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Review Article

Advanced DC–DC converter topologies for solar energy harvesting applications: a review

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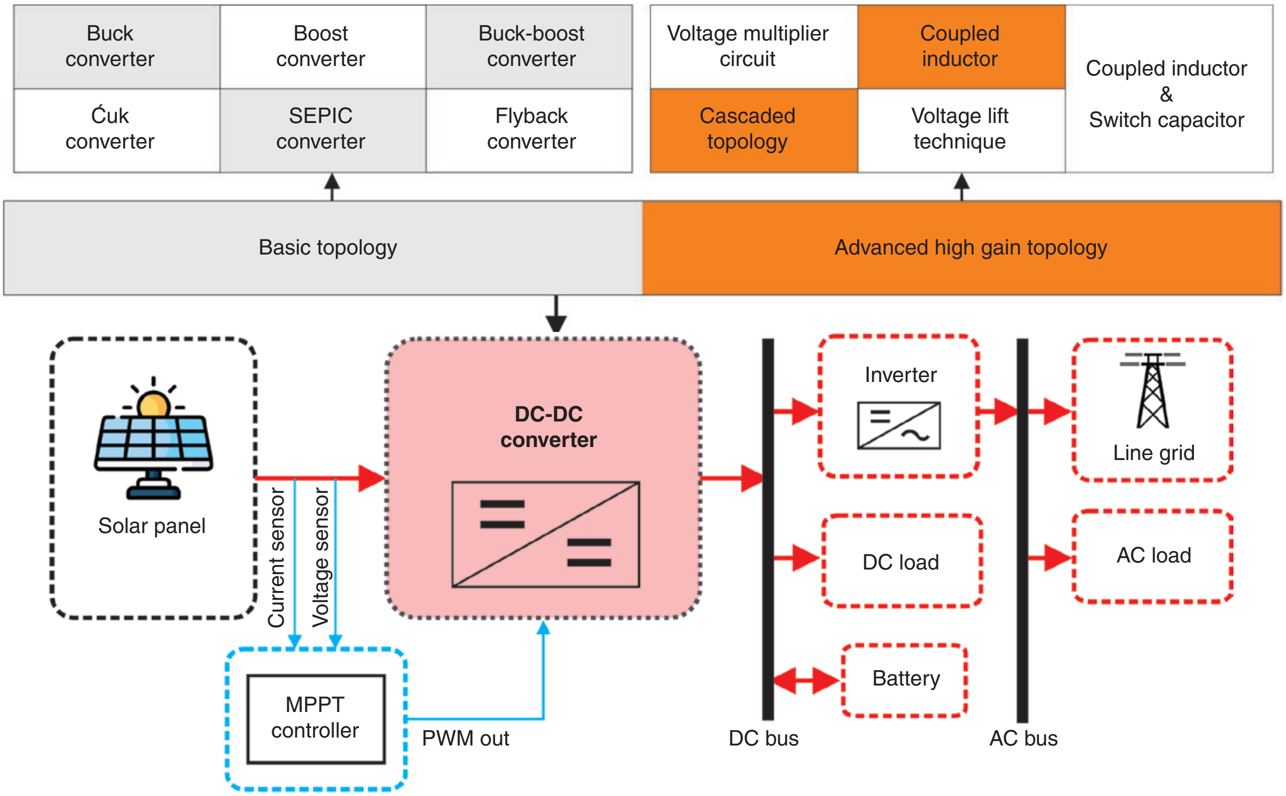
Abstract

In this study, the advanced topologies of a DC–DC converter for applications involving the harvesting of solar energy are discussed. This work's primary contribution is a guide for choosing the most effective topology for a DC–DC converter when developing solar energy collection systems. Several topologies of a DC–DC converter for solar energy harvesting applications are compared in terms of the range of power levels they can oversee, the complexity of the underlying hardware, the cost of implementation, the tracking efficiency and the overall efficiency of the converter. This article explains five innovative approaches for adapting boost converters to function as standard DC–DC converters to capture solar energy, consisting of (i) voltage-multiplier cell, (2) coupled inductor, (3) coupled inductor and switch capacitor, (4) cascaded topology and (5) voltage-lift technique. Because of the boost converter's restrictions, it is necessary to deliver high performance. The comparison findings demonstrate that the voltage-lift-based boost-converter topology performs more effectively than the alternatives. In conclusion, the information presented in this paper can be utilized when developing solar energy collection systems to determine the sort of direct current to direct current converter that will be most effective.

Graphical Abstract



Keywords: boost converter; DC–DC converter; energy harvesting; renewable energy; solar photovoltaic

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Introduction

Renewable energy has become very interesting to utilize since the enormous amount of fossil-fuel exploitation affects environmental issues [1–3]. It makes many researchers try to explore more renewable energy resources (RESs). Photovoltaic (PV)-based power plants have become the most favourable due to several advantages, such as longer life, environmental friendliness, less maintenance, greater mobility and portability, and the ability to produce more power to meet load requirements [4]. However, tracking solar energy's maximum power point (MPP) becomes a significant problem due to the non-linear current–voltage (*I*–*V*) characteristics of the PV array [5]. Therefore, maximum power point tracking (MPPT) was introduced to achieve MPP during the operation of PV systems [6].

The production of high-efficiency power converters has inspired the development of a great deal of MPPT algorithmic research. It is conducted because the electricity generated by the PV panels is highly dependent on the circumstances of the atmosphere, particularly the amount of solar radiation and the general temperature of the environment. As a result, it is essential for PV systems to make use of MPPT with an algorithm [7]. In addition, when combined with MPPT, DC–DC converters should be able to match the load and obtain increased power from PV systems [8–10].

In solar energy harvesting systems, which convert a DC voltage to various levels, a DC–DC converter has played a pivotal role due to its ability to convert between multiple DC voltage levels [11]. As a result, it offers a voltage more suitable for many applications when PV panels are used as the source [12]. When choosing a DC–DC converter, it is imperative that several criteria be satisfied. These criteria include high efficiency, high reliability, low conduction losses, low switching losses and low cost. Due to this, scientists worldwide are continually researching and inventing new topologies for DC–DC converters [13–16]. It increases the total number of DC–DC converters that can be used for a variety of power-conversion operations.

This paper looks at the trend for using DC–DC converters for solar energy harvesting systems and examines them. This study focuses on the fundamental topological structure and the more sophisticated strategies that can be used to increase its performance. As part of the development of renewable and sustainable energy sources, the principles of solar energy collecting systems are discussed in the second half of this article. Section 2 then analyses the positive and negative aspects of each typical DC–DC converter. Section 3 discusses more sophisticated strategies to increase the performance of typical DC–DC topologies, notably step-up converters. In Section 4, a comparison is made between each conventional DC–DC converter and the innovative approaches taken into consideration. The final part of the article is the conclusion, which can be found in Section 5.

1 Solar energy harvesting system

Energy harvesting is the acquisition of usable electrical power by collecting and transforming the energy already in the surrounding environment from various sources [17]. The world's ever-increasing demand for energy might be met in several ways, one of which is solar energy collection [18]. The solar energy harvesting system comprises a PV array, MPPT controller, DC–DC converter, battery, load (AC/DC) and an inverter. The comprehensive block diagram of the solar energy harvesting system is shown in Fig. 1.

Solar PV arrays are solar energy collectors that transform photons into electrons to create electrical power [19–21]. The output is sent to the DC–DC converter to achieve a power output that is more beneficial [22]. The DC–DC converter converts the variable DC voltage generated by a PV cell into a constant voltage based on the load requirements or the DC bus [23]. The MPPT controller simultaneously achieves MPP conversion from a PV module, resulting in the duty ratio value or the reference voltage [24]. Then it is compared to the sawtooth signal to generate a pulse width modulated (PWM) signal to regulate the period switching in the DC–DC converter [25]. The output of the DC–DC converter can supply load sides such as DC load or batteries, or it can be connected to the inverter device, in which case the output can either be connected to the grid or supply an AC load.

