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Review

Modern DC–DC Power Converter Topologies and Hybrid Control Strategies for Maximum Power Output in Sustainable Nanogrids and Picogrids—A Comprehensive Survey

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Abstract: Sustainable energy exhibited immense growth in the last few years. As compared to other sustainable sources, solar power is proved to be the most feasible source due to some unanticipated characteristics, such as being clean, noiseless, ecofriendly, etc. The output from the solar power is entirely unpredictable since solar power generation is dependent on the intensity of solar irradiation and solar panel temperature. Further, these parameters are weather dependent and thus intermittent in nature. To conquer intermittency, power converters play an important role in solar power generation. Generally, photovoltaic systems will eventually suffer from a decrease in energy conversion efficiency along with improper stability and intermittent properties. As a result, the maximum power point tracking (MPPT) algorithm must be incorporated to cultivate maximum power from solar power. To make solar power generation reliable, a proper control technique must be added to the DC–DC power converter topologies. Furthermore, this study reviewed the progress of the maximum power point tracking algorithm and included an in-depth discussion on modern and both unidirectional and bidirectional DC–DC power converter topologies for harvesting electric power. Lastly, for the reliability and continuity of the power demand and to allow for distributed generation, this article also established the possibility of integrating solar PV systems into nanogrids and picogrids in a sustainable environment. The outcome of this comprehensive survey would be of strong interest to the researchers, technologists, and the industry in the relevant field to carry out future research.

Keywords: solar power generation; intermittency; modern DC–DC power converter topologies; unidirectional and bidirectional converter topologies; control for maximum power outcome; hybridized maximum power point tracking; nanogrid and picogrid architecture

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1. Introduction

Renewable sources of energy are achieving worldwide importance in the present era, especially with the incremental awareness about the rapid decline of conventional sources of energy, like coal and petroleum products [1]. On the basis of the statistics from the monthly energy review article given by U.S Energy Information Administration in June 2021, energy consumption consists of 58.8% natural gas, 39.1% electricity, and 9.6% and 7% petroleum and renewable energy, respectively. In India, there is a higher dependency on petroleum and coal. As a result, conventional resources are depleting very rapidly. Now, energy harvesting from renewable sources has become a key research interest among researchers. When more than one renewable source are acting together, the resulting system is called a hybrid renewable energy system (HRES).

Besides all other advantages, the major drawback of all forms renewable energies is their intermittent nature. The output of the sources is always variable as the output is weather dependent. So, the aim must be to make an HRES that is able to surpass the power quality issues and to provide superior quality of power to load. The power quality and system immutability can be accomplished by applying suitable control techniques embedded into the power converter control circuit. To deal with the intermittency and to achieve better dynamic performance of an HRES, several stable sources and storage devices should be embedded within the system, such as batteries, fuel cells, super capacitors, and diesel generators, either in standalone mode or in grid-connected mode [2]. At the time of breeding of electric power, DC–DC power converters have a more pronounced contribution due to the far-reaching usage in various applications.

Photovoltaic generation naturally suffers from lower energy conversion efficiency along within congruous immutableness and spasmodic properties. As a result, there should be an approach to ensure access to the optimum power that can be cultivated from solar PV generation [3] as the power generated by a PV panel only depends on meteorological factors, like solar irradiation, and the cell's reachable temperature. The parameters change depending on the weather. Hence, it is mandatory to employ maximum power point trackers (MPPT) [4]. The main factor that influences solar PV systems is the unwanted availability of solar irradiances. To overcome this problem and to provide unvarying supply to load, different DC–DC power converters are embedded within the solar generation system. Since the 1920s, PV systems were equipped with the DC–DC power converters.

The prime focus of the power electronic converters is to displace the application of prevalent circuit components, like rheostat and voltage divider circuits. The main disadvantage of this approach is that the output voltage acquired is less than the input, resulting in inferior efficiency [5]. The European Union declared an intention to achieve 20% renewable energy consumption by 2021 in order to foster the production of renewable energy. Compared to nonconventional resources, the production of solar energy has been shown to have a lower impact on the environment. To generate the most power possible from solar energy, an MPPT (maximum power point tracking) algorithm must be used. The selection of an appropriate power converter topology is a crucial component of solar energy generation since it affects the way photovoltaic (PV) systems behave [6].

PV power is directly proportional to solar irradiance and inversely proportional to panel temperature [7]. A PV array can be represented as a circuit-based model of a solar cell comprising a current source connected in parallel with a diode. The current source illuminates a photon-generated current. The resistance $\boldsymbol{R_s}$ defines the losses due to contacts and connections. The leakage current in the diode is depicted by the shunt resistance $\boldsymbol{R_{sh}}$ [8]. A prediction of the electrical behavior of solar power generation is very much needed as it is the lowest value of the energy that will be delivered. This is the most crucial step of design of a PV system [9]. Smart grids are considered as prime solutions to solve current power security issues. Among these suggestions, microgrids are intended to mingle with distributed generations (DGs), such as photovoltaic (PV) systems, in the network, and the control of DG output power is a keen interest among researchers.

The nonlinearity of P–V characteristics of PV arrays were affected by solar irradiance, panel temperature, and load. Thus, various maximum power point tracking (MPPT) methods have been evolved in order to enhance power output [10]. The furtherance of renewable energy systems (RESs) is more pronounced and beneficent due to the impacts of fossil fuels. The application of wind turbines and photovoltaic generation is found to be numerous [11] since this kind of RES has been researched for a long time. Due to the absence of electricity, 1200 million people are living without the advantages of power in many developing countries [12,13]. There are numerous spots where power grids are expensive, such as in standalone systems without any power lines [14].

In recent days, different kinds of control strategies have been developed for the maximum power point tracking (MPPT) of photovoltaic power generation. Various kinds of MPPTs are evaluated in terms of energy efficiency, energy conversion capability, and dynamic pursuance and dependability with respect to different weather conditions [15]. The performances of prevalent MPPTs are restricted to uniform weather conditions [16]. It has become challenging to extract optimum energy from photovoltaic systems by using MPPT during partial shade conditions [17]. The P–V curve of PV systems shows multiple peaks under different constraints of working and variations in atmospheric phenomenon, which destroys the effectiveness of conventional MPPTs [18]. Photovoltaic systems are drawing more attention to smart grid systems. In order to obtain optimized energy output, the maximum power point tracking (MPPT) algorithm should be incorporated into PV systems. But due to the constraints of clouds and partial shade, MPPTs are becoming less efficient. To overcome these problems, MPPTs must be able to learn and respond to the changing state of the online system [19]. Considering the stated discussions, this literature is focused on the detailed discussion of DC–DC power converter topologies and control strategies for maximum power outcome from solar power generation. The major contributions of the proposed work are as follows:

1 The classification of the different control topologies of the modern DC–DC converters and an amalgamation of various MPPT approaches integrated with sustainable nanogrid and picogrid architectures for the enhancement of technoeconomic feasibility in the power sector of a country.
2 The promotion of the environmental impact of solar power generation to be interfaced with grid either in standalone mode or grid-connected mode for empirical development. Statistical data from the U.S. Energy Information Administration regarding the percentage of conventional or renewable energy used in the environment is considered.
3 Addressing the intermittency issue of solar power generation. A control strategy will be established by realizing maximum power point tracking, voltage and current of DC links, and q-axis by applying adaptive strategies and simulating different controllers.
4 The discussion of the proposed controller with respect to smaller oscillations, less power loss, fast convergence, and the capability of following true maximum power point (MPP) under rapidly varying ambient conditions. The benefits are that it will be able to enhance the operating area of controllers; thus, it will be able to implement a more accurate signal to get optimum output from the converter as per the load requirement within the proved step response to work under the desired width.

This article is framed in the following manner: Section 2 presents the interfacing of solar power generation, Section 3 reports the various control strategies for maximum power extraction from solar energy, Section 4 reviews the details of solar PV systems, Section 5 reviews the details of various modern unidirectional DC–DC power converter topologies applicable for solar power generation, Section 6 reviews modern bidirectional DC–DC converter strategies in a sustainable PV architectures, and Section 7 discusses future research directions and the conclusion accordingly.

2. Interfacing of Solar Power Generation

Along with the nonrenewable sources of energy, solar energy also plays an important function in unreliable and stable power generation and in providing uninterrupted and superior quality of power to the end users. Primarily, photovoltaic cells convert solar energy into direct current electricity. Practically, solar radiation hits the outer atmosphere at around 1300 W/m^2, but in truest sense, some of the radiation is diverted due to reflection, refraction, and absorption. Finally, the amount of irradiation that reaches the Earth's surface is much lower than 1000 W/m^2 [20]. Solar power can be interfaced with the DC bus and then to the DC load, by employing a proper DC–DC power converter, and lastly to the AC load or utility grid via the proper arrangement of DC–AC converters, i.e., inverters [21]. Because of the intermittent nature of PV energy generation, it may not serve as a reliable, stable, controllable energy source and may not be able to provide ancillary services like a conventional energy source. To mitigate this problem, one solution is to upgrade solar power generation by incorporating an energy storage device into it. A storage device can be added to store or release energy as a buffer when necessary [2]. A block diagram is depicted in Figure 1, showing a PV source interfaced with a DC bus and an AC utility grid along with an energy storage device. In this configuration, the PV panel is interfaced with an MPPT controller in order to harvest maximum energy output during solar power generation. The MPPT controllers will providethedutycyclefortheemployedDC–DCboostconvertertoregulateitsinconsistentoutput [22].

