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Modernisation of DC-DC converter topologies for solar energy harvesting applications: A review

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ABSTRACT

Solar photovoltaic (PV) power generation has grown in popularity as a renewable energy source due to the numerous advantages it provides. These advantages include the ease with which it may be assigned, the absence of noise, the longer life, the absence of pollution, the shorter installation time, the high mobility and portability of its parts, and the ability of its output power to satisfy peak load needs. DC-DC converters are commonly used in solar energy harvesting systems because they enable more efficient usage of solar cells. One of the challenges is selecting an appropriate converter, which has an impact on the operation of the PV system. The modernization of various distinct DC-DC converter topologies for solar energy harvesting systems is discussed in this article. Boost, buck-boost, single-ended primary-inductance converter (SEPIC), Cuk, Zeta, and Z-source are some of these topologies. The topologies have been compared in order to provide extensive information on the hardware complexity, implementation cost, efficiency of the energy transfer elements, tracking efficiency, and converter efficiency. This paper will be useful as a handy reference in choosing the best converter topology for solar energy harvesting applications.

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1. INTRODUCTION

Because of the huge increase in the extraction of fossil fuels, which has a negative influence on the environment, it has become increasingly desirable to employ renewable energy sources. It motivates a large number of researchers to devote more effort to researching renewable energy sources (RES). Solar photovoltaic (PV) technology is becoming increasingly popular in power plants for a variety of reasons, including the fact that these plants have a significantly longer lifespan, are less harmful to the environment, require less maintenance, and can generate more power to meet the demands of various loads. The most essential aspect is that solar energy is really renewable. It is available every day and can be used anywhere in the world. This solar energy harvesting technology is becoming more popular as an alternative to fossil-fuel-generated electricity. A solar water heater is an excellent example of a solar energy harvesting application that is widely used in sunny climates around the world [1]–[22].

Power electronic interfaces or power converters, such as DC-DC converters, are required to convert the low DC output voltage from a solar PV energy harvesting system to the voltage rating required by any suitable utilization voltage. The topologies of DC-DC converters are intended to fulfill the specific demands of DC loads. There are numerous types of DC-DC converters that can operate as switching-mode regulators, regulating the unregulated DC voltage with conversion to an appropriate utilization voltage by increasing or reducing the value of the DC output voltage. Each converter requires a power switching device to turn on and off as needed. In addition, load matching and increased power output from the PV systems should be possible with the usage of DC-DC converters in conjunction with maximum power point tracking (MPPT) [16], [22]–[43].

However, the low DC output voltages that are generated by the PV array are subject to a wide range of variables, such as solar irradiation, sudden shifts caused by the effects of shadowing, ambient temperature, the cleanliness degree of the PV module surface, mismatching of PV modules, and a number of other factors. These variables can have a significant impact on the low DC output voltages that are generated by the PV array. Diverse power electronic DC–DC converters are developed so that this issue may be resolved, as well as so that a steady output voltage may be provided. The DC–DC converter has been around since the 1920s and was designed specifically for use with solar PV systems. It is an extremely important requirement that a DC-DC boost converter be developed in order to regulate the low and irregular DC output voltage coming from the PV arrays [7], [9], [44]–[46].

In recent years, the DC-DC converter has become an increasingly important component of systems that collect solar energy. It delivers a voltage that is better suitable for a wide variety of applications that use photovoltaic panels as the source [46]–[113]. When selecting DC-DC converters, it is important to take into consideration a number of different criteria, including high efficiency, high reliability, low conduction loss, economic viability, and low switching loss. As a direct consequence of this, researchers all around the world are consistently working on the creation of DC-DC converter topologies [114]–[118]. This paper provides a wider range of options for selecting DC-DC converters that are appropriate for a variety of power conversion applications. The tendency toward modernization of the DC-DC converter that is used for solar energy harvesting systems is the topic of discussion that is carried out in this study. It is connected to the topological structure, which includes both the benefits and the drawbacks. Additionally, a comparison of topologies is carried out in order to provide particular information and future research work linked to the development of DC-DC converters for solar energy harvesting systems. This comparison is carried out in order to offer specific information.

2. STRUCTURE OF A SOLAR PHOTOVOLTAIC ENERGY HARVESTING SYSTEM

Energy harvesting is the process of obtaining useful electrical power by gathering and transforming the energy that is already present in the surrounding environment from various sources. One of the interesting and potentially fruitful solutions to meet the ever-increasing energy demands of the globe is to collect energy from the sun. The total system for collecting solar energy is made up of a variety of different devices and components, including as PV arrays, MPPT controllers, DC-DC converters, batteries, loads (both AC and DC), and inverters [9], [11], [12], [16], [17], [58], [119], [120]. The comprehensive schematic block of the solar energy collecting system is shown in Figure 1.

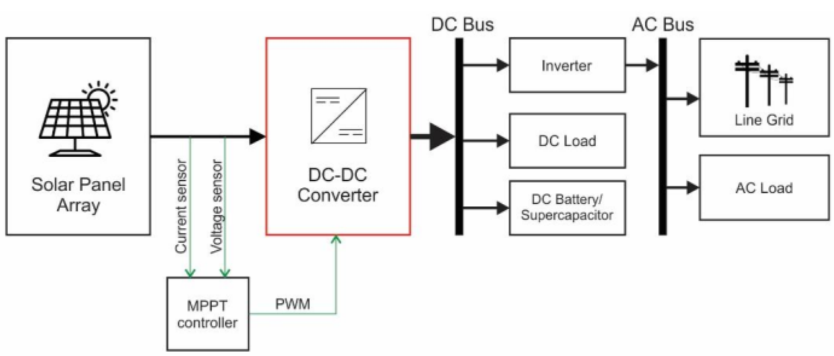

Figure 1. Structure of a solar photovoltaic energy harvesting system

Solar energy is converted or harvested by the solar photovoltaic array and then converted into electrical energy. To produce a more usable power output, the output is transmitted to the DC-DC converter. This component converts the PV-produced variable DC voltage into a fixed voltage that is proportionate to the load requirements. The MPPT controller simultaneously works to achieve MPP conversion from PV and provide a pulse width modulation (PWM) signal to drive the DC-DC converter's switching mechanism [22], [23], [25], [27], [28], [32], [38], [39], [42], [43], [52], [77], [81], [93], [94], [98], [108], [112], [121]–[146]. These two processes happen simultaneously. The output of the DC-DC converter may then either be connected to the inverter device, at which time it can either be connected to the grid or provide an AC load, or it can be used to supply load sides such as batteries or DC loads [21], [25], [38], [43], [50], [60], [88], [95], [107], [128], [147], [148].

