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Review

Single-Stage Buck–Boost Inverters: A State-of-the-Art Survey

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Abstract: Single-stage buck–boost inverters have attracted the attention of many researchers, due to their ability to increase/decrease the output voltage in one power conversion stage. One of the most important uses of these inverters is in photovoltaic applications, where the voltage of the solar panels varies in a wide range. In recent years, many new inverters have been proposed to improve the performance of existing structures. In this paper, the state of the art of these single-stage buck–boost inverters is discussed. The advantages and disadvantages of each structure are examined from different perspectives, such as the number of components, losses, and performance. Finally, in a general comparison, the properties of all structures are discussed and summarized in a table.

Keywords: single-stage inverter; buck–boost operation; survey

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1. Introduction

In electrical engineering, power electronics converters are of particular importance in the power conversion process. Today, power electronic converters are used in many devices and are increasingly replacing previous systems with their promising features. Paying attention to these converters, in terms of reliability, volume, and weight, is the subject of many studies. Considering the importance of renewable energy, many researchers have focused on converters of renewable systems, especially solar systems. Since solar panels have a low voltage, and this voltage varies under the influence of shading and temperature changes, in the existing common structures, a dc–dc boost converter is used in the first stage, and then a voltage source inverter (VSI) is used in the second stage. Two power conversion steps, and separate control of each of these converters, reduce the overall efficiency and increase the complexity of the system. It should also be noted that the use of transformers is not acceptable, due to the high volume and weight [1]. In the last decade, research has shifted to single-stage buck–boost inverters. The main application of these structures is mainly in PV systems and electric vehicles (EVs). Due to environmental concerns and reduced consumption of fossil fuels, addressing this area and providing a structure with high capabilities is of great importance. In this regard, different structures are presented. Meanwhile, the current source inverter (CSI) has not received much attention, due to its large inductor, and only the boosting ability [2] and Z-source inverter (ZSI), due to limited gain, shoot through (ST) problems and reliability [3]. Other structures have been developed over the years, and they have been analyzed in the following literature. In reference [4], several of these structures have been compared, based on the operating mode. Of course, this reference does not deal with the new structures. In reference [5], the author examines a limited, and relatively old, number of structures, along with some control methods of these inverters. Reference [6] examines the history of buck–boost single-stage inverters over the past 25 years. In this study, the author addresses the challenges of these inverters, as well as their lack of acceptance in the industry, and compares these converters from different perspectives. The main focus of this study is mainly on Z-source family inverters and several differential converters, while other structures have not been studied.

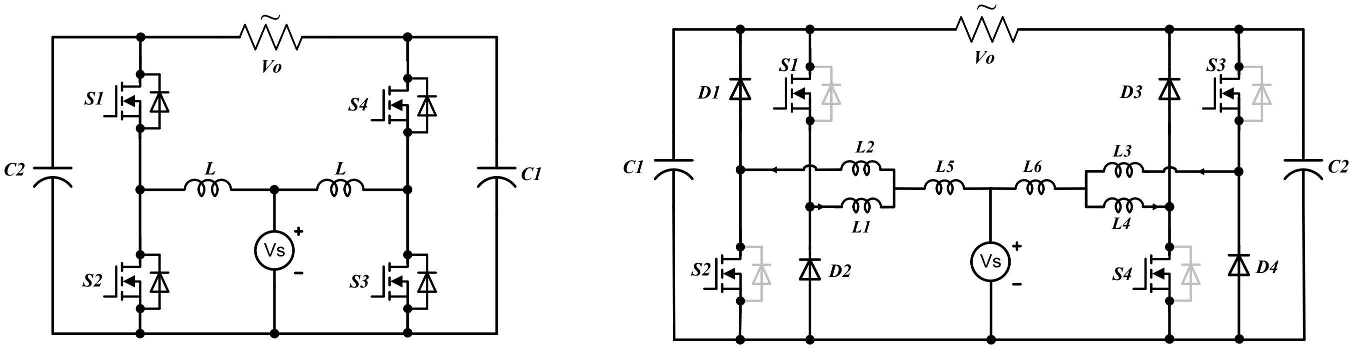
Investigating the latest research, in this paper, the state of the art of single-stage buck–boost inverters has been studied. In general categorization, these inverters are divided into five different types. For each category of these inverters, several general circuits of them are illustrated, and each inverter has been examined from different perspectives, such as the number of components, losses, etc. For a general evaluation, the characteristics of different inverters are given in a table. This review and categorization will shed a light on the path of those researchers who want to do research in this area.

2. Review of Single-Stage Inverters

Single-stage buck–boost inverters are inverters capable of increasing/decreasing the output voltage in single power conversion. More attention of researchers to this type of inverters, in the last decade, various structures of these inverters have been presented. Although all of these structures have common features, they can be categorized. In this study, these inverters are divided into five categories including differential connection, split source, impedance source family, dc–dc converter combination, and multi-level based. For each category of these inverters, several structures are introduced, and their general characteristics are discussed.

2.1. Differential Connection

Differential connection of dc–dc converters is one of the earliest methods for single-stage inverters. It could be argued that researchers' attention on single-stage inverters began with the well-known structure proposed by Caceres in 1999 [7]. This single-stage boost inverter is shown in Figure 1a. In this inverter, which is obtained from the differential connection of two boost converters, bipolar output is directly achieved by controlling the duty cycle of boost converters. This structure uses four switches, two inductors, and two capacitors. All switches operate at high switching frequencies. The high voltage, across semiconductors in the buck mode, and hard switching are among the disadvantages of this inverter. Many researchers have worked to address these disadvantages. In references [8,9], to increase the gain of this inverter, coupled inductors are used, instead of the existing inductors, which increases the gain of the converter, in proportion to the turn ratio. However, this structure also has disadvantages, such as hard and simultaneous switching of all components, resulting in more switching losses. To reduce the stress across the switches, the authors of reference [10] modified the structure of Figure 1a by adding two switches, in the path of the inductors, and relocating the capacitors. However, adding switches can cause losses and additional costs. In other attempts, i.e., in reference [11], separate diodes and adding additional inductors are used to solve the reverse recovery problems of MOSFET diodes at high frequency.



