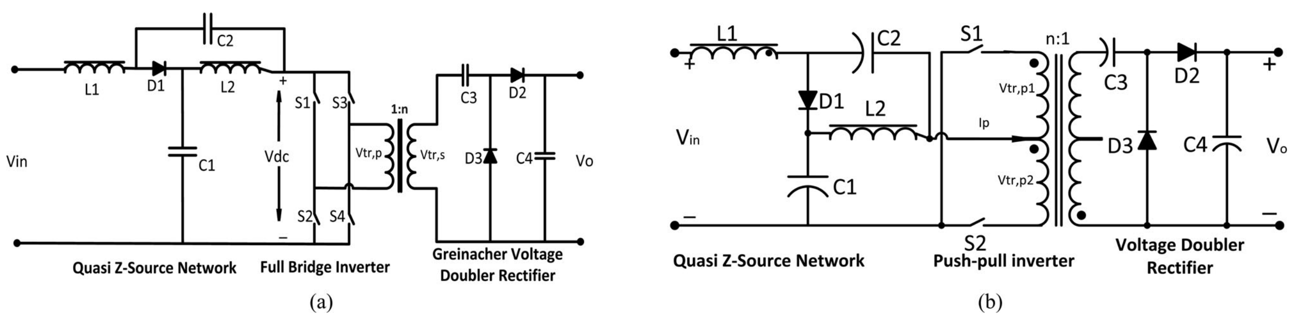


Fig. 8. qZSI-based-isolated dc–dc converter with (a) intermediate H-bridge switching topology and (b) push–pull topology.

For example, a dc–dc converter realized using a qZSI with two- or three-leg H-bridge switching topology is proposed for distributed generation [44], [45] as shown in Fig. 8(a). A new quasi-Z-source push–pull converter topology with a reduced number of switching device is also proposed in [46] and [47] as shown in Fig. 8(b). It has the same gain as in [44] and [45], however, with reduced complexity in gate circuit design.

A dc–dc converter with a trans-Z-source network is implemented in [48] as shown in Fig. 9(a), with the aim of achieving higher boost at a lower shoot-through time period of the switch. Proper implementation could reduce the turns ratio of the transformer as compared to other qZSI-based topologies. This advantage is utilized to design the converter to operate in parallel [49] to achieve higher power level and premium power quality along with improved system efficiency.

An isolated Z-source dc–dc converter is presented in [50] and [51] using coupled inductors. The topology achieves high voltage gain even at a small shoot-through duty cycle. In addition, the topologies have the advantage of minimum device stress.

A new dc–dc converter topology called a $Z-H$ converter inspired from a ZSI is presented in [52] by eliminating the front-end diode as shown in Fig. 9(b). The concept of using the shoot-through duty cycle to control the output voltage is ruled out completely by simple control of the duty cycle of the switches. The converter can achieve two-quadrant operation modes (II and IV quadrant) by varying the duty cycle of the complementary switch in the 0–0.5 and 0.5–1 range, respectively. However, the boost factor remains the same as that of a traditional ZSI in all modes of operation.

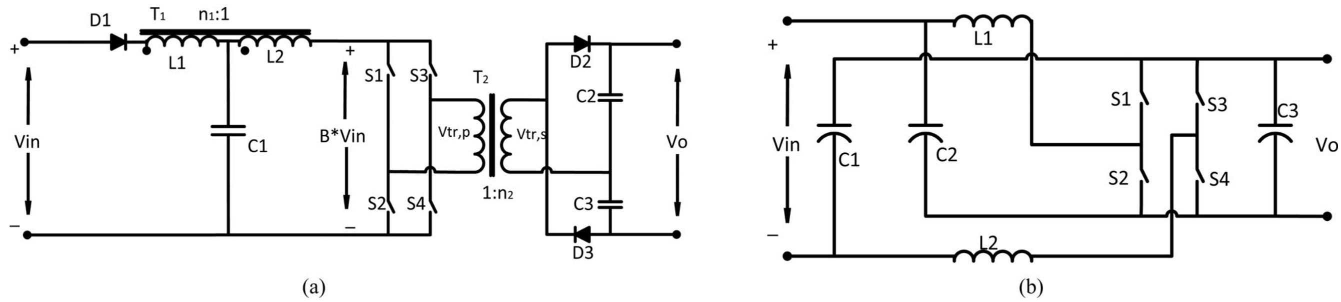


Fig. 9. Trans-Z-source converters: (a) trans-Z-source dc–dc converter and (b) $Z - H$ dc–dc converter.

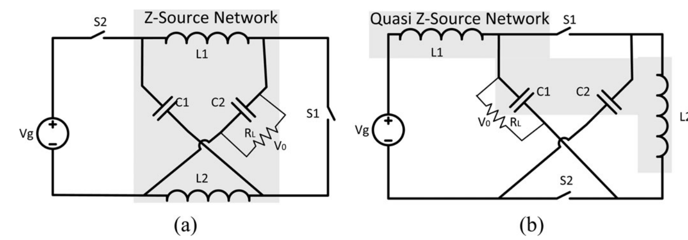


Fig. 10. Family of four-quadrant dc–dc converters using (a) Z-source and (b) quasi-Z-source network.

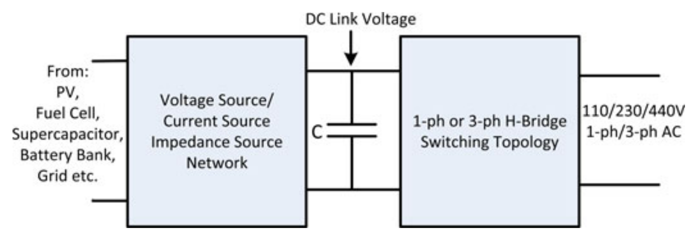


Fig. 12. General impedance-source inverter for one-phase or three-phase.

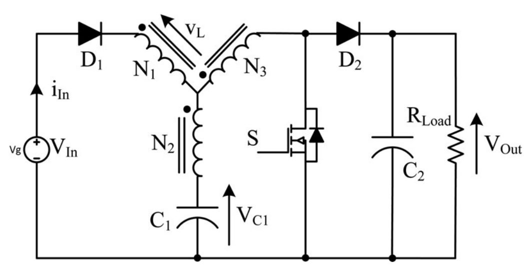


Fig. 11. Y-source boost dc–dc converter.

A family of four-quadrant dc–dc converters using a Z-source or a quasi-Z-source network with a minimal number of switches and passive devices is presented in [53]. The converter provides four-quadrant operation using four-quadrant switches. Two basic converter topologies derived from ZSI and qZSI are shown in Fig. 10. The converter has both buck/boost characteristics in the 0–1 range of the duty cycle. This feature along with changing the polarity of the load voltage by just controlling the duty cycle of the switch makes the converter very simple and more economical for many applications, e.g., dc-drives and other renewable energy systems.

A new boost dc–dc converter topology was proposed in [54] with three coupled inductors and called a Y-source converter as shown in Fig. 11. It can achieve a very high boost at a lower shoot-through duty cycle of the switch and has one more degree of freedom to choose the voltage boost. The converter can be designed very compactly with integrated magnetics, and fewer components are required to attain a high voltage boost. An isolated high-voltage boost converter using a Y-source impedance-source network is also proposed in [55] which reduced the number of switching devices and the corresponding switching complexities.

In addition to the aforementioned dc–dc converter topologies, various other dc–dc converter topologies are prevalent in the literature, e.g., a bidirectional Z-source dc–dc converter [56], an isolated bidirectional with a bivariate coordinated control strategy [57], a resonant [58] and Z-source dc–dc converter with common ground [59]. The voltage stress and power rating of the devices can be reduced with cascade [60] and series-in-parallel-out [61] topologies. However, this increases the size and cost of the system and requires a complex control.

