



A Review on Single-Phase AC-AC Z-Source Converters

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ABSTRACT: First, the impedance source idea is used to alleviate the problems of Voltage Source Inverters (VSI), and Current Source Inverters (CSI), which leads to the introduction of the Z-Source Inverter (ZSI). Afterwards, not only did the Z-source cells were used in the inverter topologies, but they were also added to other power electronic converters, such as dc-dc choppers, ac-dc rectifiers, and ac-ac converters. Moreover, these power electronic converters, which have Z-source cells, are widely used in different applications. In particular, the existing single-phase ac-ac Z-source converters are reviewed in this paper, and their different features are studied in detail. In the past decades, the single-phase Z-source ac-ac converters have attracted significant attention due to their unique features, such as single-stage power conversion, boost in-phase, and buck out-of-phase features. Therefore, several modified or improved structures along with different control methods have been introduced to solve their problems and limitations. Based on the four features, these structures can be categorized into four groups: without magnetic coupling, with magnetic coupling, able to change the frequency, and inherent commutation. In this review, a general diagram is depicted, which many of the existing topologies can be obtained from it. Additionally, new topologies can be obtained by having this general diagram. After studying these structures, a comparative study is made to obtain the advantages and disadvantages of each. In the end, some advice and recommendations are given to develop and obtain new structures.

Review History:

Received: Dec. 31, 2021

Revised: Jan. 22, 2022

Accepted: Jan. 22, 2022

Available Online: Jun. 01, 2022

Keywords:

Single-phase ac-ac converter

Z-source ac-ac converter

safe commutation

1- Introduction

As an inevitable part of the industry in the last decade, the power electronic converters were highly developed [1-4]. These converters roles are interfaces between the input and output sides to do power conversion. Moreover, the topologies with high efficiency, small size, simple control method, high power, and especially high reliability, are required to respond to the increasing demand for these converters in industrial or home appliances.

The type of input side can be either voltage source [5-7], or current source [8-11]. Nevertheless, due to the higher availability of the input voltage sources, the voltage source converters have a higher diversity. As a type of power electronic converters, inverters have two types of Voltage Source Inverters (VSI), and Current Source Inverters (CSI). Generally, the conventional inverter structures are simple and have a simple control method. However, they suffer from inherent problems; for instance, the conventional VSI structures can only work as a buck converter, meaning they cannot have an output voltage gain higher than one. Moreover, there is a limitation in their control method due to the possibility of turning on two switches, which are in a leg, since turning on two switches from a leg can lead to a short-circuit

of input voltage source. There are similar problems in the current source inverters since they can only work as boost converter, and two switches in a leg cannot be turned off at the same time. As a result, the reliability of these inverters is low [12] [13]. In 2002, a topology called Z-source Inverter (ZSI), which is a solution for the problems of the conventional VSIs and CSIs [14], was presented. It is obtained that this topology can give both buck and boost gains. Moreover, two switches from a leg can be turned on, leading to a Shoot-Through (ST) state; hence, the reliability of this structure is increased. After ZSI, several Z-source-based inverters have been presented to add more advantages to the inverters [15-21]. The mentioned advantages of ZSI can be added to other kinds of power electronic converters, such as dc-dc converters [22-26], ac-dc rectifiers [27-28], and ac-ac converters [29], by adding impedance cells to them. These kinds of power electronic converters that include impedance cells are widely used in different applications, such as renewable energies [30-35], electric vehicles [36-39], uninterruptible power sources [40-42], drive of electric machines [43-46], fuel cells [47-49], energy storage systems [50], and dynamic voltage restorers [51-54]. Nowadays, developing converters containing impedance cells is important and gets great attention regarding these applications.

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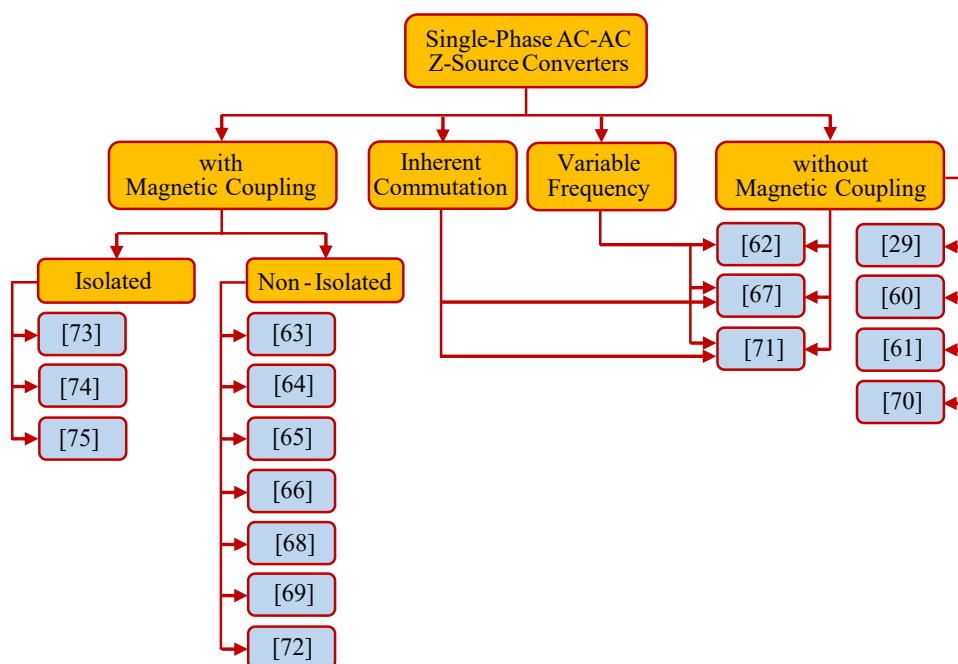


Fig. 1. Classification of the different Z-source ac-ac converters.

Z-source ac-ac converters got great attention in the past years as one of the power electronic converters contains impedance cells. The first single-phase Z-source ac-ac converter was presented in 2005, three years apart from ZSI introduction. Unique features of this topology, such as boost in-phase, buck out-of-phase, single-stage power conversion, and a simple control method have made it superior to the matrix converters [55-57] and indirect converters [58] [59]. Since 2005, the Z-source ac-ac converters have been developed in two kinds, the single-phase [60-75], and three-phase [76]. Additionally, it is good to note that three phase Z-source matrix converters [77,78], which are a combination of the impedance cells and matrix converters, were presented to alleviate the problems of the matrix converters.

In this paper, a review of the single-phase Z-source ac-ac converters are performed. A high number of these structures can be obtained from a generalized structure that depicts the generalized diagram and how to obtain each topology. Primarily, the existing topologies are studied and analyzed in detail. Subsequently, the commutation problem in the basic single-phase ac-ac converter is studied. Afterwards, the presented solutions to solve this problem are described to familiarize the existing control methods for this kind of Z-source ac-ac converters. Thereafter, the existing single-phase Z-source ac-ac converters are compared to the features, and devices count perspectives. The results are listed in a table, and a numerical comparison to the total voltage stresses on the capacitors, switches, and diodes to distinguish the best topology is presented. Ultimately, some recommendations are suggested to develop the single-phase Z-source ac-ac converters by considering the problems and limitations of the existing structures.

2- Single-phase Z-source ac-ac Converters Development

Ac-ac converters are widely used in industrial applications, such as induction heating and lighting control, by developing controllable semiconductor devices. Ac choppers are the first type of ac-ac converters that provide the desirable output voltage on the output side by controlling the firing angle of the thyristors. However, regarding this type of ac-ac converter, it can be illustrated that its applications are limited due to some problems, such as high harmonic distortion in output voltage and input current, requiring the bulky Inductive-Capacitive (LC) filter on the input and output sides, and a low power factor [79]. Therefore, the matrix and two-stage AC-DC-AC converters that can regulate the magnitude of the output voltage and frequency, were presented to alleviate these problems. It should be noted that in these applications, where only the control of the magnitude of the output voltage is required, the direct PWM converters [80] are better choices due to their small size and low cost. The direct PWM converters are the developed dc-dc converters, and can include buck, boost, buck-boost, cuk, or isolated converters.

The first impedance source ac-ac converter was presented in 2005 [29]. In this converter, some unique features like boost in-phase and buck out-of-phase were added by using an X-shaped impedance network. After introducing the basic single-phase ac-ac Z-source converter, various topology of single-phase ac-ac Z-source converters were presented and published. We can categorize them based on four distinguishing features.

These features are: 1. without magnetic coupling; 2. with magnetic coupling; 3. Being able to change the frequency; 4. Inherent commutation. It should be noted that the converters having a magnetic coupling can be categorized into two groups, where the topologies of the first group are isolated

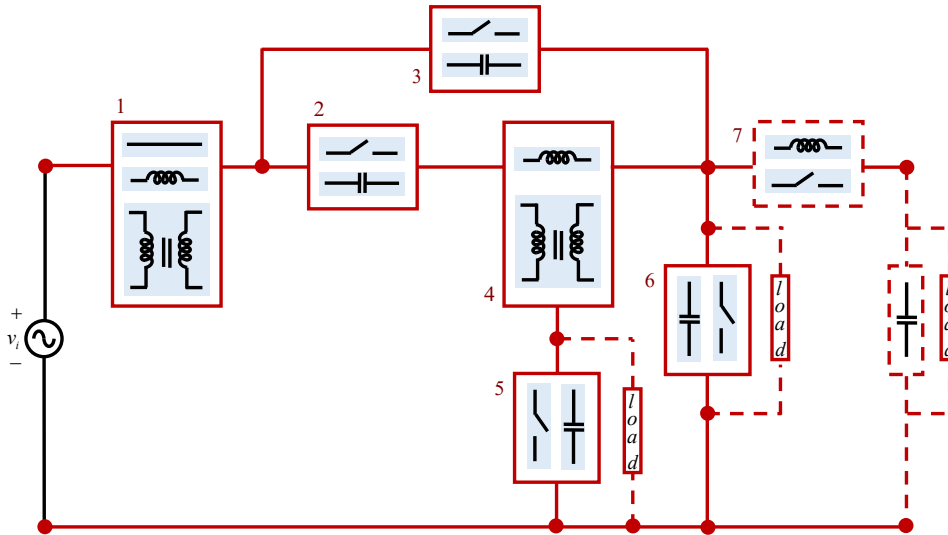


Fig. 2. The generalized structure of single-phase ac-ac Z-source converters.

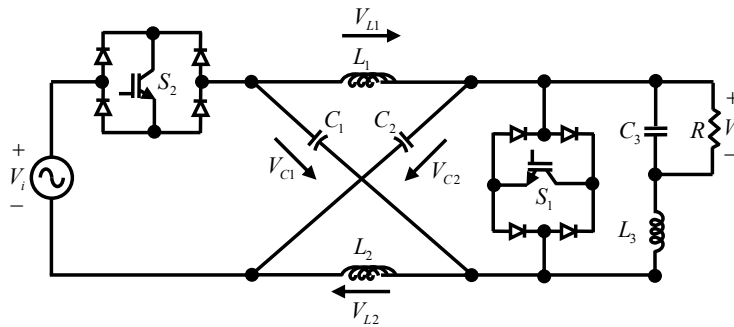


Fig. 3. Z-source ac-ac converter [29].

with a High-Frequency Transformer (HFT), and the second group are non-isolated. A categorization is depicted in Fig. 1.

