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Review Article

A review on non-isolated low-power DC–DC converter topologies with high output gain for solar photovoltaic system applications

Tole Sutikno[1,2,*], Hendril Satrian Purnama[2], Nuryono Satya Widodo[1], Sanjeevikumar Padmanaban[3] and Mohd Rodhi Sahid[4]

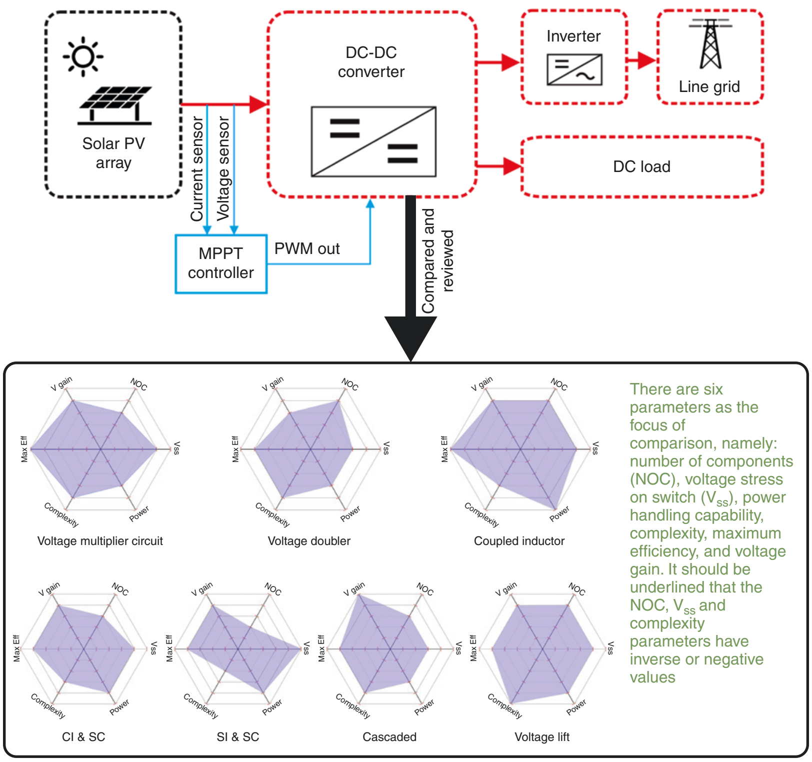
[1]Department of Electrical Engineering, Industrial Technology Faculty, Universitas Ahmad Dahlan, 55191 Yogyakarta, Indonesia
[2]Embedded System and Power Electronics Research Group, 55191 Yogyakarta, Indonesia
[3]CTiF Global Capsule, Department of Business Development and Technology, Aarhus University, Herning 7400, Denmark
[4]School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

*Corresponding author. E-mail: tole@ee.uad.ac.id

Abstract

The major challenges of the high-gain DC–DC boost converters are high-voltage stress on the switch, extreme duty ratio operation, diode reverse-recovery and converter efficiency problems. There are many topologies of high-gain converters that have been widely developed to overcome those problems, especially for solar photovoltaic (PV) power-system applications. In this paper, 20 high-gain and low-power DC–DC converter topologies are selected from many topologies of available literature. Then, seven prospective topologies with conversion ratios of >15 are thoroughly reviewed and compared. The selected topologies are: (i) voltage-multiplier cell, (ii) voltage doubler, (iii) coupled inductor, (iv) converter with a coupled inductor and switch capacitor, (v) converter with a switched inductor and switched capacitor, (vi) cascading techniques and (vii) voltage-lift techniques. Each topology has its advantages and disadvantages. A comparison of the seven topologies is provided in terms of the number of components, hardware complexity, maximum converter efficiency and voltage stress on the switch. These are presented in detail. So, in the future, it will be easier for researchers and policymakers to choose the right converter topologies and build them into solar PV systems based on their needs.

Graphical Abstract



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Introduction

Due to the massive usage of fossil fuels that causes some big environmental issues and global-warming problems, the development of technology in terms of renewable energy sources is increasing rapidly [1–5]. Solar photovoltaic (PV) power sources have become the most favourable energy sources due to their clean and emission-free energy sources with high reliability and low cost [6].

Because of the limitations of PV power sources that have a low-voltage output of between 12 and 60 V, the high output-voltage gain of the DC–DC converter is needed to level up the output voltage for some applications [7], e.g. in grid-connected applications. Grid-connected power applications are operated at ~375–400 V for full-bridge inverters [8] and ~760 V for half-bridge inverters [6]. The conventional boost DC–DC converter topology cannot achieve that level of voltage gain or it will cause an extreme duty ratio and high voltage stress on the power semiconductor device. As a result, many researchers have developed and modified the conventional boost converter topology in recent years to achieve a high voltage gain with higher efficiency and reliability [9–18].

To cope with the direct current (DC) bus voltage for grid-connected inverters, a conventional solution is normally used by connecting the PV panels in series. Due to the large space requirements and high cost, the series/parallel combination of PV panels is not a viable solution for increasing voltage/current [19–21]. Thus, a DC–DC converter with a high-gain voltage-conversion ratio is required to achieve high-voltage outputs [22].

In this paper, the modified topology of a non-isolated DC–DC converter with a high-gain voltage that is >15 times the size is discussed. Other than that, the performance analysis and comparison of such a topology are provided. The paper is organized as follows. Section 1 will outline the major challenge of the high-gain voltage of a DC–DC converter; Section 2 will describe high-step-up DC–DC converter application on PV power systems, step-up DC–DC converter classification for PV application and the very-high-step-up DC–DC converter with high voltage gain (>15 times); Section 3 will provide a discussion and comparisons of the selected DC–DC converter topology; and Section 4 will provide concluding remarks.

1 DC–DC converter configuration on PV power-generation systems

Solar PV power sources have various limitations in terms of harvesting power. It is because the energy-conversion process by PV panels is greatly affected by the radiation received by the panel surface [23]. Therefore, the production of power (current and voltage) from PV panels is greatly affected by climate change and the effect of shading, especially for PV panel installations in urban areas [24]. Due to these problems, a power converter that can operate optimally and is able to change the PV varying input voltage level to a fixed or variable voltage level according to load requirements is needed. In addition, the output voltage of the PV panels only ranges from 12 to 60 V, so a DC–DC converter is needed. This can increase the voltage to the level required by the grid or load, which is >380 V for single-phase electricity needs. The configuration of the solar PV-based energy-conversion system using a DC–DC boost converter is shown in Fig. 1.

Basically, the converter needed to increase the DC voltage from a low voltage level to a high voltage level is called a DC–DC boost converter. The conventional DC–DC boost converter works by utilizing active and passive components such as transistors, inductors, diodes and capacitors. The task is to produce an output DC voltage that is greater than the input DC voltage. It works by varying the duty cycle of the pulse-width modulation (PWM) switching on the transistor to charge the inductor and capacitor alternately. The equivalent circuit of a conventional DC–DC boost converter is shown in Fig. 2.

However, the use of a conventional DC–DC boost converter has limitations in terms of increasing the voltage level. Therefore, the modification of the basic converter topology and circuit is needed. So, the voltage can be raised to the level needed by the grid system if performance and efficiency are taken into account.