B. DC–AC Inverter Topologies

Different topologies inspired from the traditional converter topologies are implemented to utilize the basic properties of the impedance-source network, e.g., two-level H-bridge, multilevel/neutral-point clamped (NPC), as well as the dual bridge. The retrofitting of these different classical topologies produces a new converter (see Fig. 7) with better performance and expected reliability. However, all the traditional PWM schemes and control methods are still valid with some modifications to accommodate the shoot-through state.

Topologies of different converters proposed so far with such modifications will be discussed in detail in the following sections:

1) Two-Level H-Bridge Topologies: The impedance-source network was originally implemented with a 3-ph H-bridge switching topology as voltage source and a current source to demonstrate its superiority over the traditional VSI and CSI. Both single-phase well as three-phase inverters can be implemented with an impedance source using the H-bridge circuit. There are numerous topologies and architectures for PV, fuel cell, super-capacitor, battery bank as well as grid-connected drives, and UPS systems [1]–[25]. Most of the topologies derived for two-level voltage inversion have the general topology shown in Fig. 12.

A unique topology is presented in [26] using two switches and a one-cycle control method. It has the same voltage transfer ratio as the full-bridge inverter. This topology is suitable for applications that need common grounding between source and load.

A two-level switched boost inverter similar to the ZSI is presented in [27]. It also works on the principle of a shoot-through state across the inverter bridge to boost the voltage at the output. In addition, this topology exhibits advantages similar to the ZSI with fewer passive components; however, it requires more active components.

2) 2) Multilevel/NPC: The concept of utilizing multiple small voltage levels or a split capacitor bank to perform power conversion by using a multilevel approach is prevalent in the literature. The advantages of this multilevel approach compared to two levels include premium power quality, excellent electromagnetic compatibility (EMC), low switching losses, and high voltage capability. However, larger numbers of switching semiconductors are required to implement it, along with a complex control system. In addition, small voltage steps must be supplied on the dc side, either by a capacitor bank or by isolated voltage sources.

The concept of this multilevel approach is being adopted with an impedance-source network to overcome some of the disadvantages of the classical multilevel topologies. Various impedance-source multilevel topologies with special modulation techniques are proposed to control the multilevel converter to get reduced harmonic distortion and device commutations. Fig. 13(a) shows a three-level NPC converter using two ZSIs [62]–[66]. The neutral point is connected to a common point of the two ZSIs and is grounded. There are other topologies implemented with a reduced number of passive [67]–[70] and active devices [71] to reduce the size and cost of the system [see Fig. 13(b)]. A qZSI-based NPC topology is also presented in [72] with a modified modulation technique [see Fig. 13(c)].

Recently, a seven-level single-phase grid-tied inverter was proposed for a PV system using a cascaded multilevel qZSI topology [73] as shown in Fig. 13(d). The topology is effective in tracking the maximum power point for each PV module separately. In addition, the independent dc-link voltage control loop balances the dc-link voltage of each H-bridge module.

A three-level impedance-source inverter can also be implemented using a traditional dual H-bridge concept. A three-level inverter for motor drives is realized using two cascaded ZS VSIs and a three-phase transformer in [74]. The inverter can supply to generic Δ or Y-connected loads with a single or two isolated dc source as shown in Fig. 14.

C. AC–AC Converter Topologies (Matrix Converter)

The matrix converter consists of nine bidirectional switches that allow any output phase to be connected to any input phase. It is a direct ac–ac converter with sinusoidal input/output waveforms and a controllable input power factor.

The maximum voltage gain of a traditional matrix converter does not exceed 0.866. In addition, the switches are more vulnerable to shoot-through on the same output phase leg. These limitations are overcome by the impedance-source matrix converter [75]–[78] as shown in Fig. 15. A traditional matrix converter with an impedance network can buck–boost the voltage as well as frequency for the ac load requiring adjustable voltage and frequency, e.g., motor drives. Many modulation and control methods, e.g., simple maximum boost control, maximum boost control, maximum gain control, and hybrid minimum stress control have been proposed to improve the performance and reliability of the converter [79]–[82]. Single-phase Z-source ac–ac converters [83]–[86] and single-phase quasi-Z-source ac–ac converters sharing a common ground [87], [88] with the load are also presented with suitable PWM techniques.

D. AC–DC Converter Topologies

Rectifiers based on an impedance-source network have the capability to both buck and boost the input voltage in a single stage compared to a traditional rectifier. In addition, they can provide good input power factor, low line-current distortion, regeneration and improved reliability. Fig. 16 shows Z-source [89]–[92] and quasi-Z-source [93]-based rectifier topologies. A new concept of a bidirectional converter based on a matrix converter is also presented in [76]. The advantages of the ac–dc matrix converter are controllable input power factor, tight dc voltage regulation, wide bandwidth with quick response to load variations, and single-stage buck voltage ac–dc power conversion.

III. Impedance-Source Network Topologies

All diverse power converter topologies with impedance-source networks are mainly derived from the Z-source network by modifying the original impedance network, or by rearranging the connections of inductors and capacitors [94]–[137]. Each Z-source network topology yields unique features for different or particular application needs. New Z-source topologies are still being developed, mainly for four reasons: 1) reduction of the Z-source network component count and rating; 2) extension of voltage gain range; 3) achieving higher power density; and 4) application-oriented optimization and improvement.

In addition, the voltage of the network can be increased by integrating traditional switched-inductor, switched-capacitor, tapped inductor, diode-assisted, and capacitor-assisted extension to the Z-source/quasi-Z-source network, which however requires more components.

The impedance-source network is broadly classified into two categories based on magnetics: 1) nontransformer based; and 2) coupled or transformer based as shown in Fig. 17. Each topology has distinct features and advantages and will be discussed briefly in the following sections.

A. Non-Transformer Based

1) Z-Source/ Quasi-Z-Source: Z-source converters are broadly classified into two types: voltage-fed and current-fed. However, unlike the traditional voltage-fed/current-fed inverter, the impedance-source network provides a buffer between the source and the inverter bridge and facilitates a short- and an open-circuit at any time depending on the mode of operation. Traditional voltage-fed/current-fed Z-source impedance