2.1. Mathematical model of PV cell

The output current of the module (I_{pv}) may be calculated using Kirchhoff's Current law, as shown in Figure 2. Figure 3 depicts the I-V parameters of a solar cell. The I-V characteristics (the operating points of the PV generator) are affected by the load conductance:

$$I_{pv} = n_P I_L - I_d - \frac{V_d}{R_{sh}} \tag{1}$$

where I_d represents the diode current, I_L represents the light-generated current, n_P represents the number of cells connected in parallel, R_{sh} represents the shunt resistance and V_d represents the diode voltage. The diode current is denoted as:

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

where *A* represents the diode's ideality constant, I_{os} represents the reverse saturation current, *k* represents the Boltzmann's constant, n_s represents the cells connected number in series, *q* represents the electron charge, R_s represents the series resistance, *T* represents the cell temperature in Kelvin, and *v* represents the module's output voltage. When (2) is substituted for (1), the result:

$$I_{pv} = n_P I_{os}\left\{exp\left[\frac{q(v+I_{cell}R_s)}{n_s AKT}\right] - 1\right\} - \frac{V_d}{R_{sh}} \tag{3}$$

the mathematical model is built using the preceding equations [149], [150]. The maker of a PV module gives reference values for defined operating circumstances, such as standard test condition (STC). The light produced current (I_L) is affected by temperature and irradiance offer the equation for I_L [151], [152].

$$I_L = \frac{\phi}{\phi_{ref}}\left[I_{Lref} + \mu I_{sc}(T - T_{ref}\right] \tag{4}$$

Where I_{Lref} represents the light current at the reference condition, Tref represents the reference temperature, ϕ represents the irradiance, ϕ_{ref} represents the reference irradiance, and μI_{sc} represents the manufacturer supplied temperature coefficient of the short-circuit current. I_{Lref} and µIsc are given in a manufacturer's data sheet. In [10], the reverse saturation current I_{os} is reported:

$$I_{os} = D_f T^3 exp\left(\frac{-qE}{AKT}\right) \tag{5}$$

where D_f represents the diode diffusion factor, and *E* represents the band gap energy at 300 K. (1.12 eV for Si, 1.35 eV for GaAs) [153].

Figures 4 and 5 illustrate the output of a photovoltaic cell under conditions of an irradiation of 500 W/m^2 and a temperature of 323 K, respectively. These results are derived from (3) through (5). The impact of temperature change with constant irradiance was tested by setting the irradiance value to 500 W/m^2 and adjusting the temperature to 323 K, 360 K, and 373 K. These temperatures were chosen so that the effect could be studied [154].

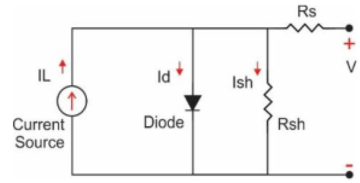

Figure 2. Circuit diagram of PV model [150]

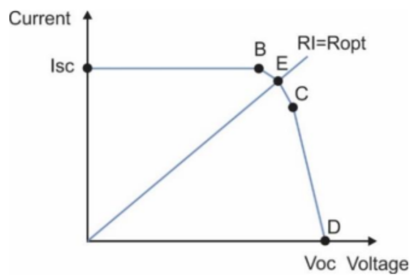

Figure 3. I-V Characteristics of solar cell with load line [150]

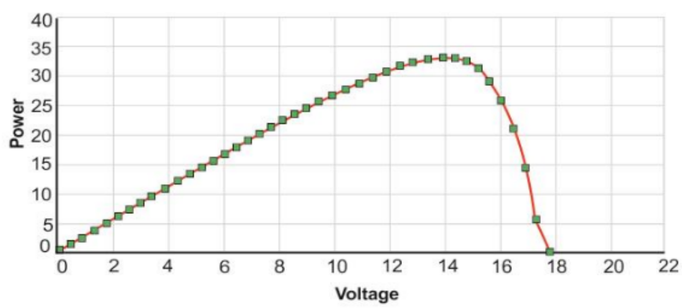

Figure 4. P-V characteristics of PV cell [150]

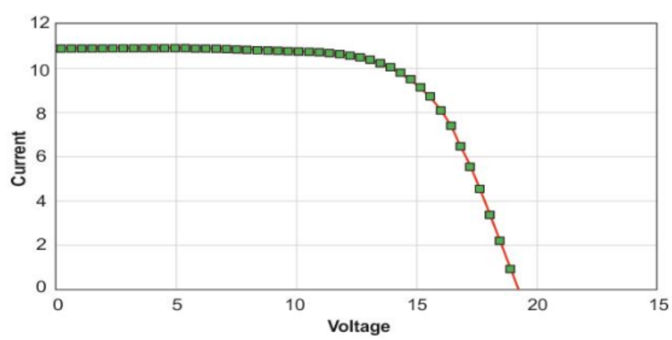

Figure 5. I-V characteristics of PV cell [150]

2.2 Maximum power point tracking (MPPT)

The operating point shifts depending on the amount of available sunlight and load. In order to make greater use of PV systems, the PV system needs to be able to perform at its optimal efficiency regardless of changes in the amount of available sunlight and the load being applied [155]. The maximum power point is the one and only location along the P–V curve at which the output power is at its highest value (MPP). Solar tracking is the traditional way that is utilized to get the most out of the energy that is collected [156][157]. One other approach that may be taken to get maximum power is called MPPT [6]–[8], [11], [12], [15], [19], [27], [28], [35], [41], [42], [48], [51], [52], [57], [62], [64]–[66], [69]–[71], [74], [77], [80], [82], [83], [85], [89], [90], [93], [95], [96], [98], [106], [108], [112], [113], [158]–[245]. The MPP can be detected with the use of an MPPT algorithm that is placed on the microcontroller [246]. This circumstance is depicted in Figure 1, which is a block diagram. Following the MPPT controller's successful tracking of the MPP, a triggering signal is sent to the converter switches. By changing the duty ratio, the load impedance may be adjusted and brought into alignment with the ideal internal impedance [247].

