KIEAE Journal, Vol. 14, No. 2, Apr. 2014, pp.21-28.

KIEAE Journal 66

Korea Institute of Ecological Architecture and Environment

State of the Art Review of Shading Effects on PV Module Efficiencies and Their Detection Algorithm Focusing on Maximum Power Point

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A B S T R A C T

This paper provides the up to date review of the shading effects on PV module performance and the associated detection algorithm related to the maximum power point tracking. It includes the brief explanations of the MMP variations due to the shading occurrence on the PV modules. Review of experimental and simulation studies highlighting the significant impacts of shading on PV efficiencies were presented. The literature indicates that even the partial shading of a single cell can greatly drop the entire module voltage and power efficiency. The MMP tracking approaches were also reviewed in this study. Both conventional and advanced soft computing methods such as ANN, FLC and EA were described for the proper tracking of MMP under shaded conditions. This paper would be the basic source and the comprehensive information associated with the shading effects and relevant MPP tracking technique.

K Y E W O R D S

Photovoltaic (PV),
shading,
maximum power point (MPP),
detection algorithm,
literature review

A C C E P T A N C E I N F O

Received February 24, 2014
Final revision received April 20, 2014
Accepted April 22, 2014

1. Introduction

Photovoltaic (PV) installations have been significantly increased for building applications during the past decades due to the keen concerns related to the energy and environmental issues these days. It is important to get the accurate understanding of the PV output characteristics for the efficient utilization of those PV modules. However, the nonlinear characteristics of PV output affected by temperature, array configuration and solar insolation are significantly complicated to predict and deal with. In addition, the non-uniform insulation due to the partial shading caused by clouds, adjacent trees, building, utilities or unexpected structural development would make the characteristics of PV output further complicated. Shading is one of the most common factors negatively affecting the PV power generation efficiency and thus it is very important to comprehensively understand the impacts of those shading on the PV performance and their detection method.

Properly tracking the maximum power point (MPP) is one of the crucial factors in PV modules for both improvement of the PV power efficiencies and effectiveness of recognizing irregular behavior due to the shading. It is a taxing challenge to track the correct MPP due to the complicated I-V curve and the existence of multiple local peaks and the GP at the same time under the shading conditions, causing the oscillation around the local peaks and accordingly reducing the PV power generation.

pISSN 2288-968X, eISSN 2288-9698
http://dx.doi.org/10.12813/kieae.2014.14.2.021

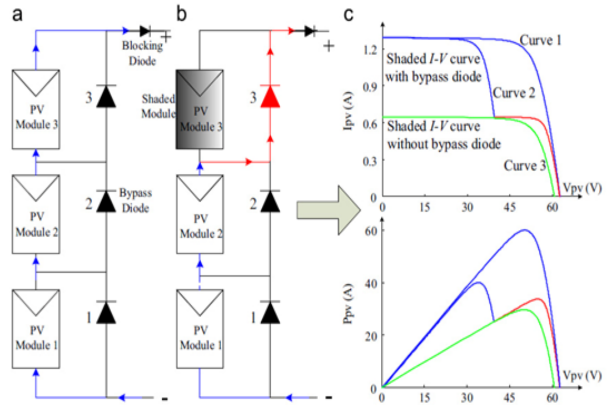

Fig. 1. Operation of PV under uniform insolation (a), under shading condition (b) and I-V and P-V curves for (a) and (b) [15]

Due to the significance of MPP tracking technique in PV modules, numerous studies have been performed thus far and a variety of papers have been published. However, those numerous MPP tracking techniques show extremely wide range of cost, effectiveness and complexity and thus the summary of state of the art MPP algorithms, especially for the shading conditions, is important in this circumstance. This study performed the state of the art review of the literature dealing with the shading effects on PV module efficiencies and their detection algorithm focusing on MPP, aimed at providing the basic source and the latest information associated with the shading effects and relevant MPP tracking technique.