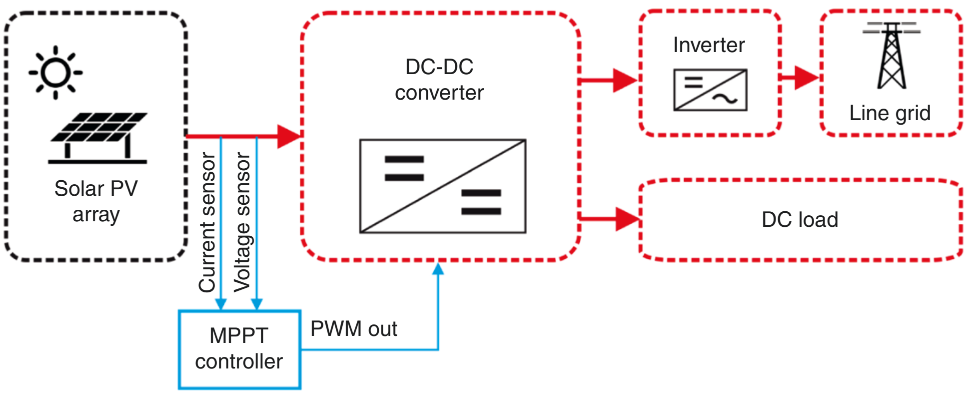

Fig. 1: PV array configuration to the load.

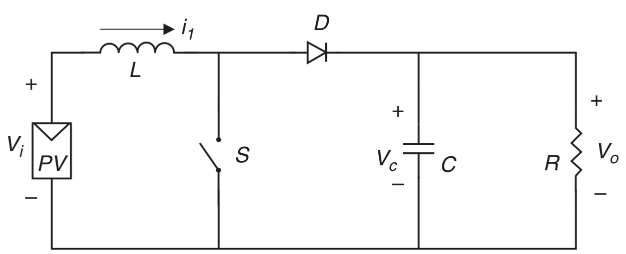

Fig. 2: Conventional boost DC–DC converter circuit.

1.1 Solar PV array power characteristic

The power output from PV can be modelled by Kirchhoff's current law. From Fig. 3, it can be obtained using Equation (1):

$$I_{pv} = n_p I_L - I_d - \frac{V_d}{R_{sh}} \quad (1)$$

where I_d represents the current on the diode, I_L represents the light-generated current from the PV panel, n_p represents the number of cells connected in parallel, R_{sh} represents the resistance of the shunt and V_d represents the voltage of the diode.

Then the current on the diode can be written as Equation (2):

$$I_d = n_p I_{os} \left\{ \exp \left[\frac{q(v + I_{cell} R_s)}{n_s AKT} \right] - 1 \right\} \quad (2)$$

Fig. 3a shows the equivalent circuit of a PV cell and Fig. 3b shows the I–V characteristics of solar/PV cells with a load line.

1.2 Maximum power point tracking controller

Maximum power point tracking (MPPT) is a technique that is commonly used in wind turbines and in PV power-generation systems. It is extensively used to maximize power extraction under various environmental conditions [25, 26]. MPPT implementation uses an algorithm that takes a sample of the output voltage and current from the PV panel and then adjusts the duty ratio as needed. A microcontroller is usually used to implement the algorithm. Modern applications often use high computer requirements for their analytic and load-forecasting needs. In general, the MPPT controller algorithm is implemented in power-converter systems from PV to storage or load systems. The most commonly used power converter in PV systems is the DC–DC converter. Much research has been conducted in recent years to implement the high-gain DC–DC converter for MPPT applications, which can be found in the literature [27–33].

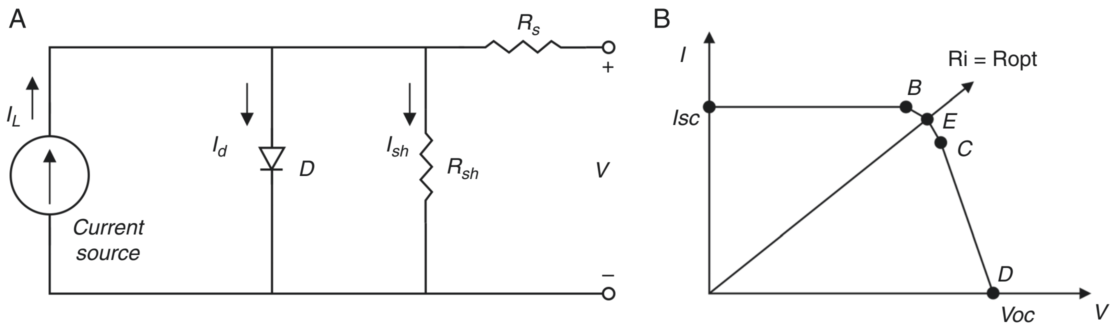

Fig. 3: (a) Equivalent circuit of PV model, (b) I–V characteristics of solar cell with load line.

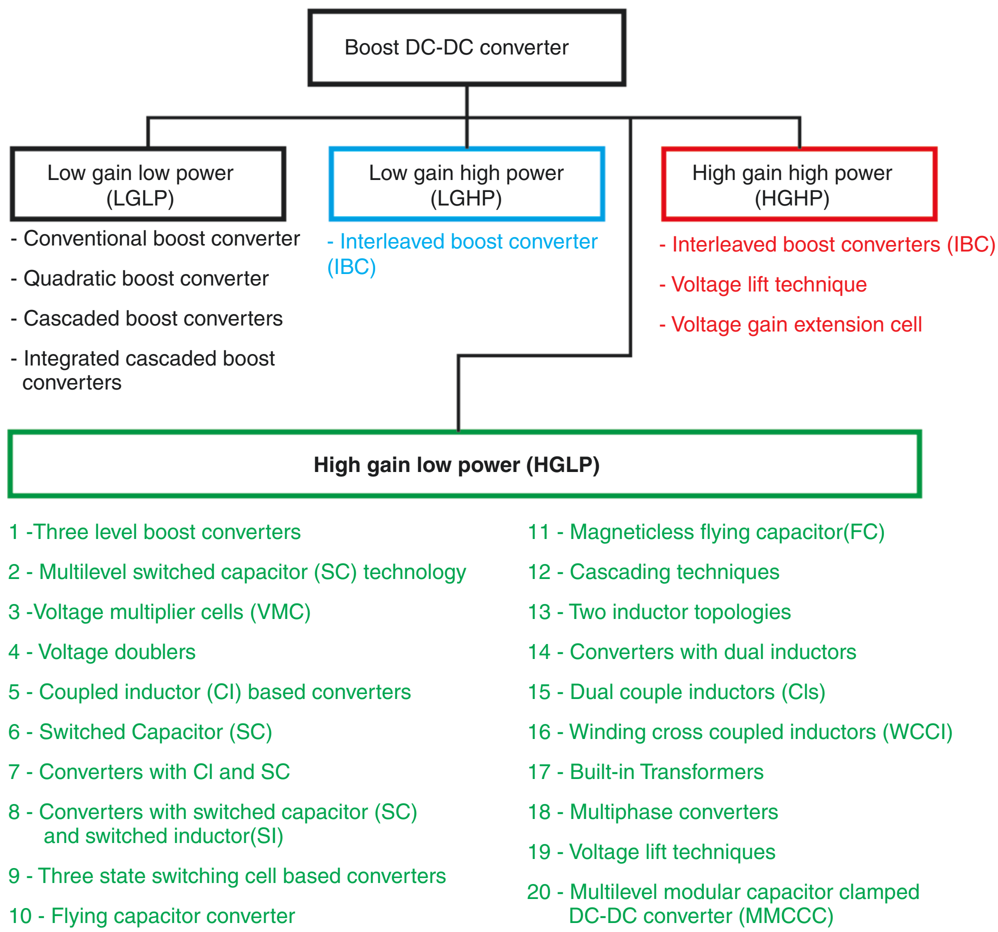

Fig. 4: Various topologies of the boost DC–DC converter classified based on voltage gain and rated power level.