(a) (b)

Figure 1. Differential connection types of single-stage inverters. (**a**) Proposed single-stage inverter in [7]; (**b**) proposed single-stage dual-based inverter in [12].

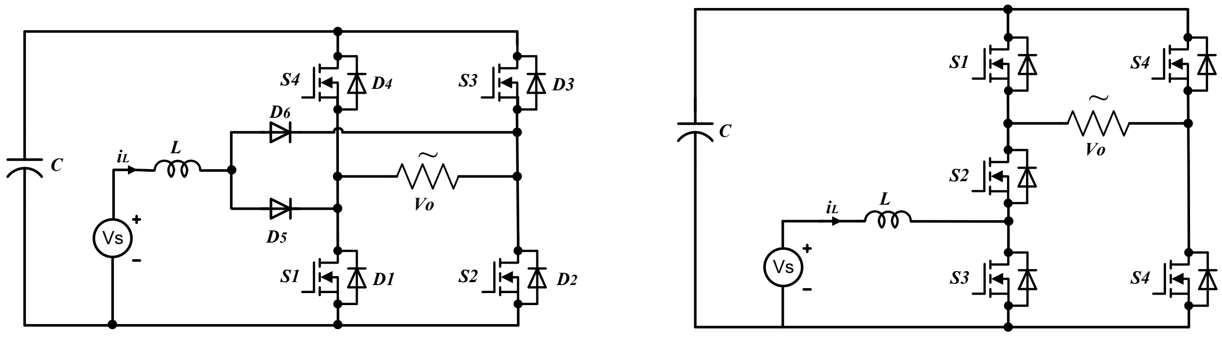
Considering the structure of Figure 1a, for a more comprehensive structure in [12], the authors present a symmetric dual-based structure with the same number of switches. As shown in Figure 1b, this structure consists of four switches, six inductors, four separated diodes, two capacitors, and a source. The absence of shoot-through (ST) problems in this structure will be associated with increased reliability. In this structure, using MOSFETs and separate diodes, the worry of reverse-recovery issues of MOSFET body diodes is eliminated. Therefore, high-frequency switching can be achieved by silicon semiconductors, which ultimately leads to a reduction in the volume of passive components and increase in efficiency. Additionally, according to the author of the same reference, current stresses have been eliminated for half of the switches. In addition to these advantages, this structure has drawbacks, such as many inductors and complex inductor current control on each side of the converter. In reference [13], the same author suggests the use of coupled inductors for the same structure in Figure 1b, in order to reduce the size of inductors. It should also be noted that differential-mode inverters suffer from current circulating problems and usually require large output capacitors. In the same reference, the author has proposed the use of clamping switches, connected back-to-back and parallel to the output capacitor, to solve the problem of circulating current in the output.

Some other similar differential structures are found in references [14–17]. Although, in most differential structures, the boost converter has been used with some slight changes; in some studies, such as reference [18], the differential inverter was obtained by cascading a boost converters and a buck–boost converter. In this converter, the output voltage is obtained from the voltage differential of the two converters. Although, in this structure, the number of switches is minimal. However, there are still common differential converter problems.

2.2. Split-Source Inverters (SSI)

Split-source inverters (SSI) have proved to be an attractive single-stage inverter, due to their compact structure with the continuous input current. Many researchers have considered these inverters and discussed them [19,20]. As can be seen in Figure 2a, this structure is based on a full-bridge inverter and two boost converters with variable duty cycles. In the positive half cycle, *S1* and *S3* conduct simultaneously for the inverter operation, and *S1* and *D4* complement the boost operation. In the negative half cycle, *S2* and *S4* are used simultaneously for inverter operation, and *S2* and *D3* are used complementary to boost operation. Diodes *D5* and *D6* are used to prevent short circuits. In [21], by changing the location of the source and direction of the input diodes, an alternative configuration for this type of inverter is provided. Other similar topologies, with changes in overall structure, have been examined in references [22–24]. Similar to the above topology, in these inverters, all switches operate at high frequency; in the case of using MOSFET, the reverse-recovery issues of the MOSFET body diode are inevitable.

In case the input voltage of the inverter is variable (PV applications), due to the coupling of the boost and inverter stages, SSI suffers from the low dc-link voltage utilization problem. In such cases, there will be additional dc-link voltage, increasing the system cost and switching losses. For more utilization of the dc source, as well as more control of charge and discharge of inductor, in reference [25], with modification of SSI structure, an active split-source inverter (ASSI) is introduced. In this structure, two diodes (*D5* and *D6* (Figure 2a)) are replaced with reverse blocking switches, and six operating modes are extracted for this inverter. By creating more working modes and removing the limitation of the ac modulation index, better control over the inverter and charge/discharge of the inductor has been achieved. In this study, the author has introduced different structures for this inverter by considering two switches, instead of diodes, one switch and one diode, or placing the switch on the negative side of the dc source. Although the inverter will be better controlled by using the added switches in this structure, the number of switches and the operation of all these switches at high frequency are the disadvantages of this structure. Reverse-blocking switches are also made by a MOSFET or IGBT, in series with a diode, which ultimately increases the total number of components. The current flow through the switch body diodes in these structures can limit the use of MOSFETs because, at high frequencies, reverse-recovery problems of the MOSFET body diodes occur. Additionally, due to the limitation in increasing the duty cycle of the boost converter, the capability of this structure in voltage increase is limited.

