Energy 53 (2013) 1–13

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Review

Solar power generation by PV (photovoltaic) technology: A review

G.K. Singh*

Department of Electrical Engineering, Indian Institute of Technology, Roorkee 247667, India

ARTICLE INFO

Article history:
Received 3 October 2012
Received in revised form
22 December 2012
Accepted 27 February 2013
Available online 27 March 2013

Keywords:
Solar energy
Maximum power point tracking
Photovoltaic
Renewable energy

ABSTRACT

The various forms of solar energy – solar heat, solar photovoltaic, solar thermal electricity, and solar fuels offer a clean, climate-friendly, very abundant and in-exhaustive energy resource to mankind. Solar power is the conversion of sunlight into electricity, either directly using photovoltaic (PV), or indirectly using concentrated solar power (CSP). The research has been underway since very beginning for the development of an affordable, in-exhaustive and clean solar energy technology for longer term benefits. This paper, therefore, reviews the progress made in solar power generation research and development since its inception. Attempts are also made to highlight the current and future issues involved in the generation of quality and reliable solar power technology for future applications. A list of 121 research publications on the subject is also appended for a quick reference.

1. Introduction

The fast depleting conventional energy sources and today's continuously increasing energy demand in the context of environmental issues, have encouraged intensive research for new, more efficient, and green power plants with advanced technology. Since environmental protection concerns are increasing in the whole world today, both new energy and clean fuel technologies are being intensively pursued and investigated. Most of the renewable energy from wind, micro-hydro, tidal, geothermal, biomass, and solar are converted into electrical energy to be delivered either to the utility grid directly or isolated loads [1–4]. Human race has been harnessing solar energy, radiant light and heat from the sun since ancient times using a range of ever-evolving technologies. Solar energy technologies include solar heating, solar photovoltaic, solar thermal electricity and solar architecture, which can make significant contributions towards solving some of the most pressing energy problems now faced by the world [5].

For the generation of electricity in far flung area at reasonable price, sizing of the power supply system plays an important role. Photovoltaic systems and some other renewable energy systems are, therefore, an excellent choices in remote areas for low to medium power levels, because of easy scaling of the input power source [6,7]. The main attraction of the PV systems is that they produce electric power without harming the environment, by directly transforming a free inexhaustive source of energy, the solar energy into electricity. Also, the continuing decrease in cost of PV arrays and the increase in their efficiency imply a promising role for PV generating systems in the near future [8,9]. Unfortunately, the technologies associated with photovoltaic (PV) power systems are not yet fully established, and therefore, the price of an energy unit generated from a PV system is an order of magnitude higher than conventional energy supplied to city areas, by means of the grid supply.

The efficiency of energy conversion depends mainly on the PV panels that generate power. The practical systems have low overall efficiency. This is the result of the cascaded product of several efficiencies, as the energy is converted from the sun through the PV array, the regulators, the battery, cabling and through an inverter to supply the ac load [10,11]. Weather conditions also influence the efficiency, which depends non-linearly on the irradiation level and temperature. For example, a cloud passing over a portion of solar cells or a sub-module will reduce the total output power of solar PV arrays. Under certain cloud conditions, the changes can be dramatic and fast. A method is required to assess the cost of such fluctuations and their effect on other systems to which a solar array may be connected e.g. utility [12,13]. Several methods have been developed to predict the solar PV array output power. An estimation method used in Ref. [14] proposes that the power output of a PV system is proportional to the insolation levels measured for the surface of a solar cell at any angular position. Since power supplied by the solar arrays also depends on temperature and array voltage, it is necessary to draw the maximum power of the solar array. Various techniques have been proposed and developed to maximize the

* Tel.: +91 1332 285070; fax: +91 1332 273560.
E-mail addresses: singh_girishkumar@yahoo.co.in, gksngfee@gmail.com.

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.02.057

List of symbols

PV	photovoltaic
CSP	concentrated solar power
WG	wind generator
BIPV	building-integrated photovoltaic
I	PV array output current
V	PV array output voltage
N_s	number of cells connected in series
N_p	number of cells connected in parallel
T	cell temperature
I_d	cell reverse saturation current
A	ideality factor (pn junction)
T_c	cell reference temperature
E_g	band gap energy of the semiconductor used in the cell
I_{ph}	photo current
I_{scr}	cell short circuit current at reference temperature and radiation
K_i	short circuit current temperature coefficient
S	solar radiation in mW/m^2
Q	charge of an electron
K	boltzman's constant
P	PV array power
P & O	perturb and observe
MPOP	maximum power operating point
MPPT	maximum power point tracking
MPP	maximum power point
VMPPT	voltage based maximum power point tracking
CMPPT	current based maximum power point tracking
PIC	peripheral interface controller
RCC	ripple correlation control
IncCond	incremental conductance
DERs	distributed energy sources
TEG	thermoelectric generator
HEP	hydroelectric plant

output power [14–19]. The wide acceptance of a PV power generation depends on the cost and on the energy conversion efficiency. Attempts have, however, been constantly made to improve sun tracking system to increase the efficiency to make solar energy attractive. In current technology condition, utilization of tracking PV system is an optimum selection of enhancing system efficiency and reducing cost.

This paper, therefore, deals with a state-of-the art discussion on solar power generation, highlighting the analytical and technical considerations as well as various issues addressed in the literature towards the practical realization of this technology for utilization of solar energy for solar power generation at reduced cost and high efficiency. One hundred twenty-one publications [1–121] are reviewed and classified in 6 parts.

2. Concept and benefits

2.1. Concept and feasibility studies

Becquerel [20] for the first time in 1839 discovered the photovoltaic effect. Later on in 1877, the photovoltaic effect in solid Selenium was observed by Adams and Day [21]. Fritz in 1883 developed the first photovoltaic cell and its efficiency was less than 1% [22]. A paper on photovoltaic effect was published by Einstein in 1904 [21]. In 1927, a new type of photovoltaic cell was developed using copper and semiconductor copper oxide. This device also had an efficiency of less than 1% [20]. Ohl in 1941 developed the silicon photovoltaic cell. Further refinement of the silicon photovoltaic cell enabled researcher to obtain 6% efficiency in direct sunlight that was further increased to 11% by Bell laboratories in 1954 [22]. In 1958, the Vanguard satellite employed the first practical photovoltaic generator producing a modest 1 W. In the 1960s, the space program continued to demand improved photovoltaic power generation technology. Scientist needed to get as much electrical power as possible from photovoltaic collectors, and cost was of secondary importance [23]. Later on, rapid depletion of conventional energy sources, environmental concern, high energy demand have forced the researcher to investigate the PV technology for large scale energy generation and application both in stand-alone and grid-connected (without storage) configuration. The latter has been extensively investigated and has become the reference model because it has appeared as the most feasible technical and economical solution. Right from the start, the development has had a dynamic and articulate characteristic and has been managed both in R&D and demonstration fields with particular emphasis on technical feasibility and cost effectiveness. The industrial production has always looked at the actual dimension of the unassisted intermediate market as a reference that has allowed the PV market to increase continuously [24]. Although, it is still relatively an expensive technology, the costs for solar power are coming down and markets are expanding [25]. Costs of production have been reduced in recent years for more wide spread use through production and technological advances, and are set to fall further.

2.2. Benefits and applications

Solar energy has become a promising alternative source due to its advantages: abundance, pollution free and renewability. Some of the key advantages are: direct use of heat resulting from the absorption of solar radiation, direct conversion of light to electricity through a simple solid-state device, absence of moving parts, ability to function unattended for long periods as evident from space program, modular nature in which desired currents, voltages and power levels can be achieved by simple integration, low maintenance cost, long effective life, high reliability, rapid responses in output to input radiation changes, high power handling capabilities from microwatt to kilowatt and even megawatt, high power to weight ratio, which is more important for space applications than terrestrial (may be favorable for some terrestrial application), amenable to onsite installation, decentralized/dispersed power; thus the problem of power distribution by wires could be eliminated by use of solar cells at the site where the power is required. They can be used with or without sun tracking, making possible a wide range of applications. The major factors that limit the use of solar energy for various applications is that, it is cyclic time-dependent energy source. Therefore, solar system requires energy storage to provide energy in the absence of insolation [26]. Comprehensive research and advancement in energy storage technologies offers benefits for solar in energy application. There is considerable work being done on fuel cell technology, which should offer a cheaper and more efficient mechanism for storing energy. Solar systems, which when not connected to the grid, store energy in conventional lead acid battery. Similarly, hydrogen offers considerable potential as a major power source, and tests are being done to use solar to produce hydrogen as a power source [27].

The use of solar energy is usually divided into two main areas: solar thermal and solar electricity. The first uses the sun as a direct source of heat energy and is most commonly used for supplying hot water to houses and swimming pool. The solar electricity seeks to convert light from the sun directly into electricity through a process known as photovoltaic. Photovoltaic system may be categorized as stand-alone photovoltaic system, photovoltaic system for vehicle applications (solar vehicles), grid-connected photovoltaic system and building systems.

The stand-alone system does not supply power to the grid. It may vary widely in size and application ranging from wrist watches or calculators to remote building or spacecraft. Billinton and Karki have presented a simulation method that provides objective indicators to help system planners decide on appropriate installation sites, selection of PV arrays or diesel units in capacity expansion and optimum PV penetration levels when utilizing PV energy in small isolated system [28]. A comparative study of the potential contribution of solar electric power in form of photovoltaics to meet future US energy demand with the projected volume of oil estimated to be available in Artic National wildlife Refuge is presented by Byrne et al. [29]. After publication of the results of this comparison, PV-based energy supply is more broadly considered in relation to future energy supply from known US oil reserves as means of gauging this technology relevance to the country's energy future. Knaupp and Mundschau in Ref. [30] have analyzed the solar hydrogen systems regarding their usability as energy supply system for high altitude platform. The main attention during the analysis of the whole solar-hydrogen energy system was directed to characteristic of current or near term available technology. They have also assessed the specific power/weight of photovoltaics, electrolyzer, fuel cell and gas tanks, and their dependence on operation mode and power range. Authors in Ref. [31] have developed a methodology for the optimal sizing of hybrid, stand-alone PV/WG system. They have also discussed the selection criteria for commercially available system devices, the optimal number and type of PV modules, WGs and PV battery chargers, the PV module's tilt angle and the normal capacity. Friling et al. have presented a mathematical modeling of the heat transfer of building integrated photovoltaic modules [32]. A detailed analysis of gains and losses of fully-integrated flat roof amorphous silicon photovoltaic plants is reported in Ref. [33]. Hwang et al. have analyzed the maximum electrical energy production based on the inclination and direction of photovoltaic installations, and the effects of the installation distance to the module length ratio [34].

