A comprehensive review on power converters of photovoltaic system

Abbas Ali, ID 15632

ABSTRACT

The choice of the right type of power converters to meet the different necessities for any application has a great effect on the optimal performance, especially in Solar Photovoltaic (PV) system. Power electronic converters are generally used to convert the power from the renewable sources to tie the load request and grid necessity. The purpose of this review is to deliver a comprehensive variety on architecture of grid-connected solar PV system and its basic modules such as solar cell, PV array, maximum power point tracking, filters, DC-DC converters, single-phase inverters, and three-phase inverters to the researchers, designers, and engineers working on solar energy and its addition into the utility grid. Brief summary of control techniques for the single and three-phase inverters has also been reviewed. More than 30 research publications on the topologies, configurations, and control techniques of grid-connected solar PV systems and their key component components have been comprehensively studied and classified for quick reference.

1. Introduction

Renewable energy (RE) sources are very good solution to provide alternative energy to overcome the global energy problem [1]. Further, the development in grid integration technologies, for these resources during the last decade, has increased the use of RE sources. Solar photovoltaic (PV) system has become a promising RE source due to its capability of generating electricity in a very clean, quiet, and reliable way [2]. The PV systems are solar energy supply systems, which either supply power directly to an electrical gazette in its stand-alone mode or feed energy into the utility electricity grid in its grid-connected mode [3]. As the cost of PV panels' production is continuously decreasing due to advances in the material and PV array fabrication technology, it is expected that the solar bulk power generation will be competitive with other forms of RE sources [4]. However, solar power generation has the problem of low conversion efficiency of the solar cells, and the output power of PV array is dependent on irradiation and temperature. Therefore, maximum power point tracking (MPPT) circuitry should be used for utilization of the PV array at full efficiency. The solar PV systems have relatively low voltage output characteristics and demand high step-up voltage gain for grid integration [5]. This is achieved by the use of high efficiency DC-DC converters for such practical applications. These converters are able to interface different level inputs and combine their advantages to feed the different level of outputs for solar PV applications. The inverter converts DC power to AC power through a solid state switching action used to feed energy generated by a PV generator into the utility grid. High efficiency of these converters is a major requirement [6]. The solution to control the power injected into the grid are essential for effectiveness of the system. In the real and reactive power control system, the real power output reference is a function of the incident solar irradiance and the temperature of the pn diode junction. The reactive power output reference is selected based on the system rating and adopted voltage regulation scheme. This paper is divided into five sections. Starting with an introduction in sections 1. Section 2 covers the basic architecture of grid-connected solar PV system, solar cell, PV array, MPPT, and filters. Section 3 covers the DC-DC converters such as buck, boost, buck-boost, and cuk used for the grid connected solar. The overall performance of solar PV system, cost estimation and future scope are detailed in the Section 4. Finally, the conclusions are drawn in the Section 5.

2. Grid-connected photovoltaic system

Grid-connected solar PV (GCPV) systems include building integrated PV (BIPV) systems and terrestrial PV (TPV) systems. TPV systems include plants in desert, tide, and saline-alkali land [7]. The major elements of a grid-connected solar PV system are shown in Fig. 1. The inverters and DC-DC converters are discussed in separate sections, whereas all other components are detailed in the following subsections.

2.1. Solar cell

Solar cell consists of a p-n junction fabricated in a thin layer of semiconductor like a p-n diode. Its operational characteristics are also same as p-n diode and depend on the solar radiations as well as surface temperature. An electrical equivalent circuit of a solar cell can be represented by a single or double diode model [8]. Although the double-diode model is more accurate under certain operating conditions, the single diode equivalent model has simplicity with sufficient accuracy, and allows for the development of explicit models.

Single diode equivalent circuit with parallel and series resistances is shown in Fig 1.

The relationship between output voltage (V) and output current (I) for the single-diode equivalent circuit of a solar cell can be described by the following relation [9].

$$I = I_{ph} - I_0\left\{\exp\left[\frac{q(V+IR_s)}{AkT}\right]-1\right\} - \left(\frac{V+IR_s}{R_{sh}}\right) \tag{1}$$