2. Maximum Power Point under Shading Conditions

MPP is basically the operating point matching between the PV array and the power converter. When PV modules are under the shaded condition, P-V curves would generate multiple local peaks and a single global peak (GP). Typical PV array configurations are illustrated in Figure 1. Under the uniformly distributed solar insolation condition presented in Figure 1-(a), P-V curve generates a single MPP as shown in Curve 1 in Figure 1-(c). On the other hand, under the shaded condition presented in Figure 1-(b), the difference in the solar radiation between the adjacent modules activates the bypass diode, causing the multiple local peaks and a single global peak as shown in Curve 2 in Figure 1-(c). Properly tracking the correct MPP is one of the crucial factors in PV modules for both improvement of the PV power efficiencies and effectiveness of recognizing irregular behavior due to the shading, since the PV power generation would be significantly reduced due to the unnecessary oscillation between local peaks and GP without properly tracking MPP.

3. Shading Effects on PV Module Performance

As stated earlier, PV systems are often subject to the shading caused by the clouds, adjacent buildings and trees and thus a variety of studies have been carried out to investigate the impacts of the partial shading on the PV system performances. Since numerous studies have been performed on this subject, only the selected publications having distinguished achievements would be dealt with in this study.

Martínez-Moreno developed the simple mathematical simulation model that can directly calculate the power generation and power losses due to the shading without the need of I-V curve consideration [5]. The model has the capability to consider both the shaded fraction of PV array area and the number of blocks. The model was validated against the experimental results. According to the simulated results of 3 x 18 block PV array, the power energy losses due to the shading can be in the range of 2.1% ~ 11.3% under the simulated condition in the study.

Dolara performed the experimental study to look into the shading effect on poly-crystalline and mono-crystalline PV modules operation [6]. The I-V and P-V curves of the installed photovoltaic modules were created and analyzed based on a bunch of experiments with and without shaded conditions. Similar to the curves presented in Figure 1-(c), the shading created multiple local peaks with the significant reduction of the output power. Shading 50% of a single PV cell reduced the power generation of the PV module by greater than 30%, indicating that shading of a single cell can have large impact on the performance of the entire module. Another finding from this study was that the vertically, horizontally, and diagonally shading profiles applied to PV module determine similar results as the ones obtained by shading a single cell [6].

Kawamura also quantitatively evaluated the relationship

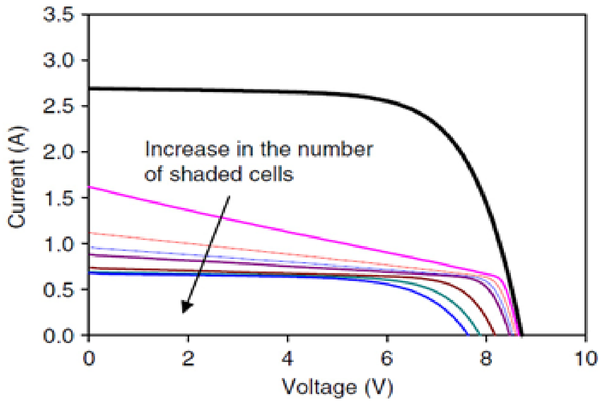

Fig. 2. Effect of increasing the number of shaded cells [9]

between the power output reduction due to shading of PV cells and the change of I−V characteristics (Figure 1) using the simulation method [2]. The simulation results showed that the change of I−V characteristics of a PV module with shaded PV cells is discussed by the shift of the avalanche breakdown voltage of shaded PV cells. In addition, it was found that if only a single full cell was shaded, the voltage of the entire module will drop by 50% and that 80% power losses can be induced due to the shading [2]. Alonso-Garcia also developed the computer simulation model to assess the influence of the amount of shading, the type of reverse characteristic of the cell, and the number of shaded cells on the power losses of PV modules [9]. It turned out that results were completely different when cells are shaded in different strings. A reduction in power of 61% was observed for the case in which the same shading is present in all the strings of the array ash illustrated in Figure 2, indicating that this case should be avoided as it produces maximum power reduction.