2 Overview of conventional DC–DC converter topology for solar energy harvesting system

Power-converter technologies have been dramatically altered due to the development of power-electronics technology, particularly those involving harvesting power from renewable sources. This work analyses and discusses the solar PV energy-harvesting

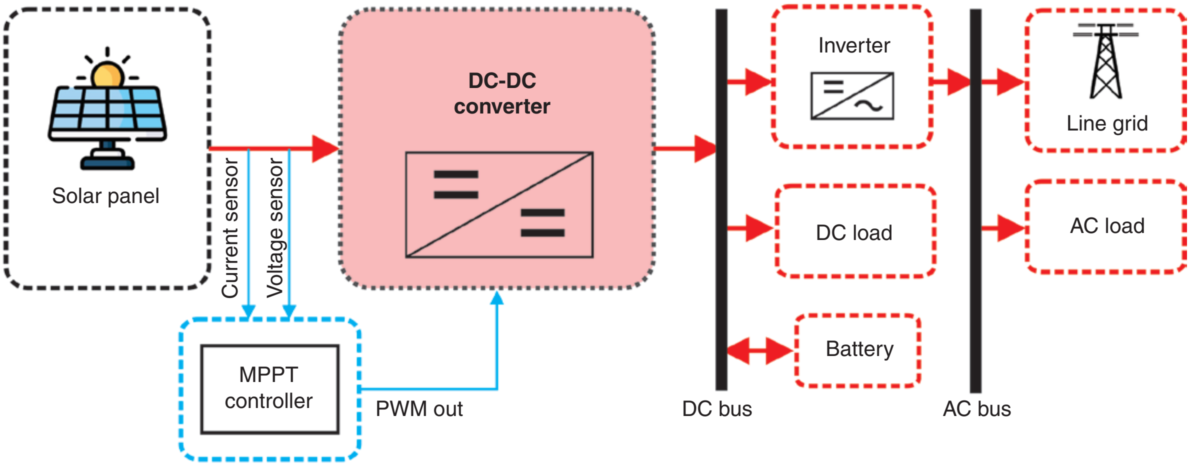

Fig. 1: Block diagram of overall solar PV energy-harvesting systems

technology known as the DC–DC converter. Non-isolated and isolated kinds are the categories used to classify DC–DC converter topologies [26]. In a DC–DC converter, the term ‘isolated type’ refers to an electrical barrier placed between the input side and the output side of the device [15], and the use of high-frequency transformers realizes this barrier. It is put to work as a device for converting high voltage and it may be set up in either a positive or a negative configuration, similar to a flyback converter. Unfortunately, the barrier on the power converter is cumbersome relative to the size of the converter and the power losses induced by the barrier are also relatively significant. As a result, a non-isolated converter is an option that may be considered in order to circumvent the disadvantages above. In recent years, switching out isolated kinds has been standard practice. Common types of DC–DC converters include the buck converter, boost converter, buck–boost converter, Ćuk converter and single-ended primary inductance converter (SEPIC) [27]. They are appropriate for PV applications depending on the voltage-level conversion required. Fig. 2 shows the structural structure of each standard DC–DC converter used in solar energy harvesting systems.

2.1 Buck converter

The buck converter offers an output voltage (V_{out}) less than the input voltage (V_{in}), which means that this circuit decreases the DC voltage [28]. This converter consists of a switching device (*S*), a diode (*D*), an inductor (*L*) and a capacitor (*C*), as shown in Fig. 2a. This converter is the basic step-down topology in a switching-mode power supply. Equation (1) can be used to determine the output voltage of the buck converter according to the duty cycle of the switching device (D_t):

$$D_t = \frac{V_{out}}{V_{in}} \tag{1}$$

The input of the buck converter can come from a battery, an AC rectifier or an RES such as PV systems or fuel cells. This allows the converter to be used in various settings and applications. The output of the buck converter can be utilized for low-level voltage devices, such as battery-management systems or solar battery chargers. The buck converter typically has two different operating modes: the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM). When the buck converter operates in CCM mode, the current through the inductor will never be equal to zero because it will always be greater than zero. In the meantime, while DCM is being carried out, the current flowing through the inductor will stop entirely not long after the switching period concludes [29–31]. To get more excellent performance from the buck converter, a different working mode has been introduced.

2.2 Boost converter

The inductor (*L*), diode (*D*), switching device (*S*) and capacitor (*C*) are the components that make up the fundamental circuit of the boost-converter topology, which is depicted in Fig. 2b. The output voltage, V_{out}, will be raised to be higher than the input voltage, V_{in} [32, 33]. It can function as an interface between the PV array, the high input voltage of a battery bank and various DC loads [34]. As a result, this topology is excellent for applications dealing with renewable energy, which often produce low voltages and are unsuitable for various applications. To determine the duty cycle of the boost converter, Equation (2) is utilized:

$$D_t = \frac{V_{out} - V_{in}}{V_{out}} \tag{2}$$

Operating modes CCM and DCM are frequently utilized with the boost converter. Additionally, research concerning this topology has been undertaken by the other operating modes applied to improve the system’s performance. Recent advances in research on boost converters used in solar energy harvesting systems have focused on power-quality management, specifically as it pertains to eliminating harmonics, regulating zero voltage, load balancing and power-factor correction (PFC) [35–37].

2.3 Buck–boost converter

The topology circuit of the buck–boost converter is comparable to that of the boost converter; the primary distinction between the two lies in the location of the switching device, as shown in Fig. 2c. A buck converter and a boost converter are the two fundamental topologies in this multilevel topology. Henceforth, it is also referred to as a step-up/down converter because it can either raise or lower the input voltage. It is common practice to use a buck–boost converter to connect the voltage of the PV array to either the voltage of the DC load or the voltage of the battery [34]. Changing the duty cycle in this way will cause a different output voltage. The converter operates in buck mode whenever the duty cycle is <50%, which causes the output voltage to be less than the input voltage. When the applied duty cycle exceeds 50%, the converter will operate in boost mode so that the output voltage will be greater than the input voltage [29]; to determine the output voltage of a buck–boost converter, Equation (3) is utilized:

$$V_{out} = -V_{in}\left(\frac{D_t}{1 - D_t}\right) \tag{3}$$

2.4 Ćuk converter

Fig. 2d presents the Ćuk converter topology for viewing pleasure. This converter can step the input voltage up or down. The polarity of the output voltage that is created will be backward. If its connections are made correctly, the Ćuk converter will have a tiny ripple output, making it acceptable for a wide range of load application needs [38–40]. The voltage produced by a topology such as the buck–boost converter may be determined by using Equation (3).

In the research that has been published [41–45], several types of traditional Ćuk converters have been provided. However, the modified Ćuk converter has a better efficiency level for controlling voltage and current in bidirectional operation [46]. Sliding mode control (SMC) and proportional-integral (PI) control are two of the many methods utilized in the closed-loop system architecture. It is also possible to integrate it with a fuzzy logic controller (FLC) to determine the voltage output by the Ćuk converter [47, 48]. In addition, the Ćuk converter is appropriate for brushless DC (BLDC) motors and renewable-energy systems applications such as PWM-based PV power-generating systems [49–53].

