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A hybrid maximum power point tracking for partially shaded photovoltaic systems in the tropics

Lian Lian Jiang [a,*], D.R. Nayanasiri [b], Douglas L. Maskell [a], D.M. Vilathgamuwa [c]

[a] School of Computer Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[b] School of Electrical & Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
[c] Science and Engineering Faculty, Queensland University of Technology, 2 George St, GPO Box 2434, Brisbane, QLD 4001, Australia

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ABSTRACT

Partial shading and rapidly changing irradiance conditions significantly impact on the performance of photovoltaic (PV) systems. These impacts are particularly severe in tropical regions where the climatic conditions result in very large and rapid changes in irradiance. In this paper, a hybrid maximum power point (MPP) tracking (MPPT) technique for PV systems operating under partially shaded conditions witapid irradiance change is proposed. It combines a conventional MPPT and an artificial neural network (ANN)-based MPPT. A low cost method is proposed to predict the global MPP region when expensive irradiance sensors are not available or are not justifiable for cost reasons. It samples the operating point on the stairs of *I–V* curve and uses a combination of the measured current value at each stair to predict the global MPP region. The conventional MPPT is then used to search within the classified region to get the global MPP. The effectiveness of the proposed MPPT is demonstrated using both simulations and an experimental setup. Experimental comparisons with four existing MPPTs are performed. The results show that the proposed MPPT produces more energy than the other techniques and can effectively track the global MPP with a fast tracking speed under various shading patterns.

1. Introduction

Solar photovoltaic (PV) systems are of particular interest due to their low maintenance, the abundance of the energy source, almost zero post-production pollution and the continually improving efficiency due to advancements in semiconductor and power electronic devices. The output power of PV systems varies with the intensity of the solar irradiance and the environmental temperature. Due to the nonlinear current–voltage (*I–V*) characteristic of the solar cell, there is a unique maximum power point (MPP) on the power–voltage (*P–V*) curve. In order to extract the maximum power, an MPP tracking (MPPT) device is usually inserted between the PV array(s) and the system load.

As more and more PV systems are installed worldwide, often in locations with a less than optimal solar irradiance profile (such as in the tropics), it is becoming more important that appropriate techniques for maximizing the energy capture be employed. Tropical climates are characterized by a large number of rapid irradiance changes [1] due to the prevailing environmental conditions. For example, in Singapore, which is just 1.5° north of the equator, there is little variation in temperature year round (usually the diurnal variation is between 22 °C and 35 °C), with a high relative humidity (the mean annual relative humidity is 84.2%). Unlike tropical regions further from the equator which have well defined wet and dry seasons, Singapore has no distinct wet or dry season, with significant rainfall throughout the year. Thus, there is significant moving cloud cover which results in rapid temporal and spatial irradiance change [1]. These irradiance changes contribute to partial module/array shading and rapid ramp rates, both of which can impact on the energy capture. Therefore, the ability to rapidly track the global MPP under partial shading conditions (PSCs) so that the power output from the PV array can be maximized is important for PV systems in tropical regions. This must be coupled with a low cost and a simple implementation.

In recent years, a large number of MPPT methods to increase the power harvest have been reported in the literature [2–7]. These methods can be classified mainly into three general categories: conventional optimization algorithms [2,3,8–17], artificial

* Corresponding author. Centre for High Performance Embedded Systems (CHiPES), School of Computer Engineering, N4-02a-32, Nanyang Avenue, Nanyang Technological University, Singapore 639798, Singapore. Tel.: +65 83589341; fax: +65 6792 0774.

E-mail addresses: ljiang2@e.ntu.edu.sg (L.L. Jiang), mdul0001@e.ntu.edu.sg (D.R. Nayanasiri), asdouglas@ntu.edu.sg (D.L. Maskell), donmahinda.vilathgamuwa@qut.edu.au (D.M. Vilathgamuwa).

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intelligence based MPPT algorithms [3,4,18–27], and other methods [28–32], and can be found in both centralized [1–4,26], distributed [28], and combined [6,7] MPPT configurations.