Patel developed Matlab based simulation model to investigate the I-V and P-V characteristics PV arrays under the partial shading condition [1]. Using the newly developed model, effects of shading patterns on PV panels with different configurations were evaluated. The simulated results clearly showed the similar patterns to Figure 1 producing multiple local peaks. More importantly, it was found that the array configuration has significant impact on the maximum power to be extracted under partial shading condition, indicating that the simulation model can be very handy tool to design the optimized configuration of PV array. In another study [7], Rodrigo developed the simple but accurate mathematical model to calculate the energy losses without the need of the full I-V curve under different shading scenarios after validating against the well-known detailed model. Similar to other studies cited thus far, the results showed the significant impact of the shading on the annual cumulative energy losses [7].

Zegaoui performed both experimental and simulation (Direct and Reverse Mode Model) research to evaluate the influences of partial shading on PV cell performance [10]. Results indicate if some cells are partially shaded, both shaded and adjacent healthy cells suffer from the rapid increase in the cell temperature, adversely affecting the cell current by around 50%. Alonso-Garcia also carried out the experimental study in direct and reverse bias to assess the power loss impacts of the shading characteristics [11]. The results highlighted that the shading of a single cell can cause the power loss ranging from 19% through 79% depending on the shaded cell position, indicating that the shading of a single cell can have significant impact on the overall module performance. Drif [8] performed interesting study about the shading effect in grid-connected BIPV systems using both simulated and monitored data. The results showed that loss of energy was approximately 1.79 kWh/day, corresponding to a shading factor of 14.4%.

Although there are other studies dealing with the shading impact on PV modules, they are not addressed in this paper due to the redundancy with the contents of the literature discussed and reviewed thus far. In summary, the literature survey concludes that the shading has significant impact on the overall PV array performance. Specifically, even the partial shading of a single cell can drop the module voltage and power efficiency to half, indicating that the shading impact is greater than expected and that it should be avoided.

4. Maximum Power Point Tracking Technique

4.1. Overview

Properly tracking the maximum power point (MPP) is one of the crucial factors in PV modules for both improvement of the PV power efficiencies and effectiveness of recognizing irregular behavior due to the shading. Despite the simple concept of MPP, tracking the correct MPP is a significant challenge due to the complicated I-V curve and continuously unsteady sate surrounding conditions such as outdoor temperature and solar insolation. In addition, building integrated photovoltaic (BIPV) applications require more complex MPP tracking algorithm. Conventional MPP tracking techniques would not be able to distinguish between the GP and local peaks, causing the oscillation around the local peaks and accordingly reducing the PV power generation.

Due to the significance of MPP tracking technique in PV modules, numerous studies have been performed thus far and a variety of papers have been published. However, those numerous MPP tracking techniques show extremely wide range of cost, effectiveness and complexity and thus the summary of state of the art MPP algorithms, especially for the shading conditions, is important in this circumstance. Since Ishaque et al. [3] performed the comprehensive review of conventional and advanced MPP tracking techniques for shading conditions, this sub-section will cite the information from [3].

MPP tracking techniques can be largely divided into two categories: conventional algorithm and soft computing technique. Conventional algorithm includes Incremental Conductance (IC), Hill Climbing (HC), Perturb and Observe (P&O), Parasitic Capacitances (PC), Constant Voltage Control (CVC), Constant Current Control (CCC) and Pilot Cell (PC). On the other hand, soft computing technique taking advantage of state of the art low cost and high speed computer availability includes Artificial Neural Network (ANN), Fuzzy Logic Controller (FLC) and Evolutionary Algorithms (EA), which are considered to be properly suitable for the shading conditions of PV modules.