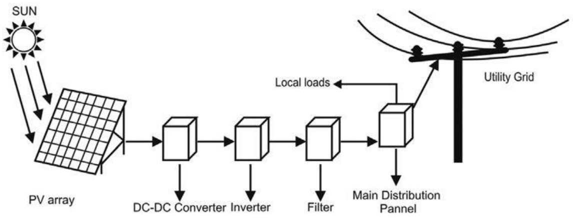


Fig. 1. *Grid-connected solar PV system.*

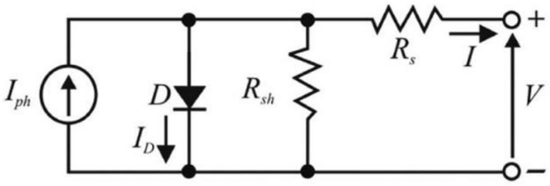
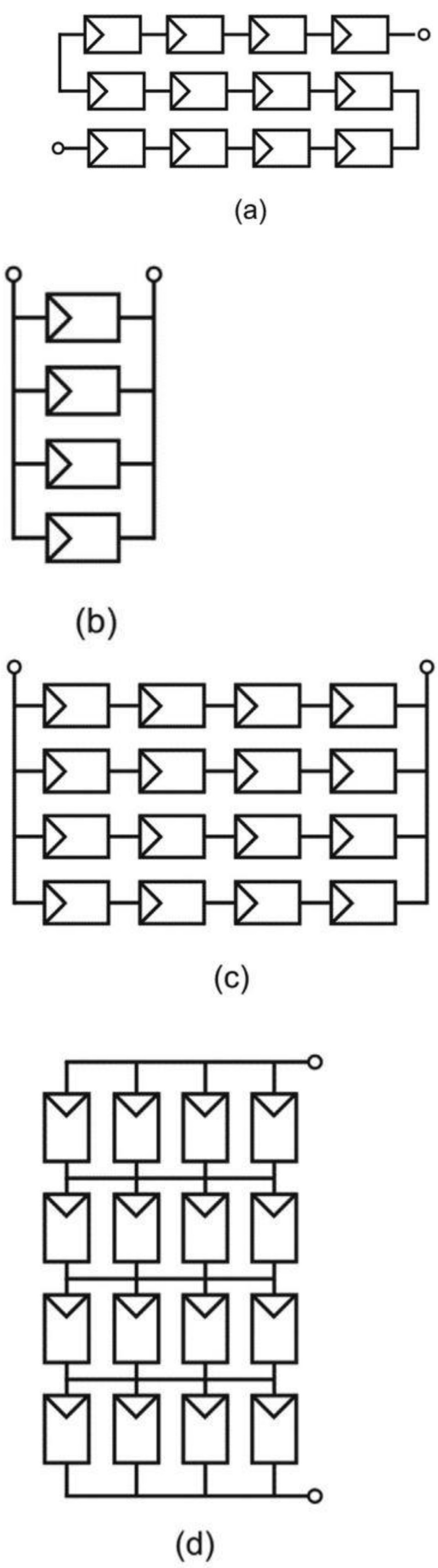


Fig. 2. *Single-diode equivalent circuit of a solar cell.*

2.2. PV array

The output power from a single PV cell is relatively small. The required voltage and power is produced by grouping the PV cells in series and parallel forming the modules [10]. Modules are combined to form PV panels. These panels are connected together to build up the entire PV array and any desired current-voltage characteristics could be generated. Different connection topologies of solar PV array are detailed in Fig. 3. These connection topologies of solar PV arrays have been utilized in both grid-connected BIPV and TPV systems [11]. However, the PV inverter topologies may differ depending on the rooftop area available for the installation of BIPV systems. The grid connected large scale



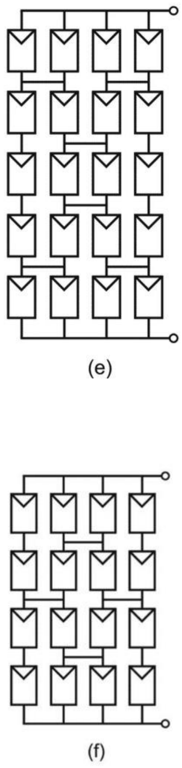


Fig. 3. *Topologies of solar PV array (a) series (b) parallel (c) series-parallel (d) total-cross tied (e) bridge-link, and (f) honey-comb.*

BIPV systems are gaining momentum due the introduction of net-metering concept by the utilities for the electricity users [1].