1.3 DC–DC converter

The DC–DC converter converts a DC source into the desired voltage level at the output [34]. The range of converted power varies widely, from very low power (i.e. battery) to very high power (high-voltage power transmission). Basically, the DC–DC converter is divided into two main topologies, namely isolated and non-isolated DC–DC converters. On the isolated DC–DC converter, the transformer is used to step up or step down the input voltage, whereas on the non-isolated DC–DC converter, semiconductor components are used to convert the voltage so it has a more compact size, higher efficiency and lower production costs.

In PV applications, a non-isolated DC–DC converter is used as an input voltage converter that varies from a range of 12–60 V to a fixed output voltage with a range that varies between 24 V (for batteries, lighting applications, etc.) and 760 V (for power-system line-transmission applications) [12]. A high-step-up DC–DC boost converter is required due to the high-output-voltage requirement with very limited input voltage.

Table 1: Various modified topologies of high-voltage-gain DC–DC converters (refers to Fig. 4)

Topology number	Reference	Voltage-gain range (×)		Component count	
		Minimum	Maximum	Minimum	Maximum
1	[36–39]	4 [37]	12 [36]	13 [38]	18 [39]
2	[40, 41]	9 [41]	12 [40]	10 [40]	20 [41]
3	[42–46, 110]	9.5 [43]	15.8 [44]	10 [45]	22 [42]
4	[51–54]	7.9 [52]	19 [51]	8 [52]	12 [51]
5	[59, 111–116]	5.55 [115]	16.66 [114]	8 [115]	15 [116]
6	[66, 67]	5 [67]	10.8 [66]	10 [67]	16 [66]
7	[57, 68–71]	5.68 [70]	16.66 [68]	8 [69]	18 [70]
8	[71, 77, 78]	9.1 [77]	20 [71]	5 [77]	18 [71]
9	[83–85]	7.91 [85]	8.33 [83]	14 [84]	20 [85]
10	[86]	5 [86]	–	7 [86]	–
11	[87]	5 [87]	–	15 [87]	–
12	[88]	6 [88]	–	8 [88]	–
13	[117]	20 [117]	–	10 [117]	–
14	[93]	12.66 [93]	–	12 [93]	–
15	[94]	8.33 [94]	–	15 [94]	–
16	[95]	11.1 [95]	–	8 [95]	–
17	[96, 97]	8.44 [97]	9.5 [96]	7 [96]	15 [97]
18	[98–100]	9.5 [98]	9.5 [100]	14 [99]	16 [100]
19	[101–103]	5 [101]	9.5 [102]	9 [101]	26 [103]
20	[104–109]	9.5 [104]	15.3 [105]	12 [104]	15 [105]

–, data not available.

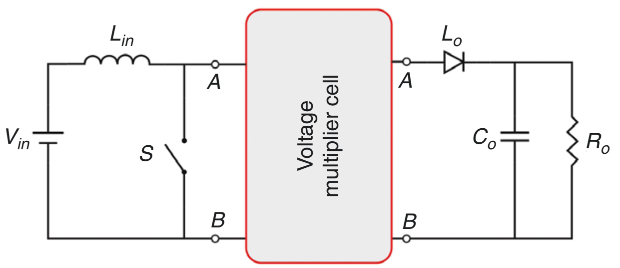

Fig. 5: Basic circuit of DC–DC boost converter with VMC [110].

1.4 Various topologies of the high-voltage-gain DC–DC converter

Conventional boost DC–DC converters have limitations in increasing the voltage to a high level, where the level is the grid voltage level. Many studies have been carried out by modifying the conventional DC–DC converter boost circuit into a variety of new topologies [12, 35]. These can increase the voltage to very high levels while maintaining high reliability and efficiency. The changed topology of the boost DC–DC converter circuit can be divided into four different plans:

(i) low-gain low-power (LGLP);
(ii) low-gain high-power (LGHP);
(iii) high-gain low-power (HGLP);
(iv) high-gain high-power (HGHP).

Out of the four gain and power ranges of the modified topology, the HGLP topology group has been used in PV systems the most.

A general classification of the modified DC–DC boost converter topology is shown in Fig. 4. In the HGLP converter group, there are many developed topology modifications by researchers, including: (i) three-level boost converters [36–39]; (ii) multilevel switched-capacitor (SC) topology [40, 41]; (iii) voltage-multiplier cells (VMCs) [42–50]; (iv) voltage doublers [51–56]; (v) coupled-inductor (CI) converters [52, 57–65]; (vi) SC converters, also known as charge pumps [66, 67]; (vii) combination of CI and SC converters [57, 68–76]; (viii) combination of SC and switched-inductor (SI) converters [71, 77–82]; (ix) three-state switching converters [83–85]; (x) flying-capacitor converters [86]; (xi) non-magnetic flying-capacitor (FC) converters [87]; (xii) multilevel modular capacitor-clamped DC–DC converters [88]; (xiii) cascading techniques [89–92]; (xiv) two-inductor topologies [93]; (xv) converters with dual inductors [94]; (xvi) dual CIs [95]; (xvii) winding-cross-coupled inductors [96, 97]; (xviii) built-in transformers [98–100]; (xix) multiphase converters [101–103]; and (xx) voltage-lift (VL) techniques [104–109].

From all the topologies in the HGLP group that we have studied in this paper, we will discuss in more detail the HGLP topology group, which has a voltage gain of >15 times the input voltage. The topologies include: (i) VMC with 9.5–15.8 times the voltage gain; (ii) voltage doubler with 7.9–19 times the voltage gain; (iii) CI-based boost converter with 5.55–16.66 times the voltage gain; (iv) CI- and SC-based boost converter with 5.68–16.66 times the voltage gain; (v) SI- and SC-based boost converter with 9.1–20 times the voltage gain; (vi) cascading technique with 20 times the voltage gain; and (vii) VL technique with 9.5–15.3 times the voltage gain.

1.5 Major challenges of a DC–DC converter for a PV system with high voltage gain

Besides minimizing current ripple at the input port and keeping the switch from operating at an extreme duty ratio, it is worth noting that the high voltage stress on the switch followed by high peak currents at the low-voltage port are the main concerns in high-step-up conversion systems [12]. Several DC–DC converter topologies that inherit the capability of high voltage gain are also reviewed. However, on the other hand, those converters are suffering from too much voltage stress to increase the voltage from a very small source [65]. Furthermore, the efficiency of some of these converters is also drastically reduced if the conversion ratio voltage is too high.

2 Low-power boost DC–DC converter for PV application with very high gain

Based on the literature, 20 variations of the topology modification of the DC–DC converter circuit have been selected and categorized as high-gain DC–DC converters. The technical variations and topologies are presented in Table 1. It is found that out of 20 converters, 7 of them give an outstanding conversion ratio of >15. This voltage gain is unusual for a non-isolated DC–DC converter and, in some literature, it is also regarded as a 'very high-gain DC–DC converter'.

2.1 VMC

The structure of the boost converter circuit with the VMC circuit consists of the basic components that construct the boost converter and the VMC circuit [12]. Fig. 5 shows the basic circuit of the VMC structure applied to the boost DC–DC converter circuit, while Fig. 6 shows the VMC circuit with the multiplier factor 'M'.