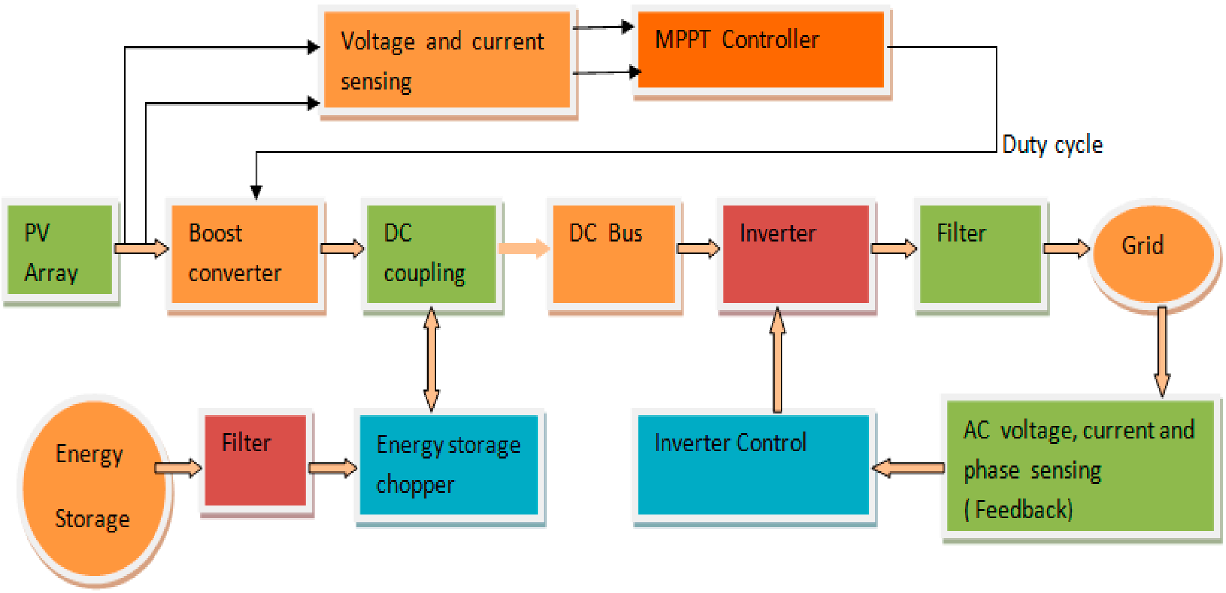


Figure 1. Solar power generators with embedded energy storage systems.

The energy storage device is interfaced with the DC bus via DC coupling through the energy storage chopper, which is a bidirectional DC–DC power converter, to affirm a stable supply demand counter balance according to its rated capacity. The common DC bus receives the supervised power from the PV array and from the energy storage device to supply DC load to have a constant magnitude of DC voltage at the input of DC–AC inverter. A single DC–AC inverter acts as an interfacing medium between the common DC bus and AC bus. The AC bus delivers power in inverted form to the AC load and must also have the ability to merge with the utility grid when the power induced from the renewable energy system is not sufficient to meet the load demand. From the above configuration, it is evident that power converters employed in the system needs simple control algorithms because source-side converters are dependable only for cultivating optimum power from the photovoltaic sources. Load- or utility-grid-side converters are the converters that are controlling the active, reactive voltage and load frequency and harmonics to confirm optimal quality of power to be supplied to the load.

The output of RESs can be resiliently directed by DC–DC power converter topologies to achieve the desired input of the DC–AC inverter [23]. Most of the RESs and the storage devices are DC-based, so the interfacing of these with the DC bus line is very simple [24]. The extant scenario of power demand is in need of renewable energy resources. Among all other sustaining renewable energies, working with photovoltaic (PV) energy is less complicated due to some prominent advantages, such as PV energy being suitable for different climatic conditions around the whole world and causing less pollution to the environment. Besides the benefits, PV energy has some disadvantages too. The power generated from PV energy generation is purely nonlinear and very much difficult to evaluate. Furthermore, the voltage and current depend on the solar irradiation and panel temperature, which are also nonlinear in nature. Now, to generate maximum power from PV energy generation, it has to be able to operate at optimal operating conditions, which is called Maximum Power Point (MPP).

2.1. DC Nanogrid and Picogrids Architecture and Control

Nanogrids are generally categorized as a small-scale grid model, which must carry one load and contains a gateway to the passage. Moreover, nanogrids can supply both AC as well DC and can be integrated into a utility grid. The basic configuration of a nanogrid consists of a form of energy storage, like a battery, and any sustainable energy source, like solar, wind, wave, etc. Compared to microgrids, they have a lower capacity of around 15–20 kW. On the other hand, picogrids have a very small capacity grid compared to that of nanogrids as they also consist of a battery model and other sources of sustainable energy.

The power level capacity of nanogrids is about 5 kW; however, no hard limit is established. It is possible for nanogrids to be configured with DC distribution through the positive and negative rail. In such topologies, the converter integrates a PV panel and a battery (energy storage) into a DC nanogrid. The DC link (rails) of the DC nanogrid is connected to the two ends of the switch-leg. The power conversion from the PV panel and the battery to the DC link of the nanogrid form two DC boost converters with discontinuous-conduction-mode (DCM) and continuous-conduction-mode (CCM) operations.

Further, the MPPT of the sustainable PV system is obtained through controlling the switching frequency and duty cycles, and in turn, further bidirectional power flow studies can be conducted. Moreover, the soft-switching topology of the proposed converters will play a significant role while controlling the various parameters of the distribution grid and power outcome. With the advancement of information and communication technology (ICT), a modification in the electrical grid and the remodeling of the components from consumer to prosumer is supposed to be an objective of smart cities. The main motto of a smart city is to efficiently employ the technological advancement to obtain the smart infrastructure.

Moreover, for the employment of smart power and industrial information integration, the trifurcation of smart grid infrastructure into small-scale grids is supposed to be a promising solution for a modern sustainable infrastructure. Additionally, the economic benefits of a prosumer can be enhanced either by selling or sharing the additional power with the main grid or the individual customer at a fixed rate. In this context, the major challenges are related to the power management system through software or hardware controllers.

Several research works are reported to investigate the smart management tools in various countries to integrate the communication between the cloud and the nanogrid and picogrid control system. As a case study, if the battery bank of the nanogrid becomes fully depleted, a notification will be forwarded to the controller. This information is passed from the controller to the cloud, which acts accordingly. The Government of India has been planning several steps to incorporate the concept of smart power in various smart cities for sustainable development. The key outcomes of the Energy Policy 2020, as decided by the Government of India, are described as follows [2–5]:

- The encouragement of entrepreneurship and employment in the agricultural sector due to the incorporation of new technologies, like smart irrigation, smart power management, climate control and change, waste management, etc.
- The prior objective of the Energy Policy 2020 was energy security with the advancement of sustainable energies in global supply contributions.
- A regulation called FAME (Faster Adoption and Manufacturing of Electric Vehicles) has been pioneered to promote the usage of e-mobility.
- The Smart Cities Mission established the need to involve more than 100 cities across the country in the reduction in energy consumption, the enhancement of infrastructure, the enhancement of energy efficiency, etc.
- The Government of India is planning to invest more into the implementation of EV charging infrastructure and suitable planning to integrate it into the distribution grid for the overall development of the region.

3. Analysis of Various MPPT Methodologies

MPP is a point that works on Maximum Power Transfer theorem, i.e., maximum power will be delivered from source to load only when Theremin's equivalent resistance is equal to load resistance. There are many methods to extract optimum power from photovoltaic sources [25–27]. The most popular methods to track maximum power from PV sources are Perturb and Observe (P&O), Incremental Conductance, Fuzzy Logic [28], and Neural Network [29]. Perturb and Observe (P&O) is gaining popularity in controlling maximum power due to its simple algorithm and less complicated implementation. It focuses on the theory of rate of change in power and will be minimum around MPP. P&O has the drawback of oscillation around MPP.

Incremental Conductance is another widely applied maximum power point tracking algorithm that works on the theory that the slope of the P–V curve will approach zero as the PV system approaches the MPP. To find the MPP, the derivative of voltage and current need to be considered. It provides less oscillation and improved MPPT even in rapidly changing climatic condition. It exhibits superior result compared to P&O. Along with the advantages, the Incremental Conductance is confined in the selection of the incremental step size. Intelligent controls, such as Fuzzy Logic [30–32] and Neural Network [29], may be applied to achieve the benefit of getting a proportionally changing power converter duty cycle added to the PV system, which consists of a solution of constant step perturbation. The working principle of Fuzzy Logic deals with the strategized rules, which also depends upon the experience of rule designer. Therefore, the prime drawback is that there is no phenomenal strategy. The neural network method needs more precise data to check and train. The quality of the data plays an important role here, which is more effortful to obtain.

The most popularly cultivated controller in industrial process is the PID controller for the reason of its simple architecture and ease of application, low cost, and robust performance with respect to wide range of modifying operating conditions. The discretion of PID controllers as MPPT controllers matches the entire above criterion. B. Ashoke Kumar et al. [33] designed a PID controller as an MPPT controller that necessitates the identification of three parameters, i.e., proportional gain and integral and derivative time constant. The continuous PID equation is dependent upon three parameters, k_p, k_i, and k_d, which can be obtained using the Ziegler–Nichols method shown in Figure 2. Different MPPT techniques on various aspects are tabulated in Table 1.

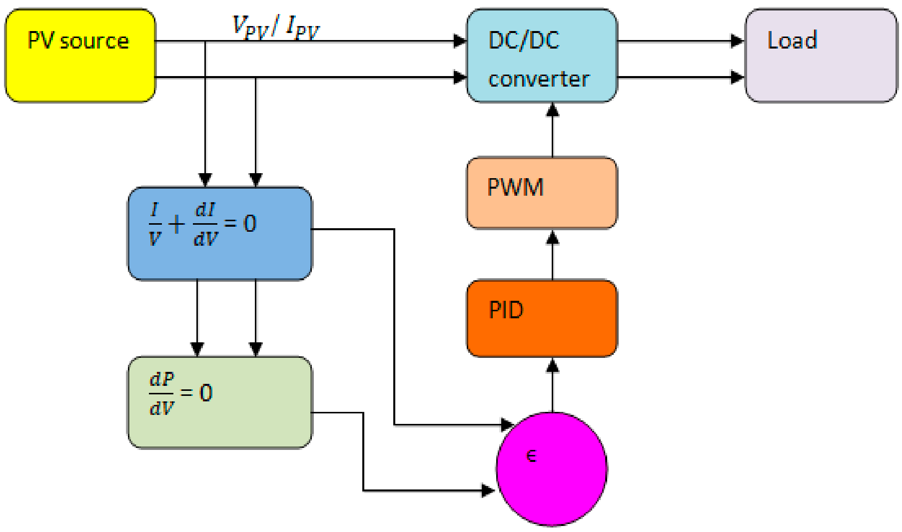


Figure 2. Block diagram of PID MPPT for PV system in [33].