In general, all of the existing structures of single-phase ac-ac Z-source converters can be summarized in Fig. 2. However, it should be noted that the basic single-phase ac-ac Z-source converter cannot be obtained from this general structure due to its different configuration of the switches. Regarding Fig. 2, it is illustrated that there are seven boxes, and two different components can replace every box.

Choosing each component in each of box can lead to an existing structure or a new structure. As shown in Fig. 2, the output load can be connected to three parts of generalized structure. There is a common ground between the input and output sides in each of these structures. If the selected component in boxes 5 or 6 is a capacitor, connecting them to the output load will be possible. It is important to note that it will be possible to omit box number seven if the load is connected to box number five or six. Using the generalized topology shown in Fig. 2, some existing single-phase Z-source ac-ac converters are obtained and are listed in Table 1. Regarding the number of boxes, the components that lead to the existing topologies along with their power circuit are listed in Table

1. It should be noted that some of the references such as [75] present a family of topologies with similar secondary parts. Regarding this fact, their primary parts can be obtained from the generalized structure. The existing Z-source ac-ac converters are shown and analyzed in the following sections.

2- 1- The conventional Z-source ac-ac Converter [29]

The first single-phase Z-source ac-ac converter was presented in 2005 [29]. The existing structure in [29] is shown in Fig. 3. This structure can boost the output voltage to the same phase as the input voltage, and can be called ‘boost in-phase’ mode. Additionally, if this structure works in the buck mode, the phase of the output voltage will have a 180 degrees shift from the phase of the input voltage, called ‘buck out-of-phase’ mode. The main disadvantages of this topology are a discontinuous input current, missing common ground in input and output sides, and high voltage and current impulses on the switches. This topology uses snubber circuits to alleviate the voltage and current impulses on the switches. However, using snubber circuits can lead to low reliability and an increased power loss. Moreover, regarding missing the common ground in the input and output sides, the output voltage

Table 1. Obtaining existing topologies using the generalized structure

Box no.	Comp.	Obtained topology	Box no.	Comp.	Obtained topology
1	<i>L</i>	<p>Existing topology in [61]</p>	1	<i>L</i>	<p>Existing topology in [62]</p>
2	<i>S</i>		2	<i>C</i>	
3	<i>C</i>		3	<i>S</i>	
4	<i>L</i>		4	<i>L</i>	
5	<i>C</i>		5	<i>S</i>	
6	<i>S</i>		6	<i>C</i>	
7	<i>L</i>		7	-	
1	<i>L</i>	<p>Existing topology in [63]</p>	1	<i>L</i>	<p>Existing topology in [65]</p>
2	<i>S</i>		2	<i>C</i>	
3	<i>C</i>		3	<i>S</i>	
4	<i>L</i>		4	<i>CL</i>	
5	<i>C</i>		5	<i>S</i>	
6	<i>S</i>		6	<i>C</i>	
7	-		7	-	
1	<i>S.C.</i>	<p>Existing topology in [64]</p>	1	<i>S-C</i>	<p>Existing topology in [69]</p>
2	<i>S</i>		2	<i>S</i>	
3	-		3	-	
4	<i>CL</i>		4	<i>CL</i>	
5	<i>C</i>		5	<i>C</i>	
6	<i>S</i>		6	<i>S</i>	
7	<i>L</i>		7	-	
1	<i>L</i>	<p>Existing topology in [66]</p>	1	<i>L</i>	<p>Existing topology in [68]</p>
2	<i>S</i>		2	<i>S</i>	
3	<i>C</i>		3	<i>C</i>	
4	<i>CL</i>		4	<i>CL</i>	
5	<i>C</i>		5	<i>C</i>	
6	<i>S</i>		6	<i>S</i>	
7	<i>S</i>		7	-	
1	<i>CL</i>	<p>Existing topology in [71]</p>	1	<i>CL</i>	
2	<i>S</i>		2	<i>S</i>	
3	<i>C</i>		3	<i>C</i>	
4	<i>CL</i>		4	<i>CL</i>	
5	<i>C</i>		5	<i>C</i>	
6	<i>S</i>		6	<i>S</i>	
7	<i>L</i>		7	<i>L</i>	

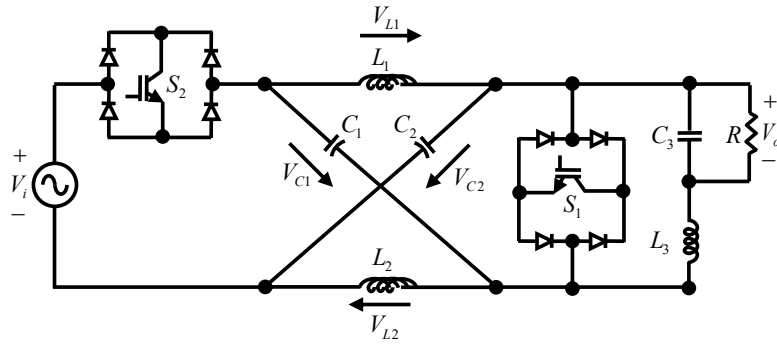


Fig. 3. Z-source ac-ac converter [29].

phase does not track the input voltage phase effectively in either the boost or buck mode. Additionally, an Inductive-Capacitive (LC) filter has to be used on input side to avoid injecting high-frequency harmonics into the grid, which increases the number of required components. Regarding this topology, the output voltage gains, the sum of the voltage stress on the capacitors and the total blocked voltage by the switches can be listed as follows

$$M = \frac{1-D}{1-2D} \tag{1}$$

$$V_{C_{total}} = \frac{3(1-D)}{1-2D} V_i \tag{2}$$

$$V_{S_{total}} = \frac{2\sqrt{2}}{1-2D} V_i \tag{3}$$

The single-phase Z-source ac-ac converters require bi-directional switches from either voltage or current views to operate correctly. Moreover, these structures have two main operating modes of Shoot-Through (ST) and (nST), the same as Z-source inverters. Generally, single-phase Z-source ac-ac converters have two or three bidirectional switches. One is used to obtain the ST state, and others are turned on in the nST state. As a result, one of the switches is controlled with a constant duty-cycle of D and a switching frequency of f_s . The state of the other switch is a complement of this switch, and therefore, it is controlled with a duty-cycle of $1-D$ and a switching frequency of f_s . Ideally, when a switch is turned off the other switch is turned on without overlap or dead time. However, in practice, due to the unideal characteristics of the switches and the delay in driver circuits, after turning off a switch, all switches turn on or turn off in a short time (known as the overlap time and dead time, respectively). If either

overlap time or dead time occurs, the switches will be damaged and the converter will not work efficiently. This problem is shown in Fig. 4 to clearly illustrate this problem.

2- 1- 1- Commutation Problem in Basic Single-phase Z-source ac-ac Converter

In the following, to clarify the commutation problem, the basic single-phase Z-source ac-ac converter depicted in Fig. 3 is analyzed in detail. As Fig. 3 demonstrates, the bidirectional switches are made by adding a diode bridge to an unidirectional switch. According to Fig. 4, there are some dead-time or overlap times after each operation modes. In this description, it is assumed that the basic single-phase Z-source ac-ac converter is the ST state, as shown in Fig. 5a. After finishing this state, S_2 turns off; however, S_1 does not turn out yet. As a result, the currents flowing across the inductors cannot find a path to flow (Fig. 5b), leading to an impulse voltage on the switches that may cause them serious damage. Furthermore, a similar condition occurs in the nST state. The equivalent circuit in the nST state is shown in Fig. 5c, where S_1 is

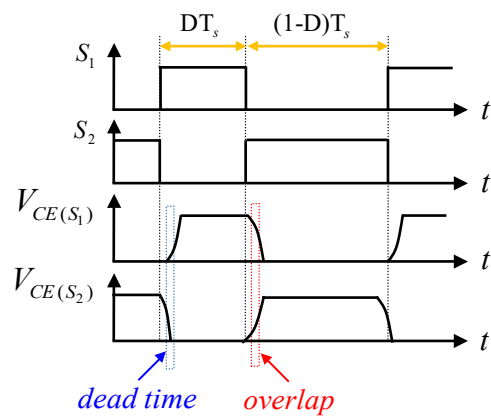


Fig. 4. The problems, which are because of the non-ideal characteristics of the switches and the delay of the driver circuits.

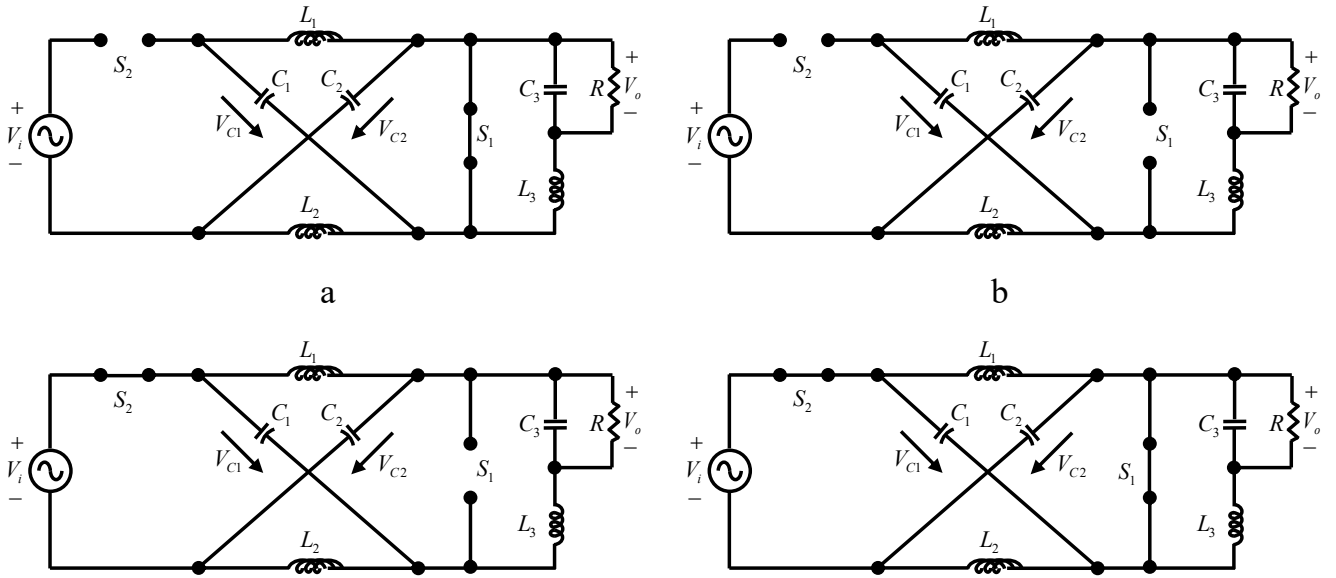


Fig. 5. Operational modes of the basic single-phase Z-source ac-ac converter, (a) ST mode, (b) dead-time state, (c) nST mode, (d) overlap state.