2.5 SEPIC converter

Fig. 2e shows the SEPIC circuit. The SEPIC converter, similarly to the Ćuk converter, can increase or decrease voltage. However, the output voltage generated does not have reverse polarity. If the time spent charging the inductor exceeds the time spent discharging it, this converter will provide a higher output voltage. This indicates that the switching period for ON-time is longer than the switching period for OFF-time. If this is not the case, the SEPIC converter will operate in a step-down mode to reduce the input voltage. Calculating the voltage that is put out by the SEPIC converter may be done with the help of Equation (4):

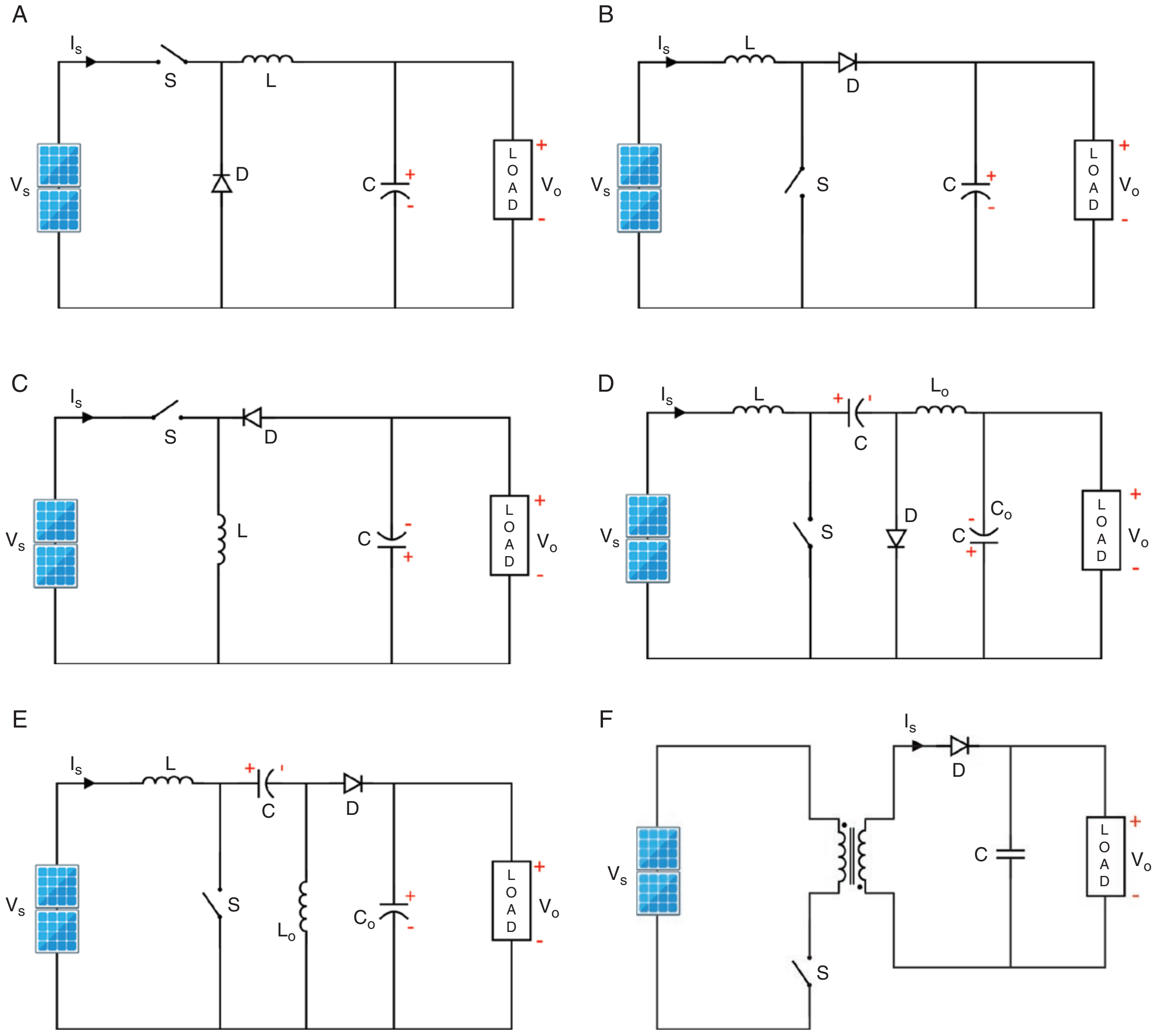

Fig. 2: Circuit topology of DC–DC converters for PV applications. (a) Buck converter, (b) boost converter, (c) buck–boost converter, (d) Ćuk converter, (e) SEPIC converter, (f) flyback converter.

$$V_{out} = V_{in}\left(\frac{D_t}{1 - D_t}\right) \tag{4}$$

Several aspects must be considered when applying the SEPIC converter, since it generates problems. This topology will produce ripple on the output side of the SEPIC converter when used with a high-frequency transformer [54–56]. In addition, specific harmonics are induced during AC–DC conversion. It causes ripples in the AC current, decreasing the power factor. So running the SEPIC converter in critical conduction mode (CRM) or boundary conduction mode (BCM) can be thought of to fix the PFC on the AC side [57].

The SEPIC converter has been widely applied to solar energy harvesting systems. To achieve maximum power, it employs various control methods, including SMC, PI control, dP/dV feedback control and FLC [58–60]. In addition, this topology can implement sensorless control of solar-powered DC motors, which means it can be applied to support green transportation [61]. In addition, a soft-switching technique can be used to achieve better performance by reducing losses during the operation of the converter [62, 63].

2.6 Flyback converter

The flyback converter is generally applied to PV systems for low power-level ranges [64]. This topology has also become a standard solution for offering a high-gain converter involving a transformer device. However, the transformer device requires significant air gaps for high-power applications to save enormous energy. Consequently, it results in low magnetizing inductance and makes this converter suffer from significant flux leakage. In addition, it is implicated in poor power-transfer efficiency. This topology is developed from the buck–boost circuit, in which the transformer device isolates the electricity between the source and the output, as shown in Fig. 2f. The transformer turns the ratio coil, the primary side (N_p) and the secondary side (N_s), which can be adjusted to regulate the output voltage. Equation (5) shows the duty-cycle calculation in the flyback converter:

$$D_t = \frac{V_{out} \times N_s}{(V_{out} \times N_s) + (V_{in} \times N_p)} \tag{5}$$

Although the flyback converter provides poorer efficiency than the Ćuk converter, it generates a non-inverting output voltage, which is more applicable to many applications. In addition, the Ćuk converter produces a high current in the switching device and the output diode, which are the disadvantages when applying it [65]. The flyback converter can partially discharge energy in the transformer magnetizing inductance. It causes the inverter to behave as an off-load voltage source. Consequently, flyback converter operations in CCM are not very popular [66], so BCM solutions provide higher power levels and a wider switching-frequency bandwidth. Due to the variable switching frequency [67], this scheme makes it difficult to obtain a precise relationship between the converter output current and good current. Meanwhile, the efficiency performance of the flyback converter can be improved by using the zero-voltage-switching technique [68] or the soft-switching method by clamping circuits and resonance-based flyback topology [69].

3 Advanced techniques considered for improving DC–DC converter performance

This article covers several types of DC–DC converters that are considered conventional. Among the various converters mentioned, it is well known that the boost converter is the topology type utilized most frequently in solar energy harvesting systems [70]. Much research has been done to build a novel topology based on boost converters to obtain a significant voltage gain using sophisticated approaches. This is because traditional boost converters only produce a limited voltage gain. Fig. 3 illustrates how the DC–DC converter topology categorization should be considered for more sophisticated solar energy collection systems.