Photovoltaic power generation has been most useful in remote applications with small power requirements where the cost of running distribution lines was not feasible. As PV power becomes more affordable, the use of photovoltaics for grid-connected applications is increasing. However, the high cost of PV modules and the large area they require continue to be obstacles to using PV power to supplement existing electrical utilities. An interesting approach to both of these problems is the integration of photovoltaics into building materials. Building-integrated photovoltaic (BIPV) systems offer advantages in cost and appearance by incorporating photovoltaic properties into building materials such as roofing, sizing and glass. When BIPV materials are substituted for conventional materials in new constructions, the saving involved in purchase and installation of the conventional materials are applied to cost of the photovoltaic system. BIPV installations are architecturally more attractive than roof-mounted PV structure. The majority of photovoltaic power generation applications are remote, off-grid applications. These include communication satellites, terrestrial communication sites, remote homes and villages, and water pumps. These are sometimes hybrid systems that include an engine-driven generator to charge batteries when solar power is insufficient. In grid-connected applications, dc power from solar cells runs through an inverter and feeds back into the distribution system. Grid-connected systems have proved their worth in natural disasters by providing emergency power capabilities when utility power was interrupted. Although, the PV power is generally more expensive than utility-provided power, use of grid-connected system is increasing [35,36]. The significant findings of the studies may be summarized as follows [20–36]:

- Since power derived from PV energy sources depend on large number of variables, application of appropriate probabilistic techniques is essentially needed for realistic cost/adequacy studies.
- It is wise to evaluate policy alternative that do not assume energy status quo, in order to understand the true magnitude of policy choice that is at stake as energy choice can be highly affected by the policy decision.
- Short-term forecast of energy options are more suitable to accurately project the tomorrow's energy demands.
- In case of solar electric energy supply at high altitude, depending on the airship size and shape, the required position accuracy and peak wind speed frequency distribution, the total electrical energy demand can be covered by a solar-hydrogen energy system. However, there are challenges regarding minimization of thermal effects through high absorption by photovoltaic generator or the introduction of efficient active measures for lifting gas temperature stabilization besides the ongoing efforts for further mass reduction.
- In case of building integrated and ventilated photovoltaic modules, the set-up including fins and high forced air velocity, both in physical and mathematical sense has the best performance. This results in the desired improvement in production of electricity due to increased heat transfer from the PV modules and decrease in the temperature of PV module.
- In case of BIPV, a greater D/L (distance between panels, D to length of the panel, L) ratio yields a greater amount of sunlight, but it is not proportionate to the amount of power generated due to a decrease in the area of power generation. Thus, it is recommended to set the D/L ratio between 1 and 3 in consideration of the required amount of power supply. The final decision would depend on additional factor including system price and visual elements.
- From an economical point of view, optimal configuration is determined by the minimum of the cost function corresponding to a loss of power supply probability equal to zero.

3. Modeling of photovoltaic cell

The semiconductor device that transforms solar light in electrical energy is termed as 'Photovoltaic cell', and the phenomenon is named as 'Photovoltaic effect'. To size a solar PV array, cells are assembled in form of series-parallel configuration for requisite energy [37–39]. The electric power generated by a solar PV array fluctuates depending on the operating conditions and field factors such as the sun's geometric location, irradiation levels and ambient temperature [40,41]. A solar cell is a non-linear device and can be represented as a current source model as shown in Fig. 1. The current source I_{ph} represents the cell photo current, I_d is reverse saturation current of diode, R_{sh} and R_s are the intrinsic shunt and series resistance of the cell respectively. Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules, which are further interconnected in a parallel-series configuration to form PV arrays or PV generators. The typical I–V characteristic of a PV array is given by the following equation [8]:

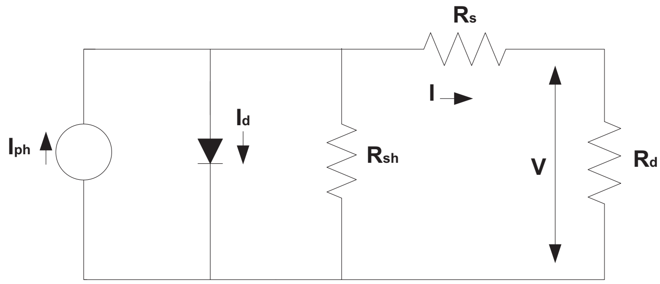

Fig. 1. Simplified equivalent circuit of a photovoltaic cell.

$$I = N_p I_{pn} - N_p I_d \left[\exp\left(\frac{qV}{kTAN_s} - 1\right)\right] \quad (1)$$

where, I is the PV array output current (A), V is the PV array output voltage (V), N_s is the number of cells connected in series, N_p is the number of modules connected in parallel, q is the charge of an electron, k is the boltzman's constant, A is the pn junction ideality factor, I_d is the cell reverse saturation current, T is the cell temperature. The factor 'A' determines the cell deviation from the ideal pn junction characteristic; it ranges from 1 to 5, 1 being the ideal value [42].

The cell reverse saturation current I_d varies with temperature according to the following equation [43]:

$$I_d = I_c[T/T_c]^3 \exp\left[\left(q\frac{E_g}{KA}\right)\left(\frac{1}{T_c} - \frac{1}{T}\right)\right] \quad (2)$$

where, T_c is the cell reference temperature, I_c is the reverse saturation current at T_c, and E_g is the band gap energy of the semiconductor used in the cell. The photo current I_{ph} depends on the solar radiation and the cell temperature as given by:

$$I_{ph} = [I_{scr} + K_i(T - T_c)][S/100] \quad (3)$$

where, I_{scr} is the cell short circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm^2. The PV array power can be calculated by:

$$P = I^*V$$

$$P = N_p I_{ph} V - N_p I_d V \left[\exp\left(\frac{qV}{KTAN_s}\right) - 1\right] \quad (4)$$

The maximum power point voltage V_{max} can be calculated by setting $(dP/dV) = 0$, thus at maximum power operating point (MPOP),

$$\exp\left(\frac{qV_{max}}{KTAN_s}\right)\left[\left(\frac{qV_{max}}{KTAN_s}\right) + 1\right] = \left(I_{ph} + I_d\right)\Big/I_d \quad (5)$$

Solving Eq. (5), V_{max} can be determined [42].

The PV cell output voltage is a function of the photo current that is mainly determined by load current depending on the solar irradiation level during the operation [44,45], and is given by:

$$V = \left(\frac{AKT}{q}\right)\ln\left[\left(I_{ph} + I_d - I\right)\Big/I_d\right] - R_s I \quad (6)$$

By making step variations in the solar radiation S and the cell temperature T in Eqs. 1–5, the I–V and the P–V characteristics of the PV array can be simulated. Ideally, a PV panel would always operate at a voltage that produces maximum power. Such operation is possible, approximately, by using a maximum power point tracker (MPPT). Without an MPPT, the PV panel operates at a point on the cell I–V curve that coincides with the I–V characteristic of the load. For evaluation of parameters in above equations, five independent pieces of information are needed. In general, these parameters are functions of the solar radiation incident on the cell and the cell temperature. Reference values of these parameters are determined for a given operating conditions and field factors. Three current–voltage pairs are normally available from the manufactures standard rating conditions (SRC): the open circuit voltage, short circuit current, and the voltage and current at the maximum power point. A fourth piece of information can be obtained by setting the derivative of the power at the maximum power point to zero [41]. Hence,

$$\frac{d(IV)}{dV} = I_{mp} - V_{mp}\frac{dI}{dV} = 0 \quad (7)$$

where, dI/dV is given by

$$\frac{dI}{dV} = \frac{\frac{-I_d}{A}e^{\frac{V_{mp}+I_{mp}R_s}{A}} - \frac{1}{R_{sh}}}{1 + \frac{I_d R_s}{A}e^{\frac{V_{mp}+I_{mp}R_s}{A}} + \frac{R_s}{R_{sh}}} \quad (8)$$

The temperature coefficient of open circuit voltage is given by

$$\mu_{V_{oc}} = \frac{dI}{dV} \approx \frac{V_{oc,ref} - V_{oc,T}}{T_c - T} \quad (9)$$

To evaluate $\mu_{V_{oc}}$ numerically, it is necessary to know $V_{oc,T}$, the open circuit voltage at some cell temperature near the reference temperature. The cell temperature, used for this purpose is not critical since values of T ranging from 1 to 10 K above or below T_c provide essentially the same result.