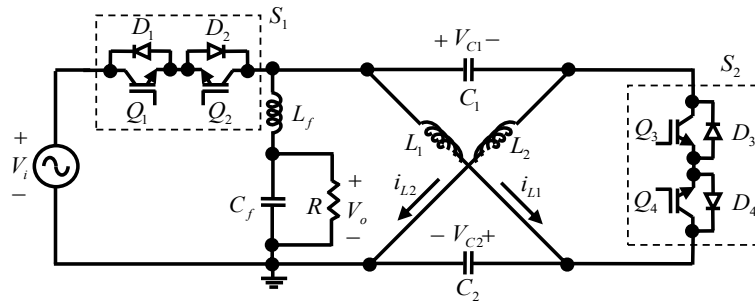


Fig. 6. Z-source ac-ac converter to solve the commutation problem [60].

turned out. After finishing this state, S_2 is turned on before S_1 is turned off (Fig. 5d). Therefore, the voltages on capacitors suddenly change, and an impulse current occurs that can damage the switches. In the basic single-phase Z-source ac-ac converter, a small snubber circuit is considered for each switch to solve the commutation problems. Nevertheless, snubber circuits can increase the total power loss, reduce efficiency, and reduce reliability [60].

2-2- Using Z-source ac-ac Converter to Solve the Commutation Problem [60]

Using Z-source ac-ac converter to solve the commutation problem was presented in 2007 [60]. The existing topology in [60] is depicted in Fig. 6. By comparing Fig. 3 and Fig. 6, it can be demonstrated that both structures have the same impedance network. However, in the presented topology in [60], the load (R) is transferred to the input side to have a com-

mon ground. In addition, this topology presents a switching pattern to make current flow paths for the inductors in dead times. Hence, two of the main problems of conventional Z-source ac-ac converter, such as missing the common ground, voltage, and current impulses on the switches are solved in this structure. Nevertheless, the input current is still discontinuous, and it is required to put an LC filter on the input side. The key factors of this structure are the same as the existing topology in [29], and are not written to avoid repetitive information.

2-2-1- Safe commutation strategy and how to implement it

In the safe commutation strategy, instead of an unidirectional switch along with a diode bridge, the common-emitter configuration of two unidirectional switches is used as a bidirectional switch. In this commutation strategy, a dead time is added between the gate pulses. Additionally, an appropriate

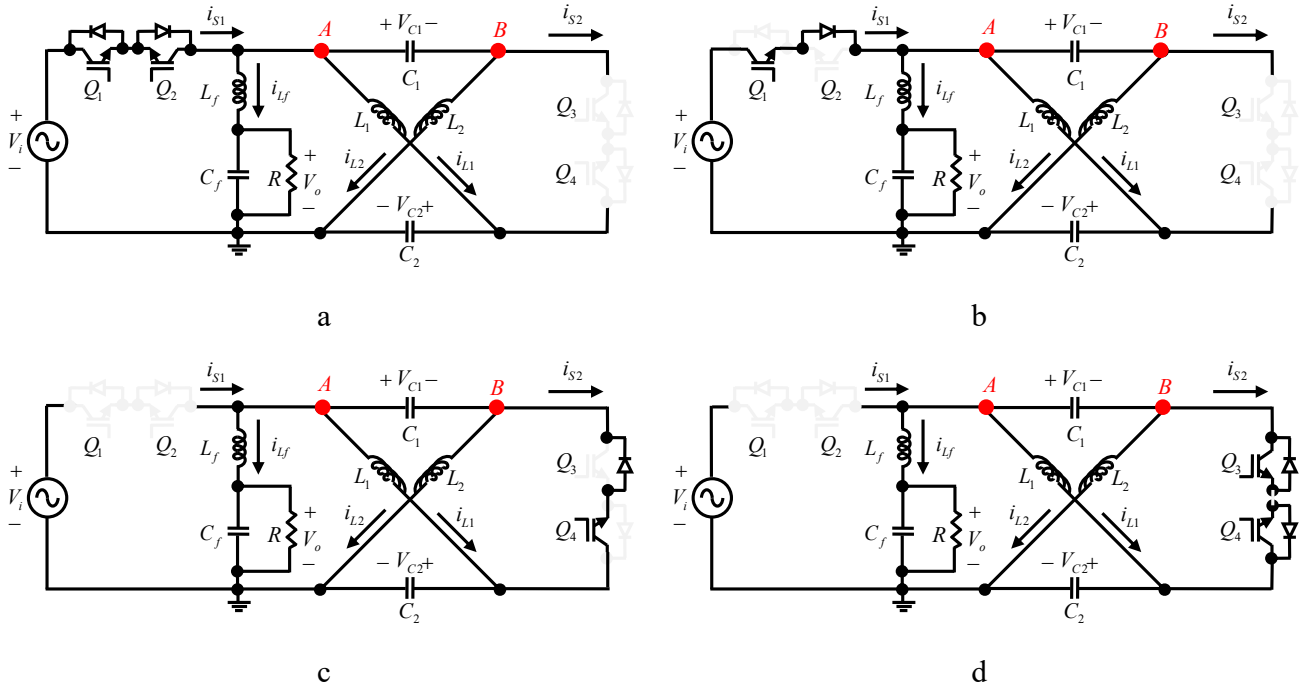


Fig. 7. States of commutation for the presented structure in [60], where $v_i > 0$, (a) nST mode, (b) when $i_{L1} + i_{L2} + i_{Lf} > 0$, (c) when $i_{L1} + i_{L2} + i_{Lf} < 0$, (d) ST mode.

switching method is applied to provide the current flow path for inductors during these dead times. The operating modes of the presented topology in [60], which is shown in Fig. 6, for studying the safe commutation strategy are analyzed in detail.

The main intent of the safe commutation strategy is to prevent switches from turning on, simultaneously. To study this strategy, the topology in its boost mode and the polarity of input voltage is supposed to be positive. Primarily, the topology is analyzed in its nST state, where the equivalent circuit is shown in Fig. 7a. S_1 and S_2 are in the on and off states in this operating mode, respectively. Regarding Kirchhoff current law (KCL) in node A, we can have:

$$i_{S1} = i_{L1} + i_{L2} + i_{Lf} \quad (43)$$

If this operating mode is finished and the dead time comes up, there will be two possible states: 1. If $i_{L1} + i_{L2} + i_{Lf} > 0$, the switch of Q_1 and the body diode of Q_2 will be turned on to provide a safe path for the currents of inductors and KCL violation in node A. The equivalent circuit of this state is shown in Fig. 7b.

2. If $i_{L1} + i_{L2} + i_{Lf} < 0$, the switch of Q_4 and body diode of Q_3 will be turned on to provide a safe path for the currents of inductors and KCL violation in the node A. The equivalent circuit of this state is shown in Fig. 7c. After this state finishes, the ST state starts, which the equivalent circuit of this

state is shown in Fig. 7d. If $v_i < 0$, the commutation states will be in a similar form, and they are not described, to cut a long story short.

Regarding these descriptions, the switching method for two states of boost in-phase and buck out-of-phase are shown. As it was seen, a dead time is added between the different gate pulses to prevent the switches from turning on simultaneously. Fig. 8a shows the switching pattern for the boost in-phase mode. If $v_i > 0$, Q_1 and Q_4 will be turned entirely on, and Q_2 and Q_3 will be switched with the switching frequency in the complementary form. Else, if $v_i < 0$, Q_2 and Q_3 will be turned entirely on, and Q_1 and Q_4 will be switched with the switching frequency in the complementary form. Besides, Fig. 8b shows the switching pattern for the buck out-of-phase mode. If $v_i > 0$, Q_2 and Q_3 will be turned entirely on, and Q_1 and Q_4 will be switched with the switching frequency complement to each other. Else, if $v_i < 0$, Q_1 and Q_4 will be turned entirely on, and Q_2 and Q_3 will be switched with the switching frequency in the complementary form.

For the other single-phase Z-source ac-ac converters, the snubber circuits can be omitted. A safe commutation strategy can be implemented by applying the same method, except for the basic topology [29], and the structures that have an inherent commutation [67] [71]. In the inherent commutation solution, the converter structure is divided into two parts. One is positive, and the other is negative; the positive and negative parts are switched on the positive and negative half-cycles, respectively. In each impedance cell, there is an active switch

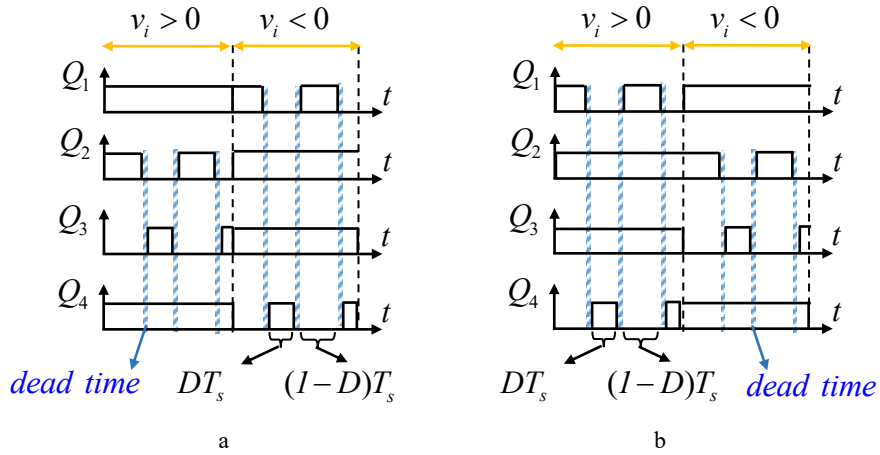


Fig. 8. Switching pattern for the existing structure in [60], (a) boost in-phase mode, (b) buck out-of-phase mode.

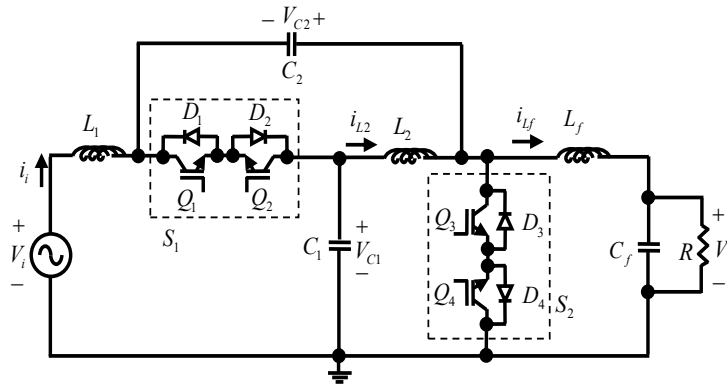


Fig. 9. Quasi Z-source ac-ac converter [61].

that its switching states make the primary operating states of the impedance cell. If this switch is turned off, the diodes and side capacitors make a current flow path, and the open-circuit state of the inductors is inherently prevented. As a result, the output voltage gain control is performed only by choosing the input voltage polarity using a simple PWM pulse in this type of commutation.

2- 3- Quasi Z-source ac-ac Converter [61]

The quasi Z-source ac-ac converter was presented in 2010 [61]. The power circuit of quasi Z-source ac-ac converter is depicted in Fig. 9. In this topology, an inductor is placed on the input side that makes a continuous input current; hence, there is no need for an LC filter on the input side. Instead, an output filter is used to eliminate the high-frequency harmonics in the output side, constructed from L_f and C_f . This structure has solved the stated problems for the existing topologies in [29] and [60]. By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and

the total blocked voltage by switches can be listed as follows:

$$M = \frac{1 - D}{1 - 2D} \tag{4}$$

$$V_{C,total} = \frac{2 - D}{1 - 2D} V_i \tag{5}$$

$$V_{S,total} = \frac{2\sqrt{2}}{1 - 2D} V_i \tag{6}$$

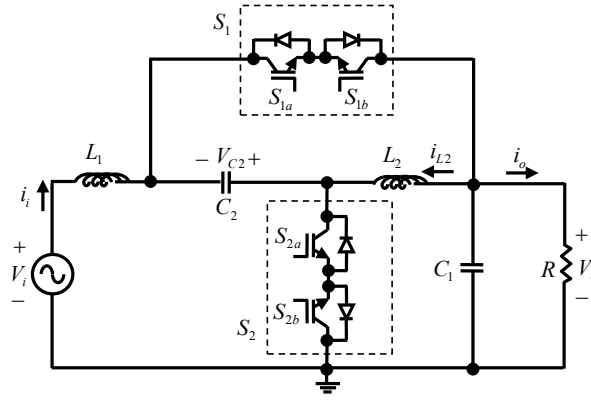


Fig. 10. Modified quasi Z-source ac-ac converter [62].

