Maximum Power Point Tracking (MPPT) of Partially Shaded Photovoltaic Cells: A Technical Review

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The world’s energy supply has been under a tremendous pressure due to the rapid depletion of fossil resources, energy security and reliability, environmental sustainability and the ever-increasing modern living sophistication. The issue of persistent hikes in oil prices, climate threats and soaring energy demand has diverted the global interest to exploiting and investing in renewable types of energy (RE), solar energy in particular. A photovoltaic (PV) system is easy to install, has no moving parts, is almost free of maintenance, has maximum reliability, reduced vulnerability to power loss and is expandable. Regardless of these advantages, PV energy costs considerably higher than fossil fuels. This is due to its lower efficiency and higher costs. An expansive study has been carried out for PV fabrication, but it is equally important to extract the maximum power by enhancing the maximum power point tracking (MPPT) capability. The review covers the detailed partial shading condition (PSC) modelling and the various MPPT techniques and algorithms employed. It describes how to extract the maximum output power under continuous varying irradiation conditions in large PV arrays to make the technology commercially viable.

Keywords: renewable energy; photovoltaic; maximum power point; efficiency

1. Introduction

The world’s energy supply has been under a tremendous pressure due to the rapid depletion of fossil resources, energy security and reliability, environmental sustainability and the ever-increasing modern living sophistication. The World Energy Forum (2011) anticipated that the fossil fuel reserves would be drained out in less than 100 years. It accounts for over 79% of the primary energy consumed in the world. The fossil energy demand will expand almost 60% from 2002 to 2030 with an average rise of 1.7% per annum [1]. The electricity generation of the world is approximately 85% on fossil resource dependency; in contrast to renewable energy (RE) which remains at 4% [2-3]. Thus, the issue of persistent hikes in oil prices, climate threats and soaring energy demand has diverted the global interest for exploiting and investing in RE. Solar PV energy is a sustainable and abundant source progressively being envisioned as a significant RE source of the future.

The uses of non-renewable fuels have various challenging effects that cause pollution, acid rain and global warming. These fossil resources are depleting at a very fast rate causing increasing fuel prices which has led the engineers and economists to use alternative resources. As more countries have ratified the Kyoto accord intended for greenhouse gas emission reduction, traditional power generation from burning fossil resources are no longer bearable for adding into the system generation capacity [4].

Solar power transforms sunlight into electricity either, directly, by using photovoltaic (PV) technology or indirectly, by transformation using concentrated solar power (CSP) [5]. PV technology is easy to install, has no moving parts,
requires less maintenance, has maximum reliability, reduces vulnerability to power loss and is expandable [6]. The PV cell also referred to as solar cells [1] generates power which is not usable on a commercial scale. In this regard, the number of cells are connected in a series and are parallel to form a module according to the application requirement. Whereas, the number of modules are also connected in a similar fashion for large arrays as shown in Fig. 1. Therefore, an ultimate energy source of photovoltaic lends several advantages.

After the full potential of PV has been anticipated, the revolution and advances in semiconductor material will be needed. The rapidly expanding photovoltaic industry has been around for the last two decades, yet it is continuing to grow at the rate of around 40%. This growth will allow photovoltaics to be the world’s largest energy source [6, 7]. PV generation systems tactlessly encounter two major issues; they are firstly, the low conversion efficacy of electric power generation, around 9 – 17%, specifically under low irradiation. Secondly, the sum of the electric power generation in a solar array varies constantly with the weather conditions. The solar irradiation is only available for a maximum of 8 - 9 hours on a shiny bright day but is not uniformly fixed at each instant [7].

2. Background

The solar PV manufacturers, regulators, installers and owners are curious to get precise knowledge of PV systems under shaded or mismatched operating conditions. The off-nominal operating conditions are inevitable, therefore, an efficient PV installation plays a significant role for power generation under shady conditions. The building integrated photovoltaics (BIPV) need to integrate the PV modules with existing building envelopes in a crowded urban environment. In order to commercialise PV systems globally or to increase the maximum output and reduce power loss, it is worthwhile to consider in depth power loss from partially shaded PV installations and their tracking mechanism.

The clean energy council (CEC), a regulatory agency, has primarily focused their interest on computing power efficiency and a rebate incentive for shaded PV systems. In order to acquire a performance assessment, the PV system modelling is essential. The PV systems under shady conditions suspiciously reduce efficiency; therefore, reimbursement incentive needs to be regulated accordingly. Several studies have already been conducted on the effect of shading and mismatched operation conditions for analysing the performance of PV systems. The first practical mission of NASA for Pioneer 1 solar modules helped the understanding of the shunt bypass diodes which benefit the power efficiency of shaded modules [8]. The upcoming space mission analysis for the operation of shaded modules was practiced to simplify its operation [9, 10]. Other studies have addressed local hot-spot degradation, reverse biased for the modules’ reliability and performance aspects. Therefore, employing by-pass diodes for PV cell strings and module test criterion is suitable to set up guidelines provided by IEC 61215 [11], ASTM E2481 [12] and UL 1703 [13].