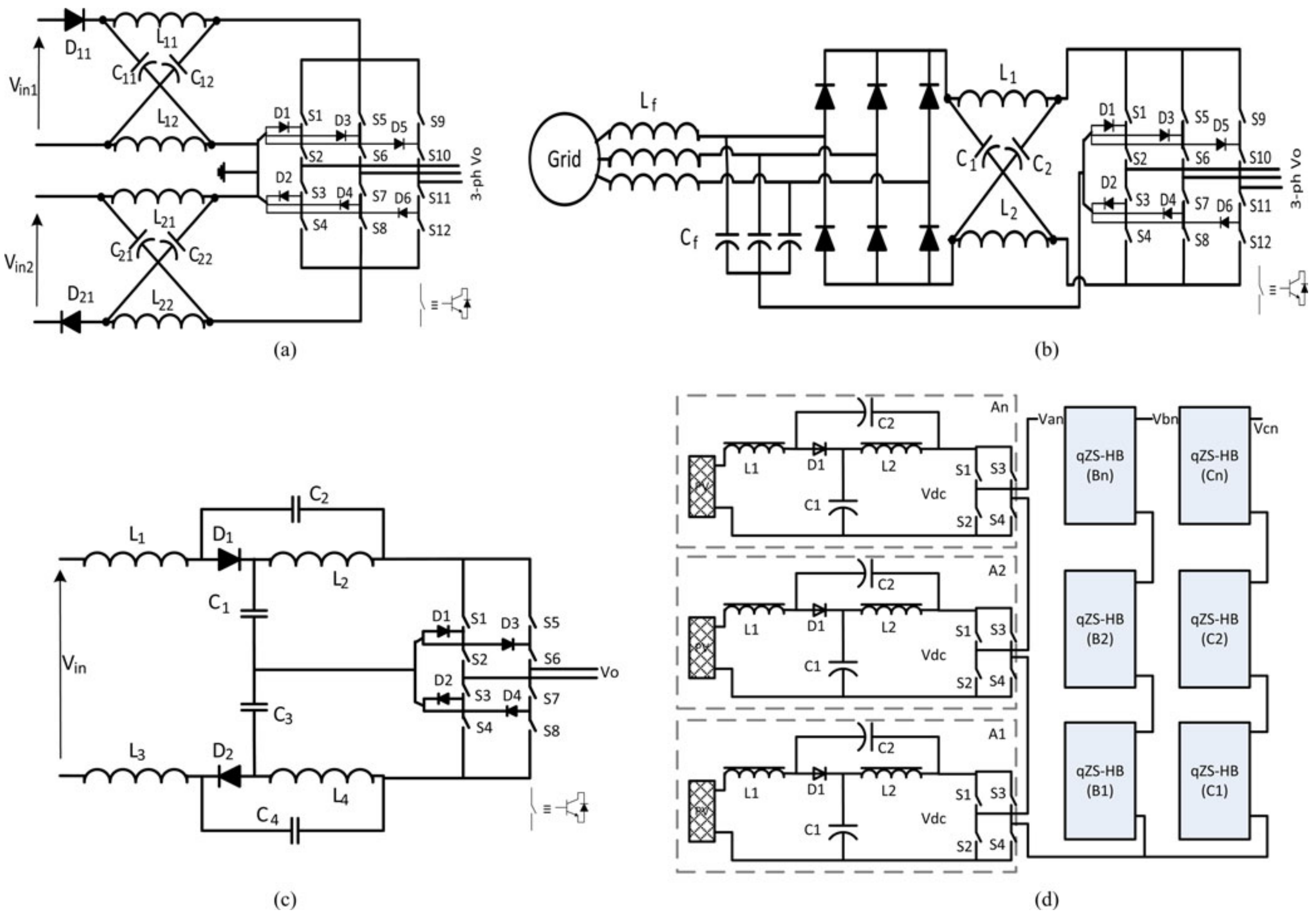


Fig. 13. Various impedance-network-source multilevel converter topologies: (a) two source NPC, (b) single-source NPC, (c) single-source quasi-Z-source, and (d) cascaded multilevel qZSI topology.

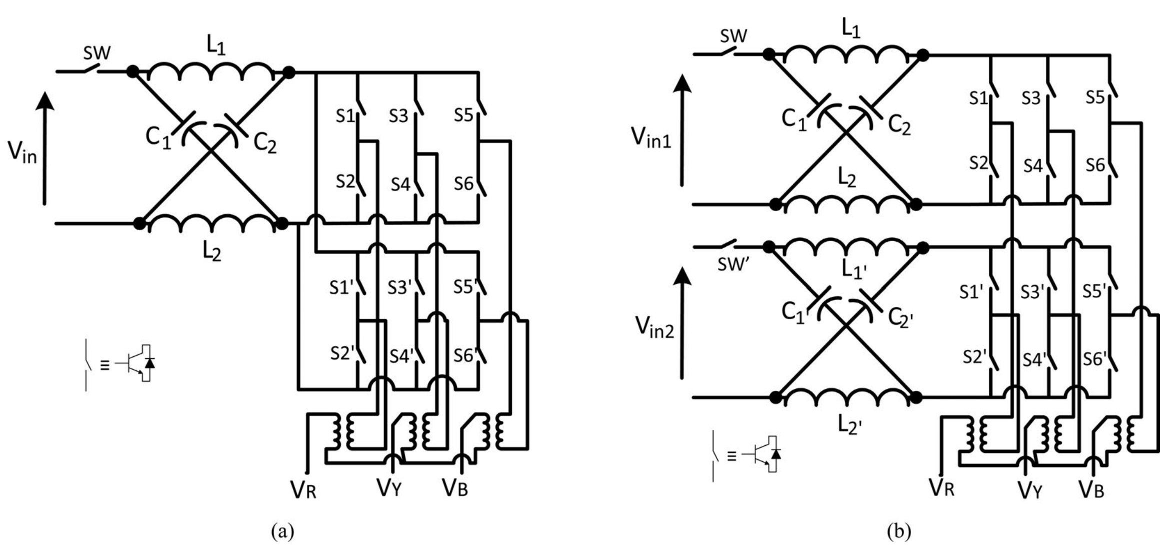
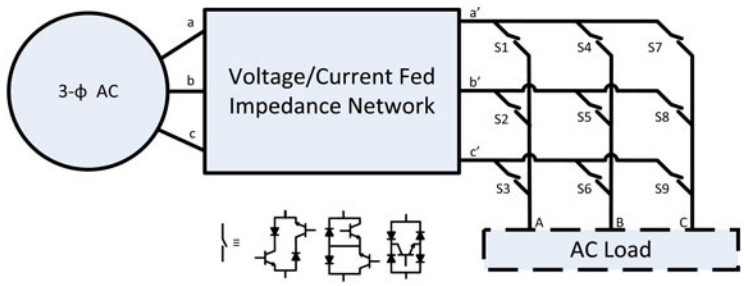
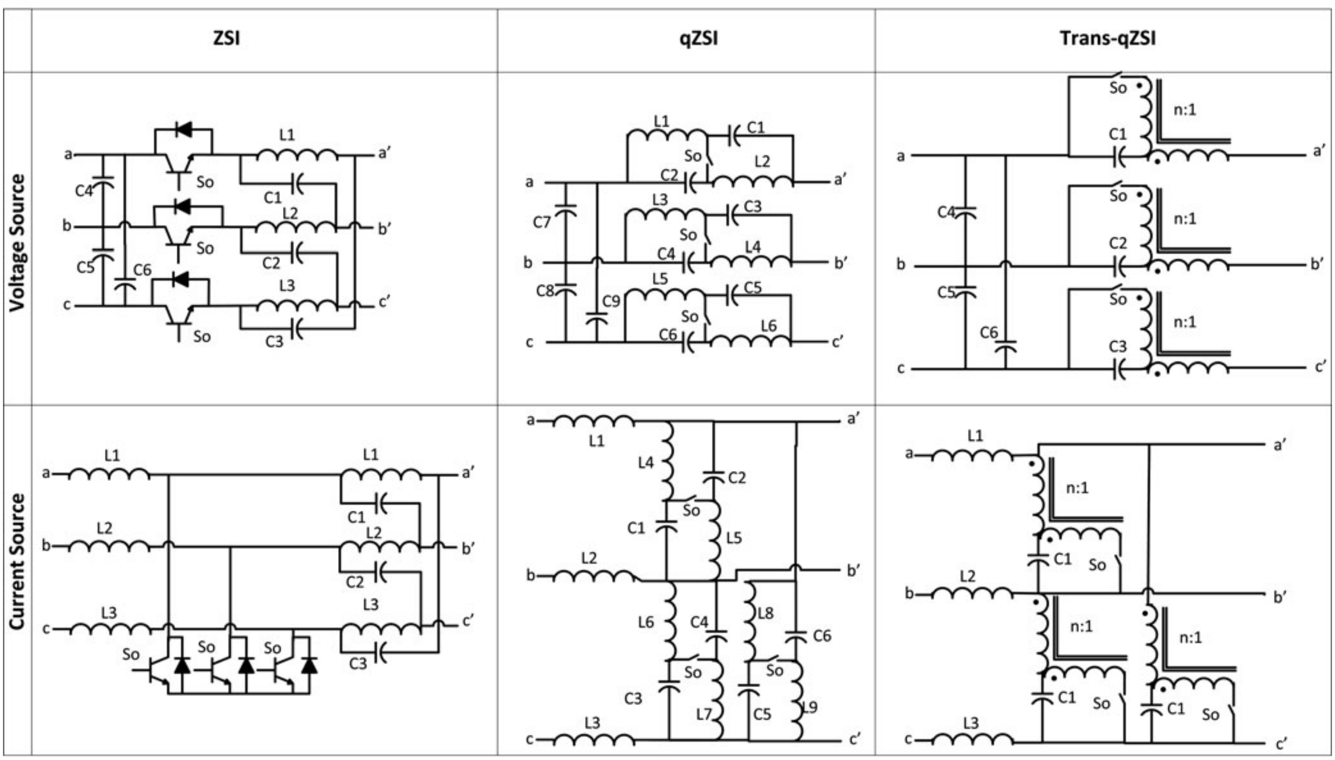