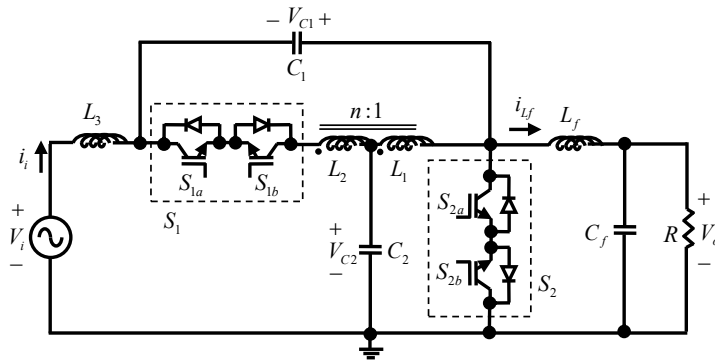


Fig. 11. Single-phase safe commutation trans-Z-source ac-ac converter [63].

2- 4- Modified Quasi Z-source ac-ac Converter [62]

The modified quasi Z-source ac-ac converter was presented in 2012 [62]. The power circuit of this structure is shown in Fig. 10. Similar to quasi Z-source ac-ac converter [61], this structure can provide both boost in-phase and buck out-of-phase functionalities. Additionally, the input and output sides have a common ground, and the input current is continuous. Nevertheless, the main feature of this structure that distinguishes from the past topologies, is using the filter capability of the impedance network that leads to eliminating the output LC filter. The output load is directly connected to the impedance network regarding this improvement. As a result, eliminating the output filter leads to a low count of devices, lower volume, and higher efficiency compared to the existing topologies in [29], [60], and [61]. By having the presented topology in [62], it is obtained that this topology and the existing topology in [61] have the same key factors.

2- 5- Single-phase Safe Commutation Trans-Z-source ac-ac Converter [63]

The single-phase safe commutation trans-Z-source ac-ac converter was presented in 2015 [63]. The presented structure in this reference is depicted in Fig. 11. This topology is the

first Z-source ac-ac converter based on the coupled inductors. Regarding the past structures, it can be shown that their output voltage gain can only be controlled by changing the duty cycle; however, this parameter can be controlled either by the duty cycle or the turn ratio of the coupled inductors in the coupled inductors-based structures. High voltage stress on S_1 is the main demerit of the presented topology in [63], which is several times as the output voltage and rises by increasing the turn ratio of the coupled inductors. It is evident that increasing voltage stress on a switch raises the ratings of this switch, and as a result, the overall cost of the structure increases.

It must be considered that the current rating of the magnetizing inductor has a direct relation with the turn ratio of the coupled inductors, where increasing turn ratio makes the magnetizing current several times as the input current. Furthermore, increasing the current leads of the magnetizing inductor to higher ohmic losses, decreases the overall efficiency. Additionally, it leads to a higher diameter of windings and increases the volume of the core. In the presented structure in [63], the output LC filter is used to alleviate the high order harmonics, and the ability of the impedance network to filter these harmonics is neglected. Therefore, the inductor used as

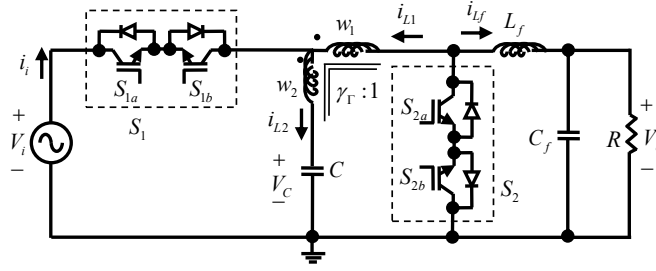


Fig. 12. Z-source ac-ac converter based on gamma structure with safe-commutation strategy [64].

a filter at the output side not only makes ohmic losses, but also reduces the output voltage gain. Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1 - D}{1 - (n + 2)D} \quad (7)$$

$$V_{C, total} = \frac{2 + (n - 1)D}{1 - (n + 2)D} V_i \quad (8)$$

$$V_{S, total} = \frac{\sqrt{2}(n + 2)}{1 - (n + 2)D} V_i \quad (9)$$

2- 6- Z-source ac-ac Converter Based on Gamma Structure with Safe-commutation Strategy [64]

The Z-source ac-ac converter based on gamma structure with a safe-commutation strategy was presented in 2016 [64]. The proposed structure in this reference is shown in Fig. 12. This figure shows that this structure includes one coupled inductor with two windings and a capacitor where the coupled inductor has a gamma (Γ) configuration. On the output side of this structure, an LC filter is used that is constructed from L_f and C_f , eliminates the high order harmonics. Unlike T configuration, in Γ configuration, the turn ratio has a limited acceptable range, $(1 < \gamma_{\Gamma} \leq 2)$, and the output voltage gain increases by lowering this ratio. The independence of the magnetizing current to the turn ratios of the coupled inductors is the other difference of this structure compared to the existing in [63]. The discontinuous input current and the requirement for a large inductor in the input current path are the main disadvantages of the presented structure in [68]. As shown in Fig. 12, this structure has a common ground between the input and output sides. However, there is a phase difference between the input and output voltages due to a

large inductor on the output side. Additionally, the voltage stress on the switch placed on the input side, suffers from high voltage stress equal to several times as output voltage. By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1 - D}{1 - \frac{n}{n - 1}D} \quad (10)$$

$$V_{C, total} = \frac{2 - 2D}{1 - \frac{n}{n - 1}D} V_i \quad (11)$$

$$V_{S, total} = \frac{\sqrt{2}n}{n(1 - D) - 1} V_i \quad (12)$$

2- 7- A Filterless Z-source ac-ac Converter Based on T Structure [65]

The filterless Z-source ac-ac converter based on T-source structure was presented in 2017 [65]. The existing power circuit in this reference is shown in Fig. 13. Similar to other T configuration-based structures, this topology has a boost, buck, common ground, and continuous input current. Regarding the presented topology in [65], it is observed that it is similar to the existing topology in [62]. Nevertheless, a coupled inductor is used instead of L_2 . Hence, similar to the existing topology in [62], the impedance cell is used as a filter, therefore the input and output LC filters are alleviated, and the output load is directly connected to the impedance cell. Additionally, a high output voltage gain can be obtained by increasing the turn ratio of the windings; however, the voltage and current stresses on the switches is increased, where the voltage stresses on the switches are several times as output voltage. By having this topology, the output voltage gains, the

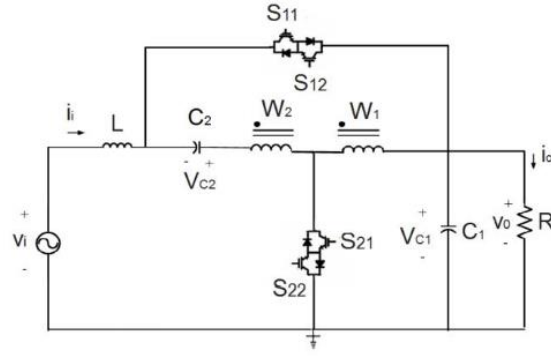


Fig. 13. A filterless Z-source ac-ac converter based on T structure [65].

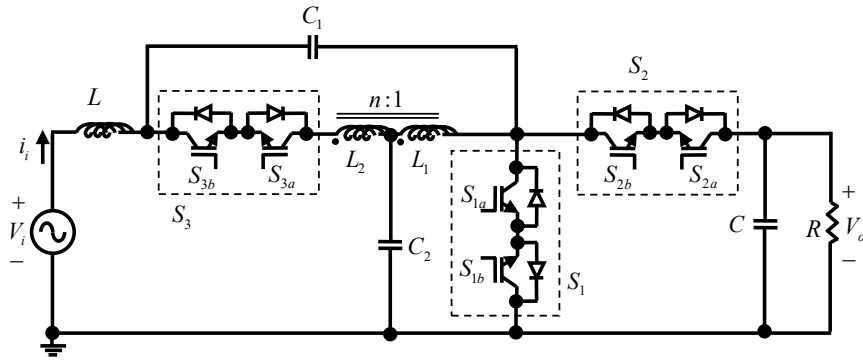


Fig. 14. Single-phase safe-commutation trans-Z-source ac-ac converter [66].

sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1 - D}{1 - (n + 2)D} \quad (13)$$

$$V_{C, total} = \frac{2 - 2D}{1 - \frac{n}{n-1}D} V_i \quad (14)$$

$$V_{S, total} = \frac{\sqrt{2}n}{n(1 - D) - 1} V_i \quad (15)$$

2- 8- Single-phase Safe-commutation Trans-Z-source ac-ac Converter [66]

The single-phase safe-commutation trans-Z-source ac-ac converter was presented in 2018 [66]. The presented structure is shown in Fig. 14. As this figure demonstrates, a capacitor is used as a filter which is a single order filter on the output side. Additionally, it is seen that this structure has a similar

configuration compared to the presented structure in [63], and the difference is a bidirectional switch is used instead of the output filter. Nevertheless, replacing the input filter with a bidirectional switch increases the output voltage gain and efficiency compared to the presented structure in [63]; however, the current stress on S_1 increases and the voltage stress on the input side switch is still high. Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1}{1 - (n + 2)D} \quad (16)$$

$$V_{C, total} = \frac{2 + nD}{1 - (n + 2)D} V_i \quad (17)$$

$$V_{S, total} = \frac{\sqrt{2}(n + 3)}{1 - (n + 2)D} V_i \quad (18)$$

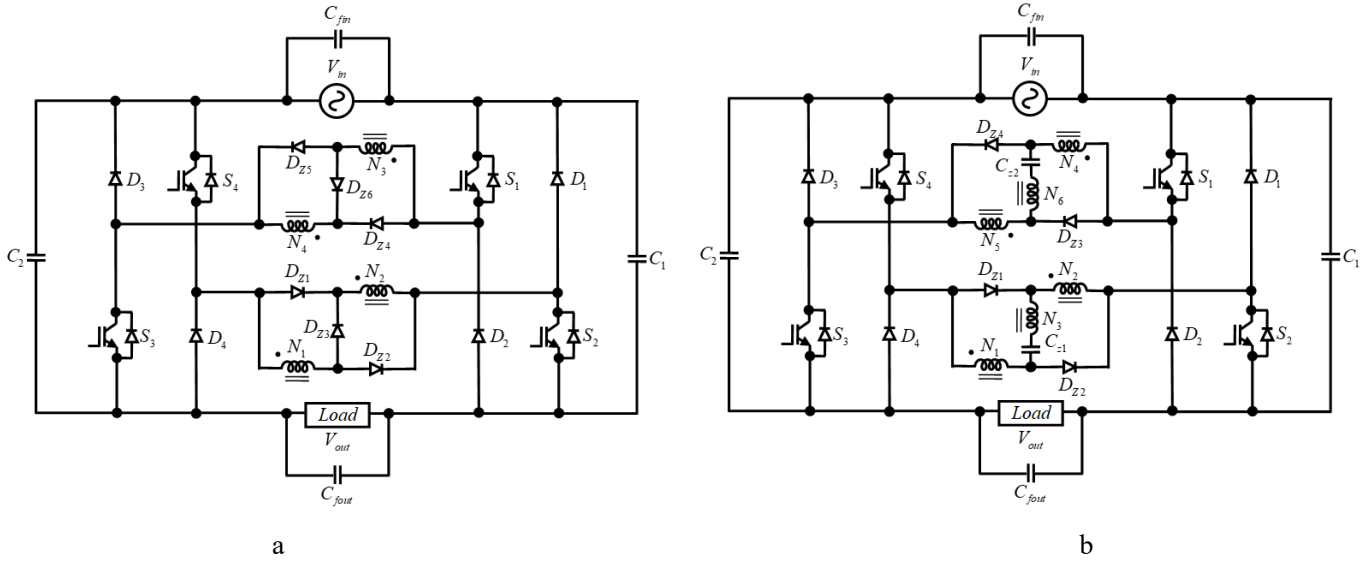


Fig. 15. Direct single-phase ac-ac converters based on series impedance networks [67], (a) with coupled inductors cell (CSL), (B) with improved coupled inductors cell (MSCL).