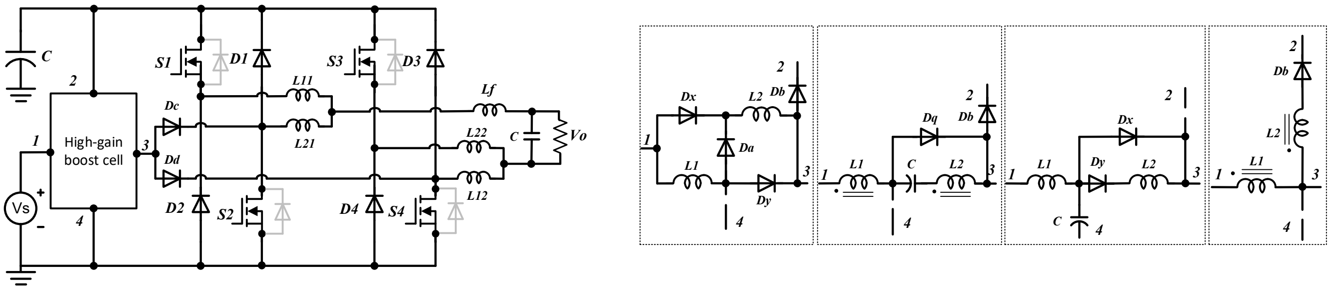


(a) (b)

Figure 2. Split source inverters: (**a**) proposed single-stage inverter based on SSI in [19]; (**b**) proposed single-stage inverter in [26].

In reference [26], the authors present a new single-stage buck–boost inverter, based on SSI. This structure consists of five switches, an inductor, a capacitor, and a source. Figure 2b shows this structure. In this structure, a switch is added to an inverter leg of the full-bridge inverter, which performs the boost operation of the converter. Since the duty cycle of the boost converter is not variable in this structure, it is easier to control the inverter. This structure is also capable of bidirectional operation. As with other SSI structures, all switches are switched at high frequencies, leading to the reverse-recovery issues of MOSFET body diode and losses. Therefore, IGBTs should normally be used, which means that the advantages of MOSFET high frequency switching, such as fast switching and lower losses, and the voltage drop across the conduction resistor cannot be used. Moreover, to avoid short circuits in this structure, dead time between switches should be considered.

In [27], a new family of single-stage buck–boost inverters has been introduced. These inverters, which are a combination of the SSI, dual-buck inverter (DBI), and high gain dc–dc converter, consist of four switches, six diodes, one capacitor, five inductors, and a boost unit, including several inductors and diodes (without active components). Figure 3a shows the general scheme of the inverter, and Figure 3b shows possible boost units. By placing each of these units in the overall structure of the inverter, a novel type of inverters has been presented. Similar to the DBI, it has high reliability because it does not have ST problems or require dead time in switch pulses. On the other hand, this inverter can work at high frequency, with no worries about the reverse-recovery of the MOSFET body diode, which is associated with increased efficiency. Voltage increase is also achieved through boost units that operate, without active switches, and can reach high gains. One of the drawbacks of this inverter is a large number of components, especially the inductors, and the current control of these inductors is the other problem.



(a) (b)

Figure 3. Combination of SSI, dual-buck inverter [27]: (**a**) proposed structure; (**b**) boost units.

The utilization of boost units, to increase the gain of single-stage inverters, to overcome the boosting limit of SSI inverters, has been considered in some other studies. In [28], a three-phase SSI, along with boost units, has been presented. The boost unit in this study consists of switches and inductors. The basis of this unit is based on parallel charging of inductors and discharging them in series. By increasing the internal floors of this unit, the inverter gain can be increased, according to a special equation. Although switching these units is relatively simple, increasing the number of switches and variable duty cycles are among the disadvantages of this structure.

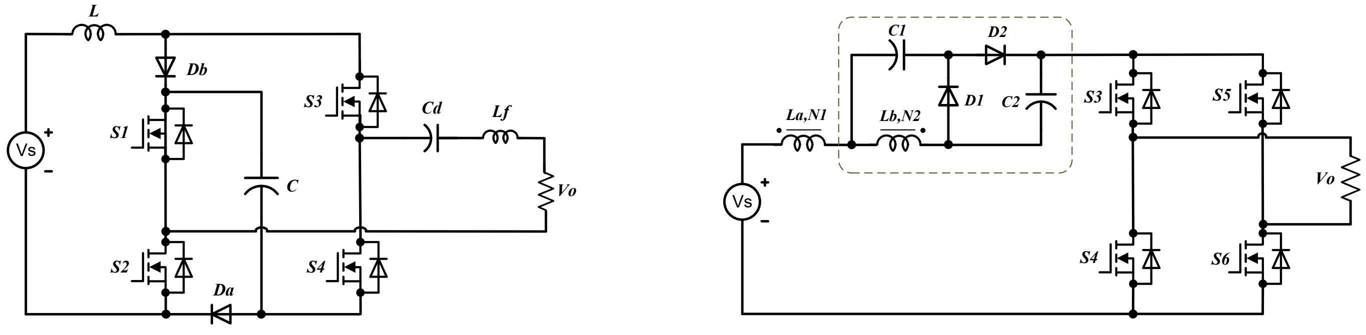
2.3. Z-Source Family

Reviewing single-stage buck–boost inverters would not be completed without considering the family of ZSIs. The impedance network, which includes the inductors and capacitors, is located on the DC side of the inverter and used to create boost operations via the shoot-through operation. Over the years, a lot of research has been done on these inverters, and various topologies have been presented. In reference [29], the author reviews the latest topology improvements in ZSIs. In reference [30], the author has comprehensively compared different types of impedance networks in Z-source family inverters. Considering all advantages of ZSI, this single-stage inverter has not received much attention in the industry, due to some disadvantages. Disadvantages include discontinuous or pulsed input currents, the need for large passive elements, high current/voltage stress across switches, and limitations in the inverter gain. To eliminate these disadvantages and improve the performance of this type of inverter, lots of research has been conducted in recent years. For example, the proposed quasi-Z-source inverter (qZSI) has a continuous input current, compared to ZSI and has less voltage stress, across the switches [31].

Based on qZSI, reference [32] provides a single-stage switch-boost structure with buck–boost capability, which requires fewer passive elements than qZSI. Figure 4a shows this inverter. Four switches, an inductor, a capacitor, and two diodes are components of this structure. According to its author, this inverter has a continuous input current and immunity in ST operation. However, this structure also suffers from low gain. In reference [33], the author compares the performance of qZSI and a type of switch-boost inverter, under the same working conditions. Finally, the author mentions the superiority of switch-boost inverter in having fewer passive elements, lower current ratings for semiconductors, and higher gain and efficiencies. Some other solutions to the ZSI and qZSI gain problems have also been proposed in the recent literature. The use of more passive elements on the dc side, in order to increase the gain and the presentation of enhanced boost-ZSI (EB-ZSI) [34] and enhanced boost-qZSI (EB-qZSI) [35], have been among these studies.