There are several VMC topology variants determined based on the combination of several passive components consisting of capacitors and inductors, which also consist of semiconductor devices such as metal-oxide-semiconductor field-effect transistors, insulated-gate bipolar transistors and diodes. The combination of these components creates a multiplier circuit with distinctive characteristics. Some topology variations of this VMC circuit can be seen in Fig. 7. Table 2 presents a comparison between each cell's topology.

The main features of the VMC circuit are modularity, simplicity and the switches' low-voltage stress. However, this type of converter has several issues, including (i) poor voltage regulation, (ii) excessive component counts, (iii) low voltage gain and (iv) a reasonable trade-off between gain selection and desired efficiency [42].

Previous researchers have developed and improved the high-gain DC–DC converter based on the VMC circuit for smart grid and renewable-energy applications [12, 13, 43, 47–50, 118]. These converters are very much suited for PV applications due to their capability to step up the low-voltage input from the PV to the desired output voltage on the grid system.

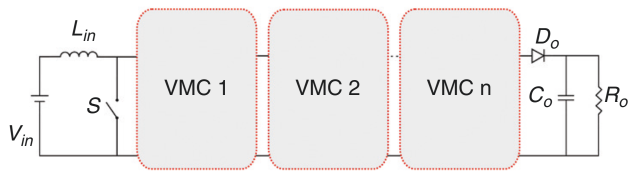

Fig. 6: DC–DC boost converter with 'M' VMC [110].

2.2 Voltage doublers

A voltage doubler can be described as a converter that has an output voltage that is twice its input value. Most voltage-doubler circuits (cells) consist of a diode and an inductor [51], while others have additional capacitors [119]. The voltage doubler works by charging the capacitor at the input side and transferring the stored energy to the load at exactly twice the input voltage. By classifying the identical levels of the doubler, a larger voltage multiplier is obtained with a larger component count, excessive losses and a decrease in efficiency.

The equivalent circuit of a DC–DC boost converter with a voltage doubler can be seen in Fig. 8 [54]. In this circuit, the three-level boost converter proposed in [119] is added together with the voltage-doubler cell proposed in [77]. The two inductors, L1 and L2, are coupled, which results in a smaller inductor size under a similar switching frequency. In general, a voltage-doubler circuit for DC–DC converters has a simpler topology, fewer components and relatively higher efficiency than VMC. However, the voltage doubler has limitations on the gain voltage that can be generated.

This voltage-doubler topology is very popular in universal power supplies, which receive an AC input voltage ranging from 90 to 265 V_{rms}. This is because it can make the rectified 90-V_{rms} input voltage go up to twice as high when it needs to.

2.3 CI-based DC–DC converters

The CI is the component of non-isolated DC–DC converters that works by storing energy in one cycle and powering the load in another cycle [5]. Since many applications do not need electrical isolation, the use of CIs provides a useful alternative enhancement technique in DC–DC converters. It can be achieved by tapping or simply combining the inductors.

In general, CIs are used to increase the voltage gain as well as to reduce the overall size of the inductor [120, 121]. This method can achieve high voltage gain and high efficiency by changing the turn ratio of CIs and energy recovery from the leakage inductance. In addition, a low off-state voltage can be provided by this method for the main switch [119]. High input current ripple and a large input filter are visible to most of these converters.

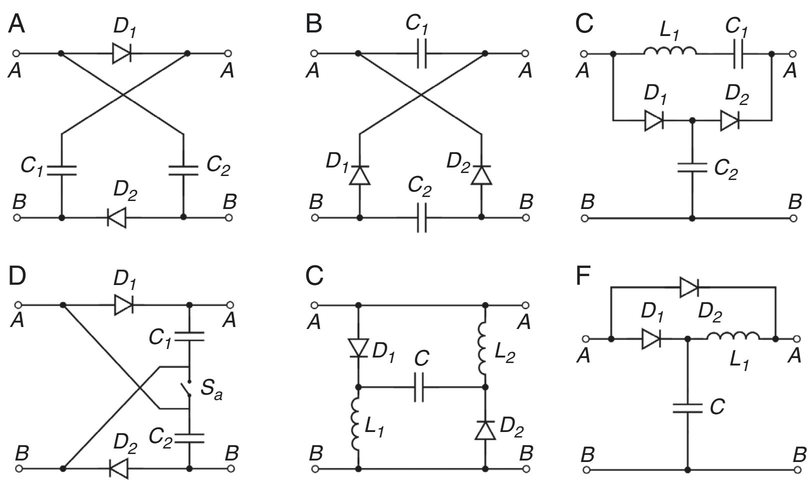

Fig. 7: Various cell topologies of VMCs.

Table 2: Comparison of various VMC cells

VMC type	Voltage-gain ratio (V_{out}/V_{in})	Passive component	Semiconductors
Fig. 7(A)	$\frac{1+D}{1-D}$	2 C	2 D
Fig. 7(B)	$\frac{1+D}{1-D}$	2 C	2 D
Fig. 7(C)	$\frac{1+D}{1-D}$	2 C 1 L	2 D
Fig. 7(D)	$\frac{1+D}{1-D}$	1 C	2 D 1 S
Fig. 7(E)	$\frac{2+D}{1-D}$	2 L	2 D
Fig. 7(F)	$\frac{1}{1-D}$	1 C 1 L	2 D

*C, capacitor; L, inductor; D, diode; S, switch.

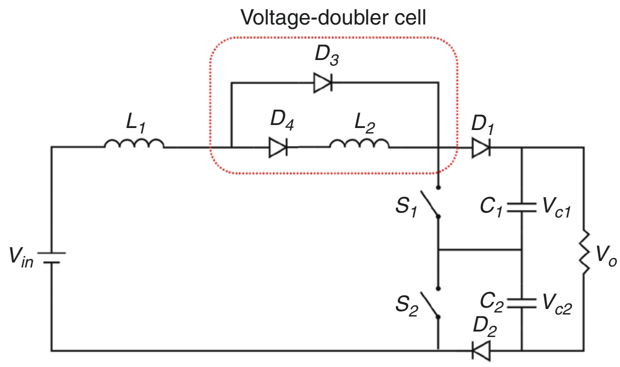

Fig. 8: Typical circuit of step-up DC–DC converter with voltage doubler [54].

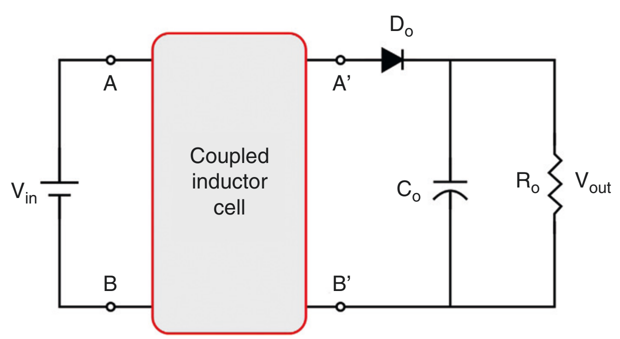

Fig. 9: Schematic of the coupled-inductor base for the high-gain converter.

As a result, the application of this method is limited. In addition, there is a delay in the reverse-recovery diode due to the leakage inductance of the CI. Another drawback is that it is more costly compared to other methods [122].

Fig. 9 shows the general configuration of a boost DC–DC converter with a CI. While the variant of the CI circuit is shown in Fig. 10a. In the boost converter with a CI, the other winding, which is connected in series with the voltage source, assists in supplying additional voltage to the circuit. The two clamping devices, namely the clamp capacitor (C_C) and clamp diode (D_C), are specifically used to recover the leakage energy. It is also noted that the clamping circuit works similarly at any point in the circuit to achieve its purpose in the leakage energy [123].