Fig. 14. Dual ZSI with three-level reduced common mode switching: (a) with single source and (b) with two isolated sources.

networks suffer from problems like discontinuous input current in the boost mode for the voltage-fed ZSI [see Fig. 18(a)] and high current stress on the inductor in the current-fed ZSI [see Fig. 19(a)]. Various voltage- and current-fed topologies derived from ZSI and qZSI [see Fig. 18(b) and (c) and Fig. 19(b) and (c)] with improved performance were proposed in [96]–[99] to solve the problem of ZSIs [98], [99]. It should be noted that all three current-fed ZSIs, Fig. 19(a)–(c), are capable of bidirectional power flow and buck–boost operation, although the switches have to be reverse-blocking devices. These new

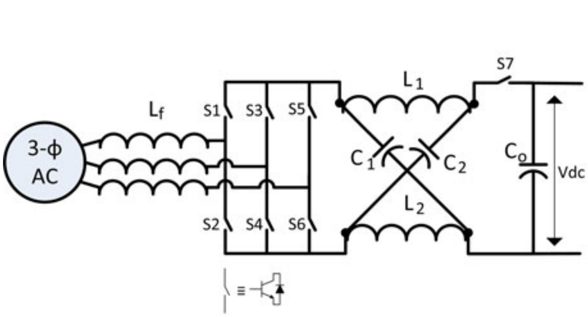


(a)

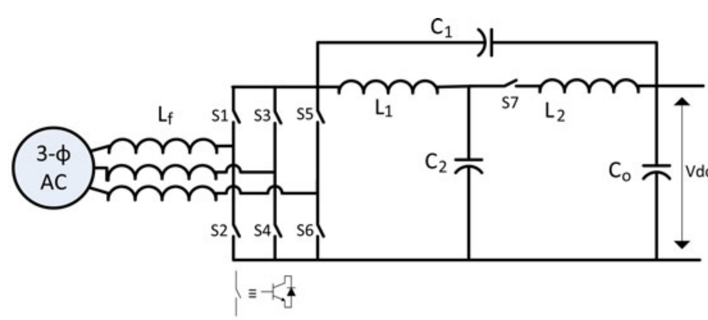


(b)

Fig. 15. Impedance-source network-based matrix converter: (a) general topology and (b) various voltage and current-source impedance-source networks for the matrix converter.



(a)



(b)

Fig. 16. AC–DC rectifier topologies based on (a) ZSI and (b) qZSI impedance network.

benefits extend this topology to applications of renewable energy generation and motor drives [1]–[26], [94]–[97].

2) Enhanced/Improved Z-Source: In the race to improve the boost capability of impedance-source networks, various modifications are proposed within the Z-source and quasi-Z-source networks. In the same context, an enhanced-boost ZSI is proposed in [100] and [101] with alternate-cascaded switched and tapped-inductor cells using some lower rated components. Similarly, an improved Z-source [102], [103] and an improved trans-Z-source [128] are proposed, respectively, to reduce the

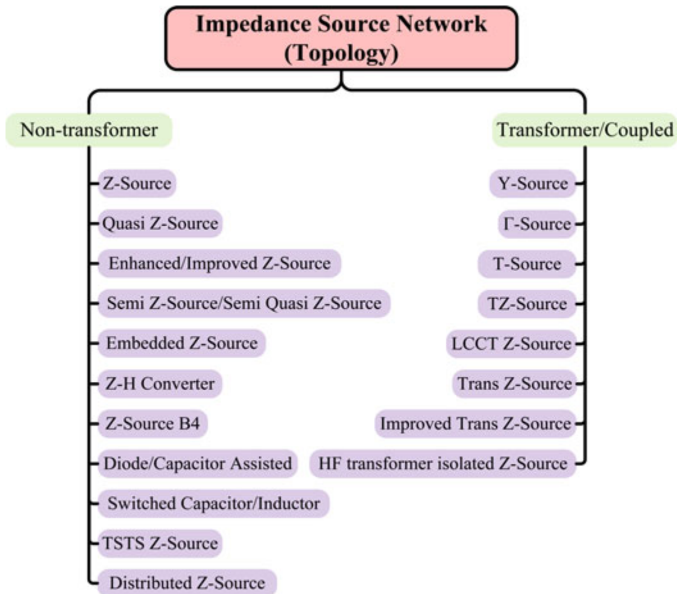


Fig. 17. Impedance-source network topologies (as of Sept. 2013).

capacitor voltage stress. These topologies are found to be effective in solving some of the problems faced by traditional ZSI and qZSI. However, additional components are required to implement the circuit. This makes the system more costly and also decreases the power density of the converter.

3) Semi-Z-Source/Semi-Quasi-Z-Source: Semi-ZSIs were proposed (see Fig. 20) to achieve low cost and high efficiency in applications such as single-phase grid-tie PV power systems. A semi-ZSI with only two active switches has a voltage boost function and a double-ground feature (both PV panel and ac output can be grounded) that eliminates the need to float/isolate PV panels without leakage current and which improves safety [104], [105]. Unlike the traditional ZSI/qZSI, a shoot-through state is not applicable to a semi-ZSI. An improved nonlinear sinusoidal PWM method is used to get the desired duty cycle to generate a sinusoidal output.

The advantage of the semi-Z-source and semi-qZSIs [106] is that they can be implemented using fewer switches compared to a traditional ZSI and qZSI, but unfortunately the voltage stress on the switching devices is high. This topology is suitable for a grid-connected micro-PV inverter with high-voltage SiC devices.

4) Embedded Z-Source: The embedded Z-source was proposed to achieve continuous input current and lower capacitor voltage rating, and its multisource feature is especially suitable for PV power generation [107]–[109]. Fig. 21 shows the circuit topology of a two-level-embedded ZSI. There are other similar embedded topologies with one or two dc sources suitable for battery storage systems.

5) $Z-H$ Converter: A new converter topology is presented in [110] with an impedance source similar to the Z-source; however, it has different connections as shown in Fig. 9(b). The proposed topology eliminates the input-side diode and the shoot-through state of the switch. The gain of the converter is similar to that of the Z-source network but it has two modes of operation, i.e., boost mode in D = [0, 0.5] with positive output voltage and boost mode in D = [0.5, 1] with negative output voltage. This converter topology can be applied to dc–dc, dc–ac, ac–dc, or ac–ac power conversion.

6) Z-Source B4 Converter: Inspired by the traditional B4 VSI, a Z-source B4 topology is proposed in [111] with a reduced number of active components, enhanced reliability, and lower cost. Fig. 22 shows the Z-source B4 converter topology for a three-phase power conversion.

7) Switched Inductor/Capacitor: Extra inductors and capacitors have been added in the Z-source and quasi-Z-source impedance network, aim of improving the boost capability of the circuit. Many topologies are presented in the literature to reduce the stress on the passive components and also to eliminate the start-up inrush current. A switched inductor/capacitor ZSI/qZSI provides continuous input current and reduced voltage stress on the capacitor [112]–[115]. An embedded Z-source with a switched inductor combines the advantages of both topologies, e.g., high boost ratio, reduced capacitor voltage stress, and low input ripple current [116]. However, this switched inductor/capacitor topology needs a large number of passive devices, which increases the cost and volume of the converter.

8) Capacitor/Diode Assisted: The voltage-boost capability of the Z-source and quasi-Z-source is extended with the aid of capacitors and diodes in order to meet the needs of applications requiring very high voltage boost [117], [118]. The impedance network can be extended by using a diodes and/or capacitors as shown in Fig. 23. The advantages of this topology are high voltage gain and reduced capacitor stress; however, this is at the cost of extra passive components.