To reduce the voltage across the switches and less harmonic distortion of the output, the utilization of impedance networks, along with multi-level inverters, has also been considered in some studies. In each study, the location of the impedance network and number of this network are different. Authors in reference [36] combine a three-level neutral point clamp structure and quasi-Z-source impedance network to provide a single-stage inverter that has both a continuous input current and reduced voltage across the switches. The combination of impedance network structures and multi-level inverters has also been studied in references [37–40]. In these structures, the high number of switches and impedance network considerations remains challenging.

In [41–43], the authors introduced new qZSI-based inverters using boost units with coupled inductors. Figure 4b shows one of these inverters. These structures are characterized by their high gain, which makes it possible to use them for PV purposes. In [44], a high-gain qZSI-based inverter is provided using boost units that include an active switch. References [45,46] also introduce and evaluate several single-stage buck–boost inverters, based on qZSI. Among the disadvantages of these structures is the need for a large number of passive elements that increase the volume and weight of the inverter. ST reliability is also another concern for these structures.

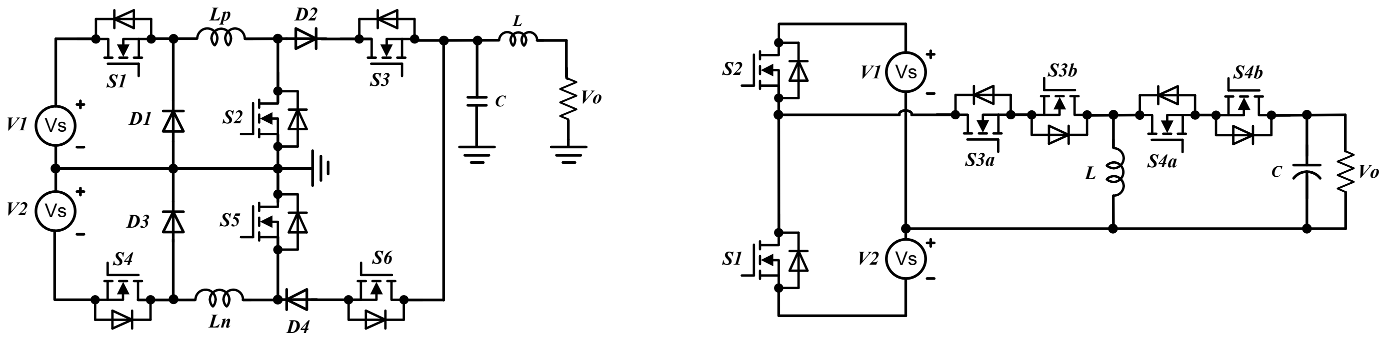


(a) (b)

Figure 4. Single-stage inverters based on Z-soucer family inverters. (**a**) Single-stage switched-boost inverter in [32]; (**b**) proposed single-stage qZSI-based inverter with boost unit [41].

2.4. Combination of Different Types of Dc–Dc Converters

Many other single-stage buck–boost inverters are based on a combination of different types of dc–dc converters, and each has its unique characteristics. Usually in these structures, in each half-cycle, one of the dc–dc converters is responsible for supplying the output. The difference is that the output of one should be negative, compared to the other. In [47], a single-phase, single-stage inverter is obtained by combining two buck–boost converters, known as the Aalborg inverter. Figure 5a shows this inverter. As can be seen, this inverter consists of six switches, two inductors, four diodes and two voltage sources. In the positive half cycle, the upper buck–boost converter is operating; in the negative half cycle, the lower buck–boost converter is operating. Since the positive side of one source and negative side of the other source are connected to the neutral of ac side, in this inverter, common-mode leakage current (CMLC) is eliminated. According to the author, one of the salient features of this structure is the minimum voltage drop of the filtering inductor in the power loop, which leads to a reduction of conduction power losses in the buck and boost mode. Since, in this structure, each inductor is used in a half cycle, their magnetic utilization rate is 50%. Additionally, the presence of two inductors requires a separate sensor for measuring and controlling the current of each of these inductors. However, according to the author, in some applications, where common mode electromagnetic interference is not an important issue, instead of using two inductors, an inductor in the middle branch between *S2*, *S5*, and *D1*, *D4* can be used, and magnetic utilization will be completed. Another disadvantage of this structure is that it is unidirectional and cannot provide reactive power. The existence of two sources is the other disadvantage of this structure. Of course, in [48], the Aalborg inverter is provided with one source. In this work, two capacitors are added to the input side, and then a control method for voltage balancing is presented.

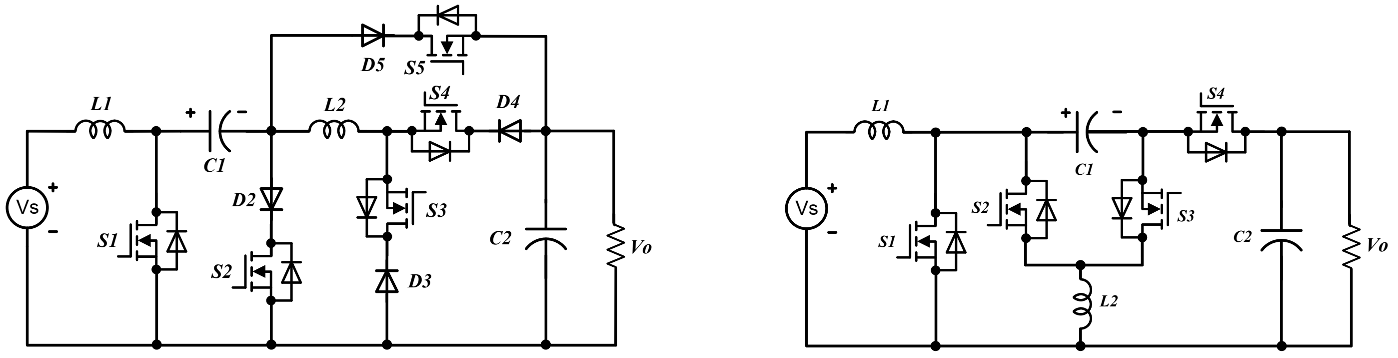


(a) (b)

Figure 5. (**a**) Proposed Aalborg inverter in [47]; (**b**) proposed single-stage inverter in [49].