The PV current varies dramatically as the weather changes. MPPT needs quick dynamic action to follow the operational range if current is employed as a fixed variable. The change in voltage, on the other hand, is limited to 70-80% of Voc. As a result, PV voltage is often used as a control variable [248]. MPPT is based on measuring PV power and regulating PV voltage. The ratio of the input and output voltages can be suitably changed by altering the duty cycle of the converter [249], [250]. Numerous methods are utilized on a regular basis to accomplish the task of tracking maximum power point in PV systems [185]. These methods include hill-climbing, perturbation and observation (P&O), look-up table, incremental conductance (Inc-Cond), linearization-based, DC-link capacitor droop control, curve fitting, extremum seeking control, feedback voltage or current, feedback of power variation with voltage, feedback of power variation with current, firefly algorithm, fractional open-circuit voltage (FOCV), fractional short-circuit current (FSCI), artificial neural network (ANN), fuzzy logic, genetic algorithm, particle swarm optimization (PSO), ant colony based optimization, one cycle control (OCC), ripple correlation control (RCC), parasitic capacitance, and sliding-mode [6]–[8], [11], [12], [15], [19], [27], [28], [35], [41], [42], [48], [51], [52], [57], [62], [64]–[66], [69]–[71], [74], [77], [80], [82], [83], [85], [89], [90], [93], [95], [96], [98], [106], [108], [112], [113], [158]–[245].

In recent years, a variety of methodologies have been developed to monitor MPP in PV systems. The combination of ANN and the P&O algorithm is one of the available approaches [52], [174], [239]. This approach can determine the MPP in a short amount of time under a variety of weather conditions since it does not require costly irradiance sensors [251]. On the other hand, significant negatives include greater power oscillations and a complicated installation. Another technique for locating the MPP, this one utilizing current sweeping and analysed by Tsang *et al*. [252]. The controller for this approach does a significant amount of mathematical work. Mohanty *et al*. devised the grey wolf optimization in order to gather the greatest amount of electricity from the PV systems while they were partially shaded. The findings of the simulation are analysed and contrasted with those of the P&O and enhanced particle swarm optimization (PSO) methods [3], [6], [14], [26], [34], [70], [212], [214], [253], [254]. The results of the tests demonstrated that the grey wolf optimization works better than traditional algorithms in terms of tracking speed, ripple content, and extraction efficiency [255]. Wang *et al*. [256] describe an MPPT approach that is appropriate for long PV string. By narrowing the searching voltage range, rapid global MPPT, also known as R-GMPPT, is able to make tracking faster. Next comes the skipping and judgment procedure, which is followed by the lowering in the voltage range. Misjudging, on the other hand, can have an effect on how well the algorithm works.

3. CONVERTER TOPOLOGIES

In PV installations, DC-DC converters are provided so that solar cells may be utilized as effectively as possible [257]. In the vast majority of converters used in the solar energy sector, power semiconductor components like MOSFET and IGBT are heavily utilized. With a limiting voltage of up to 1.2 kV, the high voltage converter switches have a switching frequency of higher than 10 kHz. Despite the fact that the switching frequency of a high voltage converter is restricted to about one thousand hertz (kHz), due to increased switching loss. This restriction on the switching frequency was alleviated because to developments in the technology used in the fabrication of switching devices. Anthon *et al*. [258] demonstrated a high-power boost converter that runs at frequencies up to 300 kHz and uses a normally-on SiC JFET as the switching device. Utilizing a MOSFET that has a low drain-source on resistance is one way to cut down significantly on the amount of conduction loss [259]. The capacity to sustain output regardless of any fluctuations in input is the primary criterion for selecting DC-DC converters in photovoltaic (PV) systems. Other important considerations are cost, efficiency, and energy flow. It is important that the effect of voltage ripple on the output side of the PV module be as small as feasible [186].

The difficulty of the hardware involved in the converter comes from a number of aspects, including the choosing of the filter size and the gate driving circuit. When compared to the other converters, the single-ended primary-inductance converter, also known as the SEPIC, has a higher output voltage ripple on the output side. The results of a comparison of the hardware requirements, costs, and efficiencies of several types of converters are presented in Table 1. These converters include boost, buck-boost, SEPIC, Cuk, Zeta, and Z-source. Calculating the effectiveness of a converter, $\eta_{converter}$ requires using the (6). The tracking efficiency may be expressed as a ratio between the power at the panel's terminals and the panel's maximum possible output of power, denoted by $P_{pv\,\max}$ [260]. The (7) that measures extraction may also be used to track efficiency $\eta_{extraction}$.

$$\eta_{converter} = \frac{V_{out} * I_{out}}{v * I_{pv}} = \frac{(v * I_{pv}) - P_{losses}}{v * I_{pv}} \tag{6}$$

$$\eta_{extraction} = \frac{v * I_{pv}}{P_{pv\,\max}} \tag{7}$$

where V_{out} represents the voltage of the converter at the output side, I_{out} represents the output current of the converter, v represents the voltage at the output of the panel, I_{pv} represents the current at the output of the panel, and P_{losses} represents the losses of the converter.

In renewable energy systems, the non-isolated topologies of converters have been studied in many papers and can be simplified into the category depicted in Figure 6. Although SEPIC, buck–boost, and Cuk converters have a significant ripple in the load current, these converters provide a great deal of leeway in terms of the output voltage they may produce. In contrast to these other topologies, the buck topology has a significant current ripple [261]. There is no way to combine the inductor into the filter and converter to make a single magnetic core for the buck and boost converters. When contrasted with SEPIC and Cuk, these converters produce a tremendous amount of output [262]. Because the output voltage of the PV array is always lower than the voltage of the grid, buck converters are almost never utilized in the role of DC-DC converters. A large capacitor is necessary in order to smooth out the array current since the current output from the array to the converter comprises significant current spikes. In their study on PV systems, Taghvaee *et al*. [263] studied the qualities of boost, buck–boost, SEPIC, Cuk, Zeta, and Z-source converters. Even if the input current has severe ripple and noise problems, the buck–boost converter is the one that is able to attain the greatest performance out of all of these converters. This is the case regardless of the environment or the load.