9) Three-Switch Three-State (TSTS) Z-Source: Three-switch three-state single-phase ZSIs (TSTS-ZSIs) were proposed recently in [119], and are classified into two groups: boost-TSTS-ZSI and buck–boost-TSTS-ZSI as shown in Fig. 24.

This topology can be assembled using fewer switches compared to the traditional impedance-source topologies, so higher power density can be achieved. In addition, it has a lower voltage stress and dual grounding which makes it suitable for PV power generation.

10) Distributed Z-Source: Distributed impedance networks such as transmission lines and hybrid *LC* components can be used for a Z-source network [135]–[137] as shown in Fig. 25. These distributed Z-source networks are difficult to implement, but a distributed ZSI does not need any extra diode or switch to achieve the voltage boost function, thus having the minimum component count. This topology could open a door for an impedance-source network to radio-frequency power converter design by utilizing the distributed inductance and capacitance prominent at higher frequencies.

B. With Transformer or Magnetic Coupling

Magnetically coupled inductors and transformers find a niche in impedance networks to improve the voltage boost capability as well as the modulation index. In addition, they reduce the number of passive components needed in the network, which

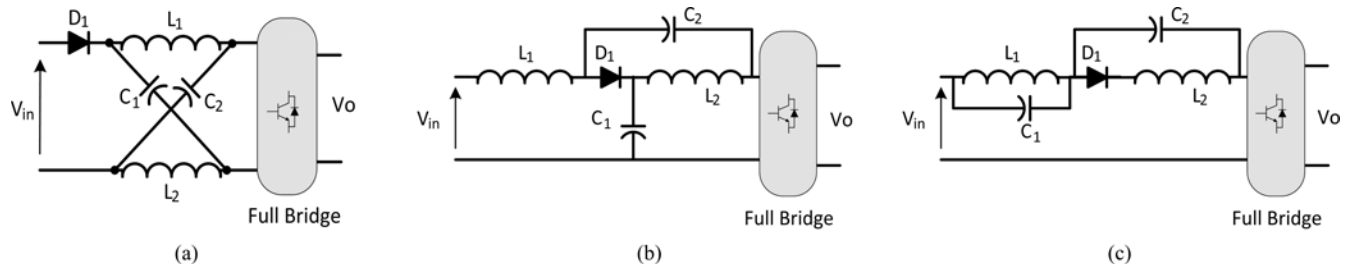


Fig. 18. Various voltage-fed ZSI topologies: (a) ZSI with discontinuous input current, (b) qZSI with continuous input current, and (c) qZSI with discontinuous input current.

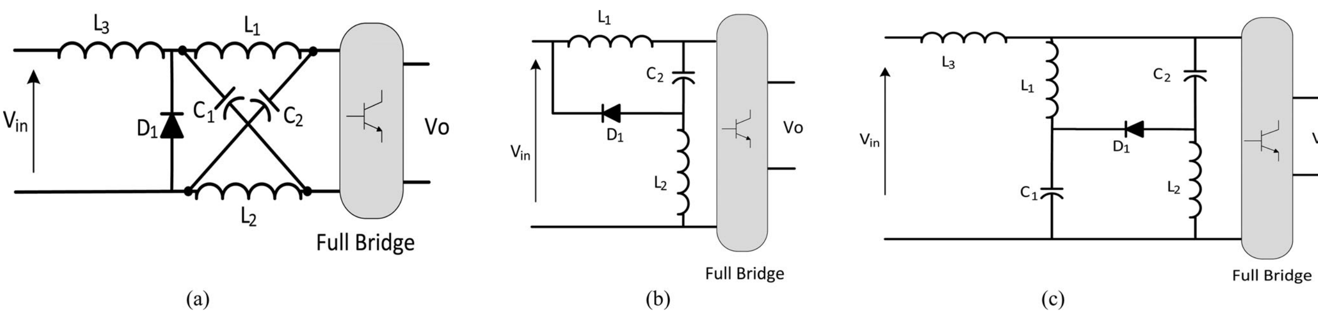


Fig. 19. Various current-fed ZSI topologies (switches have to be reverse-blocking devices): (a) ZSI with continuous input current, (b) qZSI with discontinuous input current, and (c) qZSI with continuous input current.

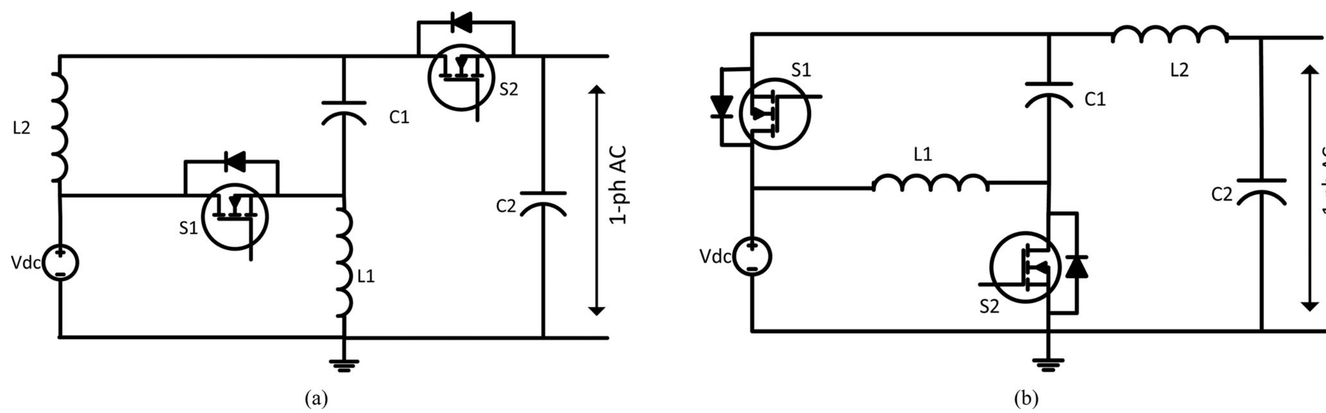


Fig. 20. Semi-Z-source topologies: (a) semi-ZSI and (b) semi-qZSI.

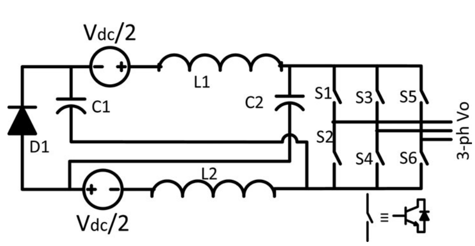


Fig. 21. Two-level-embedded ZSI.

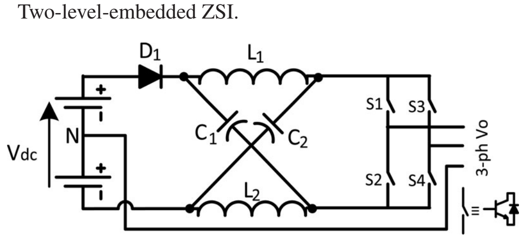


Fig. 22. B4 ZSI topology.

improves the power density and reducing the cost of the system. A generic method is presented in [120] to illustrate the derivation of some of the magnetically coupled network topologies. The following sections describe the impedance network topologies based on transformer or coupled inductor.

1) Y-Source: A unique impedance-source network called the "*Y-source network*" topology was proposed in [54] using coupled inductors with three windings $(N_1, N_2, \text{and } N_3)$ having versatile characteristics and features. The gain of the converter is presently not matched with existing networks operated at the same duty ratio. The proposed converter has one more degree of freedom (three windings and shoot-through duty cycle of switch (d_{ST})) to choose the voltage boost, as compared to a classical impedance network-based boost converter. Theoretically, any magnitude of voltage boost can be obtained by adjusting the turns ratio and shoot-through duty cycle of the switch.