3.1 Voltage-multiplier cell

As can be seen in Fig. 4, the structure known as the voltage multiplier cell (VMC) incorporates several passive components, including diodes and capacitors. Because of this, it is possible to multiply the voltage that is being put in, in order to reach a greater voltage that is being produced. To obtain a higher voltage from a DC–DC converter, it is possible to use any of several distinct cell topologies used in VMCs. These topologies are illustrated in Fig. 5. The VMC has been integrated into a more complex circuit along with several step-up DC–DC converters to produce a high-gain converter. In the paper [71], the authors offer a VMC-enhanced quadratic boost converter. The proposed converter requires only two inductors and can achieve significant voltage gain. Another suggestion in [71] is for a non-isolated high-step-up DC–DC converter paired with a VMC. As a clamp circuit, it uses magnetic coupling and a VMC, with the latter dampening the voltage spike that would otherwise occur across the switching device. Because of this, it is possible to improve the effectiveness of the systems.

The proposed converter using a VMC and an asymmetric coupled inductor (CI) has been introduced by [72]. The proposed converter can recycle the leakage energy from the inductor and manage the voltage spikes. Therefore, the efficiency resulting from this can be improved. Some topologies combine an interleaved boost converter with a VMC to achieve high voltage gain while putting minimal strain on semiconductor components [73–75]. Also, a non-isolated high-step-up DC–DC converter with a

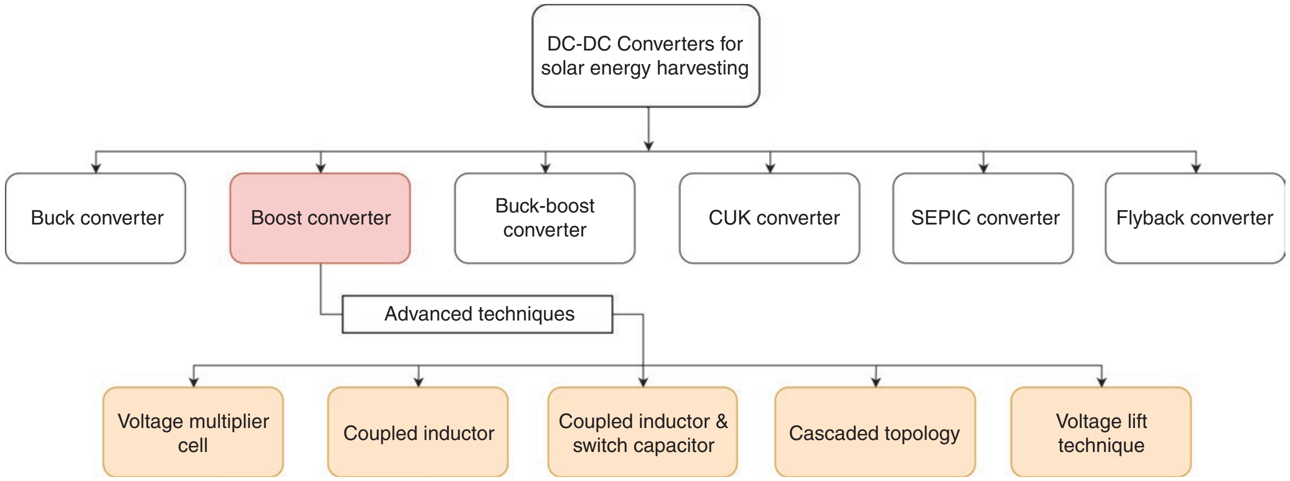

Fig. 3: Classification of DC–DC converter topology for solar energy harvesting

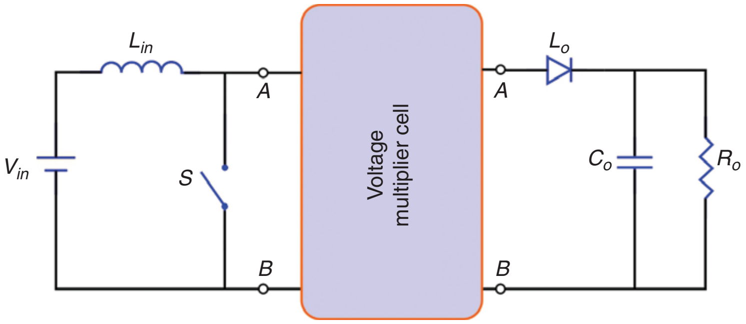

Fig. 4: DC–DC converter with VMC circuit

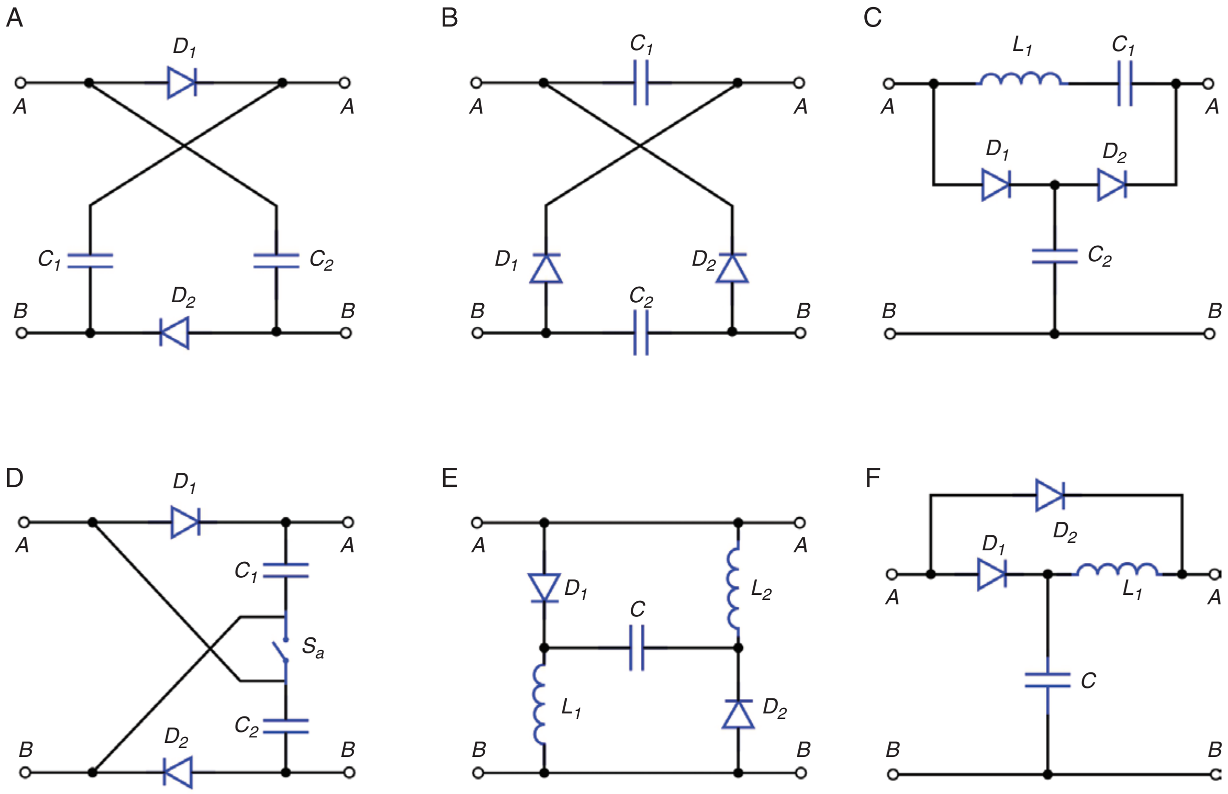

Fig. 5: Variation in VMC topologies. (a) Basic VMC cell Model 1; (b) basic VMC cell Model 2; (c) basic VMC cell Model 3; (d) VMC cell with auxiliary switch; (e) C & I-based VMC cell, (e) VMC cell that is typically inserted before the main switch.

VMC topology and a CI is proposed [76]. This results in a high gain with transfer energy saved in the coupled inductance. By adding a VMC, the proposed topology converter can enhance the output voltage more efficiently.