When the duty ratio changes from 0 to 1, the load resistance (R_L) determines how much the buck converter's input resistance shifts toward infinity. If the input resistance is the same as R_{opt}, the system will function at the MPP setting, as shown in Figure 3. Therefore, MPP tracking is not achievable in buck converters when the resistance of the load is larger than R_{opt}. When the duty ratio changes from 0 to 1, the boost converter's input resistance shifts from 0 to load resistance. This happens vice versa. Because of this, MPP tracking cannot occur if the load resistance is lower than the R opt value. When the duty ratio changes from 0 to 1, the buck boost converter's input resistance might be anywhere from 0 to infinite, depending on the setting. Because of this, buck-boost converters are capable of achieving MPP regardless of the magnitude of the load resistance [117], [270], [273], [276].

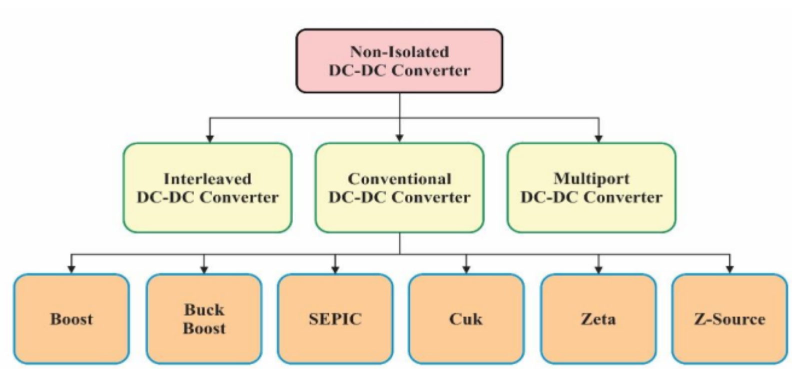

Figure 6. Non-isolated DC-DC converter category

Table 1. Comparison of various converters

Converter Topology	Hardware Complexity	Production Cost	Average Tracking Efficiency	Efficiency of the Converter	Energy Transfer Elements
Boost	L	L	L	H	***L***
Buck-Boost	M	L	H	M	***L***
SEPIC	H	M	H	M	***LC***
Cuk	M	M	H	M	***C***
Zeta	H	M	H	H	***LC***
Z-source	H	M	H	H	***LC***
References	[264], [265]	[118], [265], [266]	[267]–[270]	[148], [265], [271]–[273]	[118], [261], [274], [275]

L: Low, M: Medium, H: High, ***L***: Inductor, ***C***: Capacitor, ***LC***: Inductor and Capacitor

PV applications also make use of advanced converters such as the Luo converter (Ultra-lift and Positive-output super-lift), the KY boost converter, and the quadratic boost converter [276]. However, research on the use of these converters in PV systems is still in its early stages. Kumar *et al*. [277] explored the construction of a negative output elementary Luo converter that is utilized to produce MPP with the assistance of an Inc-Cond MPPT method. Ghamrawi *et al*. [45], [278] investigated the effect that include MPPT in the control strategy has on the stability of a quadratic double boost converter that also captures MPP. This is suitable for use in systems that work in essentially constant weather conditions, such as solar applications in space, and it is an appropriate application for use in such systems. Sivakumar *et al*. [279] investigated the achievement of buck-boost, Cuk, SEPIC, ultra-lift Luo, and positive-output super-lift Luo converters. The mathematical modelling of state space was introduced. When compared to alternative topologies, the scientists found that ultra-lift and super-lift Luo converters suffer from substantial power loss in the diode. Tomaszuk and Krupa [280] investigated high-efficiency converter topologies for renewable applications in depth.

In yet another technical evaluation of DC-DC converters using MPPT, Hossain *et al*. [281] examined the performance of several types of converters, including their control applications. Khosrogorji *et al*. [282] investigated current advances in magnetic and electric multi-input converters. Neng *et al*. [283] offered an overview of three-port DC-DC converters that meet the condition of two inputs and one output. It is possible to connect one input to the output of the solar panel. The battery can be linked to the system using the second input. The output port is able to establish a connection to the grid. When opposed to their isolated counterparts, three-port converters that are not isolated can have benefits such as cheaper costs and higher levels of dependability. In the review [45], the non-isolated DC-DC converters that are chosen for MPPT of PV systems together with their selection criteria were the primary emphasis. In their study, Zhang *et al*. [284] looked at the challenges that traditional voltage source and current source converters face, such as lower output gain and shoot-through. The authors came to the conclusion that the impedance source converters are capable of overcoming these difficulties. When the equivalent impedance approaches infinity, the impedance-source converter is classified as a current source converter. When the equivalent value of the impedance approaches the null point, the impedance-source converter is deemed to be the same as a voltage source converter.

In order to conduct an in-depth analysis of the properties of the converter, modelling of the converter is carried out. A number of different approaches, including state space averaging (SSA), circuit averaging, and decomposition of Fourier series, can be utilized in the process of circuit modelling. As a result of the incorporation of Fourier series study into a mathematical model, the capability of applying control rules is constrained when using Fourier series decomposition. In the process of designing the feedback-control loop for DC-DC converters, a simple signal model can be of great assistance. When constructing the power stage of converters, circuit averaging and SSA are two methods that are utilized [285].

4. MODERNISATION OF DC-DC CONVERTER TOPOLOGIES FOR SOLAR ENERGY HARVESTING

In this section, the modernization of DC-DC converters in terms of non-isolated step-up configuration for solar harvesting energy applications, such as boost, buck-boost, SEPIC, Cuk, Zeta, and Z-source, are presented.

4.1. Boost converter

The voltage on the load side is larger than the PV voltage in solar harvesting energy applications. It implies that the step-up voltage procedure must be carried out, and the boost converter becomes one of the several topologies that may be chosen and included into an MPPT [32], [36], [55], [58], [78], [81], [82], [93], [102], [103], [110], [132], [135], [258], [264], [276], [278], [286]–[300]. The boost converter is the most popular option, and it has been manufactured by industry [295]. Several improvements have been proposed by researchers to increase boost converter performance. Huber and Jovanovic [301] investigated the use of a cascade structure to boost voltage gain while decreasing ripples. The initial stage of the cascaded structure has minimal voltage stress and may function at a high switching frequency due to the low input voltage. The second component runs at a lower switching frequency, which reduces switching losses. However, the disadvantages include a cascaded topology structure with a greater circuit components number, EMI noise and reduced efficiency.