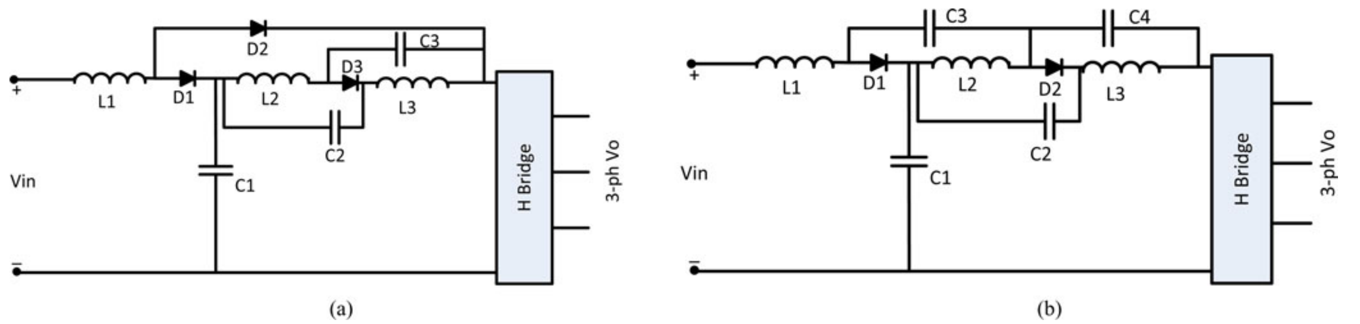


Fig. 23. Assisted qZSI topologies: (a) diode assisted and (b) capacitor assisted.

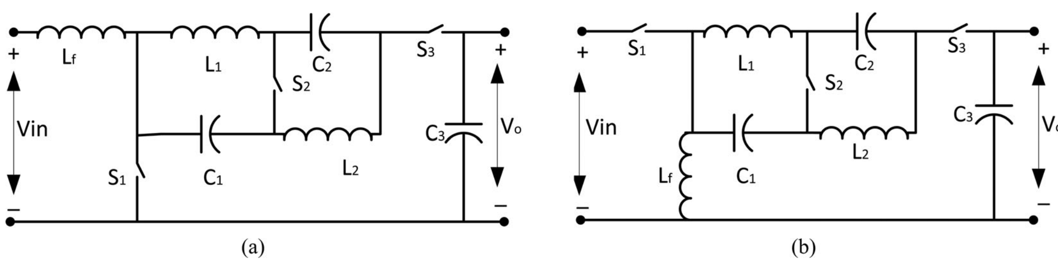


Fig. 24. TSTS-ZSIs: (a) boost topology and (b) buck–boost topology.

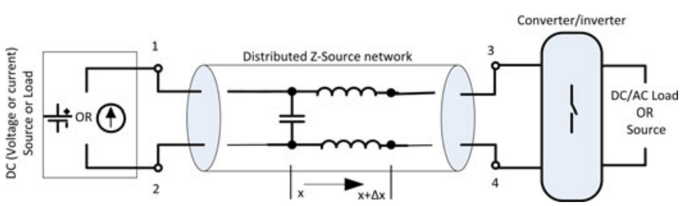


Fig. 25. General topology of a distributed Z-source converter.

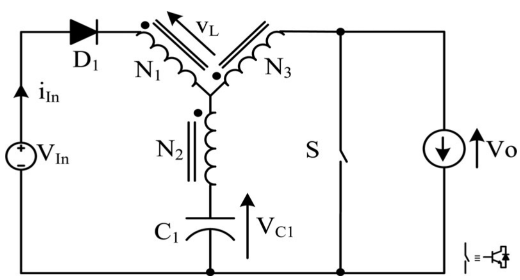


Fig. 26. Basic Y-source impedance network for power conversion.

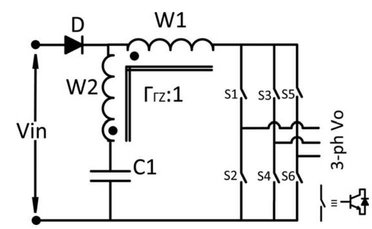


Fig. 27. Γ-Z-source network topology.

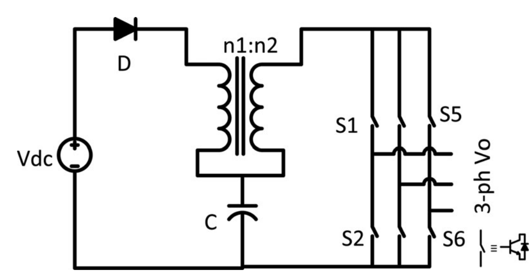


Fig. 28. T-source network topology.

Fig. 26 shows the basic Y-source impedance network for power conversion. The incommensurate properties of this network open a new horizon to researchers and engineers to explore, expand, and modify the circuit for a wide range of power-conversion applications.

2) Γ-Z-Source: A unique Γ-shape two-winding coupled transformer is also implemented in an impedance network [121]–[123] to increase the gain and modulation ratio simultaneously, while reducing the component count. Unlike other transformer-based impedance networks whose gains increases with an increased turns ratio, e.g., T-source, trans-Z-source, TZ-source or inductor–capacitor–capacitor–transformer Z-source inverters (*LCCT Z*-source), the Γ-Z-source gain increases with a decrease in the turns ratio. Fig. 27 shows the Γ-Z-source network topology for an inverter.

3) T-Source: The T-source inverter also utilizes a two-winding coupled inductor and one capacitor [124], [125] as shown in Fig. 28. The gain of the converter can be set higher than the traditional ZSI and qZSI using a transformer turns ratio greater than 1. This topology is suitable for an NPC converter as it shares a common voltage source for both the passive arrangement and the converter circuit.

4) Trans-Z-Source: Theoretically, the original Z-source, quasi-Z-source, and embedded Z-source all have unlimited voltage gain. Practically, however, a high voltage gain (>2 or 3), will result in a high voltage stress imposed on the switches. Trans-Z-source (two voltage-fed and two current-fed) inverters were proposed to have higher voltage gains while keeping voltage stress low and reducing the Z-source network to one