The value of R_{sh} can be assumed to be infinite at short circuit conditions, where slope of the I-V characteristics is almost zero. In this case, I_{ph} is equal to the short circuit current (I_{sc}) and Eq. (1) for solar cell reduces to the following relation.

$$I = I_{sc} - I_0\left\{\exp\left[\frac{q(V + I.\,R_s)}{AkT}\right] - 1\right\} \tag{2}$$

For a PV array arranged in N_p parallel and N_s series connected solar cells, the Eq. (2) reduces to,

$$I = N_p I_{sc} - N_p I_0\left\{\exp\left[\frac{q(V + I(N_s/N_p)R_s)}{N_s AkT}\right] - 1\right\} \tag{3}$$

2.3. Maximum power point tracking

The basic principle of maximum power point tracking (MPPT) algorithm depends on the exploitation of voltage and current variations caused due to pulsations of instantaneous power [12]. Analysing these variations allows us to obtain power gradient and evaluate, if the solar PV system operates close to the maximum power point. The maximum power delivered by the solar PV array is given by the relation

$$p_{max} = I_{mpp} V_{mpp} \tag{4}$$

Where V_{mpp} and I_{mpp} are respectively the optimal operating voltage and current of PV array at the condition of maximum power output. The solar cell exhibits non-linear V-I characteristics, therefore a MPPT controller must track the maximum power and match the current environmental changes. The MPPT is achieved by using DC-DC converter between PV array and inverter [13]. From the measured voltage and current, the MPPT algorithm generates the optimal duty ratio (D) in order to maintain the electrical quantities at values corresponding to the maximum power point. The most widely used MPPT techniques include perturbation and observation(P&O),incremental conductance, open circuit voltage, short circuit current, Fuzzy logic, and neural network based methods [14].

2.4. Filter

A filter consisting of inductance and capacitance is used between inverter and the grid. The filter is designed to reduce higher-order harmonics introduced due to PWM modulation of the DC/AC converter. The LCL filter design has inverter side inductance (L_i), the grid side inductance (L_g) and capacitance (C_f). The (L_g C_f) is considered as second order low pass filter. The ratio of grid side inductance and converter side inductance depends upon the ripple current attenuation. The simplified design equations for LCL filter are given as follows

$$L_i = \frac{V_g}{2\sqrt{6} f_s I_{ripple,peak}} \tag{5}$$

$$C_f = \frac{0.05}{\omega_n Z_{base}} \tag{6}$$

$$Z_{base} = \frac{V_{gLL}^2}{P_n} \tag{7}$$

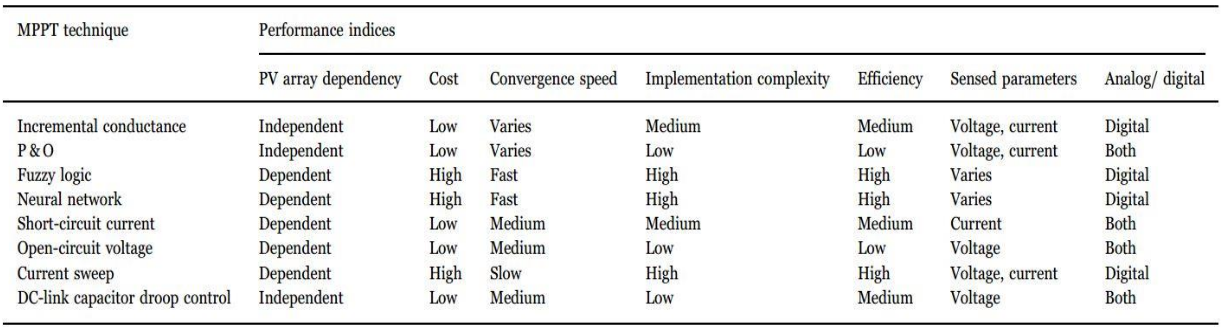
where V_g is the grid r.m.s. phase voltage; f_s is the inverter switching frequency; $I_{ripple\ peak}$, is the peak value of ripple current; P_n is the inverter rated power; V_{gLL} is the grid line voltage; ω_n is the operating frequency. A single-stage solar inverter using hybrid active filter with power quality improvement is proposed in [15].

3. DC-DC converter

A DC-DC converter is a power electronic circuit, which converts direct current of source from one voltage level to the required voltage level [16]. DC-DC converter is the heart of MPPT hardware for solar PV applications [17]. The operation of DC-DC converter forms the basis for the detection of MPP, according to the proposed global MPPT control algorithm. Practically, the output voltage of one PV string is very low despite the use of MPPT. This requires the use of front end DC-DC converter to be equipped with a step-up capability for grid connection [16]. Arrangements of DC-DC and DC-AC converters in the block scheme of grid connected PV system are shown in Fig. 4.