A linked a switched capacitor and inductor can be utilized to augment a boost converter's voltage gain. A connected inductor, as opposed to two separate inductors, can employ a single magnetic core. As a result, it offers benefits such as lower magnetic loss and ripple content. The leakage inductance of the coupled inductor assists in decreasing output-diode reverse-recovery difficulties. However, the increased switching loss and current stress are substantial drawbacks. To decrease voltage spikes at MOSFET switches, a lossless passive clamp circuit is provided [302]. Lin *et al*. [303] and Wu *et al*. [304] advocated three-level boost converters because they achieve higher voltage gain with less voltage stress than two-level boost converters. In typical interleaved boost converters, current ripples and voltage stresses in switches are considerable.

An interleaved DC-DC converter was constructed by Li *et al*. [305] utilizing winding cross-coupled inductors (WCCIs). These inductors have three winding coupled inductors, one of which links to the other phase of the converter. Active clamping is a technology that can give zero voltage transmission (ZVT) performance while also considerably lowering switching losses. This can be accomplished through the use of an active clamp. In spite of the fact that an LLC resonant converter has a limited DC voltage gain range, using one helps achieve zero switching, reduced electromagnetic interference (EMI), and good efficiency. Xiaofeng *et al*. [296] studied a two-phase interleaved step-up converter paired with a current-fed LLC (IBI-LLC) resonant converter. A fixed-frequency PWM control reduces circulating current, generates ripple-free input current, and achieves load independence. The resonant frequency is continually tuned into the switching frequency f_s. The resonant tank circuit's input voltage is achieved by matching the resonant frequency with the switching frequency f_s. The duty cycle is regulated to a very narrow range about 0.5, resulting in operating points in the middle of the range, which assures optimal performance to a large part for PV applications because MPP are often placed in the middle of voltage values. The resonant inductor and capacitor control the gain characteristics, whilst boost inductors and behavior inductance impact the zero-voltage switching (ZVS) circumstances. Setting the maximum and lowest gain settings yields the L_r and C_r values. Magnetizing inductors and boost inductors are computed using the current under ZVS and gain for known values of L_r and C_r for various combinations of quality factor and duty ratio.

Hung *et al*. [297] proposed a unique strategy for improving boost converter efficiency and lowering output voltage ripple. Their article examined the functioning of a converter in DCM with pulse frequency modulation (PFM) under the premise that PV systems provide relatively little power at low irradiance. When the switching frequency is reduced, the ripple content increases. This constraint is overcome by adjusting the turn on period based on the inductor current's peak value. Due to the size of passive parts and finite commutation periods, the conversion ratio of a PV system that requires a high-gain converter is limited. A step-up transformer can be used to remedy this problem, but it has limitations such as lower frequency and severe switching transients. A connected inductor can be used as a workaround. However, a big capacitance capacitor is necessary to avoid significant input current ripple. MPPT gain is restricted due to the possibility of MPP deviation at higher input voltage levels. Haroun *et al*. [306] used a two-stage technique to build a cascade connection of two boost converters, whose function is identical to that of loss-free resistors. Pires *et al*. [307] studied a boost-self lift Cuk DC-DC converter with increased voltage gain suitable for half bridge transformers with low VSI. This converter enables a direct connection between the solar panel and the grid's neutral wire. The incremental conductance MPPT algorithm governs the duty cycle, D. The equation for voltage gain, V_o/V_i, is provided by (8).

$$\frac{V_o}{V_i} = \frac{2}{1-D} \qquad (8)$$

4.2. Buck-boost converter

In comparison to boost converters, buck-boost converters have the ability to cover the whole I-V characteristics. Additionally, when buck-boost converters operate in continuous conduction mode (CCM), the input current is smooth and continuous with very little ripple. The voltage and current stress placed on components by two-switch buck-boost converters is significantly lower than that of single-switch buck-boost converters [22], [42], [53], [81], [87], [97], [102], [103], [115], [117], [119], [125], [133], [138], [142], [146], [164], [168], [222], [225], [263], [264], [266], [288], [289], [308]–[320]. Ahmed *et al*. [315] present a two-switch non-inverting buck-boost converter with the possibility for extra current storage. To track MPP, a P&O MPPT algorithm-based approach is utilized. The experimental findings reveal that the suggested converter has a greater efficiency under large loads. Depending on the condition of the immediate input voltage in respect to the output voltage, the system can function in one of two modes: either a PWM-controlled buck or a boost. Both of these modes are possible.

Samavatian *et al*. [321] used a magnetically connected input-output inductor to simulate an interleaved buck-boost converter. The SSA approach was used in the analysis. The dampening network minimizes active-switch voltage stress while interleaved approaches improve converter efficiency and power density. Although either the SSA approach or a signal flow graph may be used to get the differential equations, the SSA method was chosen in this research. The size of the ripple in the inductor current and capacitor voltage is governed by the gradient of the inductor current at each time interval as well as the length of the time interval. This is also true for the gradient of the capacitor voltage and the length of the time interval. In this study, the various mathematical formulas that are utilized to estimate the magnetizing inductance, capacitance, and inductance of various network components were investigated.

Ping-Ching *et al*. [288] provided a modified circuit design that takes into account the influence of the on-resistance of a MOSFET. To reduce inductor current, the time during which energy is given to the inductor is reduced to a minimal value. The phenomenon of zero voltage switching (ZVS) occurs when the switches are switched off [322]. Bae *et al*. [119]developed a soft-switched multiple-input buck-boost converter with a high power-conversion efficiency architecture. Their study delves into the operation of a two-input buck-boost converter. Although this circuit outperforms a traditional converter in terms of power conversion efficiency, it provides little insight into circuit parameter design. Chuan *et al*. [312] offered an enhanced version of the aforementioned topology that included a high frequency (HF) transformer. Utilizing logic gates, a two-switch buck-boost converter is given a two-edge modulation in order to lower the amount of inductor current ripple. This design is predicated on the supposition that the rectifier voltage's trailing edge has the potential to reduce the inductor current's ripple. When switching between no-load and full-load operation, the input voltage might cause the output voltage to become unstable due to the two-mode control system's design. To get a new working voltage range, a hysteresis voltage is introduced (buck-boost mode). The experimental findings indicate that the current ripple produced by the buck-boost topology is significantly less than that produced by other topologies. An integrated converter that consisted of buck and buck-boost converters that were coupled in parallel with a common inductor was the subject of research conducted by Mummadi [323]. Utilizing a common inductor provides users with a number of benefits. First, the results are generated in a second-order network, making it simple to analyse the dynamic behaviour. Second, the converter's and magnetic core's size are lowered. Third, a minimal filter setup can be used to decrease ripple. Dynamic equations are subjected to state-space analysis.