The soft-switching technique eliminates voltage spikes in the active clamp assist circuit shown in Fig. 10b, which improves overall efficiency and reduces voltage stress on the switch [124]. Aside from the soft-switching technique, a snubber circuit is capable of utilizing the energy due to leakage inductance and increasing efficiency [125], as illustrated in Fig. 10c. It is also clear that the charge pump (CP) and clamp circuits are capable of increasing the voltage gain in the basic boost CI converter while also suppressing the main switch voltage stress, as shown in Fig. 10d [126].

A CI in a circuit with a CP and switch capacitor method is proven to provide high voltage gain, especially when implemented in a distributed generation system [68]. As shown in Fig. 10e, this technique employs two capacitors, which are connected in parallel and series to charge and discharge the CI, respectively. On the other hand, the CIs with three windings are beneficial when high voltage gain is required. Fig. 10f shows the application of this type of circuit. The switch conduction time in [127] is reduced using this method with high-boost capability, which is beneficial in reducing the conduction losses as well. In addition, energy leakage is transferred to the output while the delay time can be adjusted to solve the reverse-recovery problem. It can be acquired by designing the primary and secondary coupler inductor currents such that they will flow in the opposite direction.

An amplifier circuit based on a triple-switch CI integrated with a CP is depicted in Fig. 10g. The voltage and current stress in this circuit are reduced by channelling the energy between the top and lower parts with the two switches. The active clamp method is implemented here to improve the efficiency with zero voltage switching (ZVS) at the switches [128]. As previously stated, the leakage inductor causes high-voltage ringing and surging in most magnetic coupling DC–DC converter switches. However, this can be improved to reduce the switching losses by adding a resonant capacitor in series with any winding of the CI and acting as a resonant circuit that further provides zero current switching (ZCS) and/or ZVS [45, 129, 130].

2.4 Converters with CI and SC

An SC and a CI operate with a wide voltage-conversion range in this type of converter [57, 68]. In addition to that, the leakage inductance of the CI is utilized to suppress the reverse-recovery problem of the output diode. The soft-switching technique is also applied to eliminate the switching losses during turn-on with ZCS operation. In [69], the passive clamp circuit is found to be implemented in other circuits that reduce voltage stress at the switch by recycling leakage energy [70, 71, 131].

Seo *et al.* [72] combined the advantages of SC, CI and VMC. The addition of an SC cell reduces stress on the semiconductor components and devices while at the same time raising the voltage gain. When the circuit is coupled with a VMC, the leakage energy from the CI is recirculated to the output terminals with lossless passive clamping performance. For high-voltage amplification, CI and SC combinations are most widely used. Its common feature is that the PWM technique is used to control the voltage-conversion ratio with the least-active switches and magnetic components. For instance, in [52, 129, 132], only one CI controlled by one active switch is used to obtain a high voltage gain. Fig. 11 shows the DC–DC converter circuit using a combination of CI and SC.

2.5 Converters with SC and SI

In the SI-based converters proposed in [71, 77, 78], the switches are operated in such a way. Hence, the inductors are connected in parallel and in series during charge and discharge operations. However, the voltage stress on the power switch of this type of converter is relatively higher [65].

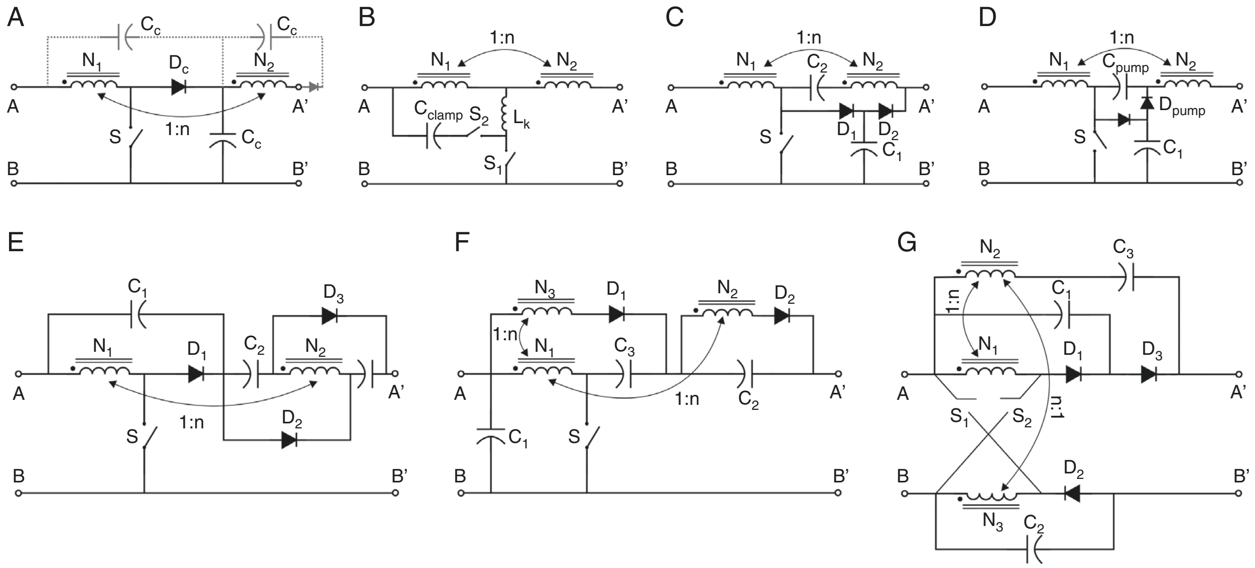

Fig. 10: Schematic of coupled-inductor family. (a) Basic type; (b) active clamp type; (c) active clamp with snubber; (d) charge pump + active clamp type; (e) high-step-up charge pump + active clamp; (f) three-winding coupled inductor; (g) three-winding with charge pump.

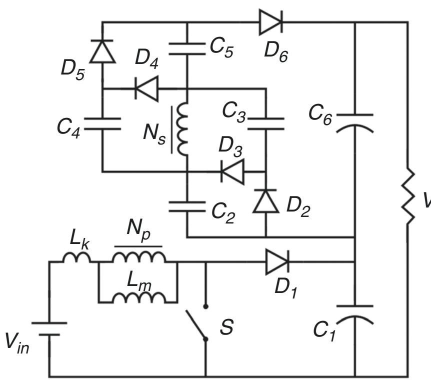

Fig. 11: Schematic of a DC–DC boost converter with CI and SC [57].

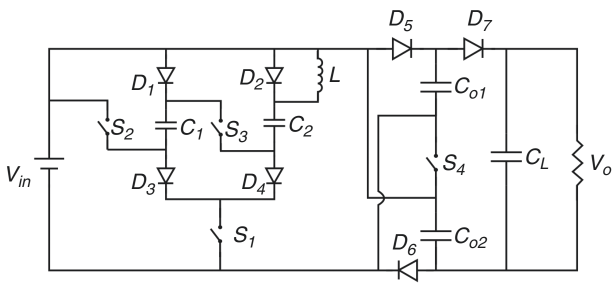

Fig. 12: Schematic of a DC–DC boost converter with SC and SI [133].

It is found that the SI and SC networks can provide an almost similar high voltage gain, but unfortunately the conduction will be slightly higher [77]. On top of that, if the negative terminal of the input and output sides is not connected properly, it can cause the earth leakage current to falsely flow in the system that is connected to the network if the connection between the input and output terminal is not properly made. The size and weight of these converters are relatively large [71, 78]. Fig. 12 shows a typical circuit of an SI- and SC-based DC–DC converter.