2- 9- Direct Single-phase ac-ac Converters Based on the Series Impedance Networks [67]

The direct single-phase ac-ac converters based on the series impedance networks were presented in 2018 [67]. The existing structures are shown in Fig. 15. In Fig. 15a and Fig. 15b, the switched inductor cell and improved switched inductor cell are used to increase the output voltage gain. The lateral capacitors are used as a free-wheeling path in these structures. Therefore, there is no need for snubbers for the switches. In each half-cycle of the input voltage, one of the series impedance cells is activated to generate the output voltage. As a result, the other cell stays inactive and is turned off. Both coupled inductors are wound on a magnetic core. In addition, the input current is discontinuous and has a high ripple. Moreover, voltage stresses on the switches are high, equal to several times as output voltage. Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{2D}{1-D} \tag{19}$$

$$V_{C,total} = \frac{2-D(9D^2-10D-1)}{1-D^2} V_i \tag{20}$$

$$V_{S,total} = \frac{\sqrt{2}(32D^2+4)}{1-D^2} V_i \tag{21}$$

2- 10- . Z-source ac-ac Converter Based on Asymmetrical Gamma Structure with Safe Commutation [68]

The Z-source ac-ac converter based on an asymmetrical gamma structure with safe commutation was presented in 2020 [68]. The power circuit of the existing structure is depicted in Fig. 16. All common features of the Z-source ac-ac structures can be found in the presented structure in [68]. These features can be named the common ground between the input and output sides, boost in-phase and buck out-of-phase functionalities, and the continuous input current. As seen in Fig. 16, a transformer with an asymmetrical Γ configuration is used to have a high voltage gain. Using the flipped gamma configuration instead of the regular can lead to a higher voltage gain for a determined duty cycle and a continuous input current. In addition, there is no need for snubbers for each of the switches regarding using a safe commutation strategy. Additionally, regarding using the filtering feature of the impedance cell, the output filter is removed, and the output load is directly connected to the impedance network. Overall, these two features can lead to lower volume, lower cost, and higher efficiency of the presented topology in [68]. Nevertheless, the voltage stress on the switch on the input side is still higher than the output voltage. By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1-D}{1-\frac{2n-1}{n-1}D} \tag{22}$$

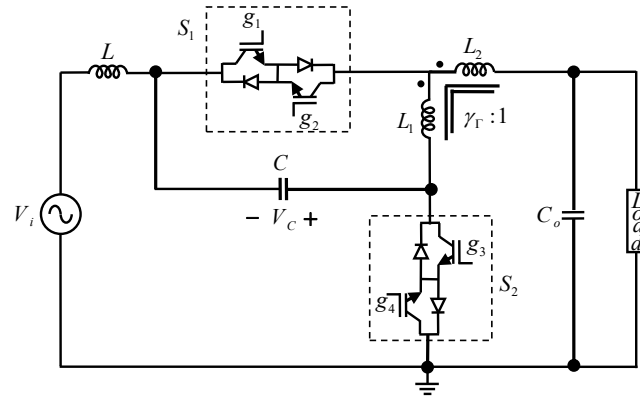


Fig. 16. Z-source ac-ac converter based on asymmetrical gamma structure with safe commutation [68].

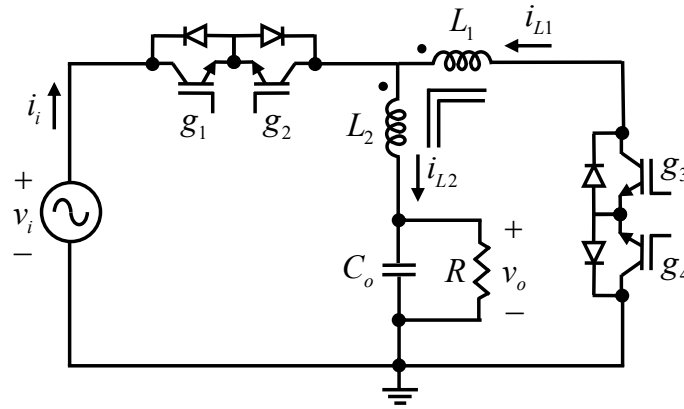


Fig. 17. Modified Z-source converter based on gamma structure [69].

$$V_{C,total} = \frac{D+n-1}{1 - \frac{2n-1}{n-1}D} V_i \quad (23)$$

$$V_{S,total} = \frac{\sqrt{2} \frac{2n-1}{n-1} D}{1 - \frac{2n-1}{n-1} D} V_i \quad (24)$$

2- 11- Modified Z-source Converter Based on Gamma Structure [69]

The modified Z-source converter based on gamma structure was presented in 2020 [69]. The existing topology in this

reference is depicted in Fig. 17. By comparing this structure with the existing topology in [64], it is observed that the existing topology in [69] is an improved type of the existing in [64] where regarding the use of filtering feature of the impedance network, the output filter is removed. Therefore, the output load is directly connected to the impedance network. Hence, the structure's functionality does not trouble to remove the output filter. Unlike the existing structure in [64], there is no phase shift between the output and input voltage waveforms. However, the switch put on the input side suffers from high voltage stress, and there is a need for the input filter due to the discontinuous input current. Additionally, if the transformer has a significant leakage inductor, there will be a need for the snubber circuit. By surveying this topology, it is obtained that this structure is similar to the existing topology in [64] from the view of the key factors.

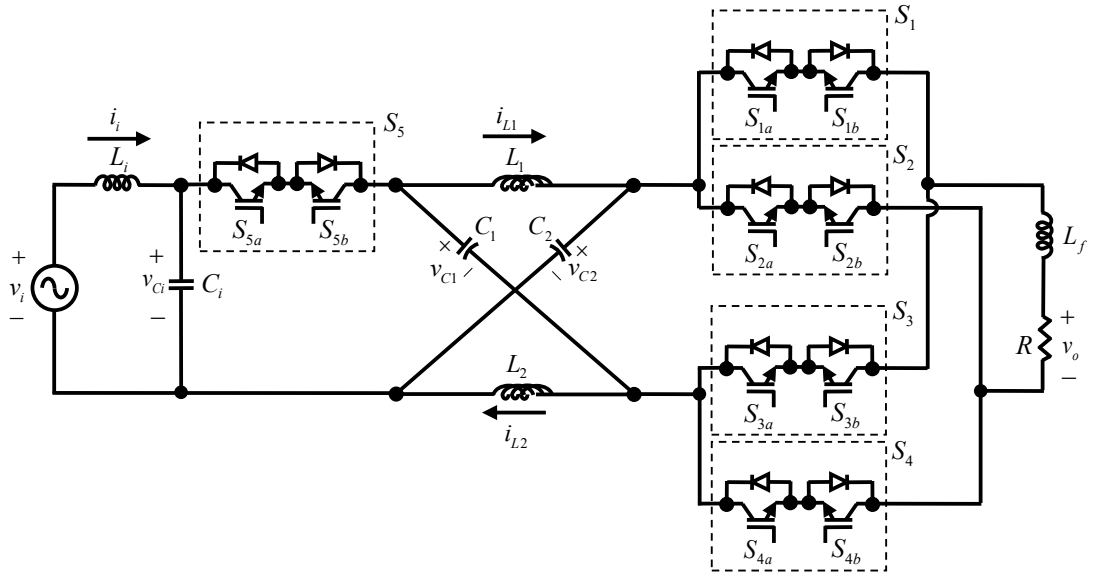


Fig. 18. Matrix Z-source ac-ac converter [70].

2- 12- Matrix Z-source ac-ac Converter [70]

The matrix Z-source ac-ac converter was presented in 2010 [70]. The presented topology is shown in Fig. 18. This topology is the first topology that has the frequency-change ability as well as the change of the output voltage gain. As seen in Fig. 18, the existing structure in [70] has the same impedance cell as the conventional Z-source ac-ac converter. As a result, it has the same limitations as the conventional Z-source ac-ac topology [29]. In addition, it has a complex control strategy regarding using a high number of switches. By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1-D}{1-2D} \quad (25)$$

$$V_{C_{total}} = \frac{D+n-1}{1-\frac{2n-1}{n-1}D} V_i \quad (26)$$

$$V_{S_{total}} = \frac{\sqrt{2} \frac{2n-1}{n-1} D}{1-\frac{2n-1}{n-1} D} V_i \quad (27)$$

2- 13- Z-source ac-ac converter with High Buck and Boost Voltage Conversion Capability [71]

The Z-source ac-ac converter with high buck and boost voltage conversion capability was presented in 2020 [71]. The power circuit of this structure is shown in Fig. 19. This figure shows that this structure is constructed from three main parts: the input voltage, impedance network, and the H-bridge cell. The primary duty of the impedance network is the output voltage change, and the H-bridge is used to change the frequency and make a 180 degrees' phase shift between the input and output voltages. Nevertheless, the impedance network of this topology rules as a buck-boost structure; however, using the H-bridge cell, the weakness of the output voltage generation in the in-phase and out-of-phase forms are solved. One of the other advantages of this topology toward the existing topology in [62] is that it gives a frequency changing functionality with a lower count of switches and a simple control method. By considering Fig. 19, it is observed that the existing structure in [71] has two similar cells. Hence, the upper cell is turned on in the positive half-cycle of the input voltage, same as the existing structure in [67]. Moreover, in the negative half-cycle of the output voltage, the lower cell generates the output voltage. As a result, only one of the cells is used in the half cycles of each input voltage.