Jintao *et al*. [324] introduced a converter design that enhances the efficiency of duty cycle consumption by including a decoupling capacitor into an H-bridge topology. This was done in order to improve duty cycle utilization. In addition, when compared to other topologies, this circuit possesses advantages such as reduced power loss and a lower overall cost than the alternatives. Kirciolu *et al*. [325] looked at buck, boost, and buck-boost converter topologies that were able to perform MPPT tracking with the use of a DSP-based MPPT controller. A proportional integral (PI) compensator is incorporated into this controller, in addition to discrete time control. MPPT strategies including the incremental conductance algorithm, the P&O algorithm, voltage feedback, and the direct technique are utilized in the tracking efficiency analysis process. Other strategies like the voltage feedback method also play a role. Because of this, as compared to other MPPT techniques, incremental conductance has a superior tracking efficiency under both slow and rapid changing conditions. When compared to the efficiency of buck converters that use other conversion techniques, the efficiency of buck converters that use these procedures is significantly higher.

4.3. SEPIC converter

SEPIC can alleviate the problems associated with buck-boost converters, such as pulsing load current and inverted load voltage [27], [40], [46], [50], [53], [56], [73], [121], [131], [141], [144], [193], [261]–[263], [274], [272], [275], [310], [311], [319], [326]–[343]. Buck-boost converters have a low efficiency when compared to SEPIC and Cuk converters [265]. Vuthchhay *et al*. [333], [336] suggested SEPIC models while operating in DCM and CCM. Three circuit states within one switching period were used to generate steady-state equations: 1) Although the MOSFET switch is activated, the diode is not conducting; 2) Although the MOSFET switch is switched off, the diode is conducting; and 3) Although the MOSFET switch is off, the diode is not conducting. The transfer function for feedback design is computed using the small-signal linear model developed for the aforementioned parameters. DCM operation improves dynamic responsiveness, reduces control complexity, and removes the reverse-recovery problem in diodes. The SEPIC operating in discontinuous capacitor voltage mode was explored for two circuit conditions during a switching time of *Ts* to produce the small-signal linear mode. In the first step, the MOSFET is turned on for *DTs* intervals, and off for an interval of *(1-D) Ts* in the second.

Because it is such an important consideration in converter design, Babaei *et al*. [334] looked at the ripple in the output voltage of a SEPIC while it was operating in CCM and DCM. The magnitude of the maximum voltage ripple was measured and recorded for each of the base values of the input voltage and load resistance. When calculating the base values of the equivalent inductance and capacitance, the minimum values of the maximum output voltage ripple were utilized since they are the most stable. Complete-inductor supply mode (CISM) and incomplete-inductor supply mode are the two operating modes that may be used with CCM (IISM). Only the IISM DCM was looked at for this test. The output voltage ripple (OVR) waveforms that were produced for each operating mode were illustrated versus the corresponding inductance for values of frequency, capacitance, and load resistance that remained constant during the experiment. Additionally, the effect that inductances have on the efficiency of SEPIC was explored in this research.

A modified SEPIC with an additional diode and capacitor was presented by Bianchin *et al*. [329]. This SEPIC has less input current ripple and may function as a pre regulator because of its characteristics. The functioning of a DCM converter reduces commutation losses and ensures both high efficiency and the absence of ripple in the input current. In addition to analysing the proposed device's properties as a converter and regulator, the study highlighted certain techniques to decrease input current distortion and constraints. These techniques include a low power factor and the requirement of an auxiliary in-rush limiter circuit for rectifier setup. The study also highlighted certain techniques to decrease input current distortion and constraints. During the design phase of the circuit, special attention should be paid to ensuring that it runs in DCM so that current ripple may be avoided. The most important need for this design is that at switching periods, each and every component of the circuit, including the voltage on the capacitor, must be deemed to be in excellent working order. A design that makes use of the resonant frequency was also shown to be effective. A predetermined resonance frequency value was chosen at random for the sake of this article, and the components were designed with that frequency value in mind. An open-loop control action with an analog implementation was used to analyse the change in total input current harmonic distortion, power factor, and efficiency across a variety of input voltage ranges. This was done in order to reduce the amount of third-harmonic distortion and maximize efficiency.

To perform steady-state and small-signal analysis on converter dynamic equations, harmonic balancing techniques, which apply Fourier analysis to dynamic equations of average and ripple values, can be utilized. These approaches use dynamic equations to represent average and ripple values. This approach is helpful in estimating the devices' ability to withstand switching stress for brief periods of time [337]. Through the utilization of soft switching technologies such as ZVS and zero current switching, input current ripple may be decreased (ZCS). When compared to hard-switched converters, the switching loss in the soft-switched PWM SEPIC developed by Kim *et al*. [310] is significantly lower. The peak-to-peak ripple current and voltage are taken into consideration when selecting the input inductor and capacitor; a ripple factor of 25% is used for this calculation. An inductor-current-control loop and an output-voltage-control loop are both present in this circuit. The inductor-current-control loop regulates the inductor current so that the reference voltage can be generated, and the output-voltage-control loop regulates the output voltage so that the command signal for the current controller can be generated. The challenge brought on by abrupt switching can be sidestepped with the use of a quasi-resonant SEPIC circuit that operates at a constant switching frequency. The fundamental conventional SEPIC circuit is modified in order to achieve ZVS switching over a broad input and output range. This is done by connecting capacitances in parallel with a MOSFET switch and a diode, and by connecting an inductor in series with a coupling capacitor. Both of these connections are made in the basic circuit.

Quamruzzaman *et al*. [344] proposed using the coupled-inductor SEPIC to achieve an array current with less ripple and enhanced dynamic responsiveness for PV sources. If there is a lot of ripples on the input side of the converter, the average value of the input current can be lower as a result. The detection of this lower average value may lead to inaccurate conclusions using the MPPT. To eliminate current ripple, a coupling coefficient of 0.97 is used to determine the values of inductors. P&O handles MPPT tracking in this article. According to the simulation findings, the linked SEPIC has an overall system efficiency of 97.01%. However, waves cannot be totally eliminated. Another issue is that voltage mismatch can generate ripple owing to non-zero DC parasitic capacitance of inductors. A circuit design described by Veerachary [332] can reduce ripple even more. This work explained how to approximate M in order to cancel the ripple in L_1 the L_2. The SSA methodology was utilized in the development of the mathematical model depicting the working of the converter in CCM. The preceding modelling approach has a drawback in that it is predicated on the assumption that the entire system is linear. This is a significant limitation of the approach.