Nguyen and Lehman have proposed a modeling and computing algorithm to simulate and analyze the effect of non-uniform changing shadows (a passing cloud) on the output of the solar PV array [12]. They have concluded that the model is able to determine the power losses in each solar cell and the hot spots of a shaded solar PV array as well as the PV output power. They have established that the model is flexible enough to simulate solar PV arrays with various configurations with or without bypass diode. In Ref. [44], a simple method of tracking the maximum power points and forcing the system to operate close to these points is presented. The principle of energy conversion is used to derive the large- and small signal model and transfer function. The simulation results have been experimentally validated by the authors. Altas and Sharaf [45] have developed a photovoltaic array simulation model to be used in Matlab/Simulink GUI environment based on the circuit equations of the photovoltaic solar cells including the effects of solar irradiation and temperature changes. Noguchi et al. in Ref. [46] have reported a short-current pulse-based maximum-power point tracking method for multiple photovoltaic-and-converter module system. In Ref. [47], a novel maximum-power-point-tracking controller for photovoltaic energy conversion system is elaborated. Gonzalez-Longatt [48] has given a circuit based simulation model to analyze the electrical behavior of PV cell for a given temperature and irradiance. Results have also been compared with points taken from the manufacturer's published curve. A dc voltage source model of a polycrystalline PV array in Matlab/Simulink has been reported by Chowdhury et al. [49]. They have presented the performance analysis under various loading and weather conditions along with the application of the model to develop a load shedding scheme for a stand-alone PV system. Authors have also given that the laboratory based cell characterization work can well be utilized for developing simplified low-burden mathematical model for different types of PV array, and will be immensely helpful for simulation studies of distributed power systems and microgrids. In Ref. [51], authors have presented a model-based PV performance monitoring system with an on-line diagnosis function in Labview environment. The collected data are compared with the estimated ones that are obtained using a single-diode practical PV model. Jiang et al. [52] have given an improved Matlab-Simulink simulation model for solar PV cell, and have compared the results with other existing models. They have also demonstrated the capability of the model in accurately simulating the *I*–*V* and *P*–*V* characteristics of the real PV module. The proposed model can also be used to design and simulate solar PV system with different power converter topologies and controllers including different MPPT control methods. The noticeable findings based on the various studies [8,13,37–53] made on modeling and analysis of PV systems are:

- Accuracy of the mathematical model of photovoltaic cell, and hence the analysis can be improved by including into the model, series and shunt resistance, temperature dependence of photo current, and the dependence of diode saturation current.
- Accuracy of the model and the analysis can be further improved by either introducing two parallel diodes with independently set saturation current or considering the diode quality factor as a variable parameter (instead of fixed at either 1 or 2).
- The open circuit voltage increases logarithmically with the ambient irradiation.
- Short circuit current varies linearly with the ambient irradiation.
- The increase in cell's temperature causes linear decrease in the open circuit voltage leading to decrease in cell efficiency.
- The increase in cell's temperature causes slight increase in short circuit current.
- Photo current and temperature have linear relationship.
- There is not significant degradation in PV cell performance between full sun and cloudy conditions.
- The power output decreases almost linearly with incident solar energy, but the efficiency is nearly flat over the region of concern.
- The power output of solar cells depends on the absolute value and special distribution of irradiance in the plane of solar cell and cell's temperature.
- Absolute value of direct normal irradiance increases with the increase in atmospheric height.
- Energy output versus irradiation can provide a better comparison between different modules in case of high value of fluctuation in daily irradiation.
- Maximum power decreases with the increase in diode quality factor.
- For extracting maximum power from solar cell, value of series resistance should be kept minimum.

4. Photovoltaic system for power generation

A basic photovoltaic system integrated with utility grid is shown in Fig. 2. The PV array converts the solar energy to dc power, which is directly dependent on insolation. Blocking diode facilitates the array generated power to flow only towards the power conditioner. Without a blocking diode, the battery would discharge back through the solar array during low insolation. Power conditioner contains a maximum power point tracker (MPPT) [14,15,54,55], a battery charge and a discharge controller. The MPPT ensures that the maximum power generated by the solar PV array is extracted at all instants while the charge discharge controller is responsible for preventing overcharging or over discharging of the battery bank required to store electricity generated by the solar energy during sunless time. In simple PV systems, where PV module voltage is matched to the battery voltage, use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from PV module. A stand-alone system does not have a connection to the grid.

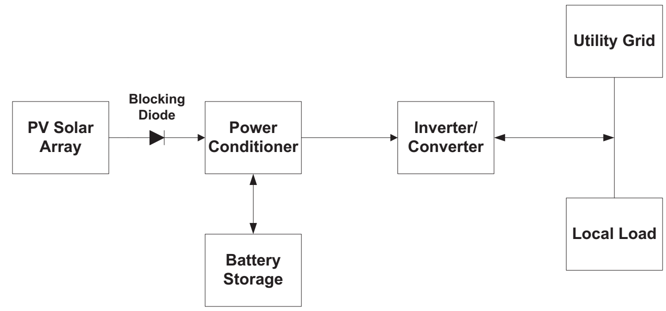

Fig. 2. Block diagram of a typical photovoltaic system.

In recent years, extensive research in form of experimental as well as simulation studies are being carried out on the application of PV systems as distributed energy sources (DERs) to harness power from the non-conventional energy sources with low environmental impacts. Borowy et al. have presented their work on the optimum sizing of a PV array for stand-alone hybrid/PV system [56]. A simple model to minimize the life cycle cost of a hybrid power system consisting of a solar PV array, engine generator and battery is given in Ref. [57]. Mendez et al. have studied the applicability of autonomous photovoltaic systems in supplying power to remote isolated villages in Morocco [58]. Wies et al. have carried out the economic analysis and environmental impact assessment of integrating a photovoltaic array into diesel electric power systems for remote villages [59]. A survey of PV hybrid system in Thailand during the last decade regarding to status of technology, performance in terms of technical and economic aspects and their prospects is given in Ref. [60].

Simulation or analytical studies mainly involve development of robust mathematical models for PV arrays as DERs which can be further utilized for the analysis of hybrid power systems. Russell has presented the accurate flexible PV array and inverter models to analyze the performance of PV system, and has addressed the issues, which are important to designers and manufacturers [61]. King et al. have developed a Microsoft Windows based electrical simulation model for photovoltaic cell, modules and arrays that can be used to analyze individual cells, to analyze the effects of cell mismatch or reverse bias heating in modules, and to analyze the performance of large arrays of modules including bypass and blocking diodes [62]. Gow and Manning have reported the development of an effective system to characterize polycrystalline PV cells and generated the device dependent data that provides a link between the environmental variables such as irradiance and temperature, and the electrical characteristics of the device [63]. A computer simulation model able to demonstrate the cell's output features in terms of irradiance and temperature environmental changes have been given by Chenni et al. They have also tested the model to simulate three popular type of photovoltaic panels constructed with different materials like copper indium diselenide thin film, multi-crystalline silicon and mono-crystalline silicon [64]. Karatepe et al. have demonstrated a PV model taking into consideration the effects of bypass diodes and the variation of the equivalent circuit parameters with respect to operating conditions.

Model is accurate enough to provide sufficient degree of precision and can be used for solar cell based analysis to study the large scale PV arrays without increasing the computational time [65]. The various studies made on photovoltaic system for power generation [14,15,29,30,54–71] reveal that:

- Geographical location has a strong impact on the level of reliability obtained by utilizing PV in small isolated power systems (SIPs) and the economical benefits from the fuel offsets.
- Inherent atmospheric characteristics of the system geographical location dictate the planning and operational decisions for PV backed SIPs contrary to conventional systems.
- The effect of local climate conditions on the temperature of module is significant and hence, affects the electrical energy generation.
- The size of the incentive, cost of residential solar PV, electrical energy price, and solar insolation decide the strength of the solar renewable energy credit policy.
- It is important to model the solar photovoltaic system to optimize system design, to improve reliability of projected outputs to ensure favorable project financing and to facilitate proper operation and maintenance.
- Precise near-term forecasting of system production for use in grid-integration, and for smart and micro grid development can be made using Regression analysis.
- Regression modeling can also be used for prediction of PV system health, and thus to identify cell and module failures in a system.