Table 1. Comparative study of different MPPTs for PV system.

Categorization		MPPT	Index of Performance					
			Complicacy	**Tracking Speed**	**Price**	**Efficiency**	**Certainty**	**Hardware Compatibility**
Traditional/ Conventional	Control on the basis of parametric choice	CVT	Poor	Average	Low	<85–90%	Poor	Simple
		OVT	Poor	Average	Low	<85–90%	Poor	Simple
		SCT	Poor	Average	Low	<85–90%	Poor	Simple
		CS	Poor	Poor	Medium	<85–90%	Poor	Simple
	Direct control	P&O	Poor	Superior	Mean	>97%	Average	Simple
		IC	Medium	Superior	Mean	>98%	Very High	Simple
		RC	Medium	Superior	Mean	>96–99%	Very High	Simple
		PC	High	Superior	Very High	>98%	Mean	Complicated
MPPT under partial shading condition		PSO	Very High	Rapid	High	>97–99%	Best	Medium
		GWO	Very High	Average	High	>98%	Average	Simple
		PO-PSO	Very High	Rapid	High	>98%	Mean-low	Easy
		GA	Very High	Fast	Very High	>98%	High	Simple
		FLC-P&O	Very High	Fast	High	98–99%	Very High	Easy
Intelligent MPPT		FLC(AI)	Very High	Rapid	Very High	>99%	Mean	Simple
		ANN(AI)	Very High	Rapid	Very High	>99%	Mean	Complicated
		SMC(Nonlinear)	Medium	Rapid	Very High	>99%	High	Easy

In this method, the algorithm controlled the tuning of the proportional, integral and derivative gain using the Z–N method. From the result obtained from the simulation, it is evident that PID MPPT exhibits superior results compared to the conventional MPPT algorithm. There was an increment in output power and the time consumed by the PID controller to obtain the optimal point, and it was faster than P&O and Incremental Conductance. The oscillations in this method have become smaller. The efficiency of the PV system is proved to be better compared to other conventional methodologies. To overcome the drawbacks of conventional MPPTs that are unable to achieve the maximum power point of PV systems even after extended operation, one of the solutions to the above constraints is an upgraded MPPT control strategies, which must be established to achieve the superior performance of PV-system-controlled MPPT. But there is some difficulty in working with paid due to its tuning problem [34]. Various approaches have been reviewed in this article to achieve the best possible tuning methodologies [35–37].

A detailed classification of various MPPT methodologies is shown in Figure 3. Better performance parameters, like settling time, rise time, and steady-state offset, can be obtained by employing hybrid AI-based systems. But, the execution of these systems is not smooth due to their complexity in computation. Emmanuel Kwaku Anto et al. [38] intended to design a PID-based MPPT for an off-grid solar photovoltaic (PV) system. The study showed that PID MPPT showed outstanding outcomes compared to P&O MPPT and non-MPPT systems by applying step, ramp, and impulse signals using a commercial SOLAR 36 W. From the point of view of better performance, Perturb and Observe (P&O) shows positive approach. The main limitation of this method is that at the steady state the operating point oscillates near the maximum power point (MPP). As a result, some quantity of energy is wasted, and the step size is increased, thereby reducing the accuracy of the system [39,40].

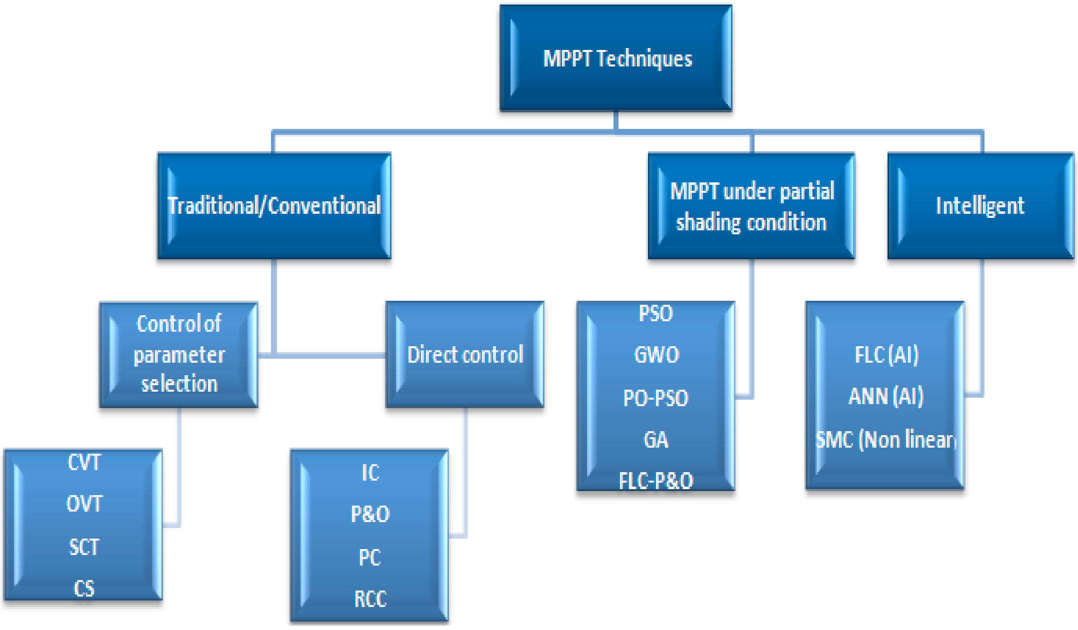


Figure 3. The MPPT algorithms considering various aspects.

To get rid of the above-mentioned aspects, modified MPPTs are proposed [39]. Nur Atharah Kamarzaman, Chee Wei Tan et al. [41] focused on MPPT classification. The conventional methods are best used for uniform solar irradiation and panel temperature. And, the probabilistic and artificial-intelligence-based algorithms are the best choice for working under partial shade conditions. The advancement of the MPPT algorithm is the easiest task considering its cost, and it can be applicable for the equipment, which are also contemporizing their control techniques [42]. These methods can be categorized as online or offline methods and hybrid methods [43]. Many hybrid methods have already been introduced, such as Genetic Algorithm Neural Network (GA-ANN) [44,45], Particle Swarm Optimization (PSO)-based Fuzzy Logic controller [46], and Genetic Algorithm Fuzzy Logic controller [47]. Anupama Ganguly et al. [48] presented a horse-herd optimized adaptive fractional order PID controller to provide the duty of the inverter to a PV interface grid-connected system. Algorithm robustness was verified by rapid and continuous change of climatic phenomenon.

The open circuit voltage V_{OC} MPPT algorithm is the simpler version that can be applied in offline (standalone) applications. A near about relationship between the open circuit voltage and the optimum output voltage of PV array under various varying climatic condition may be considered [49]. Another simpler approach of MPPT algorithm is short circuit current I_{SC} technique in which the working principle is same as open circuit voltage strategy [49]. Whenever a PV array is interfaced with DC–DC boost converter, it would introduce some voltage and current ripples due to the switching action. As a result of which the power induced by PV array must get contaminated by those ripples which in turn deteriorates the performance of PV system.

To mitigate this issue, ripple correlation control MPPT algorithm has been implemented. To achieve the MPP, the power gradient should be equal to zero. Ripple Correlation Current (RCC) correlates between rate of change of PV power, changing P versus current i or voltage V which are both changeable with respect to time [50,51]. The RCC furnishes advantages of simple and less costly analogue circuitry while quickly following MPP within rapidly varying climatic phenomenon [49]. This MPPT is unable to follow the MPP at lower intensity of solar irradiation as it requires large step size near MPP. Ameur Khaled et al. [52] designed a fast MPPT control using PID controller for the application in PV system. This paper was focused in designing a controller that can make the system responses superior, thereby shortening the tracking time.

Conventional P&O algorithm was chosen for MPPT that provides a reference voltage as input of the controller, which in turn will calculate the PWM of the converter. Pabitra Kumar Biswas et al. [53] proposed a comparative performance analysis of the hybrid MPPT to analyze the performance of boost converter in standalone photovoltaic configuration. The intended system was structured with an MPPT oriented load following techniques that permits the transmission of maximum power for changing input RF power in order to achieve desired voltage magnitude. Muhammad Ammirrul Atiqi Mohd Zainuri et al. [54] developed an Adaptive Perturb & Observe (P&O) Fuzzy control maximum power point tracking for photovoltaic (PV) boost converter. P&O is the conventional and simple MPPT algorithm to be implemented. Fuzzy Logic is also an easy tool to be widely used. The proposed strategy was the amalgamation of both the benefits. All the algorithms simulated in MATLAB platform with PV module of Kyocera KD210GH-2PU interfaced with PV boost DC–DC converter.

Adeel Feroz Mirza et al. [55] brought novelty in maximum power point tracking for the fast charging irradiance of PV system. The proposed architecture used PID controller with Genetic Algorithm to analyze the variable step size of the Incremental conductance based MPPT. The aforesaid system also tested against P&O. The intended strategy was able to estimate the global maxima (GM) for fast charging solar irradiance for adopting GA based tuning of the controller. Mohamed Nejib Mansouri et al. [56] designed a PID controller to track the maximum power point (MPP) of a PV system with Genetic Algorithm by using Energetic Macroscopic Representation (EMR). The tuning of three parameters of the controller was conducted by GA. P&O method was applied to generate the reference voltage. $\boldsymbol{V_{ref}}$ and the simulation result was analyzed in terms of Mean Square Error (MSE), percentage overshoot, and rise time.