The combination of a linked inductor and an auxiliary inductor has several advantages, including smooth voltage switching and reduced ripple content. To mitigate SEPIC's high voltage stress, Hyun-Lark [272] created a modified voltage multiplier circuit. The magnetizing inductance equation, L_m, is derived from the ZVS condition as (9). The (10) gives the sum of the auxiliary and resonant inductances, L_a and L_r. The requirement that must be met during the design of the resonant capacitor to obtain the ZCS across the diode at the output side is shown in (11).

$$L_m < \frac{V_{in} D T_s}{2n\left(\frac{M}{\eta}+1\right) I_o} \quad (9)$$

$$L_a + L_r = n(1-n)L_m \quad (10)$$

$$d_{op} < 1 - D \quad (11)$$

where D represents the duty ratio, I_O represents the output current average, n represents the turns ratio of coupled inductor, M represents the gain of voltage, T_s represents the period of switching, V_{in} represents the input voltage, η represents the efficiency, and d_{op} represents the output-diode current-reset timing ratio.

Even though resonant capacitors and inductors are intended to cut down on switching loss, the values of the capacitors and inductors still need to be thoroughly investigated in order to ensure that all switches have smooth switching. Sheng *et al*. [342] showed that a multiple-input isolated SEPIC (MIISEPIC) might work in CCM when connected with an interleaved inductor. In order to construct a current-control loop for MPP control, the focus of this study was placed on the input current range's capabilities. The construction of a connected inductor that has a high magnetizing inductance to leakage inductance proportion and that can offer a wide controllable input-current range and good efficiency was the subject of this research. A unique triggering mechanism and zero-ripple technology were created in order to increase the effectiveness of the converter and lengthen its lifespan. Inductor current, capacitor voltage, and output voltage dynamic equations for MIISEPIC were obtained after doing research on the converter with two inputs. A variety of input switching sequences, switching frequencies, and magnetizing inductance value ranges were also studied in connection to possible input current ranges.

A circuit that generates a constant output current was reported by Al-Saffar *et al*. [338]. This circuit was created by adding a high-frequency transformer to a conventional SEPIC. An active clamp subcircuit is supplied, and its purpose is to reset the transformer. Despite the greater voltage stress across the primary power switch, this arrangement provides advantages such as continuous output current, less output voltage ripple, and lower switching current stress. In the course of CCM and DCM, this effort also analysed the configuration of the system. A SEPIC equipped with peak input current mode control was developed by De Melo *et al*. [345]. While the input voltage regulating circuit is responsible for producing a current signal, MPPT and the battery-charging loop are responsible for producing a voltage signal. In order to compute the value of the input inductor, the peak-to-peak value of the input current is employed. When determining the value of the capacitor on the input side, the equivalent series resistance is what is employed for the calculation. In addition to that, the study outlined a transfer function approach to the process of creating a voltage controller. Incorporating current-mode control makes things more complicated, which makes things more complicated all around.

The level of ripple in the input current serves as the basis for calculating the value of the input inductance. The values of the series capacitance and multiplier capacitance may be determined by using the voltage ripple produced by a high-frequency capacitor. In order to calculate the output capacitance value of a low-frequency capacitor, the voltage ripple of the capacitor is employed. When the duty cycle value is getting closer to one, this circuit is able to achieve its maximum potential static gain. Magnetic coupling is the only method that permits an increase in static gain without requiring a corresponding change in the duty cycle [345]. Nur *et al*. [335] looked at how the properties of SEPIC were affected by the parasitic resistance of inductors. The MPPT calculation is carried out via the P&O algorithm. The voltage dips that are induced by the parasitic resistance are what make up the average voltage that is measured across the inductor. Both efficiency and ripple will be affected as a result of this. As the amount of parasitic resistance in the circuit grows, the converter's voltage gain, current gain, and output power all decrease. The findings of the simulation indicate that a greater amount of parasitic resistance can help reduce peak-to-peak current ripple.

4.4. Cuk converter

A negative capacitive output is characteristic of a Cuk converter, much like that of a buck-boost converter [28], [31], [116], [138], [147], [319], [326], [327], [341], [346]–[351]. The Cuk converter is unusual from other comparable devices in that it stores energy and transmits power using a capacitor rather than an inductor. This makes it possible for the Cuk converter to perform both functions simultaneously. The polarity of the input voltage is inverted in the Cuk converter, which results in the output voltage having the opposite sign. This particular converter, when properly connected, offers free ripple output, which may be useful for a wide range of applications [352]. Depending on the Cuk converters, several converter circuit topologies are introduced in [353]. The efficiency of the revised Cuk converter has substantially improved. This converter is renowned for its good bidirectional performance in managing current and voltage [116]. Furthermore, many forms of traditional Cuk converters have been published in the literature [147], [308], [326], [340], [352], the modified Cuk converter having a higher efficiency level for controlling voltage and current in bidirectional operation [319]. Sliding mode control (SMC) and proportional-integral control (PIC) are two strategies used in the closed-loop system concept (PI). It may also be used in conjunction with a fuzzy logic controller (FLC) to calculate the output voltage of a Cuk converter [346], [353]. Furthermore, the Cuk converter may be used in brushless DC (BLDC) motor and renewable energy system applications such PWM-based solar energy harvesting [351], [354]–[357].

The converter that is presented in [348] incorporates the switched-inductor and the switched-capacitor into the Cuk converter, which significantly enhances the voltage gain of the Cuk converter. This is done in order to improve the voltage gain of the Cuk converter. It is proposed in [286] that a high-gain boost-Cuk converter may be constructed by merging the quadratic boost converter and the Cuk converter; however, the output current of this converter is not continuous. A quadratic Cuk converter with an isolation transformer is proposed in [347]. This converter allows the voltage gain to be altered by changing the turns ratio of the transformer; however, this results in a relatively large amount of voltage stress on the switching device as well as input current ripple. Not only may magnetic integration of the inductors in interleaved converters lower the current ripple in the inductors, but it can also increase the converter's dynamic responsiveness [358], [359]. A two-phase transformer magnetic integrated equivalent circuit model was suggested in the aforementioned piece of literature [360], and it was then used to a two-phase interleaved forward converter.