2.6 Cascading technique

The multistage converter connection is the simplest approach to increasing the voltage gain. The schematic of a cascaded DC–DC converter is shown in Fig. 13 [134]. As can be seen from the schematic, the family of this converter is built based on cascading several types of boost-type converter (quadratic type) or other high-gain converter (hybrid type).

2.6.1 *Quadratic boost*

As depicted in Fig. 13a, this converter is built by cascading two boost converters [135]. With this type of circuit configuration, it is found that the voltage stress at the first boost is lower compared to the preceding boost. Thus, the first boost converter is capable of operating at a high frequency, which is suitable for low-power-density applications. On the other hand, the second boost circuit operates at a relatively lower switching frequency and further reduces the switching losses. A multistage version of this converter with multistage boost converters is presented in [136]. To reduce the complexity of the circuit, the multistage boost converter switches can be integrated into a single switch in a structure called the quadratic boost converter [137].

The configuration of the quadratic boost converter is shown in Fig. 13b. Unlike the cascaded boost converter, the operation of this converter must be controlled with two PWM signals, which are generated in a more complex way. However, this problem is mitigated by the multistage version, which only requires one switch to control several boost modules [138]. The converter in Fig. 13c has a high voltage gain and is based on a modified three-level DC–DC converter [139]. Fig. 13d–g shows several other structures that belong to the quadratic boost converter families. One of the advantages of the quadratic boost converter is its capability to allow its duty cycle to have very narrow changes while giving significant changes in the voltage gain. Thus, it shows that the design procedures are simpler yet give high performance on the converter itself [140]. This feature is almost unavailable in conventional PWM boost converters. Lastly, the quadratic boost converter can operate in the absence of the complex magnetic design in the circuits.

Another quadratic boost converter is shown in Fig. 13d [141], which performs admirably in terms of reducing switch voltage stress. Two quadratic boost converters are shown in Fig. 13e and f, with the only difference being the connection of the buffer capacitors [142]. Several other modifications to the conventional quadratic boost converter scheme have been

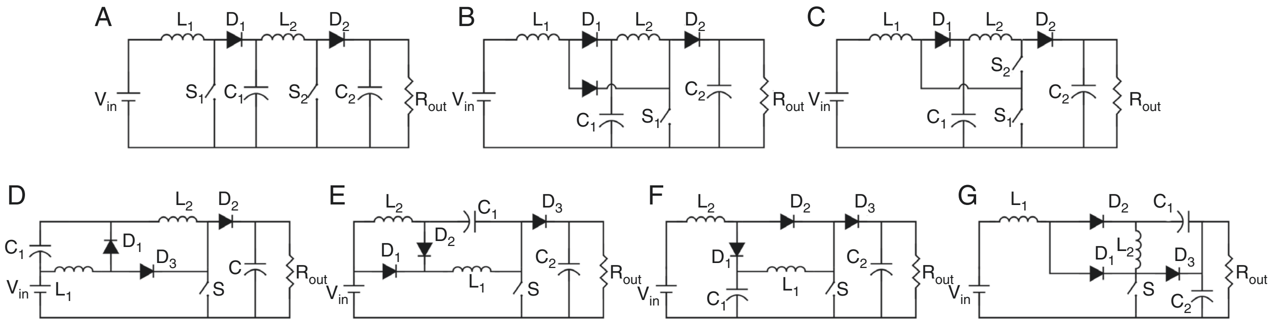

Fig. 13: Schematic of cascaded DC–DC converter families. (a) Two boost converters; (b) quadratic boost converter; (c) modified three-level quadratic boost converter; (d)–(g) several families of quadratic boost DC–DC converters.

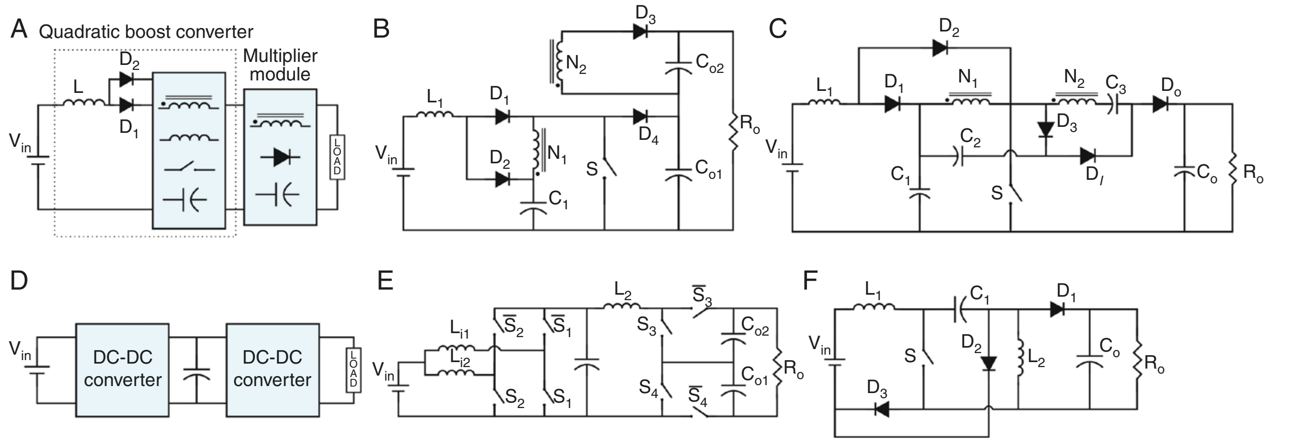

Fig. 14: Schematic of hybrid cascaded DC–DC converter families. (a) Generalized schematic of the quadratic hybrid cascaded converter; (b) and (c) families of quadratic-type converter with hybrid cascaded connection; (d) generalized schematic of the cascaded converters; (e) and (f) families of the conventional converter with hybrid cascaded connection.

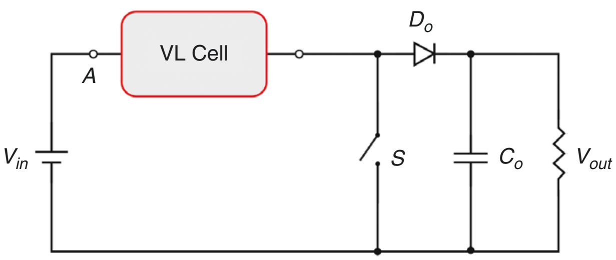

Fig. 15: Generalized schematic of a DC–DC boost converter with VL topology.

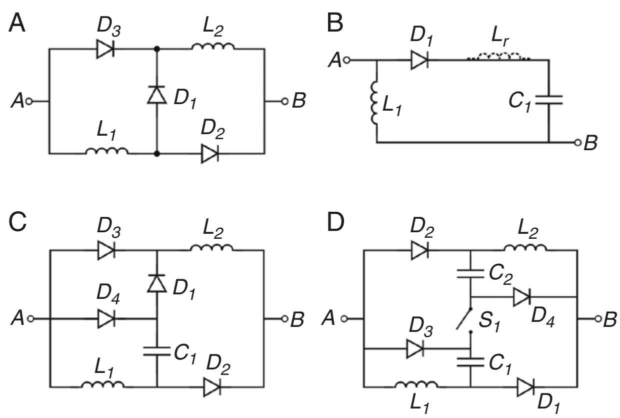

Fig. 16: Various VL cells. (a) Basic SL cell; (b) elementary-lift cell; (c) self-lift SL cell; (d) double self-lift SL cell.

proposed in other literature, such as in [80], which improves the efficiency, and in [143], which reduces the switching voltage spikes.