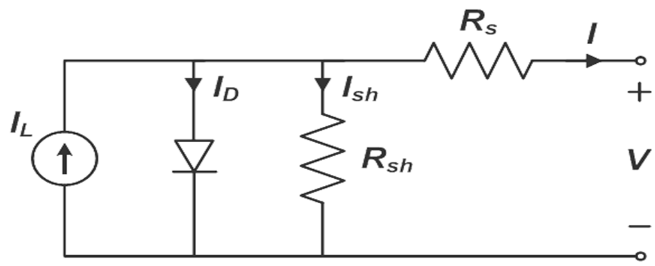
Saravanan et al. [57] discussed about various kinds of MPPT techniques both conventional and stochastic and concluded that none can be proclaimed as better compared to other unless practically implemented. Ouoba et al. [58] invented an upgraded auto-scaling variable step size MPPT for photovoltaic system. The method was assimilated with some classical approaches like fixed step size, variable step size, auto-scaling variable step size MPPT techniques and therefore winded up the system, and it was not able to produce steady outcome as the step size was large in comparison to requirement. Ali Nasir et al. [59] presented an adaptive fractional order PID controller-based MPPT for a grid connected PV system, under varying atmospheric phenomenon. AFOPID controller is enriched with the characteristics of usual PID controller, at which the adaptations are embedded in order to achieve optimized parameter gain depending on the generator and grid side parameter.

M. Mahapatra et al. [60] intended to introduce adaptive fuzzy MPPT to create the gate signal for an interleaved soft switching boost converter for a PV system. To overcome linearity in PV output with the changes in irradiation and environmental temperature, the proposed MPPT proved to be more efficient and also reduced the cost of fabrication. Diwaker Pathak et al. [61] introduced an application of nonlinear discrete PID controller for MPPT of PV system. The proposed nonlinear-discrete controller attains the usual properties of conventional proportional integral derivative (PID) controller where the integral and derivative gain were discretized by applying forward Euler formula and the integral gain was varied during simulation time as per the error. An intelligent strategy of Particle swarm Optimization (PSO) and Genetic Algorithm was incorporated to find the optimal gain during a dynamic situation. M.L. Bharathi et al. [62] proposed an Artificial Neural Network (ANN) supported Fuzzy Logic for SEPIC converter in PV system.

K. Jyotheeswara Reddy et al. introduced an Artificial Neural Fuzzy Inference System (ANFIS)-based MPPT control algorithm for a PEMFC system for electric vehicle approach [63]. Suresh Srinivasan et al. [64] proposed a novel neural network based MPPT to harvest optimum at rapidly changing operating phenomenon configured with quadratic boost converter by incorporating RBFN strategy for fuel cell application. Chiranjit Sain et al. [65] intended to focus on performance analysis and enhancement of reliability of the PV array under partially shaded condition by one time electrical reconfiguration.

4. System Description

Photovoltaic system is comprised of solar panels, Direct Current–Direct Current (DC–DC) power converter and energy storage devices. DC–DC voltage converters are employed in order to match the load features with which the solar panels are interfaced. The term "photovoltaic "derived from two different phrases that are "photo" which means light and voltaic that reveals the meaning of generating the electrical energy directly from the sun [66]. There are various kinds of model to furnish the behaviorism of PV module like single diode (SD), double diode (DD), and three diode (TD) models [67]. Solar arrays are the combinations of multiple solar modules at which every module is synthesized by a number of solar cells. Solar cells are composed of different layers of semiconductor substances, most commonly crystal silicon [66,67] A single diode PV model is comprised of a series resistance and a shunt resistance [67]. Figure 4 depicts that the amount of electrical energy induced solar energy generation by the current I_{ph} that is proportionate to the solar irradiation. The resistance in series exhibits an internal resistance while the parallel resistance shows the leakage current.



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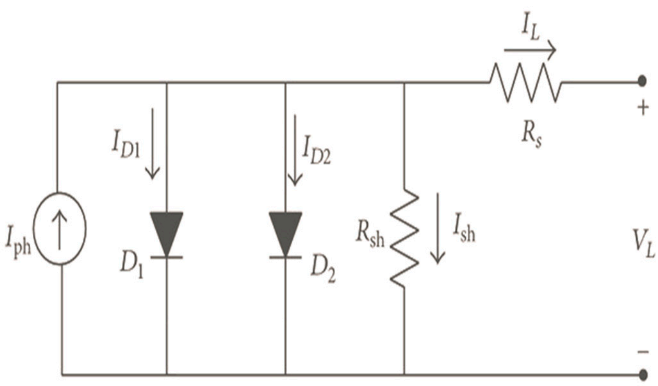


(**b**)

Figure 4. (**a**) Single diode model of PV cell. (**b**) Double diode model of PV cell [66,68].

The photovoltaic output voltage and current represented by V_{PV} and I_{PV}, respectively.

$$I_{PV} = I_{ph} - I_D - V_D/R_{sh} \tag{1}$$

The features of diode can be characterized by I_D:

$$I_D = I_0\left(e^{\frac{V_D}{V_{TA}}} - 1\right) \tag{2}$$

The voltage drop across the diode represented by V_D:

$$V_D = (V_{PV} + I_{PV}R_s) \tag{3}$$

Photo current is expressed by I_{ph}:

$$I_{ph} = \left(I_{SC} + K_1 \left(T_1 - T_{Ref}\right)\right)\lambda \tag{4}$$

where V_T depicts the thermal potential of PV modules that is equal to kT/q. V_D is the potential of the diode. K is the Boltzmann constant that is same to 1.38 × 10^{-23} J/K. T_1 is the p-n junction temperature in Kelvin. A depicts the diode ideality factor that is dependent on PV technology. I_{SC} shows the short circuit current of cell at a reliable experiment condition (1000 W/m^2) and 25 deg C, K_1 is the coefficient of cell's short circuit current, T_{Ref} is the reference temperature of the cell, R_s and R_{sh} represent the series and shunt configuration resistance, respectively, and λ represents the intensity of solar radiation in W/m^2. Table 2 shows the detailing of different configurations of PV array. P–V characteristic of PV array is represented in Figure 5, and PV array reconfiguration structures are shown in Figure 6.

Table 2. The characterization of dynamic PV array rearrangement approaches.

Configuration	Strategy	Number of Switches	Gained Parameters	Remarks	
				Advantages	**Limitations**
(a) Simple series	Series [68]	Zero	Zero	Wide application range	Poor efficacy and huge loss of power
(b) Parallel	Parallel [69]	Zero	Zero	Wide range of application and larger output current	Low efficacy and poor output potential
(c) Series–parallel	RPV [70]	6-SPDT, 5-DPST, 4-DPDT	Voltage and intensity of radiation	Wide range of application	Only dual mode of transition of connectivity
	SWS [71]	6-Switches for each SWS	Current and intensity of radiation	Better speed of convergence	Poor authenticity and high changeability
	Adaptive [70]	$6N_{FST}+3M_{FMIM} + (N_{FST}-1) + (N_{FMIM}-1)$	Current and intensity of radiation	Highly compatible	Existence of many switches and complex
	IE [72]	NS	Intensity of radiation	Better speed of convergence	High volatility
(d) Total cross tie	DS [73]	NS	Intensity of irradiation	Superior efficacy and highly reliable	Complicated
	ZZ [74]	NS	Intensity of irradiation	Wide range of application and superior efficiency	Restricted to 3 × 3 array configuration
	IE [75]	24-DPST	Current, voltage, irradiance	Smaller processing and computation duration	Highly complicated and gained only three parameters
(e) Bridge link	[76]	NS	Intensity of irradiation	Wide range of application and lower cost	Highly complicated and lower acceptance
(f) Honey comb	[77]	NS	Intensity of irradiation	Better stability	Complicated and lower acceptance

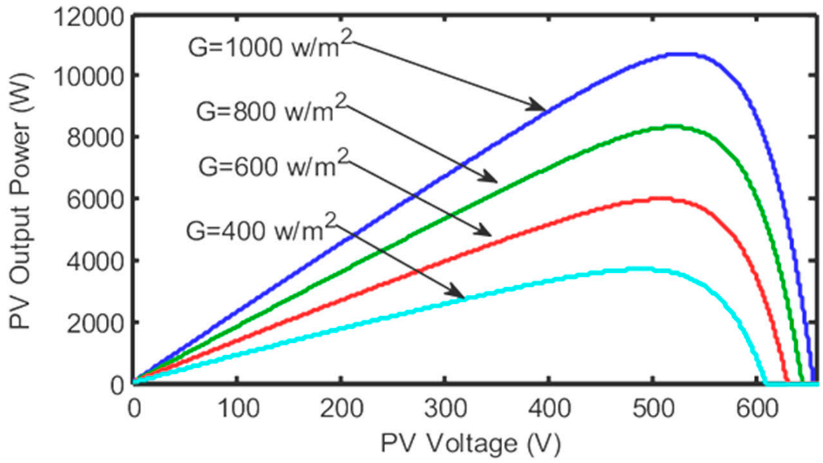


Figure 5. P–V characteristic of a PV array at constant temperature and variable solar irradiation [66,68].