The performance of each topology can be described by the following parameters

Table 1. *Comparison of MPPT techniques*



MPPT technique	Performance indices						
	PV array dependency	Cost	Convergence speed	Implementation complexity	Efficiency	Sensed parameters	Analog/ digital
Incremental conductance	Independent	Low	Varies	Medium	Medium	Voltage, current	Digital
P & O	Independent	Low	Varies	Low	Low	Voltage, current	Both
Fuzzy logic	Dependent	High	Fast	High	High	Varies	Digital
Neural network	Dependent	High	Fast	High	High	Varies	Digital
Short-circuit current	Dependent	Low	Medium	Medium	Medium	Current	Both
Open-circuit voltage	Dependent	Low	Medium	Low	Low	Voltage	Both
Current sweep	Dependent	High	Slow	High	High	Voltage, current	Digital
DC-link capacitor droop control	Independent	Low	Medium	Low	Medium	Voltage	Both

- Current gain (A_i)
- Voltage gain (A_v)
- Input impedance (R_i)
- Minimum filter capacitance (C_{min})
- Boundary filter inductance (L_b)

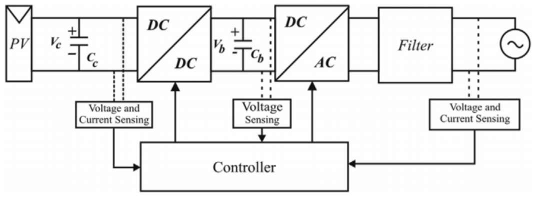


Fig. 3. *Block diagram of grid-connected solar PV system.*

3.1. Buck converter

In buck converter, the output voltage magnitude is always lower than the input voltage magnitude. Therefore, the buck converter is widely used in PV applications, such as front end step-down applications, battery charging, and maximum power point tracker. Buck converter has the disadvantage of generating a lot of electromagnetic interference noise on account of pulsating source current waveform. The basic circuit diagram of buck converter is shown in Fig. 5. Performance parameters of the buck converter are provided in Table 2, from which it can be depicted that the value of D is in the interval [18].

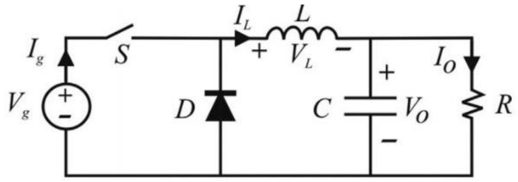


Fig. 4. *Basic circuit diagram of buck-converter.*

3.2. Boost converter

DC-DC boost converter is step-up converter and widely used for integrating the low voltage PV modules to the utility grid. It also performs the function of MPPT under the nominal utility conditions. In boost converter, the voltage is stepped up by increasing the duty cycle [19]. The boost converter has the disadvantage of high voltage stress across the switching device, higher on state resistance leading to more conduction losses in the switch, reverse recovery problem of output diode, losses in the leakage inductance, and parasitic capacitance [20]. The basic circuit diagram of boost converter is shown in Fig. 7. Performance parameters of the boost converter are tabulated in Table 2. The boost converter operates only if $R_{load} < = R_{mpp}$. The operational and non-operational regions of the boost converter on the I-V characteristics of PV modules are shown in [9], from which it is seen that boost converter does not follow the points near the open circuit voltage.

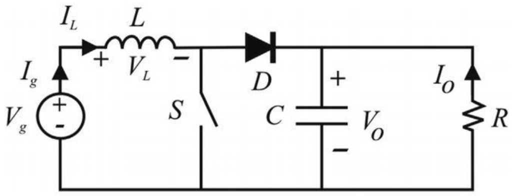


Fig. 5. *Basic circuit diagram of boost-converter.*

3.3. Buck-boost converter

In buck-boost converter, the output voltage magnitude may be lower or higher than the input voltage magnitude. Buck-boost topology can be achieved through cascade connection of buck and boost converters. In buck-boost converter the input current is always discontinuous. The main disadvantages of this topology are high input-voltage ripple and high-electrical stresses to the switch. The basic circuit diagram of the buck-boost converter for solar PV applications is shown in Fig. 7.

The performance parameters of the buck-boost converter are provided in Table 2, from which it is depicted that increasing D, decreases the input impedance thus the PV operating voltage moves to the left region of I-V curve and that decreasing the D, increases the input impedance thus operating voltage moves to the right of I-V curve. Buck-boost converter does not have non-operational region.