4.2. Conventional algorithms

In the Incremental Conductance (IC) method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change. This method computes the maximum power point by comparison of the incremental conductance to the array conductance. When these two are the same, the output voltage becomes the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated [13]. In Perturb and Observe (P&O) method, the controller adjusts the voltage by a small amount from the array and measures power. If the power increases, further adjustments in that direction are tried until power no longer increases [13]. This is one of the most commonly used conventional methods due to its ease of implementation despite the oscillations of power output. It depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point, resulting in top-level efficiency [13]. Hill Climbing (HC) method is very similar to the P&O method since it also depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. The only difference is that it updates the operating point of the PV modules by perturbing the duty cycle instead of perturbing the voltage or current employed in P&O method [3]. Although most studies related to those conventional MPP tracking techniques focused on the evaluation under the uniform solar insolation condition, limited amount of research has been carried out on the modified conventional models to be adopted under the partial shading condition. Ji et al. [15] proposed the simple linear function for tracking MPP for partial shading condition without any additional circuit, based on the IC MPP tracking method. The step size is enhanced when the slope of P-V curve goes beyond the predetermined value, and vice versa. Patel et al. [16] and Koutroulis et al. [17] developed the upgraded versions of P&O methods and Lie et al. [18] and Dhople et al. [19] proposed the modified HC methods to be applied for the partial shading conditions. However, the effectiveness of those conventional approaches can be degraded due to multiple local peaks, and those conventional algorithms have drawbacks and limitations to be applied in non-linear and complex

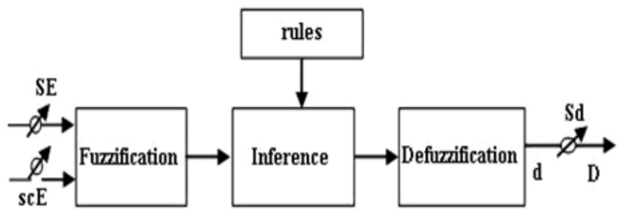

Fig. 3. General structure of Fuzzy Logic Controller [29]

shading conditions in essence. Therefore, advanced soft computing techniques have been actively studied these days due to their effectiveness in addressing complicated nature of PV operation for the dynamic environmental conditions such as solar insolation change and the partial shading.

4.3. Soft computing methods

One of the commonly used soft computing methods for tracking MPP is Fuzzy Logic Controller (FLC), which has the advantage to be robust and relatively simple to design as they do not require the knowledge of the exact model. However, they do require the PV system designer to have the complete knowledge of the PV operation. The main parts of FLC are composed of fuzzification, rule-base, inference and defuzzification ash illustrated in Figure 3. The inputs to FLC are usually error (E in Figure 3) and change in error (CE in Figure 3), while outputs can be duty cycle (D in Figure 3), current and voltage. Patcharaprakiti et al. proposed the adaptive FLC method that has the capability to deal with the partial shading conditions by the automatic fine-tuning of the relevant functions [24]. Chin et al. presented the advanced FLC method assisted with P&O algorithm, employing parallel tracking function in order to accurately search MPP [25]. It was found that FLC integrated with P&O can efficiently track the real absolute MPP during the partially shaded condition. Similarly, Subiyanto et al. introduced the FLC coupled with Hopfield Neural Network to be applied for the partial shading condition and verified the superior tracking performance to P&O and stand-alone FLC methods [26].

Another important soft computing approach is Artificial Neural Network (ANN) approach, which starts with building a model based on the multi-layer perceptron (MLP) architecture after the extensive training based on practical data. The inputs to the ANN model such as solar insolation, outdoor temperature, voltage and current are measured through data acquisition chain in order to correctly to track the MPPT in real time. Syafaruddin performed two studies for combining ANN approach with conventional MPP tracking techniques to be used for varying conditions such as partial shading [27][28]. Three-layer ANN model coupled with FLC was developed in [27], while fuzzy wavelet network model was also developed for the accurate identification of GP. However, it is considered to be impractical to include the unpredictable environmental uncertainties such as the cloud shading in the training process for ANN models. Therefore, the accurate tracking of MPP with ANN models under those unpredictable shading conditions should be further improved.