The VMC has become a popular strategy to increase the output voltage of the step-up converter. The major features offered are modular with a simple structure consisting of a diode and a capacitor. It also provides low voltage stress on the semiconductor components. Some drawbacks must be considered, such as (i) limited voltage gain, (ii) increasing the number of components while decreasing the number of multipliers and (iii) poor voltage regulation [77]. In contrast, modifying the step-up DC–DC converter with a VMC remains helpful for renewable-energy applications [73–75, 78–83]. These modified converters are very suitable for PV systems because they increase the PV output voltage to a higher level according to the load required. Moreover, this scheme is considered for application in grid-connected PV systems.

3.2 CI

When designing a non-isolated DC–DC converter, CIs have emerged as essential components. They can store energy during each switching period, which can later be transferred to the load. Since not all applications require electrical isolation, applying a CI to modify the conventional topology of the DC–DC converter becomes a technique that can be considered for safety, as shown in Fig. 6. Fig. 7 shows the variant of the CI cells that are being used at the same time. In most cases, the step-up DC–DC converter will benefit from adding this component through an increase in voltage gain. Changing the turn ratio of the CI and recovering energy from the leakage inductance are both necessary steps to complete the process. In addition, the CI can supply switching devices with a low voltage when the device is in the OFF state [84]. Therefore, involving a CI is still required for researchers in order for them to propose a non-isolated DC–DC converter.

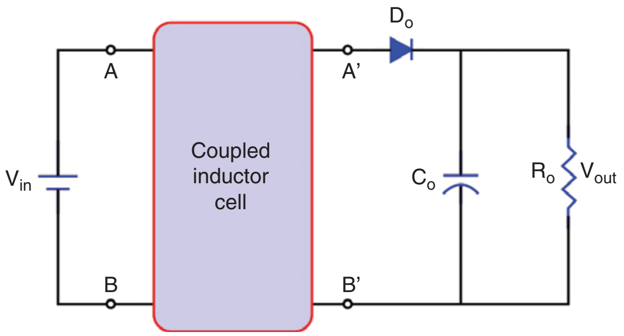

Fig. 6: Boost converter with CI cell

A high-step-up DC–DC converter that utilizes dual CIs in series connection is presented in [85]. In addition, the proposed converter uses an active clamp circuit with a combined regenerative snubber. A new high-step-up DC–DC converter involving CIs is proposed in [86]. Some researchers use an interleaving technique and a VMC is combined with CI cells to achieve high-gain conversion while maintaining good performance [76, 87, 88]. Most of the proposed step-up DC–DC converters are intended solely for RES applications, designed to raise voltages from lower levels to higher ones. One factor that must be considered is the high input-current ripple that might take place in the proposed converter. It calls for a sizable input filter and delays the reverse-diode recovery because of the leakage inductance. Adding CI components

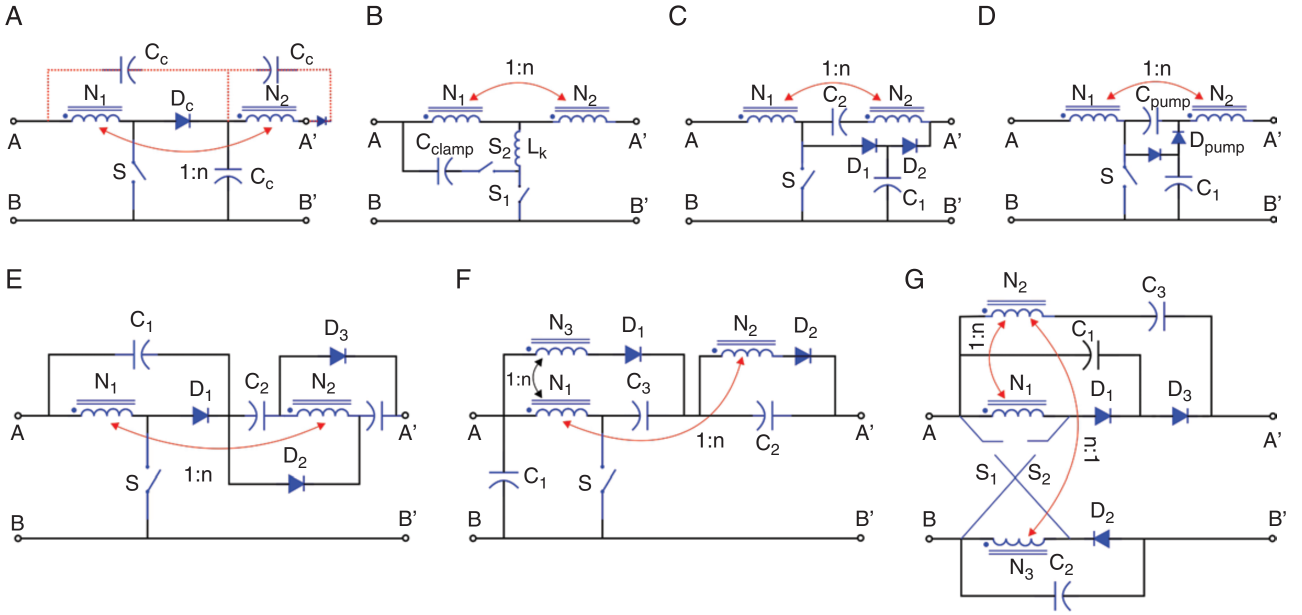

Fig. 7: Schematic of the coupled-inductor family. (a) Basic type; (b) active clamp type; (c) active clamp with snubber; (d) charge pump + active clamp type; (e) high-step-up charge pump + active clamp; (f) three-winding CIs; (g) three-winding with charge pump.

will also increase the size and cost [89]. Additionally, the structure of the DC–DC converter with the addition of a CI can be found in the literature [76, 87, 89–95]. This structure can be found in these references.

3.3 CI and switched capacitor

Fig. 8 shows the general architecture of CI and switched capacitor (SC) circuits in a DC–DC converter to obtain high voltage conversion. Moreover, it was used by the high-step-up DC–DC converter to accept a wide voltage-conversion range [96, 97]. The CI component achieves voltage gain by regulating the turn coil ratio on both the primary and secondary sides. Meanwhile, the SC circuit limits the voltage stress across the active and passive semiconductor components. Many researchers have investigated the modified step-up DC–DC converter with a CI component, and SC cells can be found in the literature [98–102]. In [98], researchers combine the advantages of SC cells, CI components and VMCs, respectively. The addition of SC cells reduces the stress of switching devices and helps to generate voltage gain. Due to the ability to raise the output voltage, combining the CI component and SC cells, as shown in Fig. 9. Using the VMC, the energy that leaks from the CI is sent back to the output terminals to perform lossless passive clamping.

Similar work is also presented by [99], but the type of CI used is three windings. In addition, SC cells and VMCs have dual structures. Current and voltage stress can be reduced by applying dual structures. It is proportional to increasing the weight and the cost converter. In [100], a similar combination converter is proposed, but no additional snubber circuit is attached. Then, it is further modified in [101] by adding one diode and one capacitor. Thus, the voltage gain can be higher and the voltage across the semiconductors is half of the output voltage.

Due to the ability to raise the output voltage, combining the CI component and SC cells, as shown in Fig. 9, has become a fashionable way to obtain more voltage-gain conversion. It increases the output voltage from PV sources, making it more useful for broad applications. The number of components must be considered when designing the step-up DC–DC converter topology with CI and SC cells. It impacts the weight and complexity of the converter layout itself. In addition, proper strategy control should be considered to achieve better performance.