Regarding the use of lateral diodes and the input capacitors, there are free-wheeling paths to conduct the currents of the inductors in the dead times that give the soft commutation ability. Therefore, there is no need to use snubber circuits. However, the input current of this structure is discontinuous, and there are bulky capacitors in the input current path that make the input current have a high ripple. As a result, this topology requires an input filter to alleviate the ripple of the

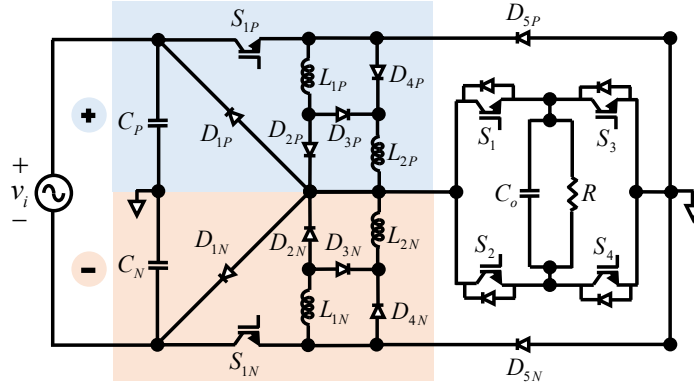


Fig. 19. Z-source ac-ac converter with high buck and boost voltage conversion capability [71].

input current. Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{2D}{1-D} \quad (28)$$

$$V_{C_{total}} = \frac{2(1+2D)}{1-D} V_i \quad (29)$$

$$V_{S_{total}} = \frac{\sqrt{2}(8D^2 + 3D + 3)}{D(1-D)} V_i \quad (30)$$

2- 14- Z-source ac-ac Converters with Magnetic Coupling and Safe-commutation [72]

The Z-source ac-ac converters with magnetic coupling and safe-commutation were presented in 2021 [72]. The power circuits of the existing structures are shown in Fig. 20. This figure shows that these topologies have a similar structure to the conventional topologies presented before. Common ground between the input and output sides, the continuous input current, boost in-phase and buck out-of-phase functionalities are from the features of the presented structures in [72]. Additionally, a free-wheeling path for the currents of the inductors is made by having the safe commutation strategy, which suppresses the high voltage stress on the switches.

Nevertheless, there are two coupled inductors in these structures, but the effect of the turn ratios only appears in the denominator of the output voltage gain. As a result, using two coupled inductors only limits the duty cycle, which increases the sensitivity of the output voltage gain to the duty cycle. In addition, Fig. 19 shows the output filters are used, so the filtering functionality of the impedance network is neglected. The other problem of this topology is the high voltage stress

on the switch on the input side. By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{1-D}{1-D \left(2 + \frac{1}{n_1-1} + \frac{1}{n_2-1} \right)} \quad (31)$$

$$V_{C_{total}} = \frac{1-D + \frac{(n_1+n_2-2)D+1}{(n_1-1)(n_2-1)}}{1-D \left(2 + \frac{1}{n_1-1} + \frac{1}{n_2-1} \right)} V_i \quad (32)$$

$$V_{S_{total}} = \frac{\sqrt{2} \frac{n_1+n_2-2}{(n_1-1)(n_2-1)}}{1-D \left(2 + \frac{1}{n_1-1} + \frac{1}{n_2-1} \right)} V_i \quad (33)$$

2- 15- A Family of High-frequency Isolated Single-phase Z-source Ac-ac Converters with Safe-commutation

A family of high-frequency isolated single-phase Z-source ac-ac converters with safe commutation techniques was presented in 2016 [73]. The existing structures in this reference are depicted in Fig. 21. As illustrated from this figure, all of these structures have a similar configuration, where there is a High-Frequency Transformer (HFT) and a cell in their output cell. As a result, it is only required to describe the input parts of HFTs. It is shown in Figs. 21a and 21b, the basic impedance network and the quasi impedance network are the input sides of these topologies. In both of these topologies, there are two freedom degrees to control the output voltage gain,

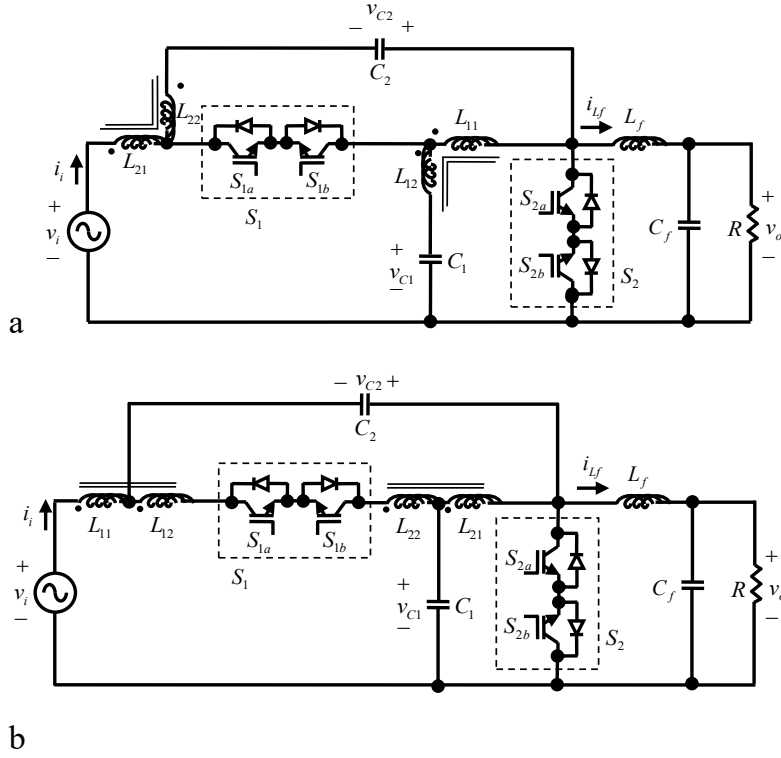


Fig. 20. Z-source ac-ac converters with magnetic coupling and safe-commutation [72], (a) based on the gamma configuration, (b) based on the T configuration

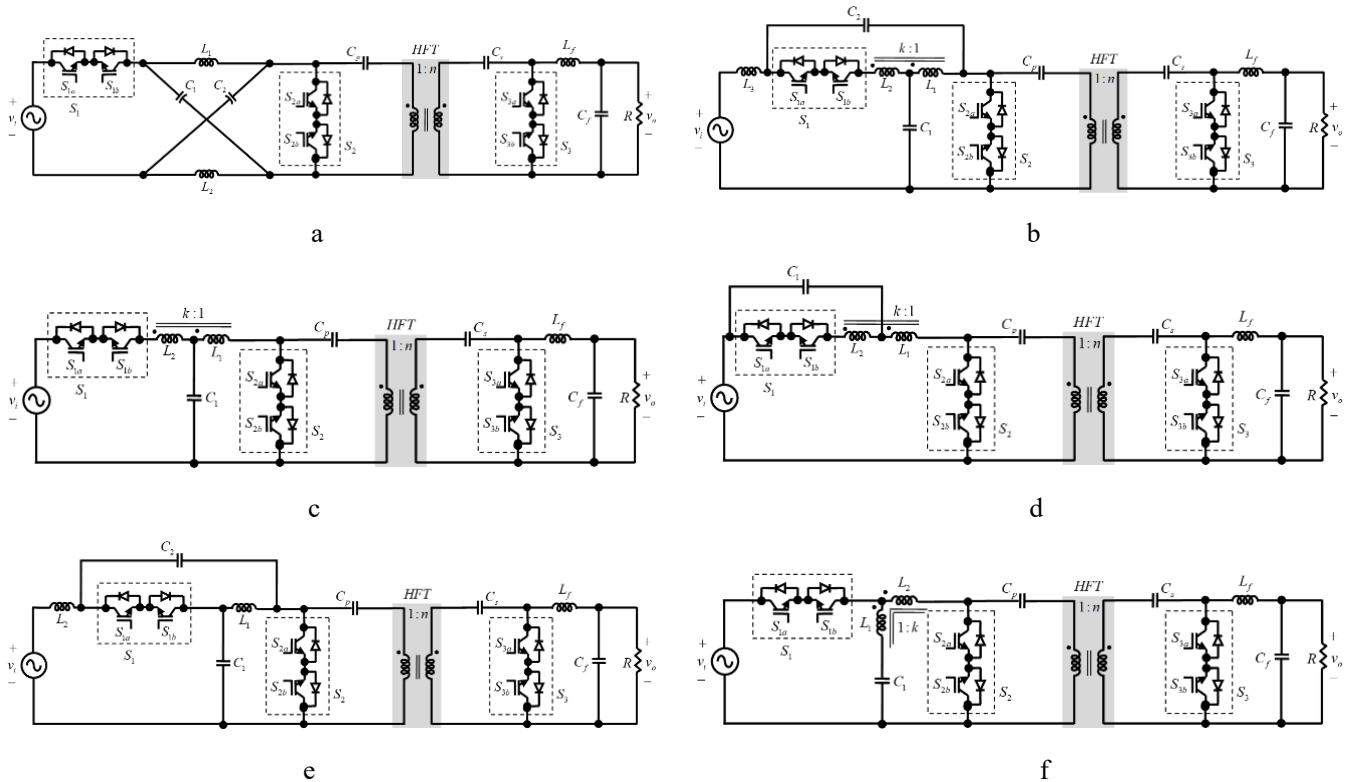


Fig. 21. A family of high-frequency isolated single-phase Z-source ac-ac converters with safe-commutation [73], (a) based on the basic impedance cell, (b) based on the quasi impedance cell, (c) based on the T configuration, (d) based on the quasi T configuration, (e) based on the improved quasi T configuration, (f) based on the gamma configuration.