Evolutionary Algorithms (EA) is a stochastic method based on the search optimization in order to accurately estimate the correct MPP regardless of varying environmental conditions. Among different EA algorithms, one of the most popular methods is Particle Swarm Optimization (PSO) method [3]. PSO algorithm has a group of particles and each of particles represents a candidate solution. Each particle emulates the success of surrounding particles and thus the position of a particle is influenced by the best particle, i.e., best solution, in the group. Shubhajit et al. presented an algorithmic technique to accurately track the maximum power point (MPP) of a PV array under the partial shading condition using upgraded PSO method after the validation process against the conventional PSO [14]. The proposed technique needed only one pair of sensors to control multiple PV arrays, resulting in lower cost and higher accuracy of 97.7% compared to conventional PSO with accuracy of 96.4%. The proposed tracking technique has been mapped onto a micro-controller for tracking and control purposes. The whole system based on the proposed algorithm has been realized on a standard two stage power electronic system configuration [14]. Fu et al. introduced the Complex method based PSO algorithm which integrates the global search ability of PSO and the local search ability of Complex system [20]. It turned out that the algorithm can accurately track the MPP with rapid convergence rate and high convergence precision. Miyatake et al. proposed the PSO method having the capability to handle the complex partial shading condition, which is simple and cost effective by using only one pair of sensors to control multiple PV arrays [21]. The proposed algorithm was experimentally validated and it was found that the method took around 2 seconds to accurately identify the global MPP. Ishaque et al. presented the improved version of PSO

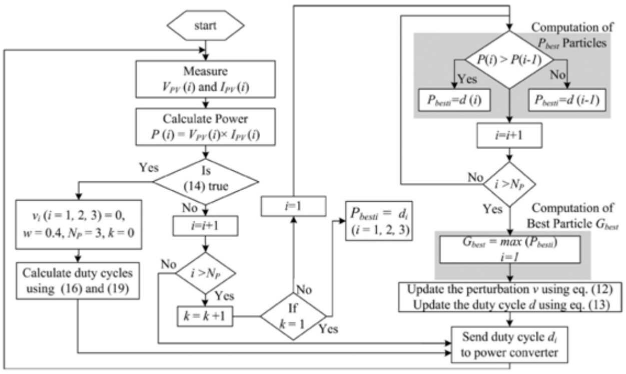

Fig. 4. Flowchart of the improved version of PSO method for MPP tracking developed by Ishaque [22]

method shown in Figure 4 that can reduce the steady state oscillation once the MPP is identified and can track the MPP for the extreme environmental condition such as partial shading condition [22]. The algorithm is validated against the conventional HC method and experimental results and showed the superior tracking speed and steady-state oscillations. Kuo et al. developed the orthogonal PSO method for the plug-in hybrid electric vehicle applications, which showed improved MPP searching efficiency under dynamic environmental conditions compared to conventional P&O) method [23].

Although other soft computing algorithms exist for the MPP tracking such as Ant Colony Optimization (ACO) and Differential Evolution (DE), they are not discussed in this review due to the fact that they have not been used as the stand-alone MPP tracker. In summary, conventional MPP tracking techniques have been extensively used for the uniform solar insolation conditions. However, due to the non-linear and complicated nature of the partial shading condition, advanced soft computing algorithms are adopted in a various applications by virtue of their effectiveness in addressing the dynamic environmental conditions such as the partial shading. Especially, upgraded versions of ANN, FLC, PSO and combined versions of those advanced techniques are of particular interest these days.

5. Conclusions

In this study, the up to date review of the shading effects on PV module efficiencies and the relevant detection algorithm is provided focusing on the MMP tracking technique. Both experimental and simulation studies done thus far by numerous researchers suggest that the shading of a single cell have significantly greater impacts on the entire PV module performance than expected and that the shading occurrence should be avoided to protect from those unnecessary energy losses. Conventional MMP tracking algorithm such as IC, HC, P&O, PC, CVC, CCC and PC as well as advanced soft computing technique taking advantage of the recently developed low cost and high speed computer availability such as ANN, FLC and EA were discussed. Compared to conventional MMP tracking methods, advanced soft computing techniques would be suitable for the MMP tracking under shaded conditions due to their effectiveness in addressing complicated nature of PV operation for the dynamic environmental conditions. This study would be the basic source and the up to date information associated with the shading effects and relevant MPP tracking technique.

Acknowledgement

This research paper being conducted by Small & Medium Business Administration is for technical development of the Korean Small Business Innovation Research Program.

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