5. Hybrid solar power system

Many experts believe that it is not possible for one single alternative renewable energy source to replace the conventional energy source (fossil fuels), but rather a combination of different types of clean energy source will be required instead. Such system is called hybrid system. A hybrid system combines PV with other forms of generation, usually a diesel generator. Biogas is also used. The other forms of generation may be a type able to modulate power output as a function of demand. However, more than one renewable form of energy may be used e.g. wind. The photovoltaic power generation serves to reduce the consumption of non-renewable fuel. Gabler et al. [72] have carried out the simulation study of a wind-solar hybrid electrical supply system. They have also studied the influence of system parameters such as size of different converters, and battery capacity on the renewable fractions and the energy payback time of the whole system. An optimization procedure of a hybrid photovoltaic wind energy system is presented by Habib et al. [73]. Elhadidy in Ref. [74] has studied the feasibility of using hybrid (wind-solar-diesel) energy conversion systems at Dhahran to meet the energy needs of a group of 20 typical two-bedroom family houses. Author has also addressed the energy generated by the hybrid systems of different component (wind farm capacity, PV area, and storage capacity). The deficit energy to be generated from the back-up diesel generator (in addition to wind plus solar plus battery) and the number of operational hours of the diesel system to meet a specific annual electrical energy demand are also presented. Authors in Ref. [75] have reported the test results on a hybrid solar system, consisting of photovoltaic modules and thermal collectors (hybrid PV/T system). Ai et al. in Ref. [76] have presented a complete set of match calculation methods for optimum sizing of PV/wind hybrid system. In this method, practical mathematical models for characterizing PV module, wind generator, and battery are adopted. Authors have concluded that according to local hourly measured meteorological data, load demand, characteristic and price of the components, and reliability requirement of power supply, the optimum configuration, which meets the load demand with minimum cost, can be uniquely determined by this method. Robles-Ocampo et al. have constructed and studied an experimental model of a bifacial PV/Thermal hybrid system. To make use of both active surfaces of the bifacial PV module, authors have designed and made an original water-heating planar collector and a set of reflecting planes. The heat collector was transparent in the visible and near-infrared spectral regions which makes it compatible with the PV module of crystalline Silicon [77]. Kaldellis et al. [78] have investigated the possibility of using either a wind power or a photovoltaic driven stand-alone system to meet the electricity demand of typical remote consumer's location in different places in Greece. A detailed energy analysis for both wind and solar driven stand-alone system is also presented including the system battery depth discharge time-evolution. In Ref. [79], a hybrid energy system combining variable speed wind turbine, solar photovoltaic and fuel cell generation system to supply continuous power to residential power applications as stand-alone loads is presented by Ahmed and others. Three individual dc–dc boost converters are used to control the power flow to load. A simple and cost effective control with dc–dc converters is used for maximum power point tracking and hence, for maximum power extracting from the wind turbine and the solar photovoltaic systems. Saheb-Koussa et al. [80] have reported the technical-economic optimization study of a photovoltaic-wind-diesel hybrid system with battery storage in Algeria. The primary aim of the study was to estimate appropriate dimension of the stand-alone hybrid system that guarantees the energy autonomy of typical remote consumer with lowest cost of energy. Secondary aim was to study the impact of renewable energy potential quality on the system size. In Ref. [81], Sopian et al. have discussed the performance of an integrated PV-wind hydrogen energy production system consisting of photovoltaic array, wind turbine, PEM electrolyzer, battery bank, hydrogen storage tank, and automatic control system for battery charging and discharging conditions. Mathematical model for each component in the system has also been developed, and the results were validated experimentally. Margeta and Glasnovic have presented the analysis of a solar-hydro power hybrid system that can provide continuous electric power and energy supply to its consumers. They have developed a mathematical model for selecting the optimal size of the PV power plant as the key element for estimating the technological feasibility of the overall solution. Sensitivity analysis (parameter analysis) has also been carried out by the authors in which, local climate parameters like solar radiation, air temperature, reservoir volume, total head, precipitation, evaporation and natural water inflow were varied [82]. Davidsson et al. have developed and evaluated a building integrated multi-functional PV/T solar window. They have introduced tiltable reflectors in construction to focus radiation on to the solar cells. The insulated reflectors also reduce the thermal losses through the window [83]. Bekete and Palm [84] have investigated the possibility of supplying electricity from a solar-wind hybrid system to a remote area detached from the main electricity grid in Ethiopia. Based on the findings of the studies into energy potential, a feasibility study has also been carried out by the authors on how to supply electricity to a model community equipped with school and health post of 200 families with 1000 people in total. The electric load consists of primary and deferrable types, and comprises lighting, water pumps, radio receivers and some clinical equipments. In Ref. [85], a methodology for the optimal sizing of desalination systems, power supplied by photovoltaic modules and wind generators is presented by Koutroulis and Kolokotsa. They have derived the optimal number and type of units amongst a list of commercially available system devices, such that the 20-year round total system cost is minimized, while simultaneously the consumer's water demand is completely covered. Genetic Algorithm has been used for the total cost function minimization. Notton et al. [86] have determined the optimal dimensions of a stand-alone wind/PV hybrid system that guarantees the energy autonomy of a typical remote consumer. Kosmadakis and others have carried out the feasibility study and economic analysis of a CPV/thermal system coupled with an organic Rankine cycle for increased power generation. In the system analyzed by the authors, a pump drives the organic fluid of the cycle, which is evaporated in the tubes of the CPV/T, and driven to an expander for mechanical power production. Authors have stated that for the condensation of organic fluid, any of the several possible alternatives can be used. That way, the PV cells can be cooled efficiently, and increases their electrical efficiency, while the reservoir heat is designated to produce additional electrical energy through the organic Rankine process, when the expander of the Rankine engine is coupled to the generator [87]. In a paper by Cherif and Belhadj [88], energy and water production estimation on a large-scale time from photovoltaic-wind hybrid system coupled to a reverse osmosis desalination unit in Southern Tunisia have been discussed. Double stage configuration in the desalination process using spiral modules is adopted extensively and validation of the steady-state model is presented. Authors in Ref. [89] have discussed a new type of renewable energy sources (RES) suitable for exploiting water course with potential-temporary water flow. The system consists of hydro-electric plant (HEP) and solar photovoltaic generator working together as one hybrid power plant, producing green energy with the same characteristics as classical hydroelectric plant. The main objective of this hybrid solution was to achieve optimal renewable energy production in order to increase the share of RES in an electricity power system. Authors have concluded that the application of such hybrid systems would increase the share of high quality RES in energy systems. Margeta and Glasnovic [90] have described the possibility of realization of the sustainable energy supply by hybrid PV-PSH power plants (pump storage hydroelectric). The stress was on the use of solar and hydro energy (two classical natural energy sources). Solar energy is used for generation of hydro energy potential (artificial water flow in upper water/energy storage). By integration with natural water sources, the typical power plant becomes more productive that otherwise are not economically viable because of large seasonal fluctuations (temporary rivers), hydro energy capacities increase and productivity of PV generator in an electric power system. In Ref. [91], Bekele and Boneya have given the design of a hybrid electric power generation system utilizing both wind and solar energy for supplying model community living in Ethiopia remote area. Vick and Neal [92] have analyzed the off-grid wind turbine and solar photovoltaic array water pumping system to determine the advantages and disadvantages of using a hybrid system over a wind turbine or a solar PV array alone. Chavez-Urbiola et al. in Ref. [93] have analyzed a solar hybrid system with thermoelectric generator. In Ref. [94], Kaldellis and Zafiralcis have presented a study for optimal sizing of stand-alone wind-photovoltaic hybrid systems for representative's wind and solar potential cases of the Greek territory. In this context, the main target of the work was to estimate the approximate size of similar system, so as to meet the energy requirement of typical remote consumers under the criterion of minimum first installation cost. The important findings of these works [72–94] are summarized as:

- The total efficiency of the system in solar-thermal hybrid systems can be improved by employing suitable cooling arrangement. Further improvement in the system performance can be achieved by providing an additional glazing to increase thermal output, a booster diffuse reflector to increase electrical and thermal output, or both, thus giving flexibility in the system design.
- The use of bifacial PV modules enhances the electrical energy production with PV-thermal solar hybrid systems.
- In regions with high or medium–high wind potential, wind driven systems are definitely the best solutions including preliminary cost aspects. In most of the other situations, photovoltaic driven installations use smaller batteries and may even have a substantial initial cost advantage.
- System power reliability under varying conditions and the corresponding system cost are the two main factors for developing a hybrid solar-wind power generation system.
- Optimal solar/wind ratio that results in the minimum capital cost is approximately 70%.
- The fluctuating output power of wind turbine and solar photovoltaic generators affects the system frequency. One of the existing methods to solve these issues is to install batteries that absorb power from wind turbine generators. The other method is to install dump loads to dissipate fluctuating power. However, these methods are expensive and not effective, and cannot guarantee continuous power flow to the load.
- A solar photovoltaic, wind turbine and fuel cell hybrid generation system is able to supply continuous power to load. In this system, the fuel cell is used to suppress fluctuations of the photovoltaic and wind turbine output power. The photovoltaic and wind turbines are controlled to track the maximum power point at all operating conditions.
- The principal advantage of solar-wind-diesel hybrid system is the enhancement of system reliability when the solar, wind and diesel power production are used together. Additionally, the size of the battery storage is reduced due to less reliance on one method of power production.
- In case of solar-hydro hybrid system, it has been established that, apart from total head (which is to be expected), solar radiation, hydro accumulation size and natural water inflow have the biggest impact on the calculated power of the PV power plant.
- Use of a reflector for focusing radiation on to the PV cells reduces the cost of solar electricity, thus allowing expensive PV cells to be replaced by considerably cheaper reflector material.
- The total cost of the desalination system is highly affected by the operational characteristics of the devices comprising the system, which affect the degree of exploitation of the available solar and wind energy potential.
- In order to achieve high energy availability through hybrid PV-wind energy system as required in some applications like lighting, remote area electrification and telecommunications, it becomes necessary to oversize the rating of the generating system. High availability of energy can also be ensured by the use of hybrid system with combination of two or more renewable energy source.
- In general, the fluctuations of solar and/or wind energy generation do not match the time distribution of the load demand on a continuous basis. But a suitable combination of these two random sources can be used to achieve a high availability and reduction in the energy storage size resulting in a lower electricity generation cost. Nevertheless, the amalgamation of such a hybrid system is accompanied by design problem such as choice of the correct size of each component, and the economic optimization of kWh production cost.
- The sizing and the profitability of wind-PV hybrid system for remote applications are greatly influenced by solar and wind energy resource characteristics.
- The use of Thermo Electric Generator (TEG) in hybrid concentrating system with crystalline silicon solar PV module

operating at high temperature enhances the thermal stability of system's electrical efficiency reducing its loss with an increase of temperature.

- TEG based system with concentration of the radiation passing through PV module will be efficient and economic, if new type of PV modules are developed, based on semiconductors with band gap essentially larger than that in C–Si used in major part of today's commercial PV modules and having neither absorption nor scattering of photons with energies below the band gap.

6. Maximizing the output power

Power supplied by solar arrays depends upon the insolation, temperature and array voltage. It is also the function of the product of voltage and current. By varying one of these two parameters; voltage or current, power can be maximized. To achieve this aim, apart from using electromechanical fixtures such as fixed, single or double axis trackers that track the direction of the sun [95–105], certain electronic circuits are also used to ensure operation of the PV source at the maximum power point during different environmental conditions. Such electronic instruments are essentially dc to dc converters called maximum power point trackers (MPPT). It ensures that the PV array provides the correct amount of current for operation at the MPP so that the load is always supplied with the maximum possible power generated under the given atmospheric conditions. Relatively a high cost MPPT is a viable option in high power systems where the cost of the gain in power is higher as compared to the price of the MPPT unit. Several MPPT methods exist in order to maximize the output power and to fix its value, in steady-state, at its high level. These techniques [8,11,44,106–116] are: Hill Climbing/Perturb and Observe (P&O), Incremental Conductance (IncCond), Parasitic Capacitance, Voltage based peak power tracking (VMPPT), Current based peak power tracking (CMPPT), Fractional open circuit voltage, Fractional short circuit current, Fuzzy logic control, Neural network, Ripple correlation control (RCC), Current sweep, DC link capacitor droop control, load current or load voltage maximization and dp/dV or dp/dI feed back control.