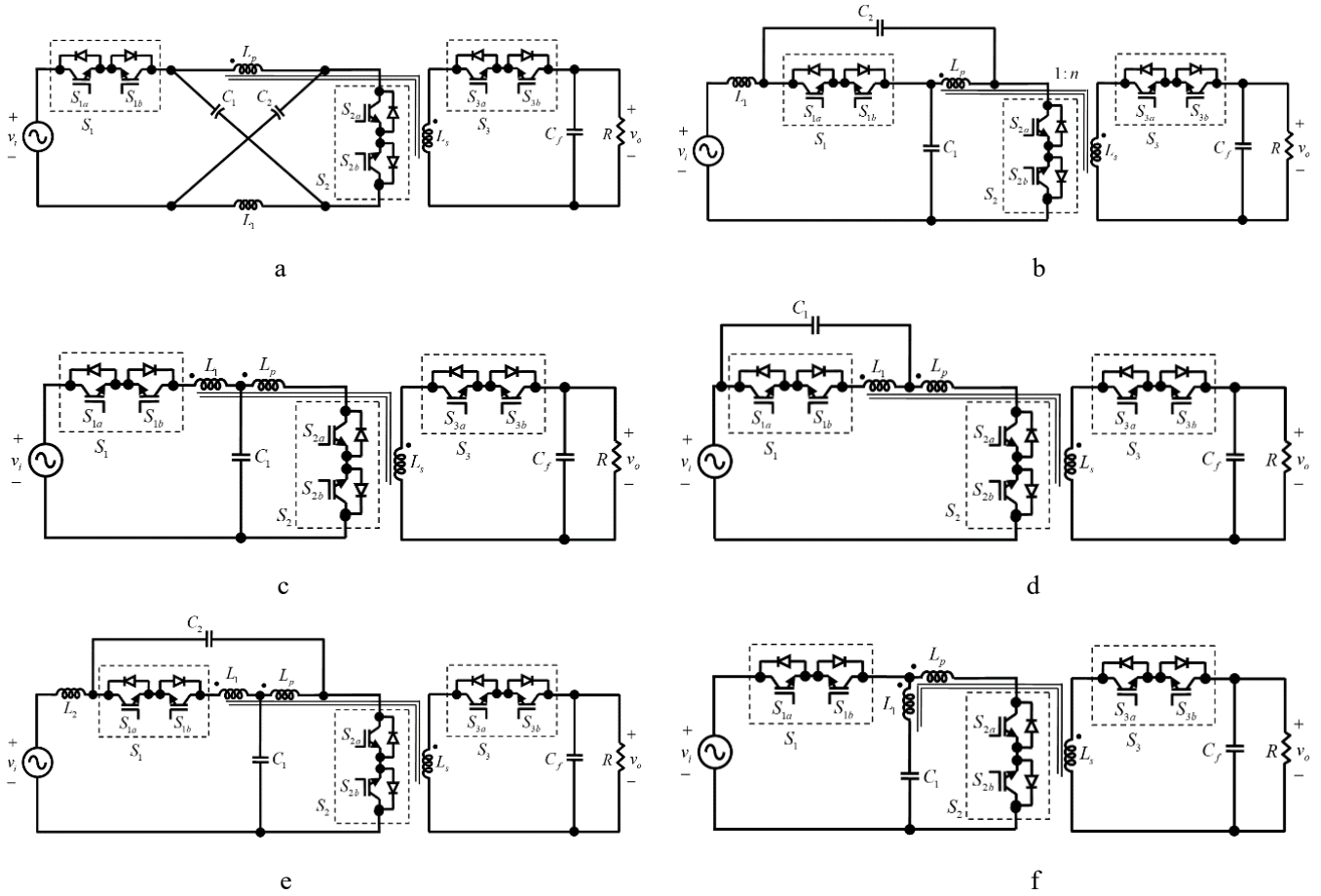


Fig. 22. A class of single-phase high-frequency isolated Z-source ac-ac converters with reduced passive components [74], (a) based on the basic impedance cell, (b) based on the quasi impedance cell, (c) based on the T configuration, (d) based on the quasi T configuration, (e) based on the improved quasi T configuration, (f) based on the gamma configuration.

the duty cycle, and the turn ratio of HFT. Moreover, regarding Figs. 21c to 21f, it is seen that these structures are based on the T configuration, quasi T configuration, improved T configuration, and gamma configuration, respectively. By having these structures, it is obtained that these structures have three freedom degrees to control the output voltage. Controlling the turn ratio of the coupled inductors is the other freedom degree that can control the output voltage gain as well as the duty cycle and turn ratio of HFT. The main advantage of these structures is using an HFT to isolate the input and output sides. Similar to the past non-isolated structures, this family of high-frequency isolated single-phase Z-source ac-ac converters have both features of the boost in-phase and buck out-of-phase. Additionally, it should be noted that the topologies, which are shown in Figs. 21b and 21e, only have a continuous input current. Moreover, the dead times are used as a safe commutation technique; however, there is a high voltage impulse on $S_{3(a-b)}$, which increases slightly in the high powers, and the snubber circuits must be used to limit this impulse voltage. Furthermore, the number of required passive components is increased due to the output filter and

the other components that are connected to HFT. Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = n \frac{1-D}{1-2D} \tag{34}$$

$$V_{C,total} = \frac{3+n-(n+2)D}{1-2D} V_i \tag{35}$$

$$V_{S,total} = \frac{\sqrt{2}(n+2)}{n(1-2D)} V_i \tag{36}$$

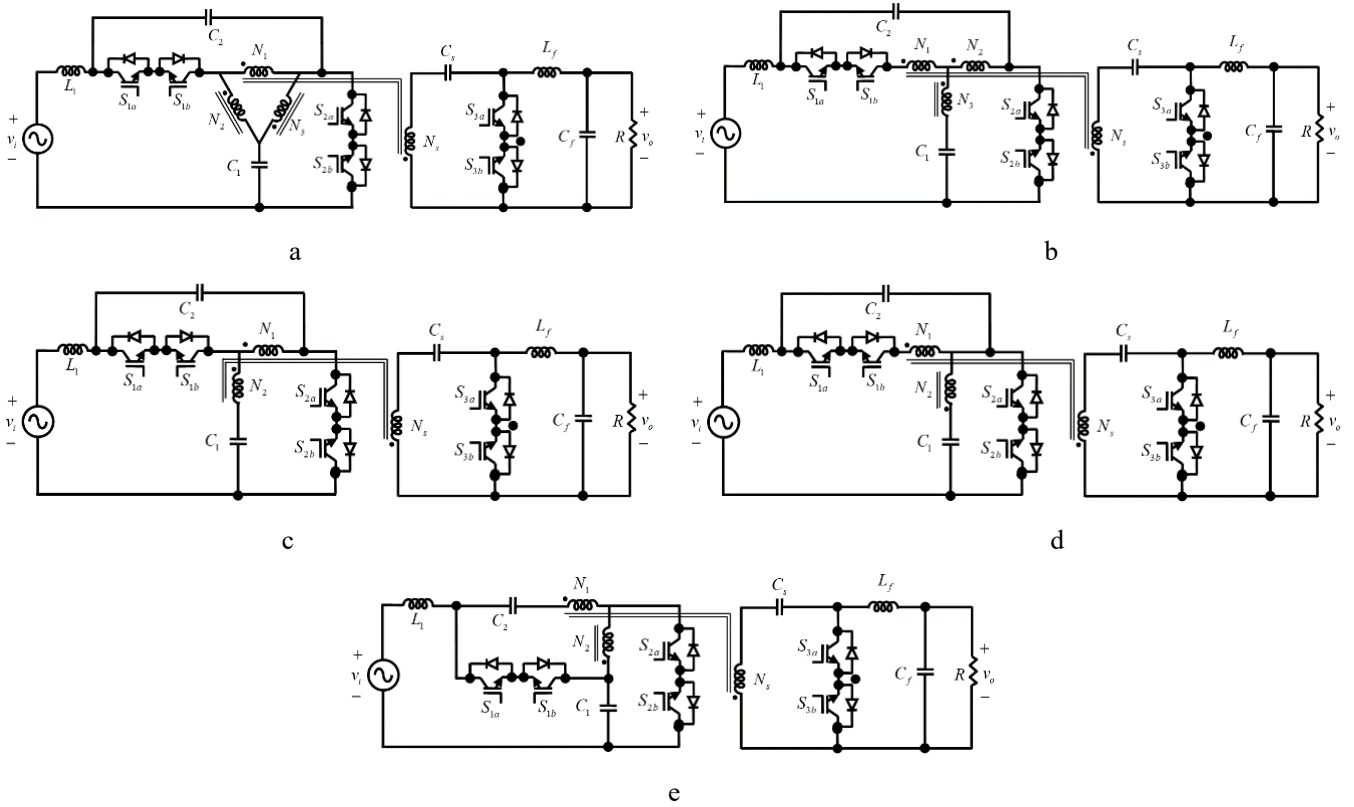


Fig. 23. A family of single-phase isolated high-frequency transformer integrated improved magnetically coupled Z-source ac-ac converters [75], (a) based on Δ -source, (b) based on Y-source, (c) based on Γ -source, (d) based on flipped Γ -source, (e) based on A-source.

2- 16- A Class of Single-phase High-frequency Isolated Z-source ac-ac Converters with Reduced Passive Components

A family of the single-phase high-frequency isolated Z-source ac-ac converters with reduced passive components was presented in 2018 [74]. The existing structures are shown in Fig. 22. By comparing Figs. 21 and 22, it is resulted that the existing structures in [74] are the modified forms of the presented topologies in [73]. In fact, one of the inductors of the impedance cells is used as the isolating transformer, and $S_{3(a-b)}$ is used as the inductor of the output filter. Thus, the number of required passive components is slightly reduced. The reduction of the passive components can lead to fewer magnetical cores that reduce the size and cost of these topologies. In Figs. 22a and 22b, the basic impedance network, and the quasi impedance network are the input sides of these topologies. In both of these topologies, there are two freedom degrees to control the output voltage gain, the duty cycle, and the turn ratio of the coupled inductor. Moreover, regarding Figs. 22c to 22f, it is seen that these structures are based on the T configuration, quasi T configuration, improved T configuration, and gamma configuration, respectively. By having these structures, it is obtained that these structures have three freedom degrees to control the output voltage. Controlling the turn ratio of the other coupled inductors is the other freedom degree that can control the output voltage gain.

By having this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked volt-

age by the switches can be listed as follows:

$$M = n \frac{1-D}{1-2D} \tag{37}$$

$$V_{C,total} = \frac{n+1-nD}{1-2D} V_i \tag{38}$$

$$V_{S,total} = \frac{\sqrt{2}(n+2)}{n(1-2D)} V_i \tag{39}$$

2- 17- A Family of Single-phase Isolated High-frequency Transformer Integrated Improved Magnetically Coupled Z-source ac-ac Converters

A family of single-phase isolated high-frequency transformer integrated improved magnetically coupled Z-source ac-ac converters was presented in 2020 [75]. The existing structures are depicted in Fig. 23. As it is shown in Figs. 23a to 23f, the improved Δ -source configuration, improved Y-source configuration, improved Γ -source configuration, improved flipped Γ -source configuration, and improved A-source configuration are used, respectively. Additionally,

all of these topologies have a continuous input current and do not require any input filters on the input side. Moreover, these topologies have two additional freedom degrees to control the output voltage source due to the integrated high-frequency transformer. It is important to note that designing a four-winding or three-winding transformer is more complicated than designing a two-winding transformer and requires higher accuracy.

Regarding this topology, the output voltage gains, the sum of voltage stress on the capacitors, and the total blocked voltage by the switches can be listed as follows:

$$M = \frac{N_{S3}(1-D)}{1-(1+N_{13})D} \quad (40)$$

$$V_{C,total} = \frac{(1+N_{S3})-D(1-2N_{S3})}{1-(1+N_{13})D} V_i \quad (41)$$

$$V_{S,total} = \frac{\sqrt{2}(2+N_{S3})}{1-(1+N_{13})D} V_i \quad (42)$$

3- Comparison of Single-phase Z-source ac-ac Converters

In Table 2, the existing single-phase Z-source ac-ac converters are compared to each other from different aspects, such as a common ground between the input and output sides, type of the input current, electrical isolation, frequency-changing ability, need for the LC filter on the input and output sides, the commutation type, and the number of required components. It is important to note that the body diodes of the switches are not considered in this table.

As the first single-phase Z-source ac-ac converter, the presented structure in [29] only can provide a boost or buck operation and requires a high number of devices. Moreover, the presented structures in [67], [70], [71], and [75] need higher components compared to others. In return, the topologies that were presented in [62], [65], [68], and [69] require a lower number of devices. From the commutation view, the presented topologies in [67] and [71] have the inherent commutation ability and do not require snubber circuits. The topologies that were presented in [62], [65], and [68], have omitted the LC filters in both input and output sides due to their continuous current and using the impedance network as a filter. In addition, the presented structures in [66] and [74] (Figs. 21b and 21e) can be considered as filterless converters since they use a bidirectional switch as the output filter inductor. Furthermore, from the frequency-changing ability view, the topologies presented in [70] and [71] can change the output voltage frequency.