Among the existing conventional centralized MPPT methods, the perturb and observe (P&O) (or hill climbing) [2,10] and incremental conductance (IncCond) [8,9] methods are widely used in commercial products. They feature a simple implementation and low system cost. However, they are efficient only when the irradiance distribution is uniform and without rapid change. When the irradiance on PV modules become non-uniform (or partially shaded), they are unable to track the multiple MPPs and often become stuck at a local MPP resulting in a significant power loss of up to 70% [33]. Ripple correlation control (RCC) and extremum seeking control (ESC), which utilize the inherent ripple to find the optimum, are considered very fast, of the order of the switching frequency of a power electronic converter [34,35]. However, like the standard P&O and IncCond algorithms, they are efficient only with PV systems with a unique MPP. In order to solve this problem, a number of global MPPTs are studied. In Refs. [11,14], the load line based MPPTs are proposed. The main idea is to move the operating point to the vicinity of the global maximum first and then apply a conventional MPPT method, such as P&O or IncCond, to search for the global MPP within the local area. These methods exhibit a much better tracking ability than the standard P&O and IncCon algorithms for the case with multiple power peaks. However, this technique is unable to ensure that the intersections for both methods are located in the vicinity of the global MPP for all shading patterns. In addition, the additional circuits for measuring the short circuit current and open circuit voltage online add complexity to the system. Sweeping methods, such as the current [36], voltage [12] and power sweep [16] methods, are based on perturbing the working point successively by increasing the current, voltage or power (based on the type of sweep) of the PV array. This type of MPPT can find the global MPP with good accuracy, but the MPP tracking speed is limited due to their iterative scan procedure. In Refs. [13], an MPPT algorithm based on the Fibonacci sequence was presented but it cannot guarantee converge to the global MPP for all circumstances. An optimization algorithm based on dividing rectangles, called DIRECT, was applied to MPPT in Ref. [15]. It has the advantage of avoiding the gradient calculation. However, the algorithm is unable to converge to the global MPP for all shading patterns and is heavily dependent on the control parameters set by the user. A voltage window search technique [37] was recently proposed, but its ability to track the MPP largely depends on the choice of the initial operating point.

Compared to conventional MPPT, various computational algorithm based MPPT methods, such as, fuzzy control [18], neural network [19,38], particle swarm optimization (PSO) [21,39], and differential evolution (DE) [23,24], etc., have been shown to provide good performance particularly in tracking the global MPP. However, they each have their own limitations. For instance, most require experience in setting the parameters for the MPPT algorithm and take a relatively long time to reach the global MPP. The computational algorithm based MPPTs are usually based on stochastic search theory and use an iterative process to control the operating voltage of the PV array according to the update scheme of the individual algorithm. Thus, these methods generally suffer from a slow tracking speed or premature convergence.

Many other methods such as the voltage compensation method [30], interconnection method [31] and multilevel dc-link inverter [32], etc. have also been proposed to solve the partial shading problem. However, they either have a complex control process or a slow tracking speed. Many other related MPPT methods can be found from literature reviews in Refs. [2–5].

Distributed MPPT [7,28] is another promising technique to extract the maximum power from the PV system under partially shaded conditions. Compared to centralized MPPT, PV systems equipped with distributed MPPT provide a significant increase in energy harvest during PSC. This increase can be up to 39% for a large plant with parallel high voltage thin-film module strings, and up to 58% for smaller systems using a lower voltage with 8 series thin-film modules per string [29]. In addition, a power increase of more than 30% has been reported for mono-crystalline Si PV modules [28]. However, the advantages of distributed MPPT are dependent on the particular installation and the cost of the additional electronics, and are only marginally cost effective for small to medium sized PV systems and are not cost effective for large PV systems.

The artificial neural network (ANN) is an efficient tool for simulating the complex nonlinear relationship between the input and output of a system and can be applied to the MPPT problem [19]. The ANN MPPT does not require knowledge of the inner detail of the PV system and has a fast response due to its ability to provide a prediction within one step. There are several different ways of applying ANN into MPPT, as summarized in Ref. [40]. The ANN is used either to predict the optimal operating point for uniform irradiance conditions or is combined with other intelligent methods, such as fuzzy logic, to predict the optimal voltage or current values of the MPP directly from the irradiance and temperature inputs. However, there are a number of disadvantages in utilizing an ANN based MPPT in this way. For example, irradiance sensors with good accuracy are relatively expensive. Additionally, the ANN requires a large number of data points for training purposes. Obtaining these training data sets requires additional equipment and electrical components, which not only increases the system cost but is also time-consuming. As the system ages, the characteristics of the PV array may change and thus, the ANN may require retraining.

In this paper, we propose an efficient and fast hybrid MPPT for PV systems operating under PSCs. It combines an ANN-based technique with the conventional P&O algorithm to track the MPP. This method has the advantage of a simple control structure and is able to quickly track the global MPP under various shading patterns. It does not need expensive irradiance sensors and instead uses the same voltage and current sensors as the conventional P&O algorithm. Additionally, because the ANN is just used to categorize the operating point within a region of operation, the training dataset can be easily obtained with sufficient accuracy by simulating the PV array using existing modelling methods. This work is an extension of that presented in Ref. [27] where we verified the effectiveness of the proposed method for tracking the global MPP under partial shading using dedicated irradiance sensors. In this paper, we propose a low cost method to predict the global MPP region when expensive irradiance sensors are not available or are not justifiable for cost reasons. Instead, the modified technique samples the operating point on the stairs of I–V curve (which occur with partial shading) and uses a combination of the measured current value at each stair to predict the global MPP region. After that, the P&O algorithm, or any other efficient optimization algorithm for unimodal functions, such as ESC or IncCond, is applied to the local area so that the system achieves the global MPP. Additionally, we examine more complicated shading patterns, demonstrate the transient performance by comparing with several widely studied MPPT techniques and present a more detailed discussion.

2. Solar array model

In this work, the two-diode model [41] is used to characterize the PV array. Suppose that the PV array contains N_{ss} PV modules in