Roth et al. [95] have designed an electromechanical system to follow the position of the sun. It operates automatically guided by a closed loop servo system; and has a facility for automatic measurement of direct solar radiation. A four quadrant photo detector senses the position of the sun and two small dc motors move the instrument platform keeping the sun image at the centre of the four-quadrant photo detector. Under cloudy conditions, a computing program calculates the position of the sun and takes control of the movement, until the detector can sense the sun again. They have also concluded that it can be used to work with larger installations like solar cell panels, concentrators etc. In Ref. [96], authors have explained the design and construction of a two axis sun tracking system. The programming method of control was used for control of the sun tracking system. It is shown that the two axis tracker results in an increase in total daily collection of 41.34% as compared with that of tilted 32^0 fixed surfaces. Experimental results showing the effect of using different type of sun tracking systems on the voltage current characteristics and electrical power generation of flat plate photovoltaic are given in Ref. [97]. It is shown that there was an increase in electrical power gain. A hybrid tracking system that consists of a combination of open loop tracking strategies based on solar movement models and closed loop strategies using a dynamic feed-back controller is reported by Rubio et al. [98]. They have also taken into account the energy saving factors. The results were verified experimentally and compared with classical open-loop tracking strategy. A solution for increasing the energy efficiency of the photovoltaic system using mechanical tracking system is given in Refs. [99,100]. The key idea was to minimize the energy gained through orientation, and to minimize the energy consumption for tracking the sun path. The optimization was made by reducing the angular revolution field of the panel, and consequently operating time of the motor, without significantly affecting the incident radiation. Nabulsi et al. [101] have reported the design and implementation of a two-axis stand-alone rotary sun tracker. The aim of the work was to analyze the effects of introducing both physical sun tracking system and MPPT on PV system's efficiency in the Gulf region. Astronomical method was used to determine the position of the sun. The sun azimuth and elevation angles were continuously updated throughout a day with the help of digital signal processor. P&O method was to keep the system power operating point at its maximum value. In Ref. [102], researchers have developed the prototype of a two axis solar tracking system based on PIC (Peripheral interface controller) microcontroller. The parabolic reflector was constructed around two feed diameter to capture the sun's energy. The design of parabolic reflector and the gear was carefully considered and precisely calculated in this system. In Ref. [103], the principles and key technologies of automatic sun tracking control system in PV generation have been introduced to operate reliably in poor environment for a long time. Authors in Ref. [104] have discussed the two-axis sun tracking system to maximize the electrical energy production of the photovoltaic system considering the tracking system power consumption. A stochastic search algorithm called as differential evolution was used as optimization tool. Experimental validation of a probabilistic model for estimating the double axis PV tracking energy production is reported in Ref. [105]. They have analyzed the two components of the global efficiency that is the effect of PV cells' temperature on the module efficiency and the dc/ac converter efficiency. Simulation results were also verified experimentally. Enslin Ref. [106] has described an industrialized MPPT regulator. Author has also performed some simple cost analysis, and concluded that MPPT techniques, even for smaller remote area power supply (RAPS), can be implemented economically, and in some cases are necessary to size the RAPS accurately. Maximum power point tracking is achieved through optimized Hill climbing, expensive microprocessor based algorithm. Hussein et al. in Ref. [8] have studied various techniques followed in tracking the maximum power operating point of PV arrays with particular reference to P&O technique. The drawbacks of the P&O algorithm, especially in case of rapidly varying atmospheric conditions are discussed and analyzed. Authors have discussed the IncCond algorithm based on the fact that the array terminal voltage can always be adjusted towards $V_{\max}$ by comparing the incremental and instantaneous conductance of the PV array. Hua and others in Ref. [44] have reported the implementation of a DSP-controlled photovoltaic system with peak power tracking. The principle of energy conversion was used to derive large- and small- signal model and transfer function. It has been shown that the drawbacks of the state-space-averaging method can be overcome. In Ref. [107], mathematical modeling and performance evaluation of a stand-alone polycrystalline PV plant with MPPT facility under various loading and weather conditions is given. The authors also felt that the laboratory based cell characterization work can well be utilized for developing simplified low burden mathematical models for different types of PV arrays, and will be immensely helpful for simulation studies for distributed power system and microgrids. A comparative study of MPPT algorithm using an experimental programmable microprocessor controlled test bed is described in Ref. [108]. It is concluded that though the Incremental conductance method is able to provide marginally better performance, the increased complexity of the algorithm will require more expensive hardware, and therefore, may have an advantage over P&O only in large PV arrays. In Ref. [109], a detailed theoretical and experimental study of photovoltaic systems with voltage and current based MPPT is presented. A microprocessor controlled tracker capable of online voltage and current measurement and programmed with VMPPT and CMPPT algorithms is developed. Water pump and resistance were taken as a load. As stated by the authors, the main advantage of the proposed MPPT is the elimination of reference (dummy) cells which results in a more efficient, less expensive and more reliable PV system. An adaptive P&O algorithm to improve the efficiency of PV systems has been proposed in Ref. [11]. The algorithm has been set up to reduce the main problems that arise in utilizing traditional P&O algorithms. The basic principle of the proposed algorithm is to adapt the perturbation amplitude to the actual operating conditions. Large perturbation amplitude is chosen far from the maximum while small ones are used in proximity to the maximum. The algorithm has been validated by means of numerical simulations, considering the PV panels that have been experimentally identified and characterized. Esram and Chapman [110] have reported a detailed comparative study of various techniques for maximum power point tracking of photovoltaic arrays. Authors have identified 19 distinct methods available in literature, and have critically examined each and every technique. They have also provided the basis for selection of appropriate technique, which can best suit the application needs. Researchers in Ref. [111] have proposed a sliding mode observer for the estimation of solar array current in grid-connected PV system. The said observer has been constructed from the state equation of the system, and the convergence of the error system is proved using equivalent control concept. Using the proposed observer, the robust tracking performance against parameter variations and uncertainties has been verified by simulation and experimental results. It has been concluded that the proposed system is able to reduce the expensive current sensor, and shows superior performance than the conventional system. A novel method for maximum power point tracking is presented in Ref. [112]. The method combines fuzzy MPPT with an appropriately design FCN (Fuzzy Cognitive Network) to speed up the procedure of reaching the accurate MPPT of a PV array under varying environmental conditions. It is concluded that due to the existence of the FCN, the method can track and adapt to any physical variations of the PV array through time. Mutoh et al. [113] have described a method for maximum power point tracking control while searching for optimal parameters corresponding to weather conditions at that time. In the proposed method, the optimal current reference needed to converge the output current on the optimal operating point of the production line is determined by dividing P–I characteristics into two control fields using two properties, i.e. linear relationship satisfied between the maximum power and the optimal current, and the short circuit current and the optimal current. In this case, the voltage coefficient of the prediction line was identified using the Hill climbing method in order to compensate for temperature changes of solar panels. The effectiveness of the method was verified through experiments under various weather conditions. A stability analysis for an MPPT scheme based on extremum-seeking control is developed in Ref. [114] for a PV array supplying a dc–dc switching converters. The global stability is demonstrated by means of Lyapunov's approach. Subsequently, the algorithm is applied to an MPPT system based on the P&O method. The tracking algorithm leads the array coordinates to maximum power point by increasing or decreasing linearly the array voltage with time. Experimental validation of the scheme under different operating conditions is also presented by the authors. In Ref. [115], the problem of optimization of the P&O strategy for PV MPPT is given. In this work, the classical constant duty cycle perturbation is replaced by variable duty cycle, which linearly reduces with the increase in power drawn from the PV field. Simulation results are verified through experimental measurements. Mutoh et al. [116] have discussed a control method charging series-connected ultra electric double layer capacitors (ELDCs) suitable for photovoltaic generation systems combining MPPT control method. The MPPT control has been performed based on the fact that is linear relationship between the maximum power and the optimization current giving its maximum. The linearity was satisfied even if the solar radiation was changed as long as the temperature of the solar arrays was kept constant. When the temperature changed, the proportionality factor was corrected by a suitable value determined through the Hill-climbing method. EDLC charge control has been performed with the three charge mode: constant current charge mode, constant power charge and the constant voltage charge mode; while supervising the maximum voltage and allowable temperature of each series-connected EDLC. The effectiveness of the method has been verified analytically and experimentally. The performance of the solar PV array is strongly dependent on operating conditions and field factors, such as sun geometric locations, its irradiation levels of the sun and the ambient temperature. A cloud passing over a portion of solar cells or a sub module will reduce the total output power of solar PV arrays. Under certain cloud conditions, the changes can be dramatic and fast [117]. A method proposed by several authors [117,118] measure the changes in solar insolation over a 1 min time interval. With the help of this method [119], solar insolation values may be measured in the horizontal plane and subsequently used to calculate insolation levels for any desired angle. A shadowed solar cell acts like a load because it dissipates input current. In the presence of shadows, a solar cell will heat up and develops a hot spot where there is no exposure to sunlight. To reduce the overall effect of shadows, bypass diodes are connected across the shaded cells to pass the full amount of current while preventing damage to solar cell [120]. Thus predicting the electrical characteristics of a solar PV array when experiencing passing clouds, is rather complex [121]. The noticeable findings [8,11,44,95–121] are:

- Dual axis tracking in conjunction with MPPT gives better improvement in system efficiency.
- Peripheral interface controller (PIC) based systems are cost effective and easy to maintain. Installation and operation of PIC based system is simple. It requires less number of electronic circuit components, and possesses low power consumption rate.
- An efficient and cost effective tracking system can be designed and developed with the help optimization technique based on the minimization of angular field for daily motion and minimization of the operating time. In this way, performance of the system can be predicted much earlier in the design cycle of the tracking system. This allows more effective and cost efficient design changes and reduces the overall risk substantially.
- The circuit implementation of microprocessor based MPPT with two loop control is very complex.
- Regulation of output power by changing the number of batteries needs extra hardware circuit.
- The method, which uses only an output current measurement by neglecting the variation in output voltage, simplifies the control circuits. However, this approach does not track the maximum power points rapidly.
- Classical P&O technique and its variant suffers from the lack of a solution for addressing the situation of drift. Incremental Conductance method can eminently address this issue.
- It also suffers from oscillation of the operating point around the MPP resulting in loss of power.