In reference [49], the authors present a new buck–boost inverter for a wide variation of the input dc voltage. This topology, which is shown in Figure 5b, consists of six switches, an inductor, and two sources. The steps to achieve a structure similar to Figure 5b, and how it works are presented in reference [50]. In this structure, two switches operate at low frequency (50–60 Hz), and the other four switches operate at high frequency (>10 kHz). However, in each switching period, only two of these four switches operate. Among the features of this structure are the use of an inductor and its full utilization, the ability to operate in both directions, and providing reactive power. According to the author, in case the voltage of the input sources is not equal, this structure is also able to produce sinusoidal voltage at the output. Since the neutral on the ac side in this structure is connected to the midpoint on the input side, which is the voltage source (or capacitor), the CMLC is eliminated. In this study, the author has proposed the use of one source and two capacitors in front of switches *S1* and *S2* on the input side to remove two sources in this structure. Considering all these advantages, this structure also has disadvantages. Reverse-recovery issues of MOSFET body diode at high frequency causes losses and variable duty cycle leads to voltage stress across the switches. The same author, in [51], presents a similar structure, which differs from Figure 5b, only in the location of the switches, and one more capacitor is added to the structure. In reference [52], a structure of the same model is introduced and examined. In these structures, at high frequencies, the MOSFET diode recovery problem causes losses.

In reference [53], the author has attempted to extract new single-stage inverters by combining Cuk, SEPIC, ZETA converters, and canonical switching cells (CSC). Then, in this article, the authors present four types of single-stage inverters by combining these converters and examining their performance. Finally, the author has proposed two types of converters, one of which is a new structure. Figure 6a shows this structure. Another structure is provided by the same author in reference [54]. This structure is also shown in Figure 6b. The first structure, which consists of a combination of two converters, Cuk and SEPIC, consists of five switches, two inductors, two capacitors, four diodes, and a source. Another structure (Figure 6b) is a combination of a SEPIC converter, and a CSC consists of four switches, two inductors, a capacitor, and a source. In the first structure, only one switch operates at a high frequency, while the other switches operate at a low frequency. For the second structure, two switches operate at high frequency, and the other two switches operate at low frequency. According to the author, the first structure is better, in terms of magnetic volume, gain, and controller, than the second structure, but this converter only works unidirectionally. On the other hand, although the second structure has fewer switches, all switches suffer from high stress, while the first structure has only one switch under high voltage stress.



(a)

(b)

Figure 6. Combination of different types of dc–dc converters: (**a**) combination CUK and SEPIC converter in [53]; (**b**) combination SEPIC and CSC converter in [54].

Figure 7a shows the topology of a novel single-stage buck–boost inverter, introduced in reference [55]. This inverter consists of five switches, an inductor, two capacitors, and a source. In this structure, only switch *S1* works at high frequency for the boost part of the converter, and the rest of the switches work at low frequency. According to the author, the leakage current in this structure is low because the voltages across the parasitic capacitors are clamped and have no significant high-frequency variations. Using an inductor and its full utilization causes high power density. Additionally, no need for high-frequency dead-time for switches is another feature of this structure. On the contrary, one of the disadvantages of this inverter is its unidirectional operation.

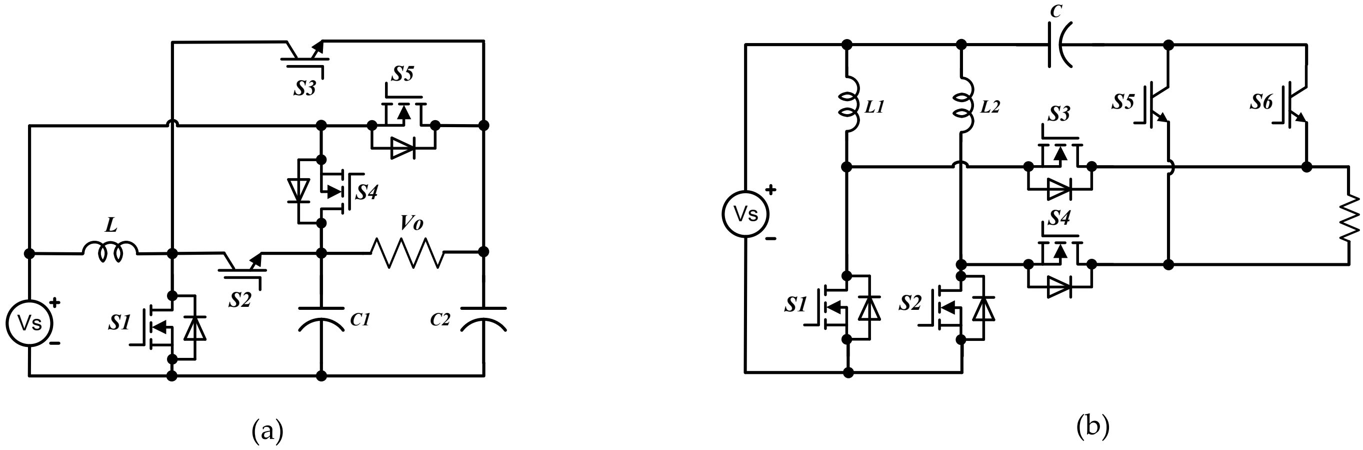
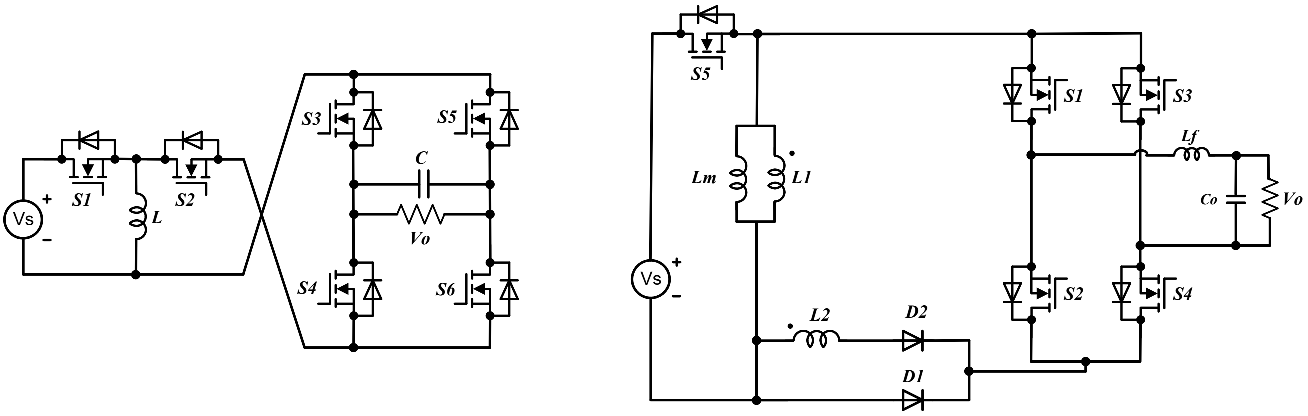