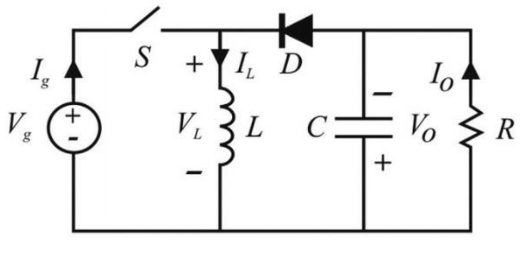


Fig. 6. *Basic circuit diagram of buck-boost converter.*

3.4. Cuck converter

Cuk converter is capable of stepping up or down input voltage like buck-boost converter with reverse polarity through the Common terminal of input voltage. The main difference between Cuk converter and buck-boost converter is the addition of a capacitor and an inductor. The basic circuit diagram of the Cuk converter is shown in Fig. 8. The Cuk converter are the same as the buck-boost converter shown in Fig. 7. There is not any non-operational region, so changing the duty cycle enables to operate the converter through short-circuit current to the open-circuit voltage of the PV modules [21]. The performance parameters of the Cuk converter are tabulated in the Table 2.

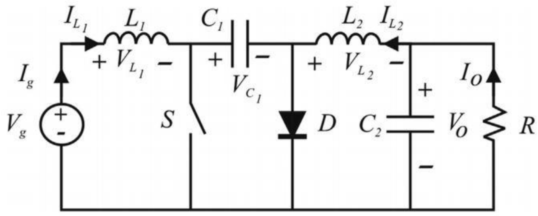
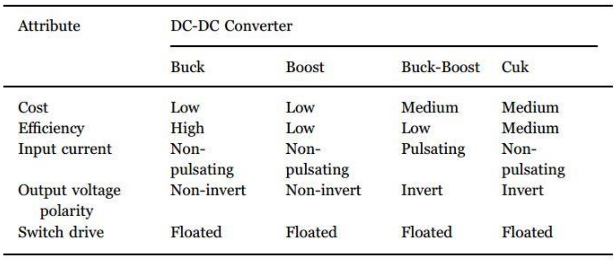


Fig. 7. *Basic circuit diagram of cuck converter.*

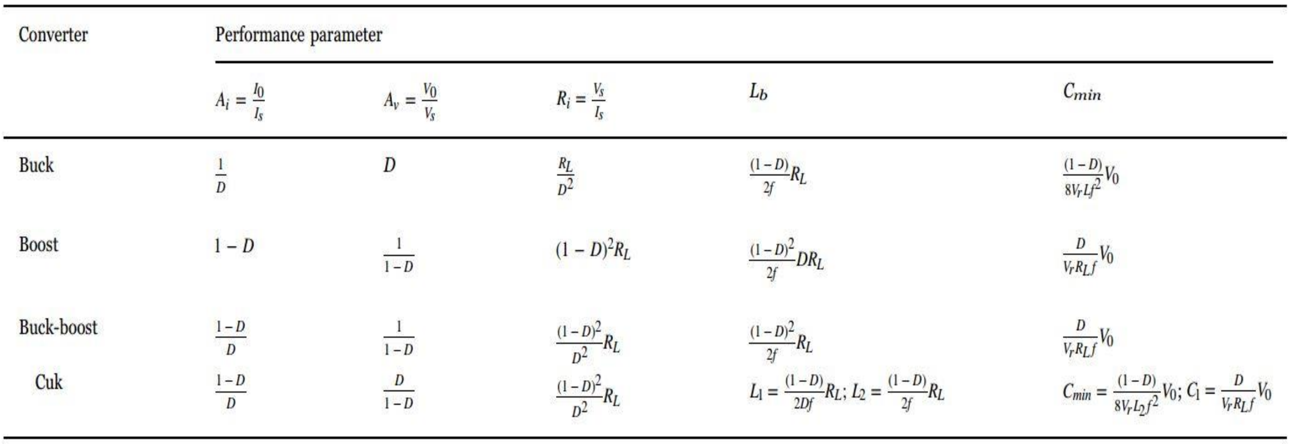
Converter with main feature that the energy storage elements such as inductors and capacitors, can be reduced in order to improve the reliability, reduce size and total cost [18].