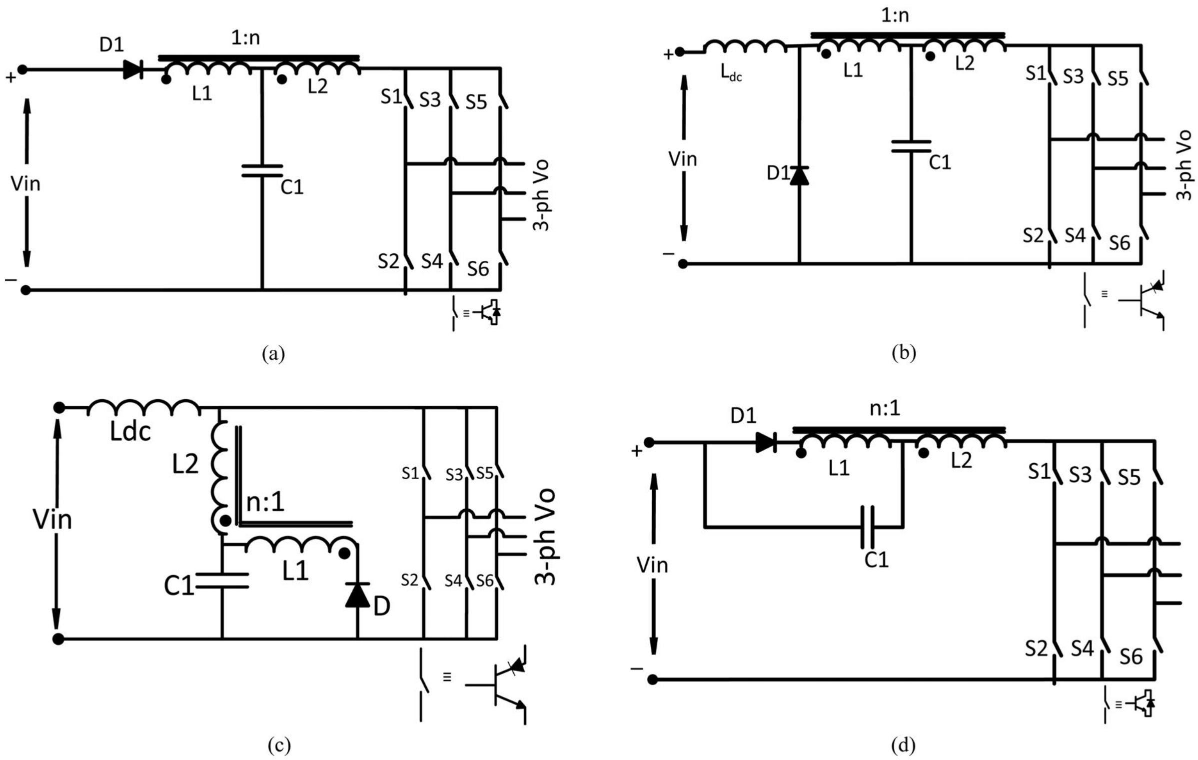


Fig. 29. Trans-ZSI: (a) voltage-fed trans-Z-source, (b) current-fed trans-Z-source, (c) current-fed trans-quasi-Z-source, and (d) voltage-fed trans-quasi-Z-source.

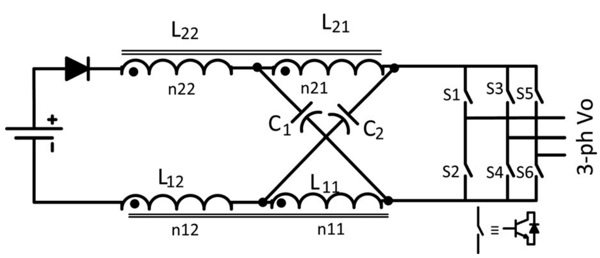


Fig. 30. TZ-source network topology.

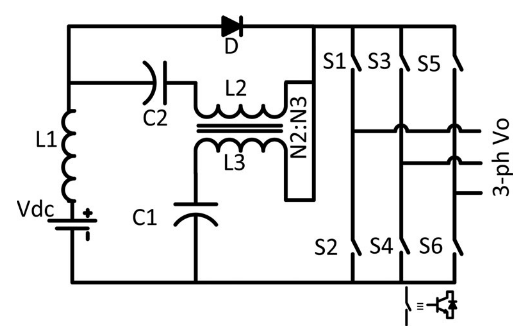


Fig. 31. *LCCT* network topology.

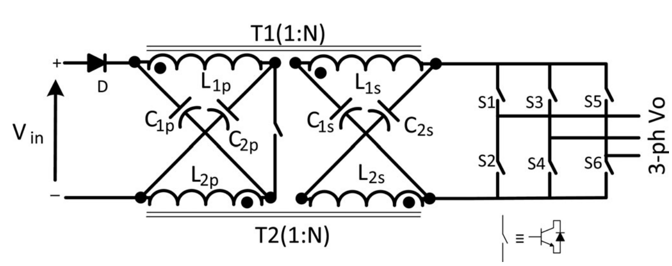


Fig. 32. HF transformer-isolated ZSI.

transformer (or one coupled inductor) and one capacitor [126]–[130] as shown in Fig. 29.

5) TZ-Source: The TZ-source also achieves high voltage gain by setting the turns ratio of the transformer to greater than 1 [131]. Comparatively, it requires a lower transformer turns ratio than the trans-ZSI; however, it requires four coupled inductors as well as the same number of other passive components as the traditional ZSIs. So, this topology is not very effective in reducing the number of components and size. Fig. 30 shows the circuit topology of the TZ-source network for a three-phase inverter.

6) LCCT Z-Source: With the inductor and a transformer integrated into a common core, the *LCCT Z*-source as shown in Fig. 31 achieve higher voltage gains and modulation index [132], [133]. This topology maintains a continuous input current even at a light load, and also filters out high-frequency ripples from the input current.

7) HF Transformer-Isolated Z-Source/Quasi-Z-Source/Trans-Z-Source: A family of impedance-source networks with intermediate HF isolation is presented with different topologies for applications requiring isolation for safety reasons [134]. These topologies inherit all the benefits of the Z-source networks along with a higher boost ratio and lower device stress. However, this topology increases the number of active and passive components. In addition, the coupled transformer must be designed properly to minimize the leakage inductance. One example of a voltage-fed HF-isolated ZSI is shown in Fig. 32.

TABLE I
SUMMARY OF IMPEDANCE-SOURCE NETWORK TOPOLOGIES

Impedance Network Topology	Boost Factor	Voltage Stress on the Switching Device	No. of Semiconductors	No. of Capacitors	No. of Inductors	Features
Z-Source [1]	$B = [1 - 2d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-2d_{ST}} V_{In}$	1 diode	2	2	• Elementary circuit to overcome the conceptual and theoretical barrier of VSI and CSI that leads to many useful derived topologies. • Discontinuous input current and higher voltage stress on capacitors. • The inductor of current-fed ZSI must sustain high currents.
Quasi Z-Source [94]	$B = [1 - 2d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-2d_{ST}} V_{In}$	1 diode	2	2	• First modification of Z-source network. • Continuous input current. • Reduced passive component ratings. • Reduced component count.
Improved Z-Source [102]	$B = [1 - 2d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-2d_{ST}} V_{In}$	1 diode	2	2	• Reduced capacitor voltage stress. • Limit inrush current at startup.
Semi Z-Source [104], [105], Semi Quasi Z-Source [106]	$B = [1 - 2d]/[1 - d]$ where, $V_o > 0$, for $0 \le d \le 0.5$, Buck and $V_o < 0$, $\begin{cases} 0.5 < d \le 2/3, & \text{Buck} \\ 2/3 < d \le 1, & \text{Boost} \end{cases}$	$\frac{1}{1-d} V_{In}$	2 Switches	2	2	• Reduced active components count. • Lower cost. • Common ground to load. • Higher voltage stress across switches compared to ZSI/qZSI. • Eliminate leakage currents and suitable for grid-connected PV system.
Embedded Z-Source [107]-[109]	$B = [1 - 2d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-2d_{ST}} V_{In}$	1 diode	2	2	• Draws smooth current from the source without adding additional components or passive filter.
Enhanced Z-Source [100]	SL Cell: $B = \frac{1+(\gamma_{SL}-1)d_{ST}}{1-(N\gamma_{SL}+1)d_{ST}}$ where, $0 \le d_{ST} \le \frac{1}{N\gamma_{SL}+1}$, $V_o > 0$	$\frac{1+(\gamma_{SL}-1)d_{ST}}{1-(N\gamma_{SL}+1)d_{ST}} V_{In}$	N+3($\gamma_{SL} - 1$)(N+1) where, N is no. of cascaded n/w	2N	γ_{SL}(N+1)	• Higher voltage conversion compared to ZSI/qZSI at small shoot-through duration. • Increases the number of components (low power rated).
	TL Cell: $B = \frac{1+\gamma_{TL}d_{ST}}{1-[1+N(\gamma_{TL}+1)]d_{ST}}$ where, $0 \le d_{ST} \le \frac{1}{1+N(\gamma_{TL}+1)}$, $V_o > 0$	$\frac{1+\gamma_{TL}d_{ST}}{1-[1+N(\gamma_{TL}+1)]d_{ST}} V_{In}$	N+2(N+1) Where, N is no. of cascaded n/w	2N	(N+1), each with turns ratio γ_{TL}	
Z-H Converter [110]	$B = [1 - 2D]^{-1}$ where, $0 \le D \le 0.5\ for\ V_o > 0$ and $0.5 \le D \le 1\ for\ V_o < 0$	$\frac{1}{1-2D} V_{In}$	4 Switches	2	2	• Front-end diode is eliminated. • No shoot-through state for voltage boosting.
Z-Source B4 [111]	$B = [1 - 2d_{ST}]^{-1}$ where $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-2d_{ST}} V_{In}$	1 diode	2	2	• Reduce the number of active semiconductors. • Simplify the control and gating circuitries.
Y-Source [54]	$B(K, d_{ST}) = [1 - Kd_{ST}]^{-1}$ where, $K \ge 2\ and\ 0 \le d_{ST} \le \frac{1}{K}$, $V_o > 0$	$\frac{K-1}{1-Kd_{ST}} V_{In}$	1 diode	1	integrated three windings	• Versatile. • More degree of freedom to choose the gain of the converter. • Very high gain can be achieved with small shoot-through duty cycle. • Higher voltage boost and higher modulation index can be achieved simultaneously. • Reduce THD of the inverter. • Better utilization of input voltage.
Γ-Source [121]-[123]	$B = [1 - (1 + [n-1]^{-1})d_{ST}]^{-1}$ where, $0 \le d_{ST} \le$ $[1 + [n-1]^{-1}]^{-1}$ and $1 < n < 2$ (decreasing), $V_o > 0$	$\frac{1}{(n-1)\left[1-\left(1+\frac{1}{n-1}\right)d_{ST}\right]} V_{In}$	1 diode	2	one inductor and one 2-winding coupled inductor	• Higher gain can be achieved by lowering the turns ratio of coupled inductor. • Better spectral performance at the inverter output.
T-Source [124], [125] Trans Z-Source [126]-[130]	$B = [1 - (n+1)d_{ST}]^{-1}$ where, $0 \le d_{ST} \le [n+1]^{-1}$, $V_o > 0$	$\frac{n}{1-(1+n)d_{ST}} V_{In}$	1 diode	1	integrated two winding	• Increases voltage gain compared to ZSI and qZSI. • Fewer reactive components compared to ZSI and qZSI. • Common ground with the load. • Reduced component stress.
TZ-Source [131]	$B = [1 - (n+1)d_{ST}]^{-1}$ where, $0 \le d_{ST} \le [n+1]^{-1}$, $V_o > 0$	$\frac{1+N_1+N_2}{1-(2+N_1+N_2)d_{ST}}$	1 diode	2	two integrated 2-windings	• Produce higher voltage boost with N.