3. Photovoltaic (PV) Modelling

Solar photovoltaics provide a single stage non-conventional energy transformation. A PV cell is primarily a current source, which is reliant on irradiation and temperature as shown in Fig. 2. The multifaceted model relationship results in non-linear characteristics that are dependent on the temperature and irradiation level [14-16] as shown in equation 1. The typical basic I–V and P–V characteristic curve for a solar cell is shown in Fig. 3 (a & b), respectively. The variations of the irradiation and temperature can be observed in Fig. 4. The dependency of power on temperature and irradiance causes a fluctuation in the power output and the maximum power point (MPP), too; thus, it is simply not a fixed point. The controller has been designed to apprise the converter duty cycle at each control sample to track the MPP effectively due to its nonlinear dynamic behaviour. Therefore, the controller should respond faster to match the MPP resulting in better extraction of the PV energy output and vice versa.

![Fig. 2 Equivalent circuit model of photovoltaic cell](image-url)
\[
I_{pv} = I_{ph} + I_d \left( \exp \left( q \frac{V_{pv} + IR_s}{A^*k^*t} \right) - \frac{V_{pv} + IR_s}{R_p} \right)
\]

(1)

Where,
- \( q \): electron charge \((1.602 \times 10^{-19} \text{ C})\).
- \( k \): constant Boltzmann \((1.38 \times 10^{-23} \text{ J/K})\).
- \( I_{pv} \): cell output current, A.
- \( I_{ph} \): photocurrent, function of irradiation level and junction temperature.
- \( I_d \): diode reverse saturation current.
- \( R_s \): cell resistance in series.
- \( R_p \): shunt resistance
- \( t \): reference cell operating temperature \((20 ^\circ \text{C})\).
- \( A \): diode ideality factor
- \( V_{pv} \): cell output voltage, V.
- \( I_{pv} \): light-generated current in Amps. at the ambient conditions (usually 25\(^\circ\)C and 1000W/m\(^2\)).

Fig. 3 Photovoltaic characteristics a) P-V curve and b) I-V curve

Fig. 4 Photovoltaic cell characteristics with various irradiation and temperature levels
3.1 The Maximum Power Point Tracking (MPPT)

The prime objective in employing MPPT is to obtain the maximum power from PV modules under rough environmental conditions [17]. This has generally been obtained with counter matching of a converter’s operating voltage and current with MPP, correspondingly. The block diagram of a PV system with an MPPT controller is shown in Fig. 5. MPPT initially measures the current and voltage level with sensors. It is fed to the MPPT technique which computes MPP at an instantaneous cycle.

The PV current and voltage reference values are delivered by MPPT. The values are then matched to the converter (most probably voltage is selected as a variable). Therefore, the comparison between the measured and instantaneous values of MPP is made. Thus, if a difference occurs in the two, then the duty cycle of the converter is adjusted to decrease the variation. As the reference and measured values coincide, the extracted power from the array would be the maximum. The block architecture of the solar module with the MPPT controller is depicted in Fig. 5.

3.2 Partial Shading

In partial shading conditions (PSCs), the tracking of the MPP gets more complex when the uniform irradiations are not obtained by the entire PV array or module [18]. This is typically due to the clouds striking on certain spots of the solar array, whereas other parts are irradiated homogeneously. The module irregularities can also exhibit the PSC; this is commonly due to the presence of one or more cracks on the module. The static I–V and P–V characteristics under the PSC are represented in Fig. 6 (a & b). Two modules in series with a varied irradiance level on each module gives a curve shape shown in Fig. 6a. The I-V curves are formed due to the PSC results; the two stair waveforms are as shown in Fig. 6b. Whereas, the multiple maxima points are characterised on the P-V curve shown in Fig. 6b. The tracking of the global maximum power must be guaranteed by the MPPT so that it is not trapped in one of the local maxima. Thus, if the algorithm is trapped at a local peak point, significant power loss is incurred.