Table 2. *Comparison of DC-DC converters.*



Attribute	DC-DC Converter			
	Buck	Boost	Buck-Boost	Cuk
Cost	Low	Low	Medium	Medium
Efficiency	High	Low	Low	Medium
Input current	Non-pulsating	Non-pulsating	Pulsating	Non-pulsating
Output voltage polarity	Non-invert	Non-invert	Invert	Invert
Switch drive	Floated	Floated	Floated	Floated

Table 3. *Performance parameters for DC-DC converters.*

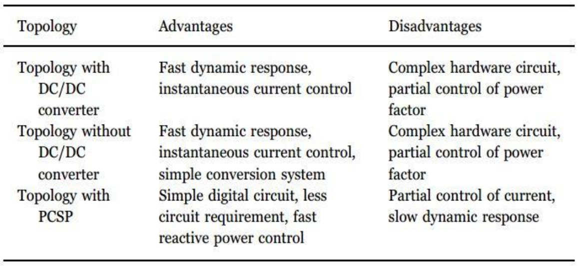


Converter	Performance parameter				
	$A_i = \frac{I_0}{I_s}$	$A_v = \frac{V_0}{V_s}$	$R_i = \frac{V_s}{I_s}$	L_b	C_{min}
Buck	$\frac{1}{D}$	D	$\frac{R_L}{D^2}$	$\frac{(1-D)}{2f}R_L$	$\frac{(1-D)}{8V_r L f^2}V_0$
Boost	$1 - D$	$\frac{1}{1-D}$	$(1-D)^2 R_L$	$\frac{(1-D)^2}{2f}DR_L$	$\frac{D}{V_r R_L f}V_0$
Buck-boost	$\frac{1-D}{D}$	$\frac{1}{1-D}$	$\frac{(1-D)^2}{D^2}R_L$	$\frac{(1-D)^2}{2f}R_L$	$\frac{D}{V_r R_L f}V_0$
Cuk	$\frac{1-D}{D}$	$\frac{D}{1-D}$	$\frac{(1-D)^2}{D^2}R_L$	$L_1 = \frac{(1-D)}{2Df}R_L; L_2 = \frac{(1-D)}{2f}R_L$	$C_{min} = \frac{(1-D)}{8V_r L_2 f^2}V_0; C_1 = \frac{D}{V_r R_L f}V_0$

4. Future cost estimation of PV system

The price of PV modules has decreased substantially over the past 30 years. The price of PV inverters has also followed a similar price trend as that of PV modules. Installation costs have decreased at different rates depending on the maturity of the market and type of application [22]. However, the prices for some of the elements of PV It is estimated that the cost of solar PV systems would decrease approximately by 75% in the year 2050 [23].

Table 4. *Advantages and disadvantages of control techniques for grid-connected single-phase*



Topology	Advantages	Disadvantages
Topology with DC/DC converter	Fast dynamic response, instantaneous current control	Complex hardware circuit, partial control of power factor
Topology without DC/DC converter	Fast dynamic response, instantaneous current control, simple conversion system	Complex hardware circuit, partial control of power factor
Topology with PCSP	Simple digital circuit, less circuit requirement, fast reactive power control	Partial control of current, slow dynamic response

5. Future scope of research

The present thrust is to increase penetration level of RE sources into the utility grid to meet the future energy demand. The uncertain nature of these sources are emerging as the main headache for the utility in terms of reliability, system stability and system security [24]. Therefore, there is need to investigate into the power electronics converters for integration of solar energy into the utility grid, with minimum harmonic injection and to meet out the requirement of grid codes specified by the utility operators. Presently the efficiency of the solar PV array is also low, therefore it is also needed to investigate into the material for fabrication of the PV panels which has maximum energy conversion efficiency [25].

6. Conclusion

A comprehensive literature review of the grid-connected photovoltaic systems is carried out. This paper presents a detailed survey on the topic of grid-connected PV system used to integrate the solar energy into the utility grid. The detailed study on the components of solar PV system such as solar cell, PV array, MPPT and filters is presented. Different types of DC-DC converters used to increase the output voltage characteristics of the solar PV are analysed critically and their comparative study is presented. According to the developed review, it can be concluded that grid connected solar PV system has been used to convert the sunlight into electricity and integrate the same to the utility grid. The major components of the system are solar cell, PV array, MPPT, filters, DCDC converter, inverter, control techniques for the DC-DC converters and inverters. A comparative study presented will help the users in selecting the particular topology and control techniques of the constituent components of the grid connected PV system that suit for the plant according to the capacity, location and requirement for grid connection. The overall performance of the grid-connected solar PV system will increase in the near future and cost will be reduced. It is hoped that this review will be beneficial to the users, designers, manufacturers, researchers, and engineers working in the field of solar energy for increasing the harnessing of solar energy and its grid integration.

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