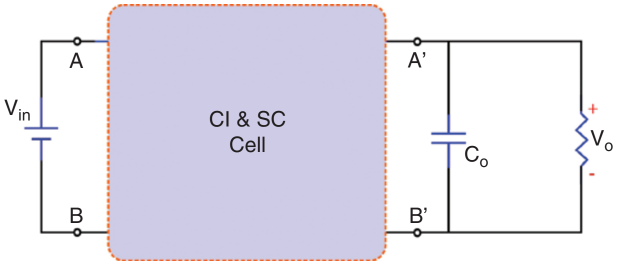

Fig. 8: CI- and SC-based DC–DC converter

3.4 Cascaded topology

The multistage converter connection is the most straightforward approach to increasing the voltage gain. It is popularly mentioned as a cascaded or multilevel topology composed of two or more step-up DC–DC converters [103]. The family of cascaded topology DC–DC converters is shown in Fig. 10. Therefore, the cascaded topology can obtain a higher voltage gain than the conventional step-up DC–DC converter [104]. Due to its ease of implementation and analysis, many researchers have developed the step-up DC–DC converter based on cascaded topology for RESs, such as solar energy harvesting system applications.

Studies in [105] and [106] proposed a cascaded converter involving a single switching device. It simplifies the semiconductor device by reducing the number of components used and parasitic elements that occur. Then, the novel cascading topology based on a boost converter is introduced by [107] with reduced conduction losses. They propose a hybrid cascaded converter based on boost topology and integrated with a VMC [108]. The main feature offered is that input-current ripples are reduced. It can be realized due to the two parallel primary windings in the CI component.

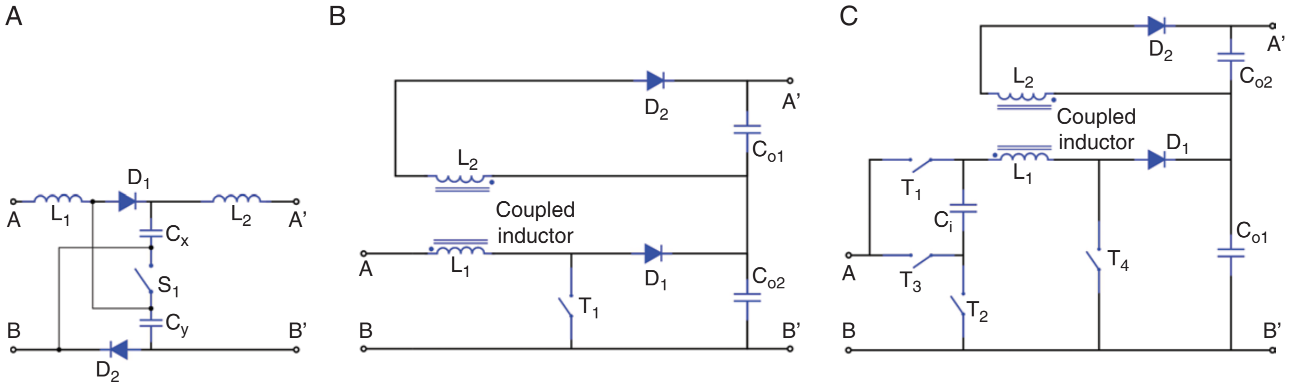

Fig. 9: The structure of CI and SC cells. (a) SC circuit, (b) CI circuit, (c) SI and SC circuit.

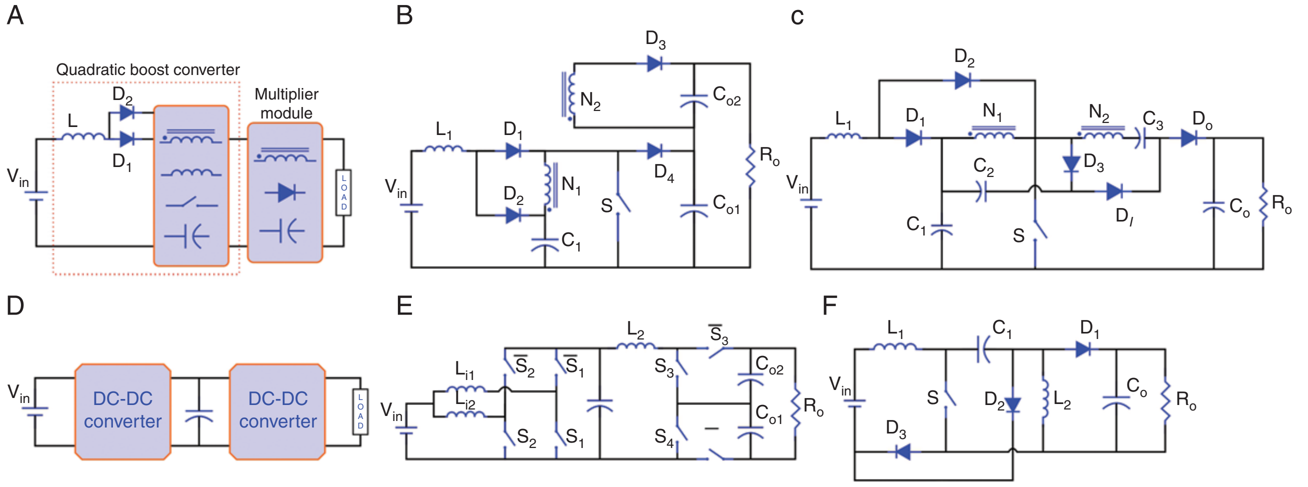

Fig. 10: Schematic of hybrid cascaded DC–DC converter families. (a) Generalized schematic of the quadratic hybrid cascaded converter; (b) and (c) families of the quadratic-type converter with hybrid cascaded connection; (d) generalized schematic of the cascaded converters; (e) and (f) families of the conventional converter with hybrid cascaded connection.

As explained previously, the cascaded converter topology is still a good technique for various voltage-amplification applications [109]. However, the main concern when applying this approach is the number of components used. These will increase weight, size, design complexity and cost for the higher voltage gain. In addition, the other technical drawback is that power losses increase due to parasitic elements, which impacts lower efficiency results. The cascading topology of the DC–DC converter is commonly used in medium- to high-power applications [110]. Furthermore, some modified topologies can be found in published works [103–108, 111].

3.5 Voltage-lift techniques

The voltage lift (VL) technique was popularly applied to the basic step-up converter. Fig. 11 shows the basic architecture of the DC–DC converter with VL cells and the variation in VL cells that can be applied in the DC–DC converter is shown in Fig. 12. This technique was introduced by [112] and has become a helpful method to raise the output voltage of the DC–DC converter. It works by charging the capacitor to a specific voltage sourced by the input voltage. The output voltage is then proportional to the voltage level of the charged capacitor. Repeating this operation with advanced capacitors creates rebound, triple-lift and quadruple-lift circuits, in which the output voltage can be improved.

Furthermore, [113–116] used the VL technique, modified with the boost converter, to achieve high-voltage-gain conversion. In [117], the VL technique is combined with a voltage doubler or VMC to the quadratic boost converter to increase the input voltage approximately four times and decrease the voltage stress through the switching devices by one-half of the output voltage. [117] proposes a modified boost converter with the VL technique and a single switch. This structure makes the design less complicated because it is easier to understand.

The performance of the VL technique is based on energy-storage elements such as inductors and capacitors. In addition to increasing the output voltage, another advantage is that it can operate over a wide power range, from low-power to high-power applications, while remaining efficient [92]. The VL technique is simpler to implement, has a higher power density and produces less output-voltage ripple than the other advanced step-up methods. As a result, the VL technique is appropriate for solar energy harvesting systems [118, 119].

4 Comparison of DC–DC converter and step-up advanced techniques considered

The variations of DC–DC converter topologies discussed in this article are the most suitable for PV energy-harvesting applications.