Fig. 6 Photovoltaic cell characteristics with various irradiation and temperature levels
Partially shaded modules have been reported with various illumination models. The planar components of direct and diffuse irradiation are typically considered separately. The PV shading of a direct irradiance obstruction is commonly evident and disruptive resulting in a visible shadow at the module causing a decreased array output to a significant amount. The diffused portion of the irradiation blocking reduces the array output which is apparently not like the obstructing direct irradiation. The computation for real time illumination is the prior step for analysing the solar cell. Quaschning et al. [19] addressed the SUNDI mathematical model estimating seasonal illumination reduction. He also devised elevation coordinates for surrounding shade obstructions. This formed the basis for a computer simulation of the PV module under shady conditions. The Drif et al. [20] methodology offers a quantitative analysis of shading. The multiple points are considered for the power output but not just simply limited at the central point shading on the solar array plane. Phimmasone et al. [21] investigated several shapes of partial shade and the speed of insolation variations. Miyatake et al. [22] studied continuous partial shading and un-shady conditions. Keyrouz and S. Georges [23] focused on the dynamic shady conditions caused by continuously uneven insolation levels. Fisheye photographs [24], scale models for heliodon analysis [25] and the triangulation of multiple-photographs [26] are other shade estimation methods.

Numerous computational techniques have already been offered [27 - 30] and in all of these, additional coefficients have been presented, which cause an increase in computational effort. The determination of the initial values of the parameters for some empirical solutions have been pursued. Whereas, physical features have been scrutinized including the electron coefficient diffusion, lifespan of marginal carriers, intrinsic carrier concentration and other semiconductor parameters [31 - 34]. The data about semiconductors is not accessible at all times in datasheets of PV cells, commercially. After realising the most approximate mathematical model of the PV cell, the prevailing of several software packages, such as PV-Spice, PV-DesignPro, SolarPro, PCad, and PVsys are easily accessible in the market. However, they are costly, unreasonably multifaceted and may seldom have provisions of interfacing between the PV arrays and power converters [35].

Thus, for shaded modelling, an improved shaded cell model [9] was presented by Bishop [36] for simplifying the 5-parametric equivalent circuits with a numerical analysis. The forward and reverse bias characteristics were coupled to enhance computations under partially shaded conditions (PSCs). Which was then applied for numerical solutions of the series strings under inhomogenous irradiations. For a more improved analysis, it suggested a two-diode model for accuracy. Typically, the real characteristics of a shaded cell are retained, except for the diode current, which relies on the incident radiation level. Further study explored the parametric attributes of a shaded cell which included the shunt resistance, ideality factor and fill factor [37, 38]. The solar cell model mimicks an analog circuit with knobs that adjust the parameters like illumination, fill factor, temperature, diode ideality factor etc. [39]. It has also been observed that the adaptive computational environment plays a vital role as an artificial mathematica [40], neural network [41] and fuzzy logic [42].

The numerical analysis of the shaded cell can be employed in several applications. The main objective is to examine the position of the shunt bypass diode [36, 37] and perform the mismatching (Monte Carlo method) analysis of the typical large PV installation [43]. On the basis of the statistical distribution, the mismatch loss has been observed in less than 1% of the installed modules. Several researchers have been motivated to investigate a more vulnerable array configuration to partial shadings when employing different interconnections and also with the placement of the inverter [44]. Thin filmed, reverse bias, amorphous silicon modules or cells have also been discussed by the PV experts [45]. Thus, the findings of the detailed investigation shows that shadowing of cells decreases the power output of the series and the parallel connected strings by an amount over proportionate to the size of the shadow [46].

4. MPPT Technological Motivation

Today the research into solar PV systems is aiming for the technological advancement in components, control algorithms, maximisation of efficiency and individuated extensive applications. The power wastage of a commercial power conditioning system (PCS) has been explored to be as high as 70% under partial shading conditions (PSCs). The major issues of MPPT efficiency and tracking speed are envisioned in most of the conventional studies [48]. The entire PV system would lose output power of more than 50% if only 10% of the PV arrays are under shade [49].

Two major complicated issues have been raised by PV insolation irradiance conditions. The PV cell generates a certain amount of power under shady condition, which traditionally cannot be obtained. The shaded cells can inhibit the generation of power from the entire string of the series-connected cells if bypass diodes are not employed. Therefore, a fraction of the generated energy by the partially shaded cells will be lost if it does not impede the collection of energy from the rest of the cells. Moreover, the total PV operating voltage in the low-voltage arrays also represents a significant fraction of the diode bias voltage. These issues are not considered significant in high-voltage stationary systems which do not have obstructions. On the other hand, in low voltage portable applications, it is quite significant where partial shading is repeatedly encountered and a fraction of the cells may be partially shaded at any one time. The nuisance of maximum power point tracking (MPPT) capability would be increased with continuously changing shadow conditions. Therefore, multiple local peaks occur and are very complex for MPPT to recognize the global maximum
power point (MPP) for the bypass diode systems. With the varying shady conditions, the MPP location fluctuates rapidly. Thus, at some instant, if one could identify the position of the global maximum point, it would be possible to alter it before the MPP tracker could possibly shift to that operating point. In other words, very fast tracking speeds, quick responses and good control stability are specifically compelled for an MPP tracker to work with the varying situations [50].