- It has slow or impeded response during changing atmospheric conditions due to fixed search step size. It can be alleviated by the introduction of variable search step methods.
- It has tendency of the operating point drifting towards the wrong direction.
- The failure of the P&O algorithm to follow rapidly varying atmospheric conditions is due to its inability to relate the change in the PV array power to the change in atmospheric conditions.
- In P&O method with DSP-based controller, maximum power tracking can be achieved rapidly and accurately by increasing the sampling frequency.
- Incremental conductance method is able to provide marginally better performance as compared to P&O. But the increased complexity of the algorithm will require more expensive hardware, and therefore, may have an advantage only in the large PV arrays.
- Both VMPPT and CMPPT techniques are fast, practical and powerful methods for maximum power point estimation of PV generator under all insolation and temperature conditions. The resulting output power is increased. The increase in output power depends on load characteristics, environmental factors (insolation and temperature), and the type of tracker used.
- Both types of trackers may be used either with buck-or boost-type converters depending on the load characteristics.
- VMPPT technique is naturally more efficient and has less circuit losses (especially for buck-mode trackers).
- Online measurement of PV short circuit current and output current make CMPPT hardware more complicated and expensive compared with (same rating) VMPPT circuitry, requiring voltage measurement only.
- The linear current function used by the CMPPT technique is a more accurate approximation of the actual non-linear PV characteristics compared with the linear voltage function of the VMPPT techniques.
- VMPPT system gives better overall performance in terms of cost, efficiency and noise in case of PV loads, which require low-voltage and high current outputs (i.e. battery chargers and low-resistance loads).
- Both types of trackers VMPPT or CMPPT are suitable for PV loads with high voltage and low current (motors and high resistance loads), but the VMPPT technique will result in simple hardware with higher efficiency and lower noise and cost.
- Hill climbing involves a perturbation in the duty ratio of the power converter, where as in P&O, a perturbation in the operating voltage of the PV array is involved.
- Incrementing the voltage increases the power when operating on left of MPP and decreases the power when operating on right of the MPP. Hence, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed.
- Oscillation in Hill climbing and P&O can be minimized by reducing the perturbation step size. However, a smaller perturbation step size slows down the MPPT. A variable perturbation size is a solution to this conflicting situation (smaller step size towards the MPP).
- Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions.
- In incremental conductance method, the increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at MPP and oscillate about it instead, so there is a trade off.
- MPPT fuzzy logic controllers perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user in choosing the right error computation and coming with the rule based table.
- In MPPT neural network controllers, since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristic of the PV array also changes with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT.
- When PV array is connected to a power converter, the switching action at the power converter causes voltage, current and power ripple on the PV array.
- MPPT techniques, which require array reconfiguration in different series and parallel combinations such that the resulting MPPs meet specific load requirements are time consuming.
- State-based MPPT techniques is robust and insensitive to changes in system's parameters and the MPPT is achieved even with changing atmospheric conditions and in the presence of multiple local maxima caused by partially shaded PV array or damaged cell.
- Partial shading of the PV array(s) causes multiple local maxima that affect the proper functioning of an MPP tracker. This leads to considerable power loss.
- The number of sensors required to implement MPPT also affects the decision process. In majority of applications, it is easier and convenient to measure voltage instead of current. Moreover, current sensors are usually expensive and bulky, and their use might be inconvenient in system that consists of several PV arrays with separate MPP trackers. In such cases, it is wise to use MPPT methods that need only one sensor or that can estimate the current from voltage.
- Though in Fractional V_{oc} MPPT technique, the PV array technically never operates at MPP, but it is less expensive and easy to implement as it does not necessarily require DSP or microcontroller control. Partial shading adds to the implementation complexity and results in more power loss.
- In fractional short circuit current method, it is difficult to measure I_{sc} during operation. An additional switch usually has to be added to the power converter to periodically short the PV array so that I_{sc} can be measured using current sensors. This increases the number of components and cost. Power is not only reduced when finding I_{sc} but also because the MPP is never perfectly achieved.
- In fractional open circuit voltage method, the PV array technically never operates at MPP. Depending on the application of the PV system, this may be acceptable sometimes. Even if fractional V_{oc} is not a true MPPT technique, it is very easy and economical to implement as it does not necessarily require DSP or microcontroller control.

7. Conclusion

Solar energy will play an increasing important role in a future where reducing the dependence on fossil fuels and addressing environmental issues are a priority. The energy technology sector is experiencing marked change from its traditional architecture of large-scale, centralized supply systems that take advantage of significant economies of scale. PV certainly fits this trend. Thus traditional cost comparisons based on large bulk power market may be misleading. PV is likely to pioneer the development of a new energy service market in which technology does not simply supply energy but must instead meet the demand for such services as energy management, back-up or emergency power, environmental improvements and fuel diversity.

Energy generation from photovoltaic technology is simple, reliable, available everywhere, in-exhaustive, almost maintenance free, clean and suitable for off-grid applications. But, photovoltaic efficiency and manufacturing costs have not reached the point that photovoltaic power generation can replace conventional coal-, gas-, and nuclear-powered generating facilities. For peak load use (no battery storage), the cost of photovoltaic power is much more than conventional power (cost comparisons between photovoltaic power and conventionally generated power are difficult due to wide variations in utility power cost, sunlight availability, and numerous other variables). Substantial progress has been made in the area of solar power generation and application covering analysis, simulation, and hardware development and testing for efficiency maximization and cost minimization. However, many problems and issues, especially those related to the development of affordable, inexhaustible and clean solar energy technologies for huge longer-term benefits, and a broad range of policies needed to unlock the considerable potential of solar energy still need to be addressed for appropriate system planning and operation of the power system to supply a good quality and reliable electric power.

Acknowledgment

Author would like to thank to the researchers/academicians whose works have been cited directly or indirectly in this paper. Author also wish to thank to Council of Scientific and Industrial Research, New Delhi.