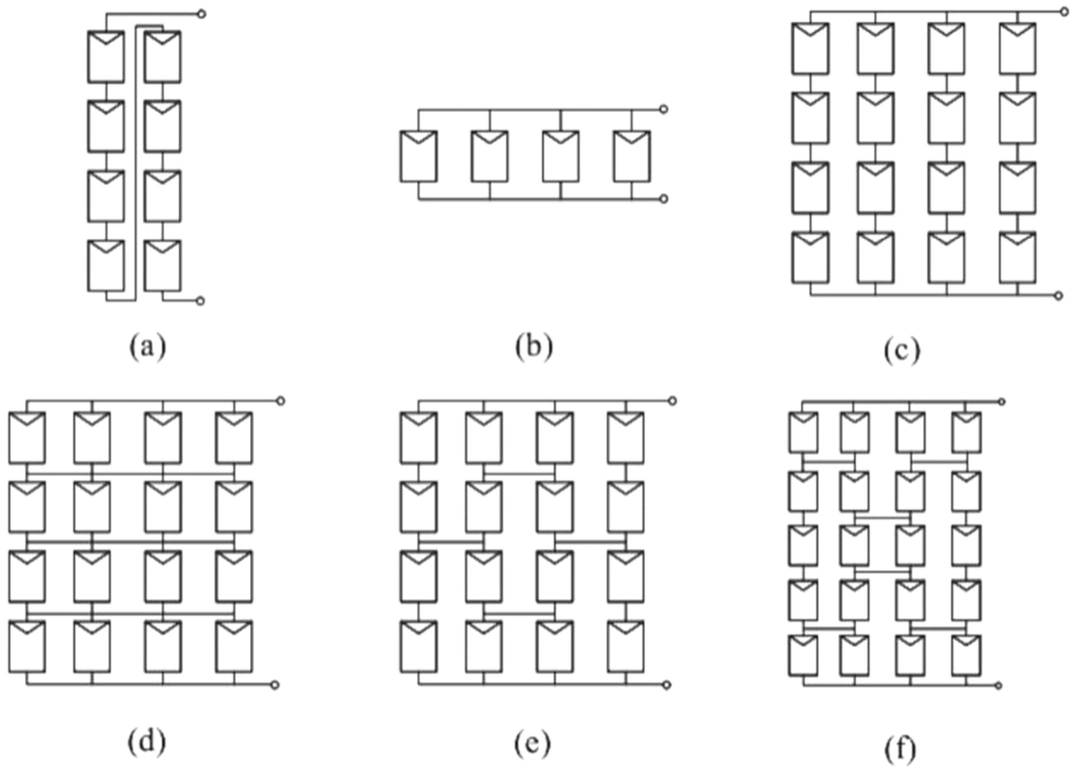


Figure 6. PV array configuration structures: (**a**) Simple Series (SS); (**b**) Parallel; (**c**) Series–Parallel; (**d**) Total Cross Tie; (**e**) Bridge Link; and (**f**) Honey Comb [67].

5. DC–DC Power Converter Topologies in Sustainable Energy System

The demand of renewable energy is increasing due to ease of access, less pollution caused, and less expenditure incurred. The thermal power plants and radioactive power plants are responsible for abrupt climatic changes that usually are generated by the thermal pollution of those plants. Considering all other renewable energy sources, PV and wind are supposed to be utilized more. These resources have the upcoming possibilities on parity of grid in India due to its environmental phenomenon [78]. Many other countries like Mexico, China, Finland, and Europe have been experimenting on renewable energy so that it can be deployed as alternative way of energy generation [79,80].

Researchers are focusing on solar generation as it is highly trustworthy and installation is less complicated. Since the solar generation is intermittent in nature due to uncertain solar irradiation and ambient temperature, to mitigate this trouble, DC–DC power converters were established to provide fixed amplitude or regulated voltage outcome. Broadly the DC–DC power converters are classified in two categories, i.e., isolated and non-isolated. In isolated DC–DC converter, the input and output ends are kept separated by applying an electrical barrier by using a high frequency transformer whose turns ratio is chosen on the basis of the desired gain. The benefit of this arrangement is that it safeguards the sensitive load. Both positive and negative output configurations can be achieved by this architecture, and it is also enriched with the ability of noise interference.

Limitations are as follows. The whole system becomes heavy, and the main switches of the converter experience high potential spikes and therefore high switching power loss due to the presence of leakage inductance. As compared to isolated architecture, non- isolated DC–DC converters are simple in design due to the absence of high frequency transformer and carry less cost. This article is mainly aimed at the discussion of non-isolated DC–DC power converter topologies. A detailed classification is portrayed in Figure 7. Considering the parameters of superior efficiencies, trustworthy control switching techniques, configuration based on the withstanding of faults and compatibility with sustainable energy applications, the DC–DC converters are developed [81–83]. Each converter topology carries its own features [84–86]. The aforementioned converters are engaged in many other applications like electric traction, electric vehicles, space stations, airplanes, machine tools, etc. [87], fuel cell embedded with the storage device [88,89], solar generation application [90], and basic and special electrical machine drives [91,92].

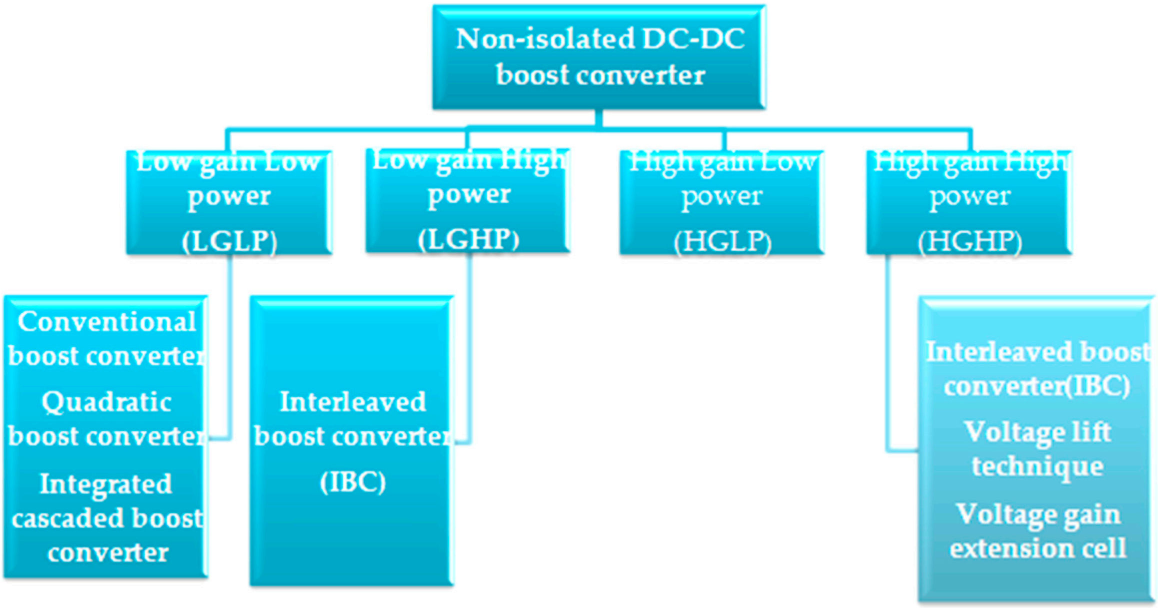
5.1. Progression of DC–DCPower Converter Topologies for Solar Power Generation

The modern topologies of non-isolated unidirectional DC–DC boost converters, bidirectional converters, and SEPIC converter applicable for PV-interfaced nanogrid and picogrid systems are elaborated in this section.

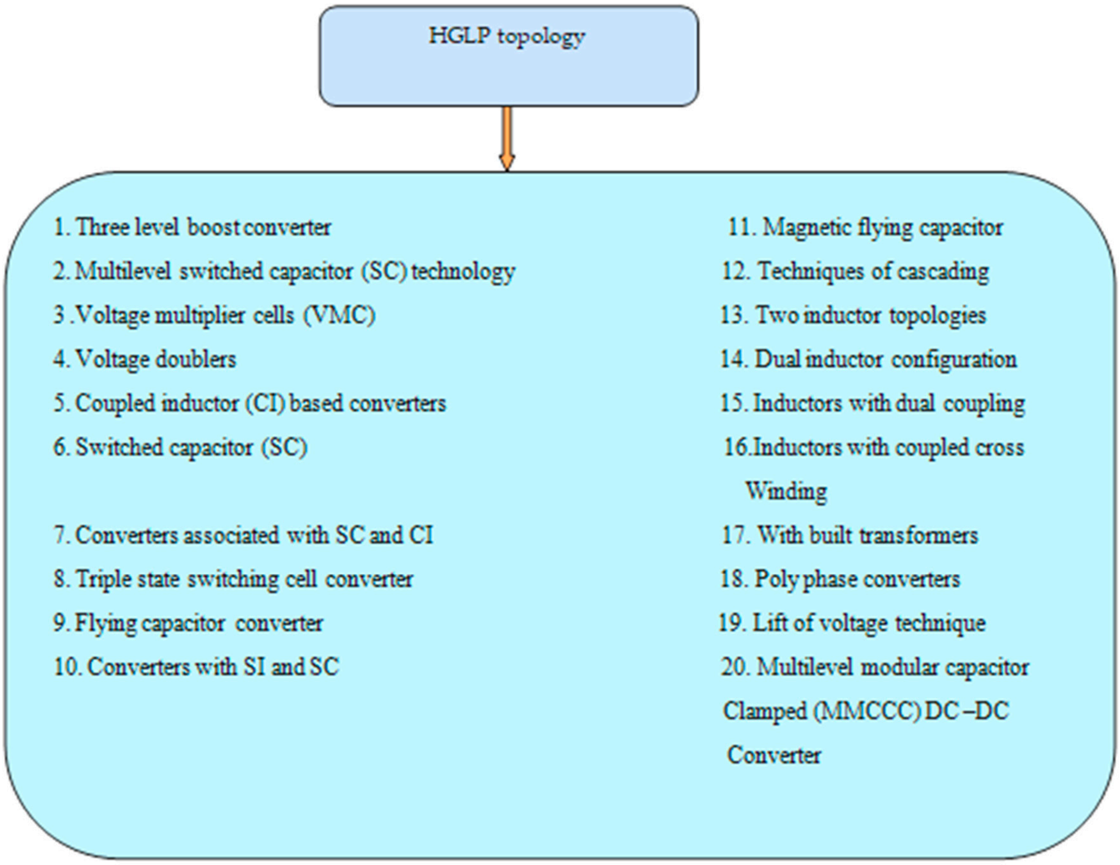
Traditional boost converters are employed in the solar power generation where the receiving end voltage is required to be high as compared to the sending end. An MPPT controller can be embedded with the boost converter considering such a condition. Huber et al. [93] made an analysis of using cascade architecture to make the output voltage gain superior and decrease the ripples. Since the magnitude of the input potential is low so the initial stage experiences less voltage stress and becomes able to operate with better switching frequency. The later stage works under lower switching frequency as a result of which switching losses have been reduced. The limitations of cascaded structure are high number of circuit elements, poor efficiency, and electromagnetic interference noise (EMI). Ghamrawi et al. [94] examined the immutability of quadratic double boost converter that performs the identification of MPP by incorporating MPPT as a control technique. Embodiment of coupled inductor and switched capacitor results in voltage gain of the boost converter. The reverse recovery challenge of output diode can be solved by the leakage inductance of the coupled inductor. The boost converter can be classified as follows depending on power consumption and potential gain.