2.6.2 *Hybrid cascaded*

This section describes two types of hybrid cascaded converters: the quadratic boost converter cascaded with the multiplier module shown in Fig. 14a and the cascaded DC–DC converter shown in Fig. 14d. For the first type, as discussed in [117] and [144], the DC–DC converters are cascaded with a quadratic multiplier in the first stage, while the second stage at the output consists of a CI module. Other topologies in [51, 145] and [146] combine the CI and VMCs, which gives high gain for the overall circuit. In [118, 147, 148], the quadratic boost converter is cascaded with various types of VMC, again for high-gain application. All these converters are depicted in Fig. 14b and c, respectively.

The second type of converter, which is shown again in Fig. 14d, clearly shows two converters cascaded. Several papers on this topic have been published, including [149], which summarized a method for determining several types of DC–DC converters that use ZVS and PWM techniques. In other literature, the quadratic multiplier converter is cascaded with the Zeta converter, which is reported in [148]. The circuit in Fig. 14e proposed by [101] combines the three-level converter discussed earlier with an interleaved multistage hybrid connection. Another converter, as illustrated in Fig. 14f, has developed multistage boost cascading with a buck-boost converter [102]. It can be summarized that the hybrid cascading method can be implemented throughout several topologies to achieve the main objective, which is high voltage gain. However, the drawback of this topology is the increasing number of total components, which can further increase the losses and costs.

2.7 VL technique

As its name implies, this converter, which is used to lift up or increase the output-voltage value of a DC–DC converter, is known as the VL technique. The energy in this capacitor will be used to lift a voltage at any point in the circuit that is required, which is normally the output voltage [150–152]. Using the same method, higher voltage gain can be achieved by increasing the number of charged capacitors that are connected in such a way that they result in a voltage that is twice or greater than the value obtained using just one charged capacitor. Fig. 15 illustrates the generalized schematic circuit of a DC–DC boost converter with the VL technique. The variation of the VL topology can be obtained in this figure by inserting different types of circuit at the VL cell. Several existing VL topologies have been proposed as depicted in Fig. 16. In Table 3, a comparison of the number of components and corresponding voltage gain for several VL cells is shown.

In terms of performance, the VL technique is one of the best techniques to increase the voltage on the DC–DC converter. Besides having high efficiency, the VL technique is also capable of operating over a wide power range, from low-power applications to high-power applications. The energy-storage elements, namely the inductor and capacitor, play an important role in the performance of the VL technique. It is worth mentioning that high efficiency, high power density, low cost, simple structure and small output-voltage ripple, especially for high voltage values, are the main features of this technique. Many researchers have developed high-step-up non-isolated DC–DC converters for renewable-energy applications using the VL technique [104–109].

Table 3: Comparison of various VL cells

VL cell	Number of semiconductors	Number of passive components	Voltage gain
Basic SL cell	3 D	2 L	$\frac{1+D}{1-D}$
Elementary-lift cell	1 D	1 L 1 C	$\frac{2-D}{1-D}$
Self-lift cell	4 D	2 L 1 C	$\frac{2}{1-D}$
Double self-lift cell	4 D 1 S	2 L 2 C	$\frac{3-D}{1-D}$

3 Discussion and comparison for very-high-gain DC–DC converters with low power application

The selection of the appropriate converter can be considered based on input and output power requirements needed by the system. Based on Table 1, there are 20 modified topologies of high-gain DC–DC converters. Then, they are selected into seven

Table 4: Categorization of each topology

Category	Number	Topology
VMC	1	Basic VMC [110]
	2	Interleaved converter with voltage-multiplier module [43]
	3	A high-step-up converter with a voltage-multiplier module [46]
	4	Improved multiplier cell for single-phase high-step-up converter [44]
	5	Built-in transformer voltage-multiplier cell for single-switch high-step-up converters [45]
Voltage doubler	6	Interleaved converter with voltage-doubler cell [153]
	7	Combination of CI and voltage-doubler circuits [57]
	8	Single-phase active clamp CI-based converter with extended voltage-doubler cell [52]
CI-based	9	Interleaved high-step-up converter with CI and blocking capacitor [111]
	10	Basic CI for high-gain boost converter [154]
	11	CI and switched clamp capacitor techniques [155]
	12	CI with soft-switching techniques [112]
	13	Multi-CI and VMC [116]
CI- and SC-based	14	Basic SI and SC [80]
	15	CI and switched clamp capacitor techniques [155]
	16	CI and resonant SC [156]
	17	Integrating CI and diode–capacitor techniques [51]
SI- and SC-based	18	Modular, extendable and high-gain DC–DC converter with SI and SC [157]
	19	SI- and SC-based high-gain hybrid DC–DC converter [158]
	20	Modified active SI and SC cells [80]
	21	Active SI and passive SC networks [159]
Cascaded techniques	22	Cascaded boost converters with sliding-mode control [160]
	23	Cascaded high-step-up DC–DC converter with single switch [117]
	24	Conventional cascaded boost converter design for solar energy systems [161]
	25	Cascade synchronous boost DC–DC converter with zero-voltage switching [162]
VL techniques	26	Coupled inductor and VL technique [152]
	27	Combination of VL, clamp mode, CI and VMC [105]

Table 5: Comparison of the various topologies based on each reference

Topology number	Number of components					Voltage stress on switch	Maximum efficiency (%)	Voltage gain (×)	Tested frequency (kHz)	Tested power (W)
	L	C	S	D	Total					
1	2	3	1	3	9	N/A	95.0	16.6	50	100
2	4	5	2	5	16	$V_o/2(n + 1)$	97.1	9.5	40	400
3	4	4	2	4	14	$V_o/2(n + 1)$	96.8	9.5	40	400
4	2	5	2	4	13	$V_{out}/2$	96.5	15.83	100	500
5	3	4	1	3	11	N/A	96.6	10.5	100	500
6	2	3	2	4	11	$V_{out}/2$	N/A	13.33	100	133
7	2	2	2	4	10	$V_{out}/2$	92.8	8.33	25	250
8	2	3	2	2	9	$V_o/(N + 1)$	96.9	9.5	100	500
9	4	4	4	4	16	N/A	96.0	7.9	100	1000
10	2	2	1	2	7	$V_{in}*2$	95.0	12.9	N/A	300
11	3	5	1	6	15	$1/7*V_o$	96.2	16.7	50	150
12	5	4	2	2	13	$V_{in}/1 – D$	96.4	15.0	100	200
13	6	5	2	6	19	$V_o/2(N + 1)$	97.2	18.2	50	1000
14	2	5	2	6	15	$1/2(1 + N)*V_o$	97.6	10.8	100	1000
15	2	5	1	6	14	$1/7*V_o$	96.2	16.7	50	150
16	1	5	2	4	12	$V_{in}/1 – D$	93.6	8.3	50	200
17	2	4	1	5	12	$V_{out}/2 + N$	94.0	21.1	40	500
18	4	5	2	7	18	$V_{out} – V_{in}/2$	94.0	12.7 (D = 0.67)	50	250
19	2	2	2	7	13	$0.45*V_{out}$	94.0	12.7 (D = 0.67)	50	120
20	4	3	4	7	18	M + 4/8 & M/4	95.0	30	50	200
21	3	3	2	2	10	M/1 + 3D	95.5	13	50	200
22	2	2	2	2	8	N/A	95.0	21	50	1000
23	2	3	1	4	10	$V_{out}/1 + nD$	93.3	20	40	280
24	2	2	1	3	8	N/A	92.0	11.8	20	300
25	3	2	2	3	10	N/A	93.0	8.3	50	200
26	3	4	1	3	11	$1/1 – D*V_{in}$	93.9	8.3	50	35
27	4	6	1	7	18	$1/1 – D^2*V_{in}$	96.8	15.4	50	300

topologies of high-voltage-gain DC–DC converters with a conversion ratio of >15. These topologies include VMCs, voltage doublers, CI, CI and switch capacitor, SI and SC, cascaded converter and VL techniques. Each technique and topology of the selected very-high-gain DC–DC converter has its own characteristics, advantages and disadvantages.