References

[1] Canale M, Fagiano I, Milanese M. KiteGen. A revolution in wind energy generation. Energy 2009;34:355–61.
[2] Kalogirou SA. The potential of solar industrial process heat applications. Applied Energy 2003;76:337–61.
[3] Tien W, Kuo K-C. An analysis of power generation from municipal solid waste (MSW) incineration plants in Taiwan. Energy 2010;35:4824–30.
[4] Mercure J-F, Salas P. An assessment of global energy resource economic potential. Energy 2012;46:322–36.
[5] Solar energy perspectives: executive summary. International Energy Agency; 2011.
[6] Enslin JHR. Maximum power point tracking: a cost saving necessity in solar energy systems. In: Proc. IECON'90; 1990. p. 1073–7.
[7] Chamboulegron. A third world view of the photovoltaic market. Solar Energy 1986;36:381–6.
[8] Hussein KH, Muta I, Hoshino T, Osakada. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. IEE Proceedings on Generation, Transmission, Distribution 1995;142:59–64.
[9] Zweibel K. Harnessing solar power. Plenum Press; 1990109–11.
[10] Snyman DB, Enslin JHR. Combined low-cost, high-efficient inverter, peak power tracker and regulator for PV applications. In: Proc. IEEE power electronics specialist conference, PESC-89, Milwaukee, USA; June 26–29, 1989. p. 67–74.
[11] Piegari L, Rizzo. Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking. IET Renewable Power Generation 2010;4: 317–28.
[12] Nguyen DD, Lehman B. Modeling and simulation of solar PV arrays under changing illumination conditions. In: Proc. IEEE compel workshop. Trou, NY, USA: Rensselaer Polytechnic Institute; July 16–19, 2006. p. 295–9.
[13] Jewell WT, Unruh TD. Limits on cloud-induced fluctuation in photovoltaic generation. IEEE Transactions on Energy Conversion 1990;5:8–14.
[14] Salameh Z, Dagher F, Lynch WA. Step-down maximum power point tracker for photovoltaic system. Solar Energy 1991;46:278–82.
[15] Siri K, Caliskan VA, Caliskan VA, Lee CQ. Peak power tracking in parallel connected converters. In: Proc. IEEE PESC'92; 1992. p. 1401–6.
[16] Rauth HU, Dress A, Pruschck R, Weidele T. Annually generated electricity of one and two axes solar tracking systems. In: Proc. 13th European PV solar energy conference, Nice; 23–27 October 1995. p. 1015–8.
[17] Poulek V, Libra M. New solar tracker. Solar Energy Materials and Solar Cells 1998;51:113–20.
[18] Poulek V, Libra M. A new low cost tracking ridge concentrator. Solar Energy Materials and Solar Cells 2000;61:199–202.
[19] Poulek V. A very simple solar tracker for space and terrestrial applications. Solar Energy Materials and Solar Cells 1994;33:183–97.
[20] Energy conversion: development of solar cells. Britannica. online, http://www.eb.com:180-cgi-bin/g? DocF=macro/5002/13/245.html; October 21, 1998.
[21] The history of PV. http://www.pvpower.com/pvhistory.html; November 15, 1998.
[22] Zweibel Kenneth, Herch Paul. Basic photovoltaic principles and methods. New York: Van Nosstrand Reinhold Company, Inc.; 1984.
[23] Hammonds M. Getting power from the sun: solar power. Chemistry and Industry 1998;6:219–28.
[24] Coiante D, Barra. Can photovoltaics become an effective energy option. Solar Energy Materials and Solar Cells 1992;27:79–89.
[25] Burns JE, Kang J-S. Comprehensive economic analysis for supporting policies for residential solar PV in the United States: solar renewable energy credit (SREC) potential. Energy Policy 2012;44:217–25.
[26] Kumaresan G, Sridhar R, Velraj R. Performance studies of a solar parabolic trough collector with a thermal energy storage system. Energy 2012;47: 395–402.
[27] Rai GD. Non-conventional energy sources. 4th ed. New Delhi, India: Khanna Publisher; 2006.
[28] Billinton R, Karki R. Reliability/cost implications of utilizing photovoltaics in small isolated power systems. Reliability Engineering and System Safety 2003;79:11–6.
[29] Byrne J, Kurdgelashvili L, Poponi D, Barnett A. The potential of solar electric power for meeting future US energy needs: a comparison of projections of solar electric energy generation and Arctic National Wildlife Refuge oil production. Energy Policy 2004;32:289–97.
[30] Knaupp W, Mundschau E. Solar electric energy supply at high altitude. Aerospace Science and Technology 2004;8:245–54.
[31] Koutroulis E, Kolokotsa D, Potirakis A, Kalaitzakis K. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. Solar Energy 2006;80:1072–88.
[32] Friling N, Jimenez MJ, Bloem H, Madsen H. Modeling of heat dynamics of building integrated and ventilated photovoltaic modules. Energy and Buildings 2009;41:1051–7.
[33] Fanni L, Virtuani A, Chianese D. A detailed analysis of gains and losses of a fully integrated flat roof amorphous silicon photovoltaic plant. Solar Energy 2011;85:2360–73.
[34] Hwang T, Kang S, Kim JT. Optimization of the building integrated photovoltaic system in office buildings – focus on orientation, inlined angle and installed area. Energy and Buildings 2012;46:92–104.
[35] Penick T, Louk B. Photovoltaic power generation. Report submitted to Gale Greenleaf December 4, 1998.
[36] Quesada B, Sanchez C, Canada J, Royo R, Paya J. Experimental results and simulation with TRNSYS of a 7.2 kWp grid-connected photovoltaic system. Applied Energy 2011;88:1772–83.
[37] Ayoubi N, Batres R, Naka Y. An approach to wicked problems in environment policy making. WSEAS Transactions on Environment and Development 2009;5:229–39.
[38] Said RA. Solar energy via photovoltaic. Solar and renewable energy – Lebanon guide 200320–1.
[39] Ibrahim M, Sopian K, Daud WRW, Alghoul MA, Yahya M, Solaiman MY, et al. Solar chemical heat pump drying system for tropical region. WSEAS Transactions on Environment and Development 2009;5:404–13.
[40] Ikegami T, Maezono T, Nakanishi F, Yamagata Y, Ebihara K. Estimation of equivalent circuit parameters of PV module and its application to optimal operation of PV system. Solar Energy Materials and Solar Cells 2001;67:389–95.
[41] Soto DW, Klein SA, Beckman WA. Improvement and validation of a model for photovoltaic array performance. Solar Energy 2006;80:78–88.
[42] Khallat MA, Rahman S. A probabilistic approach to photovoltaic generator performance prediction. IEEE Transactions on Energy Conversion 1986;3: 34–40.
[43] Vachtsevanos G, Kalaitzakis K. A hybrid photovoltaic simulator for utility interactive studies. IEEE Transactions on Energy Conversion 1987;2:227–31.
[44] Hua C, Lin J, Shen C. Implementation of a DSP-controlled photovoltaic system with peak power tracking. IEEE Transactions on Industrial Electronics 1998;45:99–107.
[45] Altas IH, Sharaf AM. A photovoltaic array simulation model for Matlab-Simulink Gui environment. In: Proc. IEEE international conference on clean electrical power, ICCEP'07; 21–23 May 2007; 1. p. 341–5.
[46] Noguchi T, Togashi S, Nakamoto R. Short-current pulse-based maximum-power point tracking method for multiple photovoltaic-and-converter module system. IEEE Transactions on Industrial Electronics 2002;49:217–23.
[47] Kuo YC, Liang TJ, Chen JF. Novel maximum-power-point-tracking controller for photovoltaic energy conversion system. IEEE Transactions on Industrial Electronics 2001;48:594–601.
[48] Gonzalez-Longatt FM. Model of photovoltaic module in Matlab™. In: Proc. 2DO Congreso Iberoamericanode Estudiantes De Ingenieria Electrica, Electronica Y Computacion (II CIBELEC 2005); 2005; 1: p. 1–5.
[49] Chowdhury S, Chowdhury SP, Taylor GA, Song YH. Mathematical modeling and performance evaluation of a stand-alone polycrystalline PV plant with MPPT facility. In: Proc. IEEE power and energy society general meeting-conversion and delivery of electrical energy in the 21st century; 20–24 July, 2008; Pittsburg, USA, 1. p. 1–7.
[50] Moubayed N, El-Aw A, Outbib R. Control of a hybrid solar-wind system with acid battery of storage. WSEAS Transactions on Power Systems 2009;6: 307–18.
[51] Chang C, Zhy J-J, Tsai H-L. Model-based performance diagnosis of PV systems. In: Proc. SICE annual conference 2010, 18–21 August 2010, Taiwan. p. 2139–45.