The measure of the power output increases with the mismatching case of the PV field but the power versus voltage characteristic appears to be multimodal. Therefore, the complication for the detection of the absolute maximum power point (MPP) of the PV field increases due to the presence of more than one peak [51]. The criteria for an MPPT method should be as follow: that it is practical in engineering and realises the strategy for MPPT which is very critical not only for the researchers but also the engineers. Finally, it should quickly reach the global maxima and must track it in the right way. MPPT should reach the global maxima without complex computations or the wrong-direction tracking; moreover, it should cost less and be highly efficient and effective with a simple architecture of only a few steps.

The drawbacks of the conventional methods and the requirements to be considered in the MPPT method under PSC have been deduced. Power Conditioner Systems (PCSs) without additional circuits have to be applied for simplicity. Under PSCs, short- or open-circuit conditions must be avoided [48]. Furthermore, the topology of the PV arrays should be considered properly [52].

In order to deal with the efficiency of the PV array, an MPPT plays a vital role. Thus, several studies have addressed that conventional MPPTs are operated on a sensing current and the voltage of the array. Some commercially well-known MPPTs are: perturb and observe (P & O) [53, 54], Incremental conductance (INC) [55, 56] and hill climbing (HC) [57]. For the least cost applications, simple methods include the Ripple Correlation Control [58], Fractional Open Circuit Voltage [59] and Fractional Short Circuit Current [60]. Other techniques include the State-based MPPT [61], DC-link Capacitor Drop Control [62], Best Fixed Voltage algorithm [63], Slide Control method [64], dP/dV or dP/dI Feedback Control [65], Linear Reoriented Coordinate [66], Load Voltage Minimisation [67], Linear current control [68].

Whereas, the soft-computing techniques are catching the interest of researchers to focus on due to their huge, effective, low cost, quick convergence, robustness and their global peak search capability. These are complexities of the MPPT issues primarily centered on the non-linear PV curve to be handled with non-linearity. The adaptive nature of these techniques has been envisaged to tackle partial shady and quick irradiance variations under adverse environmental conditions. Various studies have exploited soft computing methods, which include the artificial neural network (ANN) for parameter tuning and optimisation that also provides a hybridisation platform for other MPPT techniques [69]. A non-linear predictor executes peak matching subject to the P-V curve primarily based on the predictor function of the quadratic or parabolic methods [70, 71]. A chaotic random search for the optimised point of the dynamic system utilises the PV voltage as the optimization variable and the power as the fitness function [72]. A fuzzy logic controller creates an automatic control for non-linearity and unpredictable variations in the operating point that significantly deals with MPP [73]. The particle swarm optimization (PSO) enhances the solution of particles, iteratively, in the search space with a simplified mathematical function for the global MPP [74]. The Genetic Algorithm (GA) is an issue resolving technique based on biological evolution and a population search that finds the best solution with a random gene combination. The voltage or duty cycle parameter in finding MPP has been exploited [75]. Ant Colony Optimisation (ACO) is a swarm optimisation that uses the PV power as a target function and the duty cycle as the control voltage. The power of their attraction is that ants make transitions from lower to higher strengths [76]. The differential evolution (DE) evolutionary algorithm works stochastically, thus, maintaining and creating a population for a candidate solution with their function for best fitness [77]. The Bayesian network provides graphical probabilistic based modelling which operates the mapping of the conditional probability of a random variable and combines two or more soft computing techniques [78]. Several of the soft computing MPPT techniques have been proved to provide better capabilities than conventional techniques. As they have each been tested, extensively, under different environmental conditions.

5. Conclusion

It has been concluded from the research chronology that a lot of work has been moved to partial shading conditions which closely depict the actual picture that MPPTs are going to face in the field. While, the conventional methods operate through sensing of the current and voltage variables of the PV array. This computes power and adjusts the converter duty cycle to match MPP. In spite of common objectives, the MPPT differs in terms of cost effectiveness, convergence speed and steady state oscillations. Several techniques have been trapped somewhere at local peaks and also may track even in the wrong direction. Yet, discrete insolation variations with multi-peak MPPT techniques have been analysed but since under cloudy conditions there are continuous and rapid isolation variations, the MPPT algorithm needs to be researched and worked out practically. There are also possibilities for conventional techniques to amalgamate with soft computing techniques for better performance of MPPT.

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References


Kobayashi K, Takano I, Sawada Y. A study on a two stage maximum power point tracking control of a photovoltaic system.