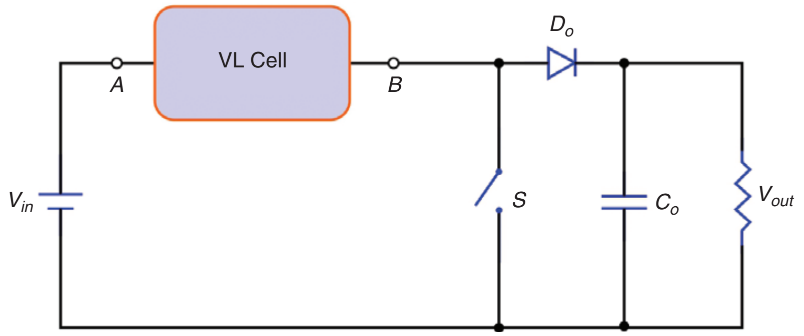

Fig. 11: Boost DC–DC converter configuration with VL cell

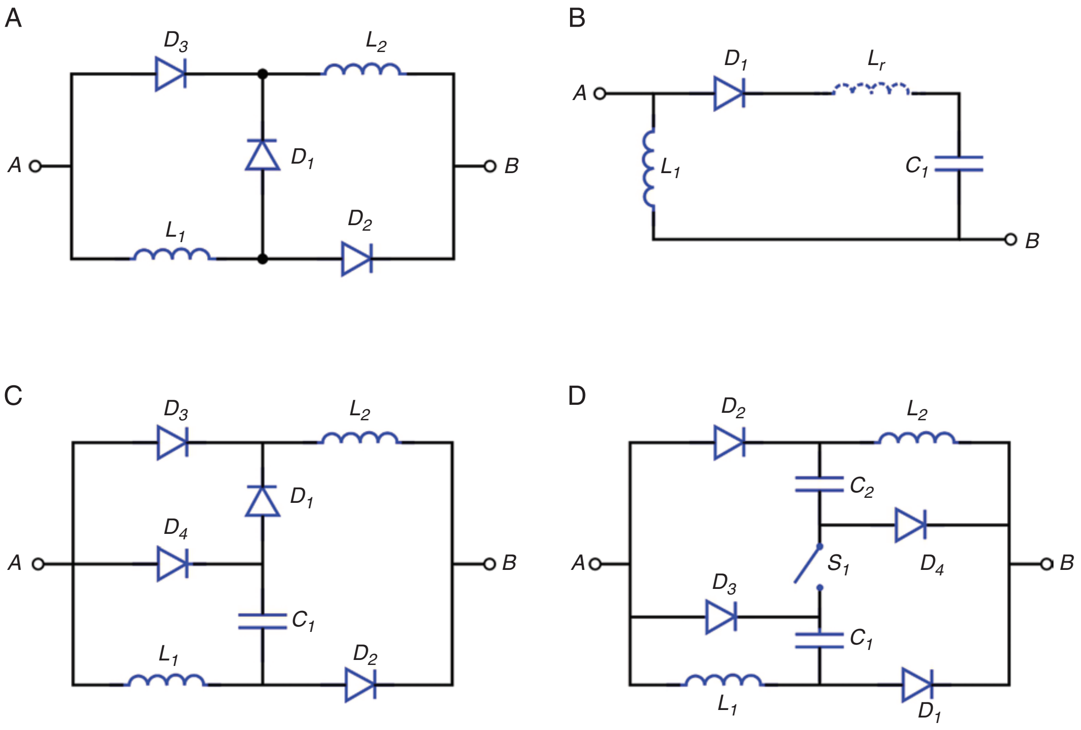

Fig. 12: Variations in VL cell topology. (a) Basic cell; (b) elementary-lift cell; (c) self-lift cell; (d) double self-lift cell.

The focus of this paper is on the step-up DC–DC converter that is used to increase PV output voltage. Boost, buck–boost, Ćuk, SEPIC and flyback converters are chosen due to the voltage step-up capability. They are widely used in many applications because of their more straightforward structure than other converter topologies, especially for PV energy-harvesting applications.

The boost converter becomes the primary topology choice for proposing a novel step-up converter dedicated to solar energy harvesting applications. A study by [120] reviews DC–DC converters based on boost topology for low power with high gain involving modification circuits. From 27 literature references, seven modification strategies are identified: VMC, voltage doubler, CI component, CI and SC cells, switched inductor (SI) and SC, cascade technique and VL technique. Each technique is judged on how well it could increase the voltage, how many parts it has, how much voltage it could manage, how much power it could manage, how hard it is to build and how well it works.

According to the evaluation results, the SI, SC and voltage-doubler topologies perform worse than the other options. Both solutions result in modified boost converters with limited gain and considerable voltage stress, which contributes to their poor efficiency. The number of components employed also increases the complexity of the hardware. As a result, the comparison provided in this article focuses solely on five modification topology options in terms of implementation cost and tracking efficiency in order to acquire maximum power in solar energy harvesting applications. Table 1 compares standard topology and advanced strategies for improving DC–DC converter performance, focusing on increasing the voltage from solar energy harvesting systems. Each comparison is examined in terms of the characteristics it provides, as well as the benefits and drawbacks that resulted.

Each advanced modification process has its own set of traits, which include: (i) VMC: low cost, modular, simple structure, better for low power ratings; (ii) CI component: popular voltage-boosting approach with high power-handling capability, used for both isolated and non-isolated applications and best for low power ratings; (iii) CI and SC: lower voltage stress on the switch than CI, a more significant number of components and a more complex structure, a common approach to produce more voltage-gain conversion, and a wide voltage-conversion range; (4)

Table 1: Comparison of DC–DC converters and advanced techniques for solar energy harvesting systems

		Features	Pros	Cons
Basic topology	Boost [121–123]	•Low hardware complexity •Simple to control •Inexpensive cost •Compact design •Familiar to use	•The dwindling number of components •Suitable for low to high PV power applications •Medium converter efficiency •Can support MPPT in achieving high efficiency	•Voltage-gain limitation •High voltage stress •Extreme duty cycle to achieve high step-up voltage
	Buck–boost [124–126]	•Low hardware complexity •Simple to control •Inexpensive cost •Compact design •Familiar to use	•The low number of components •Suitable for low to high PV power applications •Medium converter efficiency •Can support MPPT in achieving high efficiency •Non-linear relationship between duty cycle and output voltage	•Voltage-gain limitation •High voltage stress •Voltage imbalance for multi-input and multi-output applications •High output ripples •Discontinuous output current
	Ćuk [89, 127, 128]	•Low hardware complexity •Simple to control •Inexpensive cost •Compact design	•The low number of components •Suitable for low to medium PV power applications •Medium converter efficiency •Can support MPPT in achieving high efficiency and stability under varying atmospheric conditions •Using capacitors for power transfer and energy storage •Non-linear relationship between duty cycle and output voltage	•Medium voltage gain •High voltage stress •Negative output polarity concerning input •Drop efficiency in multiple output network •Need complex compensation circuit to operate converter properly •The presence of resonance of the L–C pair makes discontinuous output current uncontrolled
	SEPIC [129–131]	•Low hardware complexity •Simple to control •Inexpensive cost •Compact design •Familiar to use	•The low number of components •Suitable for low to high PV power applications •Medium converter efficiency •Can support MPPT in achieving high efficiency and stability under varying atmospheric conditions •Non-inverting output •Non-linear relationship between duty cycle and output voltage	•Medium voltage gain •High voltage stress
	Flyback [132–134]	•Medium hardware complexity •Simple to control •Inexpensive cost •Familiar to use	•The low number of components •Suitable for high PV power applications •Can support MPPT in achieving high efficiency •Component more safety from short circuit •Provided isolate electricity	•Bulk converter design •High voltage stress •Large leakage flux •Poor energy-transfer efficiency
Advanced techniques	VMC [78, 120, 135–139]	•Simple technique and modular structure •Inexpensive cost	•Can achieve extremely high gain •Suitable for low to high PV power applications •Efficiency following basic topology used •Can support MPPT in achieving high efficiency	•More component counts •High voltage stress •Poor voltage regulation
	CI [33, 121, 122, 126, 127]	•Compact structure •Familiar to use •Can integrate into various topologies	•Can achieve extremely high gain by increasing the turns ratio •The low number of components •Suitable for low to high PV power applications •Efficiency following basic topology used •Can support MPPT in achieving high efficiency •Enhanced power-handling ability •Good voltage regulation	•Bulk converter design •High voltage stress •Non-modular •Resulting leakage inductance •Complex manufacturing in dual-coupled inductors
	CI and SC [91, 97, 98, 140–143]	•Can integrate into various topologies •Familiar to use	•Can achieve extremely high gain by increasing the turns ratio •Suitable for low to high PV power applications •The low voltage stress on power switches •Increased efficiency results from basic topology used •Can support MPPT in achieving high efficiency •Energy-leakage handling capability	•More component counts •Bulk converter design •Poor voltage regulation •Inrush current
	Cascaded topology [108, 120, 144–146]	•Modular structure •More variation of topology	•Can achieve extremely high gain •Suitable for medium- to high-power PV applications •Efficiency following basic topology used	•More component counts •Bulk converter design •An auxiliary clamp circuit is required to restrict the voltage stress •Difficult to operate with the MPPT to achieve high efficiency •Poor voltage regulation