TABLE I
SUMMARY OF IMPEDANCE-SOURCE NETWORK TOPOLOGIES *(Continued)*

LCCT Z-Source [132], [133]	$B = [1-(n+1)d_{ST}]^{-1}$ where, $0 \le d_{ST} \le [n+1]^{-1}$, $V_o > 0$	$\frac{n}{1-(1+n)d_{ST}} V_{In}$	1diode	2	one inductor and one 2-winding coupled inductor	• Continuous input current even during light load. • Filters out high-frequency ripple from the input current.
HF Transformer Isolated [134]	$B = n[1-2d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$V_d = V_{sw} = \frac{1}{1-2d_{ST}} V_{In}$	1 diode 1 switch	4	two integrated 2-windings	• Input-output isolation. • Lower device stress.
Diode/ Capacitor assisted Z-source, QZS [117], [118]	Diode Assisted: $B = [(1-d_{ST})(1-2d_{ST})]^{-1}$ where, $0 \le d_{ST} \le 0.5, V_o > 0$	$\frac{1}{1-d_{ST}} V_{In}$	3 diodes	3	3	• Higher voltage boost and lower voltage stress across the capacitor compared to ZSI/qZSI. • Number of passive and active components increases with number of stages.
	Capacitor Assisted: $B = [1-3d_{ST}]^{-1}$ where, $0 \le d_{ST} \le 0.33, V_o > 0$	$\frac{1}{1-3d_{ST}} V_{In}$	2 diodes	4	3	
Switched Inductor [112]-[116]	$B = (1+D)/[1-3D]^{-1}$ where, $0 \le D \le 0.33, V_o > 0$	$\frac{(1+D)}{1-3D} V_{In}$	7 diodes	2	4	• Higher voltage boost and lower voltage stress across the capacitor compared to ZSI/qZSI. • Number of components increases with corresponding size and cost.
TSTS Z-Source [119], [120]	Boost: $B = \frac{2D_2-1}{1-D_1}$	$(2+k)V_{In}$	3 Switches	2	3	• Reduce the number of active semiconductors. • Buck-boost capability. • Common ground. • Lower device stress. • Higher power density.
	Buck-Boost: $B = 1 + \frac{1-2D_2}{1-D_1}$	$(1+k)V_{In}$	3 Switches	2	3	
Distributed Z-Source [135]-[137]	Buck: $B = \left[\sqrt{(2D^2+K)^2 + 8KD^2} - (2D^2+K)\right] / (2K)$ where, $0 \le D \le 1$, and $K = 4L_{lk}f_{sw}/R_l, V_o > 0$ Boost: $B = 0.5\sqrt{P^2 + 4(P/D)} - P$ where, $0 \le D \le 1$, and $K = R_l/4L_{lk}f_o, V_o > 0$	Distributed impedance				• Eliminates discrete active and passive components for impedance network design. • High-frequency operation could lead the converter to better transient performance, higher power density and efficiency. • Eliminate parasitic effects.

Note: 1) All the mentioned gains are referred to respective voltage-source topologies wherever it is applicable.

IV. Comparison, Contrast, and Conclusion

Impedance-source networks have added a new chapter in the field of power electronics with their unique features and properties that overcome most of the problems faced by traditional converter topologies. Since the publication of the first Z-source network, there have been numerous contributions in the literature modifying the basic topology to suit the needs of many applications. The impedance-source network overcomes the conceptual and theoretical barriers and limitations of the traditional VSI and CSI and provides a novel power conversion concept [1]–[3]. The superior performance of the impedance-source network to design more robust and versatile converter topologies for various applications attracts researchers and designers from both academia and industry to explore it in depth. Various comparisons of impedance-source networks are available in the literature based on various specific applications [138]–[144]. Many topologies were developed to overcome the limitations and disadvantages of the traditional impedance-source network. Table I summarizes the different impedance-source network topologies predominant in the literature. A close study of all the relevant topologies reveals that the modifications are motivated by one or more of the following reasons: 1) to increase the boost; 2) to reduce the number and size of both active and passive devices; 3) to reduce the voltage stress on the active and passive devices; 4) better input voltage (dc-link) utilization; 5) to improve the EMC of the system; and 6) to increase the reliability of the system, etc.

In general, each individual topology may have a niche with targeted application(s), and it would not be possible to single out any particular circuit for general purposes. However, one may identify niche applications for particular networks that can improve the efficiency, reliability, and power density of the system and can fully utilize the potentials of new devices such as SiC and GaN. New application areas such as satellite, avionics, and medical are of special interest.

The original Z-source network has been advanced to quasi-Z-source network, trans-Z-source network, distributed Z-source network, and many other types of Z-source network topologies. The original ZSI has been expanded to dc–dc, dc–ac, ac–dc, and ac–ac converters, respectively, in both two-level and multilevel structures with voltage- and current-fed from the power source. Over one thousand papers have been published and hundreds of Z-source converters have been proposed. In addition, each type (dc–dc, dc–ac, ac–dc, or ac–ac) of converter could potentially be implemented with the original Z-source network, quasi-Z-source network, trans-Z-source, embedded Z-source, semi-Z-source, distributed Z-network, switched inductor Z-source, tapped-inductor Z-source, diode-assisted Z-source, or capacitor-assisted Z-source. The number of combinations is large and the topologies are confusing. In this paper, in order to provide researchers with a global picture of the impedance-source networks proposed in the literature, major Z-source network topologies have been surveyed and categorized based on conversion functionality and switching configurations. This survey and categorization help researchers to comprehend all these Z-source network topologies and to identify their pros and cons. In Part II, PWM control schemes and targeted applications presented in the literature will be surveyed.

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