In PV application to achieve a voltage range of 12–60 V, non-isolated DC–DC converter plays a role of input voltage provider that would deliver an output voltage in the range of 24 V for batteries and 760 V for power transmission system [84]. Due to having some restrictions in raising the voltage in the range of grid level of the conventional DC–DC boost converters, some modifications are made in order to derive new improved topologies [95,96]. These derived topologies are superior in terms of high voltage output and efficiency. The modified topologies of the boost DC–DC converters can be classified into four sub-categories:

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



(**a**)



(**b**)

Figure 7. (**a**) Classification of non-isolated DC–DC boost converter. (**b**) Detailed classification of HGLP topology.

Among the above-mentioned categories HGLP topology has applications in PV systems. A detail classification is showcased in Figure 7b. Researchers are engaged in some further modifications of HGLP topology such as three level boost converter [97–100], multilevel switched capacitor (SC) topology [101,102], voltage multiplier cells (VMC) [103–106], voltage doublers [107–109], coupled inductor(CI) configuration [110,111], switched capacitor configuration [112,113], amalgamation of SC and CI topologies [114–116], amalgamation of SC and SI configuration [117–119], triple state switching converters [120–122], flying capacitor configuration [123], non-magnetic flying capacitor configuration [124], multilevel modular capacitor clamped DC–DC converters [125], technique of cascading [126], topology having two inductors [127], dual inductor configuration [128], two CIs [129],winding crossed coupled inductor [130], transformer with built-in configuration [131], poly-phase converters [132], and VL technique [133].

5.2. Low Power High Gain Boost DC–DCConverter Associated in PV Application

Based on the literature survey, it is found that 20 variations of derived and modified topologies have been sectioned as high gain low power converters whose technical aspects are tabulated in Table 3. It is evident from the result that out of 20 topologies 6 configurations provide excellent output in terms of voltage gain >15. This phenomenon may be regarded as "extra high potential gain" DC–DC converter. This section focuses on those "extra high potential gain topologies". These topology configurations include VMC, voltage doublers, CI based, converter with SC and CI, triple state switching cell converter, and MMCCC. Among them, modular structured VMC, voltage doublers, and cascading structures are studied in depth on the basis of count of elements, potential stress on switch, optimum efficacy, potential gain, and examined frequency and power, and are tabulated in Table 4 for the following advantages.

Table 3. Different topologies of HGLP DC–DC converters.

Topology Number	References	Range of Potential Gain		Number of Elements	
		Smallest	Highest	Smallest	Highest
1	[97–100]	4 [98]	12 [99]	13	18
2	[101,102]	9 [102]	12 [101]	10	20
3	[103–106]	9.45 [103]	15.7 [105]	11	22
4	[107–109]	7.89 [108]	18.97 [109]	7	12
5	[110,111]	6 [109]	17 [111]	7	14
6	[112,113]	4.97 [113]	11 [112]	9	16
7	[114–116]	5.76 [114]	16.56 [116]	8	18
8	[117–119]	8.99 [117]	19.87 [119]	6	17
9	[120–122]	8 [122]	8.34 [120]	13	19
10	[123]	5 [123]	X	7	X
11	[124]	5 [124]	X	14	X
12	[125]	5.89 [125]	X	7	X
13	[126]	19.5 [126]	X	11	X
14	[127]	12.59 [127]	X	12	X
15	[128]	8 [128]	X	13	X
16	[129]	10.99 [129]	X	7	X
17	[130]	8.23 [130]	9	7	14
18	[131]	9 [131]	9.46 [133]	13	18
19	[132]	4.85 [132]	9.43 [132]	8	25
20	[133]	9.43 [133]	15 [133]	11	13

X indicates that no data was available.

VMC is having simple configuration with lower potential stress on the switches and being modular. Voltage doublers are the modification of VMC. It is also a simple topology with superior potential gain due to the application of multiplier circuit. Since this topology uses lesser number of elements thus efficiency is better. Cascade-based topology has wide variations. It is also simple in structure and being modular.

Table 4. Comparative study of modular structured DC–DC converter topologies.

Topology	Count of Elements					Potential Stress on Switch	Optimum Efficacy	Potential Gain	Frequency (kHz)	Power (W)
	L	C	S	D	Sum					
VMC	4	3	2	5	14	$V_{out}/2(n+1)$	97.2%	15.6	50	400
Voltage doublers	2	3	2	4	11	$V_{out}/2$	93%	15.83	100	500
Cascading techniques	2	2	3	4	11	N/A	95.6%	20	45.5	280

5.2.1. VMC

There exist several VMC topologies that are determined on the basis of amalgamation of many passive elements comprising of capacitors and inductors, which consist of various semiconductor devices like MOSFET, IGBT, diode, etc. This arrangement resulting in a multiplier circuit with individual features. Figure 8 shows the fundamental circuitry of DC–DC boost converter with VMC [104]. A few topology variants are depicted in Figure 9 [106]. This amalgamation results a multiplier circuit associated with distinctive characteristics. These topologies are appropriately fitted due to their ability of stepping up low input voltage to a desired level on the grid end.

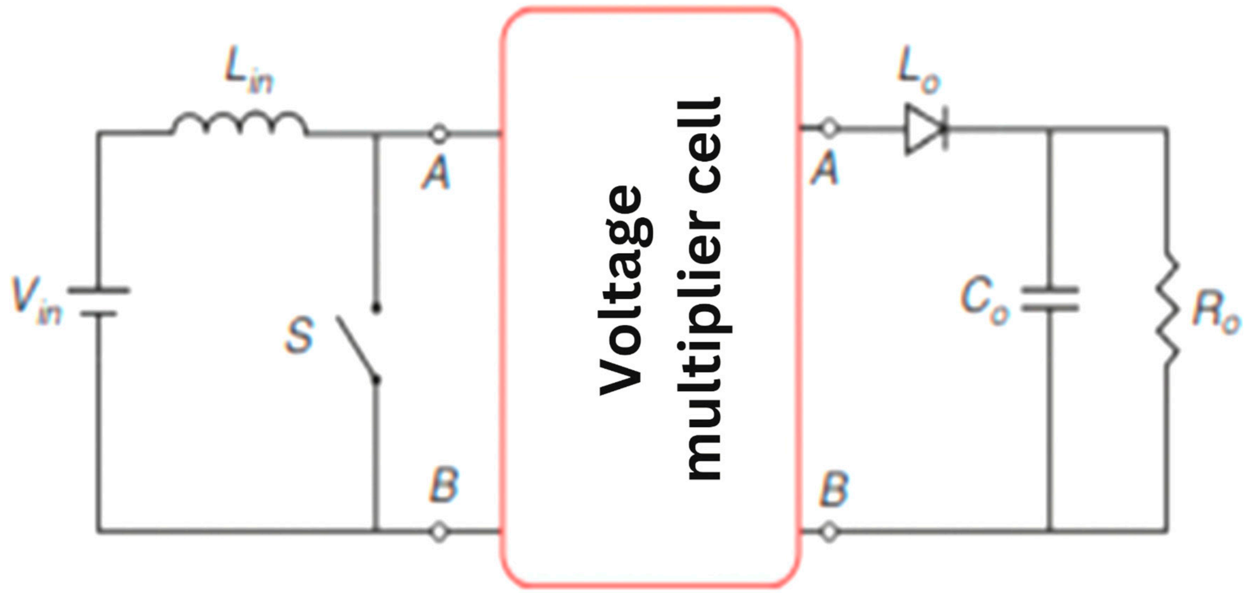


Figure 8. Basic circuitry of DC–DC boost converter with VMC [95].

5.2.2. Voltage Doublers

The converter whose output is twice the input is termed as voltage doublers. It comprises of a diode and an inductor [107]. Voltage doublers work on the principle of charging the capacitor at the input end and shifting the saved energy to the load end by accurately making double of the input voltage. Due to this potential doubling mechanism the converter suffers from high losses, thus reducing efficacy. The equivalent circuit configuration of DC–DC boost converter in association with voltage doublers is shown in Figure 10 [109].

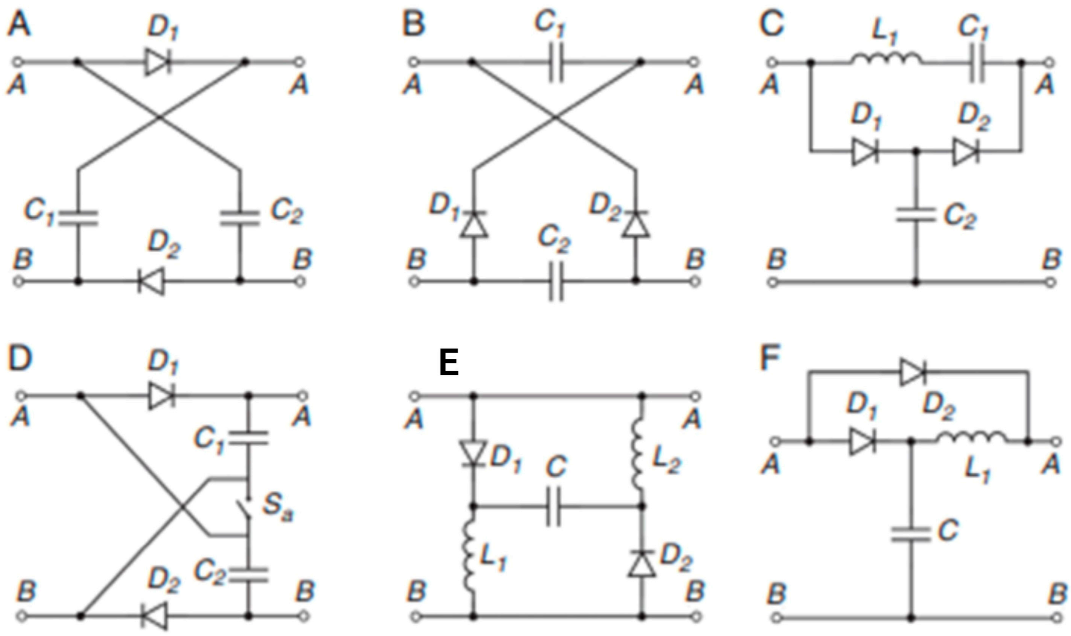


Figure 9. Different cell topologies in VMC [106].