Figure 7. (**a**) Proposed single-stage inverter in [55] (*S2* and *S3* are unidirectional switches, normally a MOSFET, in series with a diode); (**b**) proposed Manitoba inverter in [56] (*S5* and *S6* are unidirectional switches, normally a MOSFET, in series with a diode).

The Manitoba inverter is another single-stage structure, introduced in reference [56]. As can be seen in Figure 7b, this structure uses six switches. In each half-cycle, one of the two switches *S1* and *S2* works at high frequency, which is responsible for shaping the inductor's current. The other four switches operate at line frequencies and have minimal losses. Due to the presence of a capacitor that clamps the voltage between the grid (ac side) and positive terminal of the DC source, the leakage current is reduced. In [57], the same authors examine the performance and system model to provide a precise control method for this inverter. According to the author, this inverter can be used for a wide range of input voltages in PV applications; under such a control scheme, a high-quality ac grid power is guaranteed. However, the disadvantages of this inverter include the use of two inductors and a high number of switches.

Combining the performance of a buck–boost converter and line-frequency unfolding circuit, in reference [58], the authors present a new family of single-stage buck–boost inverters. These inverters are based on direct energy conversion, dc to ac, without dc-link stage and through an unfolding circuit. In this research, three types of single-stage inverters, with a different number of elements and arrangements, are presented; then, in a comprehensive evaluation, the performance of these inverters are examined and compared. Figure 8a shows one of these inverters, which is known as a buck–boost twisted inverter. This structure consists of six switches and an inductor, and it can transfer power in both directions. However, if used unidirectionally, switch *S2* can be replaced with a diode. In this inverter, four switches of unfolding circuit operate at low frequency, and only two switches operate at high frequencies, one of which operates in each operating period. This means reducing switching losses, along with reduced EMI. According to the author, one of the features of these inverters is the small size of passive elements, in a wide range of input voltage changes. Additionally, none of these proposed inverters have high-frequency switching harmonics, which reduces the size of common-mode filters, and there are no leakage current problems in PV applications. Despite all these features, this inverter also has drawbacks. These disadvantages include the high number of switches in two types of inverters, nonlinear duty cycle, and presence of zero-crossing spikes, which are not easily remedied. It should be noted that the same authors, in a recently published study, have provided an accurate control method to control this type of inverters [59].

The use of line-frequency unfolding circuits, for single-stage buck–boost inverters in PV applications, has also been considered in some other research [60,61]. In [62], the authors present a structure based on coupled inductors and unfolding circuits. Coupled inductors are used to increase inverter gain. This structure includes five switches, two diodes, and coupled inductors. Figure 8b shows this structure. Features of this structure, along with high gain, can be noted, and only one switch works at high frequency, which, in turn, is associated with reduced losses and increased efficiency. In this structure, there is no need for additional capacitors to capture the leakage energy of the coupled inductors, and this causes the size of the inverter to be compacted. On the other hand, it can be said that coupled inductors and their current control for achieving high gains are among the disadvantages of this structure.



(a) (b)

Figure 8. (**a**) Proposed single-stage buck–boost twisted inverter in [58]; (**b**) proposed single-stage inverter in [62].

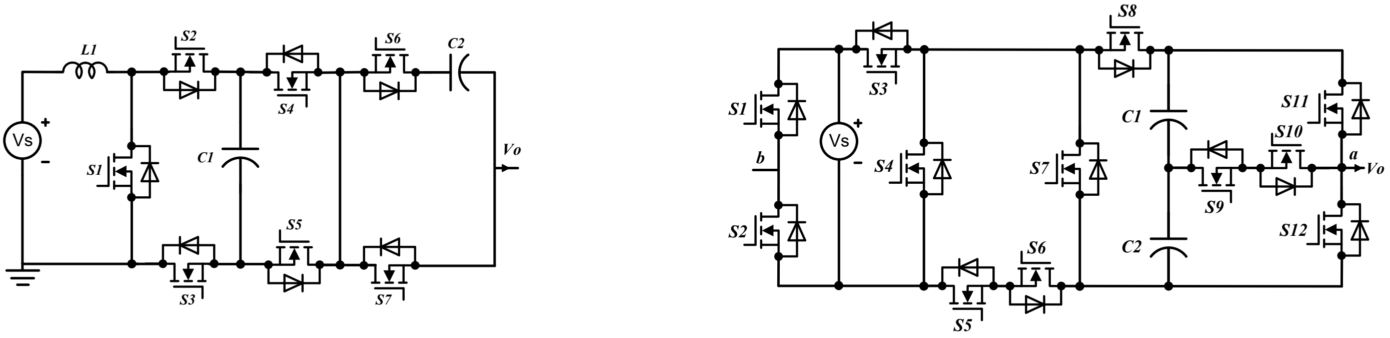
The combination of dc–dc converters for extracting single-stage buck–boost inverters has been considered in many other studies. Each of these studies is presented, with the aim of providing a new structure or modifying the performance of previous structures.