Table 1. Continued

	Features	Pros	Cons
VL technique [114, 120, 135, 147–151]	•More compact and simple structure •Familiar to use	•Can achieve extremely high gain •Suitable for low- to medium-power PV applications •Reduced voltage stress •Increased efficiency results from basic topology used •Can support MPPT in achieving high efficiency •Can integrate with CI to recycle leakage inductance energy •Reduced input-current ripple	•More component counts •Bulk converter design

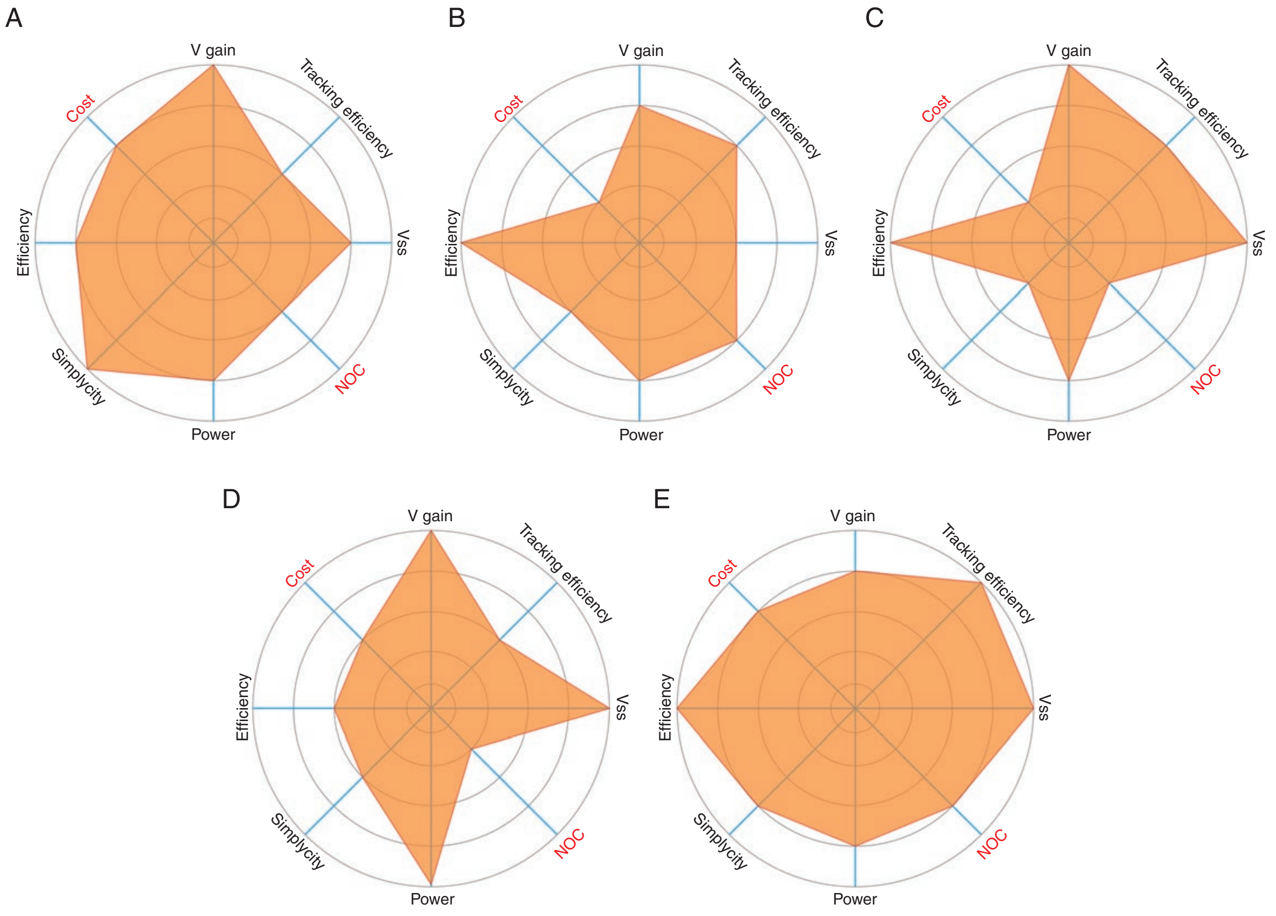

Fig. 13: Performance comparison of the advanced technique for DC–DC converters. (a) Voltage-multiplier circuit; (b) coupled inductor; (c) coupled inductor and switch capacitor; (d) cascaded topology; (e) voltage lift.

cascaded topology: it uses several stages of converter modules, voltage gains are increased linearly or exponentially, requiring more components, and it is suitable for medium- to high-power applications; and (5) VL technique: simple structure but superior performance, increased efficiency and is suitable for recycling CI leakage.

VMC, CI and VL methods can make a more straightforward hardware structure possible. When considering the cost of implementation, the most appropriate options are the VMC, CI, CI and SC, and VL approaches. In addition, the techniques have evolved to where they are now suited for fast-tracking applications that capture solar energy. Modification can be achieved by CIs using SC and VL approaches to achieve potentially productive efficiency. From the power-application point of view, low-power uses are VMC, CI, CI and SC, and VL methods. All advanced approaches can be used for medium-power applications, while VMC, CI, CI and SC, and cascaded topology can be used for high-power applications. Fig. 13 shows the final comparison of all advanced strategies discussed in this paper. It should be noted that, specifically for term cost and number of components, the assessment points are reversed, meaning that the larger the real value, the smaller the assigned value on the chart.

5 Conclusion

Various types of DC–DC converters have been evaluated, including basic topology, modified topology and innovative techniques to increase their performance, emphasizing applications of solar energy harvesting systems. Boost converters are the architecture that is the most widely used to raise the output voltage of PV systems. As a result, the development of boost converters is still being carried out by adding more complex approaches to achieve higher performance levels. Comparisons have been made between each advanced technology to provide precise information regarding the complexity of the hardware, the cost of implementation, the tracking efficiency, the efficiency of the converter and the power-level ranges. According to the comparison findings, the modified boost converter that utilizes the VL technique can be deemed more appealing in terms of performance. In conclusion, this work can be utilized to map the appropriate advanced methodologies for the design of a novel step-up DC–DC converter that is based on boost topology and is intended for usage in solar energy harvesting systems.

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Conflict of interest statement

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

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