Further studies have been carried out on the seven topologies. There are 27 references, which were elaborated to support an in-depth discussion about the seven topologies, related to their modification and development. Table 4 shows the categorization of these topologies with references that justify them. Table 5 presents the comparison of each topology based on the number of components, voltage stress on the switch, maximum efficiency, voltage gain, tested frequency and tested load power.

The VMC-based DC–DC converter topology has the advantages of a simple structure, being modular and having low-voltage stress on the switch. However, on the other hand, it also has drawbacks such as limited voltage gain (based on the number of components), a greater number of components and poor voltage regulation. The voltage-doubler-based DC–DC converter topology is a variation of the VMC circuit. It has a voltage multiplier of a factor of 2. However, the voltage-doubler circuit for DC–DC converters has a simpler topology, fewer components and relatively higher efficiency than VMC. Also, compared to VMC, the ratio of voltage gain that can be made using a voltage doubler is limited.

The construction of the CI-based DC–DC converter has varied, but it is classified as a converter topology, which is quite complex. It is because of the need for complicated CI manufacturing. While the efficiency level is the highest compared to other converter topologies, the power that can be handled is also relatively higher than with other converters. The CI- and SC-based DC–DC converter topology has a relatively higher construction and level of complexity. It is because this type of converter requires a higher number of switches and other components. The advantage of the converter with CI and SC topology is that it has high efficiency while the voltage stress is low. The SI- and SC-based DC–DC converter topology has the advantage that the voltage stress on the semiconductor components is low, and the efficiency is high. On the other hand, the SI- and SC-based converter topologies require a relatively large number of switches, so that the system becomes more complex.

The cascade-based DC–DC converter topology has various variations. The advantage of this topology is its simple and modular structure, making it easy to apply. However, this causes an increase in the number of needed components along with the higher voltage-gain requirements. In addition, the efficiency of this converter will decrease as more active and passive components are used. The DC–DC converter with the VL technique topology has advantages from various sides, namely simple converter structure, fewer components compared with other converter topologies and higher efficiency. The value of the voltage increases of the VL-based DC–DC converter is also high and the voltage stress is low.

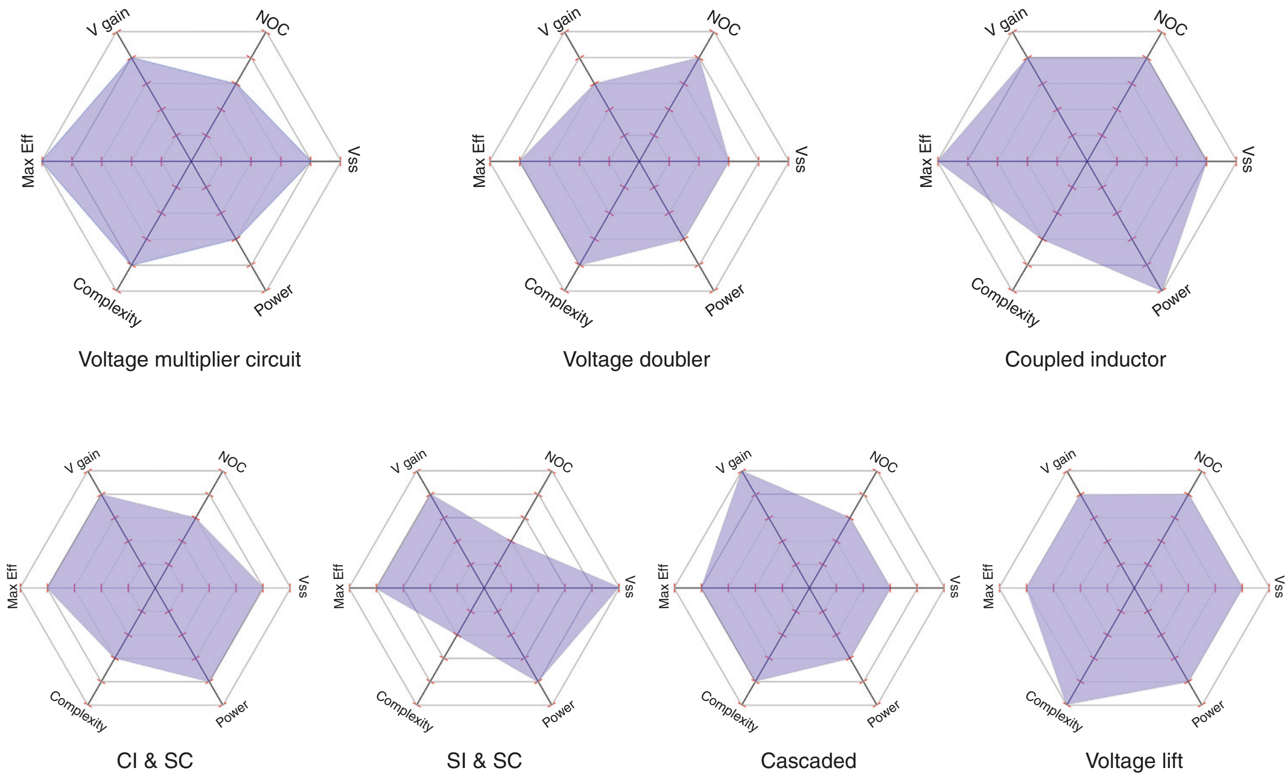

Fig. 17: Performance comparisons of each converter topology.

The final comparison of each converter has been discussed. There are six parameters as the focus of comparison, namely number of components (NOC), the voltage stress on the switch (V_{SS}), power-handling capability, complexity, maximum efficiency and voltage gain. It should be underlined that the NOC, V_{SS} and complexity parameters have inverse or negative values. That means the larger the position, the smaller the value appears on the graph, so the best converter performance assessment can be seen by measuring the total area of the rating parameter values of each converter. The overall comparison of the converter parameters discussed is shown in Fig. 17.

4 Conclusion

In this paper, the performance of several DC–DC converter topologies for PV generation system applications has been studied. The main challenges of DC–DC converter topologies for low-power solar photovoltaic applications are discussed. Twenty HGLP DC–DC converter topologies are reviewed and seven prospective topologies are selected. The selected converters have voltage gain of >15 times. There are 27 references, which were elaborated to support an in-depth discussion about the seven topologies, related to their modification and development. The comparison among the seven converters is highlighted based on the NOC, hardware complexity, maximum coverage efficiency and voltage stress on the switch. Finally, the salient features of the converters are also summarized. The comparison results from this paper are expected to be a reference for researchers or practitioners to select and integrate the right converter topology for the needs of solar PV-sourced power-conversion applications. In the future, it will also be easier for policymakers to think about the topologies of converters based on their needs and circumstances.

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Conflict of interest statement

We have no conflicts of interest to disclose. All authors declare that they have no conflicts of interest.

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