For example, in reference [63], as in the research of other categories, to increase the gain of the inverter, boost units including inductors, diodes, and inductors are used, instead of the input inductor of inverter. In reference [64], with the aim of reducing THD and improving the output current in the structure of Figure 6b, two additional sources and switches are used on the input side of the converter. Many other similar structures can be found in references [65–68].

2.5. Multi-Level Based

The combination of multi-level structures with impedance networks was briefly reviewed in the Z-Source family section. In this part, other multilevel combinations are considered, in order to achieve a single-stage buck–boost inverter.

In a different structure, the author of reference [69] proposed a novel single-stage inverter, based on a five-level active neutral-point-clamped (ANPC) inverter. This inverter is shown in Figure 9a and has the capability to increase the number of output voltage levels. Compared to the two-stage ANPC inverter with a boost converter, this structure uses fewer switches and capacitors and has less voltage stress across the switches. In this structure, a fixed duty cycle is used for inductor charging, which achieves decupled control of dc-link voltage and AC output voltage. The ability to increase voltage, better utilization of the source, and reduce leakage current (by providing common ground) are other features of this inverter. Of course, the high number of switches and high-frequency switching are still disadvantages of this structure.



(a) (b)

Figure 9. (**a**) Proposed single-stage inverter, based on a five-level active neutral-point-clamped (ANPC) [69]; (**b**) proposed single-stage SCM inverter in [70].

The switched-capacitor module (SCM) is another compact structure that has become popular in recent years. In these structures, achieving high voltage levels with a minimum number of dc sources is of great importance. In reference [70], the authors have provided a single-stage inverter, based on the SCM, with the ability to increase the voltage up to twice the input voltage. Figure 9b shows the overall scheme of this inverter. As can be seen, this inverter consists of twelve switches, two capacitors, and only one source. This structure can produce nine voltage levels and, by cascade connecting of these modules, voltage levels can be increased. According to the author, the maximum voltage across the switches in this structure is equal to the source voltage, which is reduced by half, compared to the two-stage sample of this inverter. Although the absence of inductors in this structure makes it more compact and easier to control, the gain of this structure is low, and it has limited use for PV applications. Additionally, the high number of switches and separate pulse control of each switch are other disadvantages of this structure.

Reference [71] also introduces a three-level structure for a single-stage, three-phase inverter by combining a boost converter and a T-type multilevel inverter. In this structure, only one switch operates at a high frequency, which is responsible for increasing the voltage, and the other switches operate at the line frequency. High gain, no need for variable duty cycle, and low rating of switches are among the features of this structure. On the other hand, this structure cannot be called a completely single-stage inverter, and the voltage balance of capacitors is one of the challenges of this structure.

3. General Comparison and Discussion

In this article, an attempt has been made to introduce and review the latest single-stage buck–boost inverters. To select a suitable structure for an especial application, several factors should be considered. In this review, different structures were categorized, and several examples were selected for each category. For each structure, its prominent advantages and disadvantages were highlighted. In general, the main factors that affect the use of a structure include the efficiency, size, cost, and reliability of the converter.

Investigation of losses, especially switching losses, in any structure is important. In this regard, the use of MOSFET or IGBT and converter operating frequencies can be very important.

Another important factor is the size of the converter. The operating frequency of the converter affects the size of the passive elements. On the other hand, the losses of the switches and heat generated from the losses are also effective in choosing the size of the heatsink. The voltage and current passing through the passive elements in each structure also affects their size by determining the energy level required by these elements.

As it is clear, one of the motivations for using single-stage inverters is to reduce the cost of these structures, compared to two-stage structures. By examining different structures, comparing the voltage/current stresses of semiconductor components, and, finally, choosing a structure with minimal stress on these elements, the rating of semiconductors can be reduced and, consequently, a significant reduction in cost can be brought. Additionally, the size of passive elements and total number of circuit elements are other factors affecting the cost.

The reliability of these structures also depends on factors such as the total number of components and complexity of the circuit, voltage, and current stresses of the elements and modulation.

After examining the structures compatible with the intended application, the above factors can be compared and examined at constant power, in order to provide the best option suitable for the consumer. With regard to these issues in choosing the right converter, Figure 10 provides an overview of the four main factors of converter selection and the characteristics affecting these factors. As can be seen, these characteristics affect several factors. For example, as the switching frequency increases, the size of the passive components and consequently the converter size decreases, while increasing the switching frequency increases the losses and leads to a decrease in efficiency. The color of these characteristics in this figure is proportional to their direct/inverse effect on the main factors.