Cuk and SEPIC converters are utilized as output terminals in [361] for combination converters to create a combined Cuk-SEPIC converter with a bipolar output and a longer converter life. Baptista *at al*. [350] employs parallel boost and Cuk to realize the converter's architecture, however the parallel capacitor on the output side causes the converter's output voltage to fluctuate. Li *et al*. [349] propose a unique boost-Cuk converter made up of basic boost and Cuk. By sharing the same input, a single switch boost-Cuk converter is presented. A boost- Cuk converter with a switching inductor is achieved by substituting the inductor with a switching inductor in order to increase voltage gain. The switching inductor's stray inductance is used to minimize the diode's reverse recovery. In addition, the converter's inductor is magnetically integrated to decrease the current ripple of the input and output inductors. Furthermore, the coupling magnetic integration technology reduces the input and output current ripple. As a result, this converter features a single switch, continuous input and output currents, and minimal ripple.

4.5. Zeta converter

A new soft switching converter that integrates the flyback and Zeta converters was studied by [40], [112], [144], [176], [212], [254], [294], [311], [316], [340], [362]–[364]. In the proposed converter, the flyback and Zeta topologies use the same power switches to reduce the power switch count. The output circuits in the flyback and Zeta converters are connected in parallel on the secondary side of the transformer to share the load current. The boost type of active clamp circuit is used to recycle the surge energy stored in the leakage inductance, limit the peak voltage stresses of all switches, and achieve the ZVS turn-on of all switches [67], [233], [308]. When the main switch is turned on, the power is transferred from the input voltage source to the output load through the Zeta converter. When the main switch is turned off and the auxiliary switch is turned on, the energy stored in the clamp capacitor and the magnetizing inductor is transferred to the output load through the flyback converter.

Two Zeta DC-DC converters are used for reducing the output voltage ripple. Two zeta converters are operated simultaneously for the purposes of reducing the output ripple, sharing the primary side components, and sharing the load current. The two converters are operated out of phase for this simultaneous operation [363]. A novel transformer less buck boost converter based on the Zeta converter is presented [365]. In this converter, only one main switch is used, which decreases the losses and improves efficiency. The active switch voltage stress is low and a switch with low on-state resistance can be utilized. The voltage gain of the converter is higher than that of the classic boost, buck-boost, Zeta, Cuk, and SEPIC converters. The presented converter structure is simple; hence, the converter control is simple.

A modified Zeta converter acts as an interface and is placed between the PV module and the load [254]. Equated with existing DC-DC converters, the modified Zeta converter comprises limiting of overload current ability as well as rapid parameter-based loading response. The modified-Zeta converter operates in discontinuous current mode with a high-power factor coefficient, reducing controller complexities and accurately regulating output voltage. Moreover, the modified Zeta converter has limitations over shading current behaviour as well as rapid parameter response to the load as well as supply voltage situations.

A novel high step-up DC-DC converter is named the Integrated Quadratic-Boost-Zeta Converter [294]. It is based on the combination of two well-known DC-DC converter circuits: the Isolated Zeta converter and the Quadratic-Boost converter. The output voltage boosting is accomplished by summing both the output voltages of the Zeta and the Quadratic Boost. The circuit is designed in such a way that each part of the converter outputs keeps the same characteristics as its former converter, guaranteeing their well-known advantages. Furthermore, the proposed topology has a single-switch, maintaining a low component count. In addition, because of the high current ripple presented in the quadratic-boost converter, the proposed circuit, with an adequate filter design, can ensure a low output current ripple due to the Zeta output inductor.

4.6. Z-source converter

The Z-source comprises two identical inductors and two capacitors, in which the modernization of this configuration has been fluent and conducted to achieve better performance [87], [102], [122], [166], [291], [300], [314], [366]–[368]. A modified Z-source DC-DC converter is proposed by [367]. In comparison to the conventional Z-source dc-dc converter, the proposed converter can achieve higher voltage gain while putting less voltage stress on the switch and the impedance network capacitor and operating with a wider range of loads. Therefore, the proposed Z-source dc-dc converter not only has a lower cost but also has a smaller weight and size. In this paper [366], a modified double input DC-DC Z-Source for renewable energy PV/battery applications is presented. All of the operating modes are analysed and then voltage gain is calculated for three states that show the proposed converter is very suitable for stand-alone applications. Also, due to the fewer number of switches, passive and active elements, the power loss is reduced and, because of the output voltage boosted by the modified Z-Source, it can satisfy high voltage requirements.

The suggested architecture takes advantage of the benefits offered by impedance-source converters in addition to those offered by cascaded converters. This is accomplished by contemplating the notion of cascading two Z-source networks within a typical boost converter. The suggested converter may deliver a large voltage gain by the application of specific changes, while maintaining a low voltage stress on the switch and the diodes at the same time. In addition, because the converter has such a low ripple in its input current, it is totally suitable for use in photovoltaic applications, which can lengthen the lifetime of PV panels. The high step-up DC-DC impedance source-based boost converter that has been suggested [291] consists of two cascaded Z-source networks as well as two switched-capacitor-inductor cells. A single ferrite core is used in the converter, and it has a total of six connected inductors that are included into the impedance network and the cells. Two of the most significant issues with this converter are the very high input current ripple and the high voltage stress that the switch experiences. Therefore, in order to make the converter actually usable, there will inevitably be certain modifications that need to be made. The significant input current ripple is still regarded a problem in this converter, despite the fact that the voltage stress of the switch may be clamped at a fixed value with the addition of a capacitor.

5. CONCLUSION

DC-DC converters are used extensively in solar energy harvesting systems because they enable more effective utilization of solar cells, which is the primary reason for their widespread use. The reason for this is that DC-DC converters allow for the more efficient exploitation of solar cells. However, one of the challenges is in selecting an appropriate converter, which is one of the obstacles because it has an effect on how the PV system operates. This is one of the reasons why this is such a difficult task. This study provides a comprehensive analysis of the latest developments in DC-DC converter topologies, including boost, buck-boost, single-ended primary-inductance converter (SEPIC), Cuk, Zeta, and Z-source topologies. Comparisons of the topologies have been made in order to provide specific details on the difficulty of the hardware, the cost of implementation, the efficiency of the energy transfer elements, the efficiency of the tracking, and the efficiency of the converters. These comparisons were made so that specific details could be provided. This paper can be used as a quick guide to help you choose the best converter topology for projects that involve collecting energy from the sun.

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