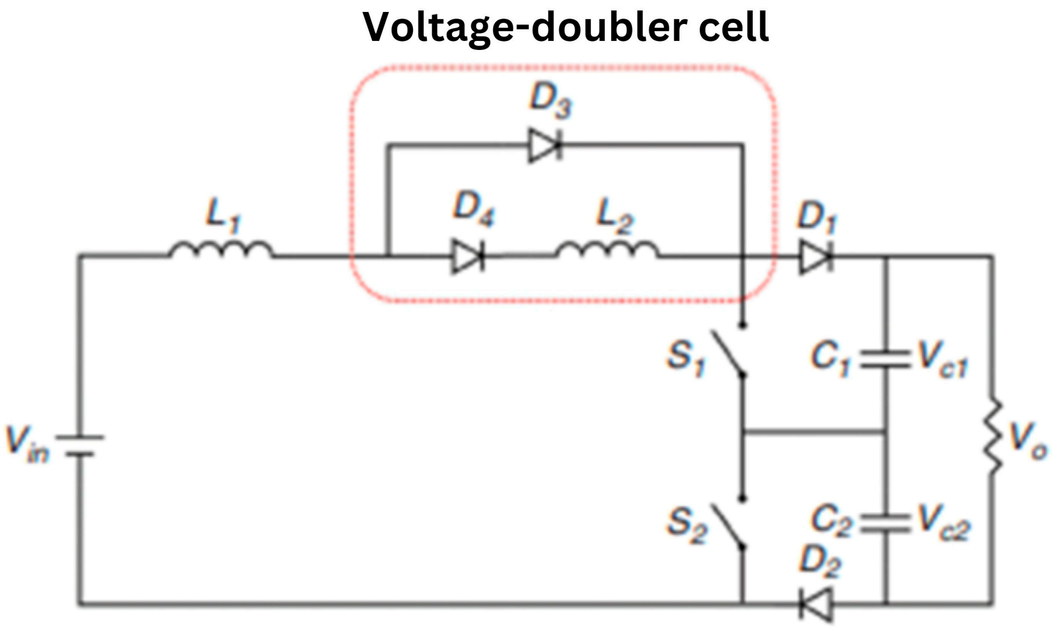


Figure 10. DC–DC boost converter in association with voltage doublers [109].

5.2.3. Cascading Topologies

In order to increase the potential gain of a converter, a multistage boost converter is one of the solutions. The diagrammatic representation of cascaded DC–DC boost converter is depicted in Figure 11 [134]. It is evident from the diagrammatic representation that the family of this topology is constructed on the basis of cascading multiple configuration of boost converter (quadratic topology) or increasing gain of converter (hybrid topology).

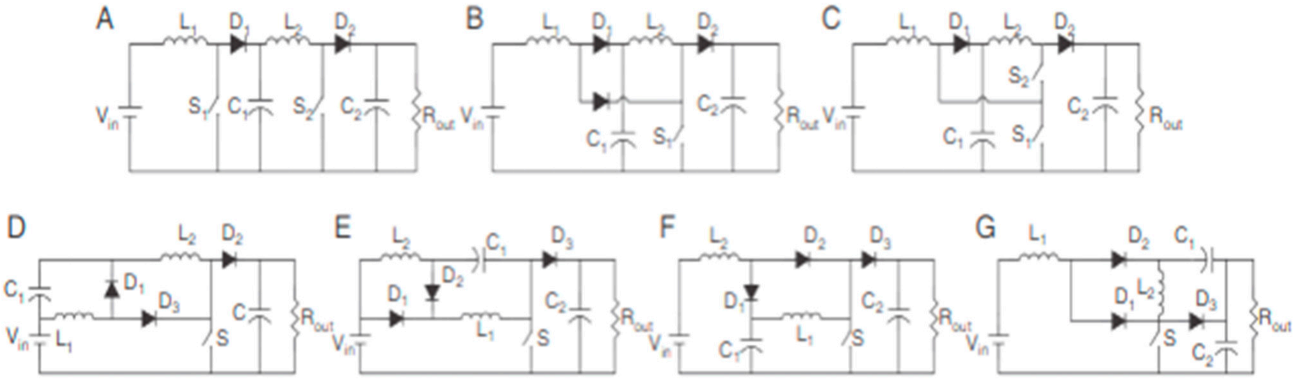


Figure 11. (**A**) Dual boost converter, (**B**) quadratic boost converter, (**C**) mutated tri-level quadratic boost converter, and (**D**–**G**) multiple members of the family of quadratic boost DC–DC converter configurations [134].

Quadratic Boost

As shown in Figure 11A, this converter topology is derived by cascading two boost converters [135]. It is evident from the circuit composition that the antecedent boost converter experiences less potential stress compared to preceding boost. Thus, the first boost converter is allowed to operate on the high frequency and less power density phenomenon. As the preceding operates at lower frequency, as a result, it experiences lower switching loss. A multiple stage boost converter for multiple stage configurations is depicted in [136] to mitigate the circuit complexity that can be integrated into a configuration consisting of one switch is called quadratic boost converter. Figure 11B shows the circuit composition of quadratic boost converter. The control of quadratic boost converter requires two PWM signals, which introduce more complications, and these are alleviated by multiple stage operation that needs only one switch to make the control less complicated [137]. Figure 11C acquires superior potential gain on the basis of altered tri-level DC–DC converter [138]. Figure 11D–G depicts multiple members of quadratic boost converter family. These configurations are capable of allowing the narrow alteration of duty cycle with the change in potential gain. Thus, design process becomes simple accompanied by high performance by the converter's end itself [139].

6. Modern DC–DC Bidirectional Converter Strategies in a Sustainable PV Architecture

6.1. Bidirectional DC–DC Converter

The Bidirectional DC–DC converter as shown in Figure 12 is a C class chopper, which can operate in first and second quadrants (i.e., positive voltage and positive or negative current). In one quadrant, it works as a boost converter and as a buck in other quadrant as per the direction of current. In this proposed work, a dual loop controller is designed to control the converter. The outer loop controls the voltage and inner loop controls the inductor current. The current reference is calculated by the difference between the voltage of the dc grid and reference voltage. In this way, converter acts in buck or boost mode to maintain a constant bus voltage.

6.2. Triple Port Integrated Topology (TPIT)

The circuit diagram of TPIT is shown in Figure 13. The bidirectional AC–DC converter interfaces the dc link with the electric grid. The bidirectional DC–DC converter (Class C) interfaces the electric vehicle batteries, and the unidirectional DC–DC converter interfaces the solar PV panel. TPIT integrates all these converters to a single common dc link such that the characteristics of each converter are maintained. The direction of power flow in each converter is decided by the operating mode of the system such that the voltage of the dc link is maintained constant. This topology given operates in four modes:

i. Renewable-to-grid (R2G) mode: In this mode, the power generated by the solar PV is given to the electric grid via a chopper (DC–DC converter) and then to a DC–AC converter. The bidirectional AC–DC converter works as an inverter in this mode.
ii. Renewable-to-vehicle (R2V) mode: In this mode, the generated PV power is used to charge the electric vehicle's battery. The bidirectional converter allows the current flow such that the battery charges and the SOC also increase.
iii. Vehicle-to-grid (V2G) mode: In this operating mode, the electric vehicle supplies the required power to grid. This mode ensures uninterrupted supply in the system.
iv. Grid-to-vehicle mode: When the required power by the vehicle is not generated by solar then the grid supplies the excess power demand via this operating mode. The ac power from the grid is converted to dc via AC–DC converter and it charges the battery. SOC of the battery increases in this case.

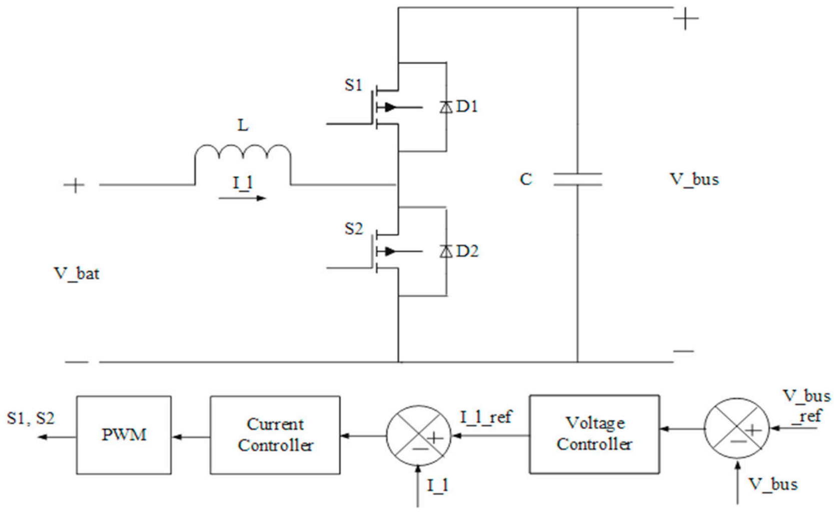


Figure 12. Bidirectional converter [60].