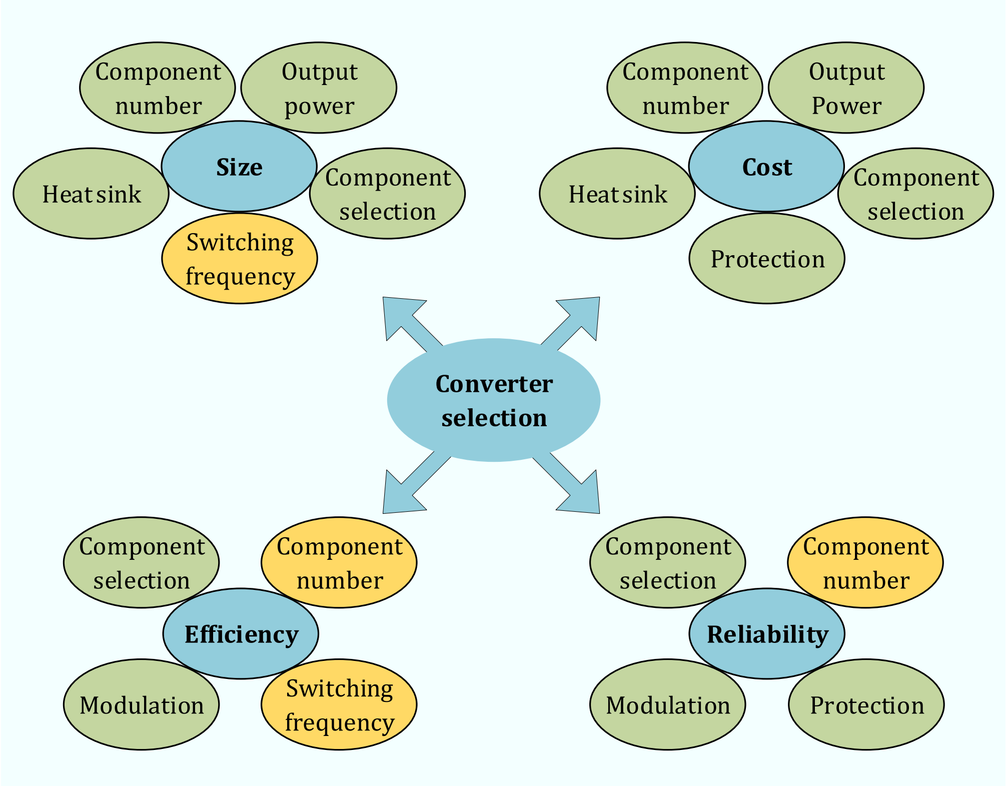


Figure 10. The main factors and other specifications in choosing the right converter.

Table 1 summarizes the advantages and disadvantages of some of the structures studied in this study. This table is intended for single-phase structures. For a more comprehensive comparison, ZSI and qZSI have also been added to this table as well-known inverters. The number of components, reverse-recovery issues of MOSFET body diodes at high switching frequencies, losses, number of input sources, leakage current in PV applications, and some other features are examined in this table. It is clear that some of the proposed new structures, reviewed in this study, are aimed at improving the performance and troubleshooting existing structures. However, to overcome some of the limitations, other elements should be added, which, in most cases, will cause other drawbacks. For example, in [12,27], separate diodes have been used to solve MOSFET reverse-recovery issues. These diodes will affect the cost, losses, and size of the converter. Boost units have been used in [27,28,41–45] to increase the gain of these inverters, which is also associated with increasing the number of components and complexity of the structure and, consequently, affecting the size, cost, losses, and reliability of the converter. However, in [58], after introducing a novel family of unfolding single-stage inverters, the authors compare and evaluate the performance of the proposed inverters, offering an inverter that has more components, but requires a smaller inductor and less voltage stress across its switches. Additionally, in [70], the use of more switches, with less voltage stress across the switches, is justified, which leads to the selection of switches with lower voltage ratings and, consequently, less $R_{\text{DS-on}}$.

Table 1. Comparison of different single-stage inverters.

Topology	Advantage	Disadvantage
ZSI [3]	-Requires four switches	-High voltage stress across switches -Limited gain -Bulky passive elements
Figure 1a [7]	-Simple structure -Requires four switches	-High losses -Hard switching -Reverse-recovery issues
Figure 1b [12]	-No reverse-recovery issues -Requires four switches	-High number of components -Variable duty cycle -Requires six inductors
Figure 2a [19]	-Requires four switches -Simple structure -Minimum components	-Reverse-recovery issues -Variable duty cycle -High losses
Figure 2b [26]	-Bidirectional operation -Fixed duty cycle	-Reverse-recovery issues -High losses
Figure 3a [27]	-Requires four switches -High gain -No reverse-recovery issues	-High number of diodes -Requires four inductors -Variable duty cycle
qZSI [31]	-Requires four switches -Continuous input current -Lower voltage stress across switches (compared to ZSI)	-Bulky passive elements -ST concerns
Figure 4a [32]	-Requires four switches -Minimum components -Continuous input current	-Limited gain -ST concerns
Figure 4b [41]	-Requires four switches -High gain -Continuous input current	-High weight and volume -ST concerns
Figure 5a [47]	-No leakage current -Reduced conduction power losses	-Two DC source -Requires two inductors -Requires six switches -Half magnetic utilization
Figure 5b [49]	-Bidirectional operation -No leakage current	-Requires six switches -Two DC source -Reverse-recovery issues
Figure 6a [53]	-Minimum switching losses -High gain	-Requires two inductors -Unidirectional operation -High number of components
Figure 6b [54]	-Requires four switches -Bidirectional operation	-High voltage stress across switches -Requires two inductors
Figure 7a [55]	-Low leakage current -Minimum switching losses	-Unidirectional operation

Table 1. *Cont.*

Topology	Advantage	Disadvantage
Figure 7b [56]	-Minimum switching losses -Reduced leakage current	-Requires two inductors -Requires six switches
Figure 8b [62]	-High gain -Minimum switching losses	-Requires two inductors -Bulky passive elements
Figure 8a [58]	-Small size of passive elements -No leakage current -Bidirectional operation	-Nonlinear duty cycle -Zero-crossing spike -Requires six switches
Figure 9a [69]	-Fixed duty cycle -Decupled control of DC and AC voltage -Reduce leakage current	-Requires seven switches -High losses
Figure 9b [70]	-Compact structures -High voltage levels -No inductor	-Limited gain -Requires 12 switches

Considering these parameters, or other important parameters, it is worth mentioning that, according to the advantages and disadvantages of each of these structures and considered requirements, a trade-off should be made to select the optimal inverter. It should be noted that some of these problems can be solved by providing an accurate and effective control method.

Single-stage inverter technology seems to be advancing rapidly. As reviewed in the previous section, the latest technologies seek to provide new solutions and solve existing problems of this type of inverters. This study attempted to provide a general overview for those researchers who work, or will work, in this field by presenting all the single-stage structures, together with the circuits of the latest structures. However, there are other structures, such as single-stage isolated structures, that are out of the scope of this study. Given the intensified efforts of researchers, in this regard, it can be said that in the not-too-distant future these inverters, with high capabilities, will find their place in various applications.

4. Conclusions

In this study, the latest single-stage buck–boost inverters were reviewed. These structures were classified into five different categories. For each category, several examples were examined, along with representations of their circuits. Then, other studies that address the problems of these structures were introduced and reviewed. Different structures were examined, in terms of performance, number of elements, switching frequency, and losses. For a general comparison, the features of some of the most prominent of these structures were summarized in a table. Given that each of the structures has advantages and disadvantages, to select the appropriate inverter in each application, a trade-off should be made between these features.

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