In addition to Table 2, the output voltage gains, turn ratio limitation for transformers or coupled inductors, and the

maximum duty cycle are listed for the existing single-phase Z-source ac-ac converters. Additionally, a numerical comparison from the total voltage stresses on the capacitors, diodes, and switches is given to have a better comparison. Moreover, all these amounts are obtained in the same conditions of converting the input voltage of $110V_{rms}$ to the output voltage of $220V_{rms}$. In other words, the output voltage gain (M) is supposed equal to 2 for all of these structures.

It is illustrated from this Table that the presented structures in [29], [60], [61], [62], and [70] have the same output voltage gains. Moreover, the total voltage stresses on the switches are the same in all of these topologies except for the existing one in [70]. From the turn ratio limitation view of the windings, the existing topologies in [64], [68], [69], and [72] can be chosen as $1 < n \leq 2$ due to the use of gamma configuration. As Table 3 demonstrates, the existing structures in [67], [70], [71], and [72] have the highest total blocking voltage on the switches. In return, the presented structures in [62], [65], [68], and [69] have the lowest voltages on their capacitors.

It should be noted that all non-isolated topologies, except the ones presented in [66] and [72], have the total blocking voltage on their switches despite their different configurations. In addition, in the presented topology in [66] which has an additional switch, the total blocking voltage on the switches is slightly increased.

Regarding Tables 2 and 3, it can be obtained that the expressed problems as follows are due to the general topology, which was shown in Fig. 2:

- The voltage stress on the switch placed on the input side (Box 2 or 3 in Fig. 2) is high.
- A buck in-phase operation cannot be obtained, which results in practical limitations in some applications like DVR.
- All the improvements that aim to improve boosting gain lead to more limitation of the allowable duty cycles. In addition, a limitation on the duty cycle can increase the sensitivity of boosting gain to the duty cycle changes.

Thus, some basic changes must be performed on the general topology to obtain further improvements. For instance, the output load can be connected to the switch placed on the input side. As a result, the high voltage stress on the input switch can increase the output voltage and a more significant boosting gain. However, the common ground feature is missed. In the following, some points are given to develop the single-phase Z-source ac-ac converters and propose a new structure:

- The first point is proposing isolated topologies that do not have commutation problems. The topologies that use a safe commutation strategy can solve these problems. Nevertheless, the safe commutation strategy leads to a complex control strategy. On the other hand, the topologies presented in [67] and [71] present some attempts to solve the commutation problems. Moreover, these topologies have a simple control strategy. Hence, it seems that we can obtain some isolated topologies that do not have commutation problems by integrating these two topologies.

Table 2. The comparison of the features and the number of components in the existing single-phase Z-source ac-ac converters

Ref.	Features					Components Count						
	Shared Ground	Continuous Input Current	Isolated	Variable Frequency	Need Input/output LC filter	Commutation	S	D*	C	L	C.L. core	Total C.C.
[29]	×	×	×	×	I/O	Snubber	2	8	4	4	-	20
[60]	✓	×	×	×	I/O	Safe	4	-	4	4	-	12
[61]	✓	✓	×	×	Output	Safe	4	-	3	3	-	10
[62]	✓	✓	×	×	-	Safe	4	-	2	2	-	8
[63]	✓	✓	×	×	Output	Safe	4	-	3	2	1	10
[64]	✓	×	×	×	I/O	Safe	4	-	3	2	1	10
[65]	✓	✓	×	×	-	Safe	4	-	2	1	1	8
[66]	✓	✓	×	×	-	Safe	6	-	3	1	1	11
[67]	×	×	×	×	Input	Inherent	4	10	4	-	1	19
[67]	×	×	×	×	Input	Inherent	4	8	6	-	1	19
[68]	✓	✓	×	×	-	Safe	4	-	2	1	1	8
[69]	✓	×	×	×	Input	Safe	4	-	2	1	1	8
[70]	×	×	×	✓	Input	Safe	10	-	3	4	-	17
[71]	×	×	×	✓	Input	Inherent	6	10	3	4	-	23
[72]	✓	✓	×	×	Output	Safe	4	-	3	1	2	10
[72]	✓	✓	×	×	Output	Safe	4	-	3	1	2	10
[73]	×	×	✓	×	I/O	Safe	6	-	6	4	1	17
[73]	×	✓	✓	×	Output	Safe	6	-	5	3	1	15
[73]	×	×	✓	×	I/O	Safe	6	-	5	1	2	14
[73]	×	×	✓	×	I/O	Safe	6	-	4	1	2	13
[73]	×	✓	✓	×	Output	Safe	6	-	5	2	2	15
[73]	×	×	✓	×	I/O	Safe	6	-	5	2	2	15
[74]	×	×	✓	×	Input	Safe	6	-	4	2	1	13
[74]	×	✓	✓	×	-	Safe	6	-	3	1	1	11
[74]	×	×	✓	×	Input	Safe	6	-	3	1	1	11
[74]	×	×	✓	×	Input	Safe	6	-	2	-	1	9
[74]	×	✓	✓	×	-	Safe	6	-	3	1	1	11
[74]	×	×	✓	×	Input	Safe	6	-	3	1	1	11
[75]	×	✓	✓	×	Output	Safe	6	-	4	2	1	13
[75]	×	✓	✓	×	Output	Safe	6	-	4	2	1	13
[75]	×	✓	✓	×	Output	Safe	6	-	4	2	1	13
[75]	×	✓	✓	×	Output	Safe	6	-	4	2	1	13
[75]	×	✓	✓	×	Output	Safe	6	-	4	2	1	13

* The body diodes are not considered.

Table 3. Numerical analysis of the existing single-phase Z-source ac-ac converters

Ref.	M	n	D _{max}	V _i = 110√2 [V], V _o = 220√2 [V]			
				D	V _{C,total} [V]	V _{S,total} [V]	V _{D,total} [V]
[29]	$\frac{1-D}{1-2D}$	-	$\frac{1}{2}$	$\frac{1}{3}$	660	660√2	-
[60]	$\frac{1-D}{1-2D}$	-	$\frac{1}{2}$	$\frac{1}{3}$	660	660√2	-
[61]	$\frac{1-D}{1-2D}$	-	$\frac{1}{2}$	$\frac{1}{3}$	550	660√2	-
[62]	$\frac{1-D}{1-2D}$	-	$\frac{1}{2}$	$\frac{1}{3}$	330	660√2	-
[63]	$\frac{1-D}{1-(n+2)D}$	n ≥ 1	$\frac{1}{n+2}$	$\frac{1}{5}$	550	825√2	-
[64]	$\frac{1-D}{1-\left(\frac{n}{n-1}\right)D}$	1 < n ≤ 2	$\frac{n-1}{n}$	$\frac{1}{5}$	440	825√2	-
[65]	$\frac{1-D}{1-(n+2)D}$	n ≥ 1	$\frac{1}{n+2}$	$\frac{1}{5}$	330	825√2	-
[66]	$\frac{1}{1-(n+2)D}$	n ≥ 1	$\frac{1}{n+2}$	$\frac{1}{6}$	477	880√2	-
[67]	$\frac{2D}{1-D}$	-	1	$\frac{1}{2}$	568	1760√2	1760
[68]	$\frac{1-D}{1-\left(1+\frac{n}{n-1}\right)D}$	1 < n ≤ 2	$\frac{n-1}{2n-1}$	$\frac{1}{5}$	330	825√2	-
[69]	$\frac{1-D}{1-\left(\frac{n}{n-1}\right)D}$	1 < n ≤ 2	$\frac{n-1}{n}$	$\frac{1}{5}$	220	825√2	-
[70]	$\frac{1-D}{1-2D}$	-	$\frac{1}{2}$	$\frac{1}{3}$	440	1650√2	-
[71]	$\frac{2D}{1-D}$	-	1	$\frac{1}{2}$	880	1540√2	1980
[72]	$\frac{1-D}{1-D\left(2+\frac{1}{n_1-1}+\frac{1}{n_2-1}\right)}$	1 < n ₁ ≤ 2 1 < n ₂ ≤ 2	$\frac{1}{2+\frac{1}{n_1-1}+\frac{1}{n_2-1}}$	$\frac{1}{11}$	550	1452√2	-
[73]	$\frac{n(1-D)}{1-2D}$	n ≥ 1	$\frac{1}{2}$	$\frac{1}{3}$	880	990√2	-
[74]	$\frac{n(1-D)}{1-2D}$	n ≥ 1	$\frac{1}{2}$	$\frac{1}{3}$	660	990√2	-
[75]	$\frac{N_{s3}(1-D)}{1-(1+N_{i3})D}$	N _{s3} ≥ 1 N _{i3} ≥ 1	$\frac{1}{1+N_{i3}}$	$\frac{1}{5}$	550	1100√2	-

▪ The other suggestion is trying to obtain a high voltage gain without limiting the duty cycle. Trying to reduce the active and passive devices count in the topologies with the frequency-changing ability. For example, the single-phase Z-source ac-ac converters with the frequency-changing ability with reduced components count can be obtained by integrating and adapting the structures presented in [70] and [71], since this topology has an impedance cell, as shown in Fig. 18; however, it includes unidirectional switches. On the other hand, the presented structure in [71], shown in Fig. 19, has two impedance networks, but the number of switches is reduced and this topology only includes six switches.

4- 5. Conclusion

Several single-phase Z-source ac-ac converters were analyzed, and are categorized into four groups according to their unique features. First, a general structure is obtained, which many of the existing single-phase Z-source ac-ac converters can be obtained from it. Following, the existing single-phase Z-source ac-ac converters were analyzed, and their key equations, including the total blocked voltage on switches, capacitors, and diodes, were mentioned. Subsequently, the commutation problem of the basic single-phase Z-source ac-ac converter was described, and the solutions to avoid this problem were introduced in detail. Finally, the existing basic single-phase Z-source ac-ac converters were compared by two tables. One of the tables shows the comparison between the features and the devices count views, and the other shows the comparison from the numerical perspective. These comparisons show that the basic structure requires a high number of components as the first single-phase Z-source ac-ac converter.

Additionally, the snubber circuits are used to face the commutation problem in this structure. Although the snubber circuits alleviate the high voltage impulse on the switches, they lead to higher power losses, reduced efficiency, and low reliability. In addition, input and output filters are the other demerits of the basic structure. After the basic topology, a structure is presented in [60] to solve the commutation problem by applying the safe commutation strategy. Although this structure is the same as the output voltage gain and the total voltage gain on switches as the basic structure, alleviating the problem of voltage impulse on the switches and reducing the active devices count are the merits of this topology. Afterwards, several topologies are presented to omit the input filter by using an inductor in the input current path [61], omit the output filter by using the impedance cell as the output filter [62], and having the inherent commutation feature [67]. Studying these structures shows that the output filter omitting is a good feature due to the total blocked voltage on the capacitors. For instance, the existing topology in [61] is the modified form of the presented structure [60] due to the omitting input filter, and the total blocked voltage on the capacitors is reduced. Nevertheless, a high number of devices is required to have the inherent commutation, which increases the blocked voltage amount on the capacitors, switches, and diodes, consequently. For instance, the total blocked voltage

on the devices is much higher in the topologies presented in [67] and [71].

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HOW TO CITE THIS ARTICLE

E. Babaei, S.M.J. Mousavi, M.A. Alami, D. Alizadeh, A Review on Single-Phase AC-AC Z-Source Converters. *AUT J. Elec. Eng.*, 54(1) (2022) 137-162.

DOI: [10.22060/ej.2022.20936.5446](https://doi.org/10.22060/ej.2022.20936.5446)