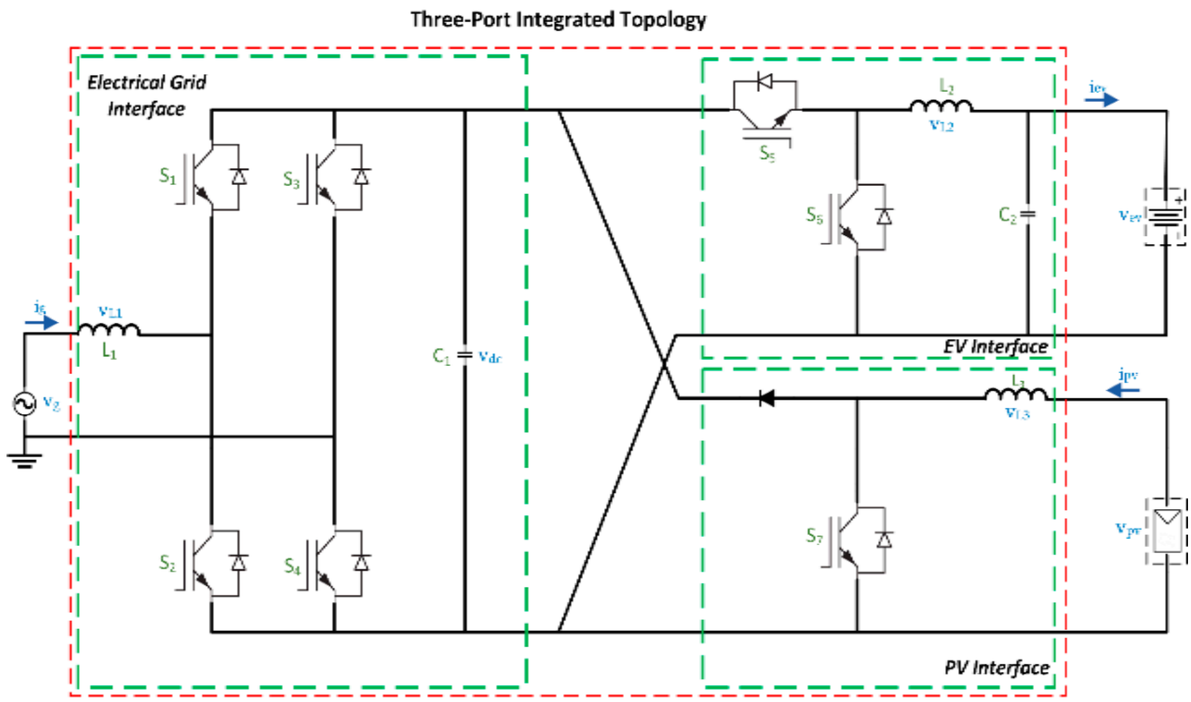


Figure 13. TPIT circuit to interface PV and EV with the electric grid.

6.3. Three-Port DC–DC Converter

Basic circuit layout of the proposed three port DC–DC converter is shown in Figure 14. In this figure, the converter blends a PV panel and a battery (energy storage) into a dc nanogrid system. The dc link of the nanogrid is combined to the two ends of the switch-leg. Further, the conversion of power from the PV panel and the energy storage to the dc link frame two dc boost converters operated in DCM and CCM modes. The purpose of this converter can supply bidirectional flow of power in the battery to indulge different requirement of the dc nanogrid. Further, the power flow between the ports varies on the basis of load demand, net solar energy, and the state-of-charge of the battery storage.

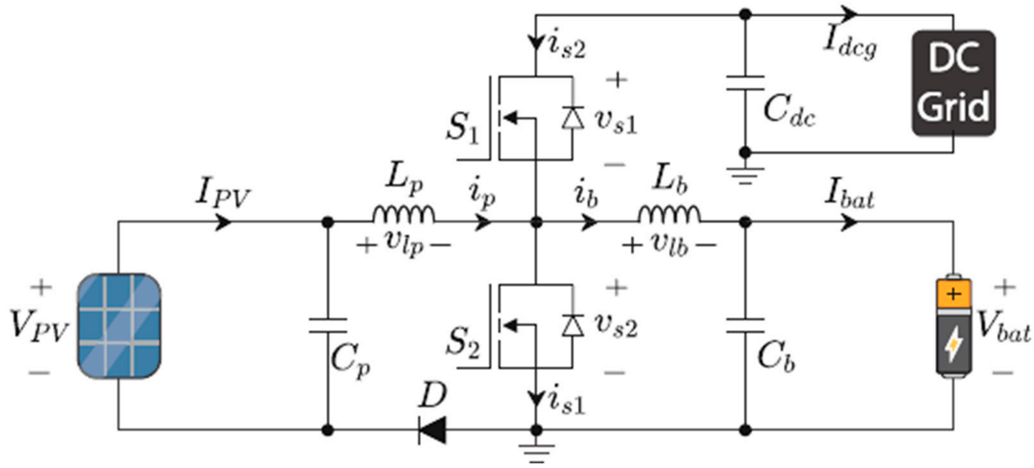


Figure 14. Three port DC–DC converter proposed in [140].

6.4. SEPIC Converter

The shortcomings of conventional buck-boost converter such as output voltage of reciprocal polarity and palpitated characteristics of load current can be overcome by SEPIC converter [141]. Rasoul Shalchi et al. [142] proposed a high step up DC–DC converter by combining an extensive switched capacitor and a conventional SEPIC converter for PV application. The main prospects of this introduced topology are lower number of elements and superior potential gain, presence of low ripples, simpler control strategies, and consistent input current. Rizky Ajie et al. [143] investigated an updated SEPIC under different criterion for grid oriented solar application. The model was simulated by PSIM. By varying the solar irradiance and ambient temperature, both the boost and SEPIC converter was tested, and the SEPIC showed better performance.

Kumaran Nathan et al. [144] proposed an extended version of DC–DC converter by combining Cuk-SEPIC which showed a good fitness in PV application. The said topology experienced low ripples in input current by incorporating integrated magnetic core to join the inductors of input and output ends, thereby improving the power delivering capability. H. Suryoatmojo et al. [145] proposed a design of revamped DC–DC SEPIC converter. The alteration to the basic SEPIC converter was conducted by incorporating capacitors and diodes. As a result of which while the conventional SEPIC was capable of stepping up to five times, the updated version could increase the gain up to ten times.

Ahmed El Khateb et al. [146] investigated Fuzzy Logic controller with SEPIC to obtain maximum power from PV application. The FLC-based MPPT was capable of following the true MPP and transferred power about 4.8% higher than usual PI controller. Babaei et al. [147] analyzed the presence of ripples of output voltage during DCM and CCM because these parameters are mandatory while designing the converter. On the basis of primary magnitude of input voltage and output resistance, the amplitude of optimum value of ripples in output voltage was witnessed. CCM was analyzed in two modes, namely, complete inductor supply mode (CSIM) and incomplete inductor supply mode (IISM).

DCM only worked on IISM. This article also focused on how the efficiency was affected by the influence of the inductor.

In order to analyze the dynamic performances like steady state and small signal stability, Fourier analysis can be conducted to reduce the ripple quantities. At the time of transient response, this method helps to reduce the potential stress on the switches [148]. Kim et al. [149] enforced a soft switched PWM-SEPIC that had evidence of small switching stress as compared to hard switching configuration. The trouble of hard switching can be minimized using a quasi-resonant SEPIC that is capable of operating at a constant switching frequency.

7. Conclusions and Future Research Directions

Researchers can gain a thorough understanding of the DC–DC converter topologies that can be used to generate electricity from solar energy through the aforementioned survey and debates. Low power conversion efficiency in solar energy generation necessitates discussion of DC–DC converter topologies suitable for low power, high gain applications. Six of the 20 modified derived high gain low power (HGLP) topologies examined produce gains greater than 15, which are referred to as extra high gain converters. Three of those extra high gain topologies—voltage multiplier circuits, voltage doublers, and cascade techniques—with modular structures are elaborated in terms of the number of components, potential switch stress, optimum effectiveness, potential gain, and frequencies and powers under consideration. In future, more extra high gain power converters may be assessed in terms of the aforementioned criterion. In addition, certain enhanced modified bidirectional converters are researched in this study to interface with grid and vehicle to execute (R2G), (R2V), (V2G), and (G2V) operations in nanogrid and picogrid configurations.

Researchers and engineers will find this study piece useful in selecting the best topologies for a PV-interfaced power conversion system. Since the production of electrical energy from solar energy is intermittent, MPPT is crucial for achieving the appropriate output at the converter's end. It provides the converter the right switching signal. Under various irradiation and partial shading conditions, various MPPT approaches are compared in terms of their complexity, cost, and speed of tracking, certainty, and hardware compatibility. The examined techniques also have certain shortcomings. In order to obtain both qualitative and quantitative energy from solar power generation, hybridization of MPPT techniques is the main focus of researchers. More suitable hybrid MPPT approaches may be developed. After a thorough review of the literature, it was decided that addressing the intermittent nature of solar power generation should be prioritized along with the effectiveness of the system as a whole. Many MPPTs are in-depth reviewed in this article.

On the other hand, the non-isolated DC–DC power converters also perform well in renewable energy sources to minimize the cost of the system and improve the efficiency. The major findings of the research are as follows.

In order to expand the potential gain and to diminish the effect ripple content, cascade architecture has a prominent role. But the shortcomings are higher EMI noise and inferior efficiency.

Interleaved converters are capable of achieving reduced switching loss, superior efficiency, reduced EMI, ripple accumulation and size of filter, better transient outcome, and elevated stratum of power. Besides all advantages, the limitation is that circuitry is complicated and expensive.

In view of the various performance index of different MPPT presented in the article, one more index must be judged to analyze and standardize the MPPT that is energy usage index, which is the ratio of power delivered by a particular MPPT to the metaphysical optimum power output ability of the same MPPT over a duration of time.

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