[52] Jiang Y, Qahouq JAA, Batarseh I. Improved solar PV cell Matlab simulation model and comparison. In: Proc. IEEE international symposium on circuits and systems (ISCAS), May 30–June 2, 2010, USA. p. 2770–3.
[53] Walker G. Evaluating MPPT converter topologies using a Matlab PV model. Journal of Electrical and Electronics Engineering, Australia, IEAUST 2001;21: 49–56.
[54] Kim SJ, Lee JR, Cho BH. Large signal analysis of space aircraft power systems. In: Proc. IEEE 24th intersociety energy conversion engineering conference 1989 (IECEC-89), 6–11 August 1989; 1: p. 2873–80.
[55] Sullivan CR, Powers MJ. A high-efficiency maximum power point tracking for photovoltaic arrays in solar-powered race vehicle. In: Proc. 24th annual IEEE power electronics specialists conference (PESC'93), 20–24 June 1993; 1. p. 574–80.
[56] Borowy BS, Salameh ZM. Optimum photovoltaic array size for a hybrid wind/PV system. IEEE Transactions on Energy Conversion 1994;9:482–8.
[57] Smiley EW, Jones JD. Optimizing photovoltaic array size in a hybrid power system. In: Proc. the twenty-eight IEEE photovoltaic specialists conference 2000; 1. p. 1640–3.
[58] Mendez L, Naravarte L, Maninach AG, Izquierdo P, Carrasco LM, Eyras R. Centralized stand-alone PV system in micro grid in Morocco. In: Proc. 3rd world conference on photovoltaic energy conversion, Osaka, Japan, May 11–18, 2003; 3. p. 2326–8.
[59] Wies RW, Johnson RA, Agrawal AN, Chubb TJ. Simulink model for economic analysis and environmental impacts on a PV with diesel-battery system for remote villages. IEEE Transactions on Power Systems 2005; 20:692–700.
[60] Phuangpornpitak N, Kumar S. PV hybrid systems for rural electrification in Thailand. Renewable and Sustainable Energy Reviews 2007;11:1530–43.
[61] Russell MC. Grid-tied PV system modeling: how and why. In: Proc. IEEE first world conference on photovoltaic energy conversion, December 5–9, 1994; 1. p. 1040–3.
[62] King DL, Dudley JK, Boyson WE. PVSIMC: a simulation program for photovoltaic cells, modules, and arrays. In: Proc. Twenty Fifth IEEE Photovoltaic Specialists Conference 1996, 13–17 May 1996; 1: p. 1295–7.
[63] Gow JA, Manning CD. Development of a model for photovoltaic arrays suitable for use in simulation studies of solar energy conversion systems. In: Proc. Sixth IEEE international conference on power electronics and variable speed drives, 23–25 September 1996; 1. p. 69–74.
[64] Chenni R, Makhlouf M, Karabacho T, Bouzid A. A detailed modeling method for photovoltaic cells. Energy 2007;32:1724–30.
[65] Karatepe E, Boztepe M, Colak M. Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells. Solar Energy 2007;81:977–92.
[66] Billinton R, Karki R. Reliability/cost implication of utilizing photovoltaics in small isolated power systems. Reliability Engineering and System Safety 2003;79:11–6.
[67] Dyk EEV, Gxasheka AR, Meyer EL. Monitoring current voltage characteristics and energy output of silicon photovoltaic modules. Renewable Energy 2005;30:399–411.
[68] Tiba C, Meltrao REA. Sitting PV plant focusing on the effect of local climate variables on electric energy production – case study for Araripina and Recife. Renewable Energy 2012;48:309–17.
[69] Burns JE, Kang JS. Comparative economic analysis of supporting policies for residential solar PV in the United States: solar renewable energy credit (SREC) potential. Energy Policy 2012;44:217–25.
[70] Andrews RW, Pollard A, Pearce JM. Improved parametric empirical determination of module short circuit current for modeling and optimization of solar photovoltaic systems. Solar Energy 2012;86:2240–54.
[71] Rahman S, El-Amin I. Performance evaluation of an off-grid photovoltaic system in Saudi Arabia. Energy 2012;46:451–8.
[72] Gabler H, Luther J. Wind-solar hybrid electrical supply systems, results from a simulation model and optimization with respect to energy pay back time. Solar and Wind Technology 1988;5:239–47.
[73] Habib MA, Said SAM, El-Hadidy MA, Al-Zahurna I. Optimization procedure of a hybrid photovoltaic wind energy system. Energy 1999;24:919–29.
[74] Elhadidy MA. Performance evaluation of hybrid (wind/solar/diesel) power systems. Renewable Energy 2002;26:401–13.
[75] Tripanagnostopoulos Y, Nousis TH, Souliotis M, Yianoulis P. Hybrid photovoltaic/thermal solar system. Solar Energy 2002;72:217–34.
[76] Ai B, Sen YH, Liao X. Computer-aided design of PV/wind hybrid system. Renewable Energy 2003;28:1491–512.
[77] Campo BRO, Vasquez ER, Sancheb HCS, Cornejomeza RC, Martinez GT, Rodriquez FJG, et al. Photovoltaic/thermal solar hybrid system with bifacial PV module and transparent plane collector. Solar Energy Materials and Solar Cells 2007;91:1966–71.
[78] Kaldellis JK, Kavadias KA, Koronakis PS. Comparing wind and photovoltaic stand-alone power systems used for the electrification of remote consumers. Renewable and Sustainable Energy Reviews 2007;11:57–77.
[79] Ahmed NA, Miyatake M, Al-othman AK. Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems. Energy Conversion and Management 2008;49: 2711–9.
[80] Koussa DS, Hadadi M, Belhamel M. Economic and technical study of a hybrid system (wind-photovoltaic-diesel) for rural electrification in Algeria. Applied Energy 2009;86:1024–30.
[81] Sopian K, Ibrahim MZ, Daud WRW, Othman MY, Yatim B, Amin N. Performance of a PV-wind hybrid system for hydrogen production. Renewable Energy 2009;34:1973–8.
[82] Margeta J, Glasnovic Z. Feasibility of the green energy production by hybrid solar + hydro power system in Europe and similar climate areas. Renewable and Sustainable Energy Reviews 2010;14:1580–90.
[83] Davidsson H, Peres B, Karlsson B. Performance of a multifunctional PV/T hybrid solar window. Solar Energy 2010;84:365–72.
[84] Bekele G, Palm B. Feasibility study of a stand-alone solar-wind-based hybrid energy system for application in Ethiopia. Applied Energy 2010;87:487–95.
[85] Koutroulis E, Kolokotsa D. Design optimization of desalination systems power supplied by PV and W/G energy sources. Desalination 2010;258:171–81.
[86] Notton G, Diaf S, Stoyanov L. Hybrid photovoltaic/wind energy systems for remote locations. Energy Procedia 2011;6:666–77.
[87] Kosmadakis G, Manolakos D, Papadakis G. Simulation and economic analysis of a CPV/thermal system coupled with an organic Rankine cycle for increased power generation. Solar Energy 2011;85:308–24.
[88] Cherif H, Belhadj J. Large-scale time evaluation of energy estimation of stand-alone hybrid photovoltaic-wind system feeding a reverse osmosis desalination unit. Energy 2011;36:6058–67.
[89] Margeta J, Glasnovic Z. exploitation of temporary water flow by hybrid PV-hydroelectric plant. Renewable Energy 2011;36:2268–77.
[90] Margeta J, Glasnovic Z. theoretical settings of photovoltaic-hydro energy system for sustainable energy production. Solar Energy 2012;86:972–82.
[91] Bekele G, Boneya G. Design of a photovoltaic-wind hybrid power generation system for Ethiopian remote area. Energy Procedia 2012;14:1760–5.
[92] Vick BD, Neal BA. Analysis of off-grid hybrid wind turbine/solar PV water pumping systems. Solar Energy 2012;86:1197–207.
[93] Urbiola EAC, Vorobiev YV, Bulat LP. Solar hybrid systems with thermoelectric generators. Solar Energy 2012;86:369–78.
[94] Kaladellis JK, Zafirkis D. Optimum sizing of a stand-alone wind-photovoltaic hybrid systems for representative wind and solar potential cases of the Greek territory. Journal of Wind Engineering and Industrial Aerodynamics, in press.
[95] Roth P, Georgiev A, Boudinov H. Design and construction of a system for sun-tracking. Renewable Energy 2004;29:393–402.
[96] Abdallah S, Nijmeh S. Two axis sun tracking system with PLC control. Energy Conversion and Management 2004;45:1931–9.
[97] Abdallah S. The effect of using sun tracking systems on the voltage-current characteristics and power generation of flat plate photovoltaics. Energy Conversion and Management 2004;45:1671–9.
[98] Rubio FR, Ortega MG, Gordillo F, Lopez-Martinez M. Application of new control strategy for sun tracking. Energy Conversion and Management 2007;48:2174–84.
[99] Alexandru C, Comsit M. The energy balance of the photovoltaic tracking systems using virtual prototyping platform. In: Proc. IEEE 5th international conference on European electricity market, EEM 2008, 28–30 May 2008; 1. p. 1–6.
[100] Alexandru C. The design and optimization of a photovoltaic tracking mechanism. In: Proc. powereng 2009, Lisbon, Portugal, March 18–20, 2009; 1. p. 436–41.
[101] Nabulsi AA, Nosh AE, Ahli A, Sulaiman M, Dhaouadi R. Efficiency optimization of a 150 kW PV system using dual axis tracking and MPPT. In: Proc. IEEE international energy conference 2010; 1. p. 400–5.
[102] Oo LL, Hlaing NK. Microcontroller-based two-axis solar tracking system. In: Proc. IEEE 2nd international conference on computer research and development 2010; 1. p. 436–40.
[103] Lu HC, Shih TL. Fuzzy system control design with application to solar panel active dual-axis sun tracker system. In: Proc. 2010 IEEE international conference on systems man and cybernatics (SMC), 10–13 October 2010; 1. p. 1878–83.
[104] Seme S, Stumberger G, Vorsic J. Maximum efficiency trajectories of a two-axis sun tracking system determined considering system consumption. IEEE Transactions on Power Electronics 2011;26:1280–9.
[105] Tina GM, Gagliano S, Graditi G, Merola A. Experimental validation of a probabilistic model for estimating the double axis PV tracking energy production. Applied Energy 2012;97:990–8.
[106] Enslin JHR. Maximum power point tracking: a cost saving necessity in solar energy systems. In: Proc. 16th annual conference of IEEE industrial electronics society, IECON'90, 27–30 November 1990; 2. p. 1073–7.
[107] Chowdhury S, Chowdhury SP, Taylor GA, Song YH. Mathematical modeling and performance evaluation of a stand-alone polycrystalline PV plant with MPPT facility. In: Proc. IEEE power and energy society general meeting – conversion and delivery of electrical energy in the 21st century, Pittsburg, USA, July 20–24, 2008; 1. p. 1–8.
[108] Hohm DP, Ropp ME. Comparative study of maximum power point tracking algorithm using an experimental, programmable, maximum power point tracking test bed. In: Proc. the 28th IEEE photovoltaic specialists conference 2000; 1. p. 1699–702.
[109] Masaum MAS, Dehbonei H, Fuchs EF. Theoretical and experimental analysis of photovoltaic systems with voltage- and current-based maximum power point tracking. IEEE Transactions on Energy Conversion 2002;17:514–22.
[110] Esram T, Chapman PL. Comparison of photovoltaic array maximum power point techniques. IEEE Transactions on Energy Conversion 2007;22: 439–49.

[111] Kim IS, Kim MB, Youn MJ. New maximum power point tracker using sliding mode observer for estimation of solar array current in the grid-connected photovoltaic system. IEEE Transactions on Industrial Electronics 2006;53: 1027–35.
[112] Kottos TL, Boutalis YS, Karlis AD. New maximum power point tracker for PV arrays using fuzzy controller in close cooperation with fuzzy cognitive networks. IEEE Transactions on Energy Conversion 2006;21:793–803.
[113] Mutoh N, Ohno M, Inoue T. A method for MPPT control while searching for parameters corresponding to weather conditions for PV generation systems. IEEE Transactions on Industrial Electronics 2006;53:1055–65.
[114] Leyva R, Alonso C, Queinnec I, Pastor AC, Lagrange D, Salameru LM. MPPT of photovoltaic systems using extremum-seeking control. IEEE Transactions on Aerospace and Electronic Systems 2006;42:249–58.
[115] Femia N, Granozio D, Petroner G, Spagnuolo G, Vitelli M. Predictive and adaptive MPPT perturb and observe method. IEEE Transactions on Aerospace and Electronic Systems 2007;43:934–50.
[116] Mutoh N, Inou T. A control method of charge series-connected ultraelectric double-layer capacitors suitable for photovoltaic generation systems combining MPPT control method. IEEE Transactions on Industrial Electronics 2007;54:374–83.
[117] Jewell WT, Unruh TD. Limits on cloud-induced fluctuations in photovoltaic generation. IEEE Transactions on Energy Conversion 1990;5:8–14.
[118] Yanagawa S, Kato T, Kai W, Tabata A, Yokomizu Y, Okamoto T, et al. Evaluation of LFC capacity for output fluctuation of photovoltaic power generation systems based on multi-point observation of insolation. In: Proc. power engineering society summer meeting 2001; 3. p. 1652–57.
[119] Tamura J, Nakamura H, Inoue Y, Otani K, Kurokawa K. A new method of calculating in-plane irradiation by one-minute local irradiance. In: Proc. 3rd world conference on photovoltaic energy conversion 2003; 3. p. 2265–68.
[120] Vorster FJ, Van dyk EE, Leitch AWR. Investigation on the I–V characteristics of a high concentration, photovoltaic array. In: Proc. twenty-ninth IEEE photovoltaic specialists conference 2002; 3. p. 1604–7.
[121] Dzungd N, Brad L. Modelling and simulation of solar PV arrays under changing illumination conditions. In: . Proc. IEEE compel workshop, vol. 1. Troy, NY, USA: Rensselaer Polytechnic Institute; July 16–19, 2006. p. 295–9.