Energy and Buildings 58 (2013) 227–236

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

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

A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions

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ARTICLE INFO

Article history:
Received 18 September 2012
Received in revised form
26 November 2012
Accepted 2 December 2012

Keywords:
Maximum power point tracking
Photovoltaic systems
Ant colony optimization
Partially shaded conditions

ABSTRACT

In order to achieve maximum efficiency a photovoltaic (PV) arrays should operate at their maximum power point (MPP). Therefore, an MPP tracking (MPPT) scheme is implemented between the PV system and the load to obtain maximum power. When the irradiance distribution on the PV arrays is uniform, many traditional MPPT techniques can track the MPP effectively. However, when the PV arrays are partially shaded, multiple MPPs show up, which usually results in the failure of finding the global MPP. Some researchers have reported this problem and tried to solve it, but most of the MPP control schemes are relatively complicated or fail to guarantee the MPP under all shading circumstances. In order to overcome this difficulty, this paper presents a novel ant colony optimization (ACO)-based MPPT scheme for PV systems. A new control scheme is also introduced based on the proposed MPPT method. This heuristic algorithm based technique not only ensures the ability to find the global MPP, but also gives a simpler control scheme and lower system cost. The feasibility of this proposed method is verified with the irradiance of various shading patterns by simulation. In addition, the performance comparison with other traditional MPPT techniques, such as: constant voltage tracking (CVT), perturb and observe (P&O), particle swarm optimization (PSO), is also presented. The results show that the proposed algorithm can track the global MPP effectively, and is robust to various shading patterns.

1. Introduction

The use of renewable energy has experienced consistent growth due to the limited supply of fossil fuel based energy and the constantly growing environmental concerns associated with burning fossil fuels. Solar energy systems as a renewable energy source is of particular interest due to their lower maintenance, the abundance of the energy source, almost zero post-production pollution and the advancements in semiconductor and power electronic devices. Among the different ways of converting sunlight into electricity, the PV systems directly convert solar radiation into electricity by the photovoltaic effect. Assemblies of solar cells make solar modules and the large-scale PV systems usually consist of many solar modules connected in series or parallel. Due to the nonlinearity between the PV output voltage and current, there is a unique maximum power point (MPP) in the power–voltage (P–V) characteristics under uniform weather conditions. When the PV arrays are directly connected with the load, potential power that could be extracted from the PV arrays is wasted because the power output of the PV arrays mainly depends on the characteristic of the load. In order to maximize the power from the PV system, an MPP tracker is usually inserted between the PV arrays and the load to make sure that the system operating point is adjusted to be located at the MPP.

Over the years, many researchers have studied MPPT algorithms. Buciarelli et al. [1] proposed the perturb and observe (P&O) (or hill climbing) based MPPT algorithm which is widely used in commercial products. Hussein et al. [2] proposed the incremental conductance (IncCond) method, which is more efficient under rapidly changing conditions as it uses the fact that the derivative of the power with respect to the voltage (dP/dV) at the MPP is zero. However, when the PV systems are operated under partially shaded conditions, which are usually caused by the passing clouds, nearby trees or buildings, long-lasting dust, etc., the characteristic of P–V curve shows multiple peaks. This results in these two traditional MPPT algorithms becoming trapped at a local maximum, causing a significant energy loss of up to 70% [3].

To tackle this problem, Kobayashi et al. [4] proposed a two-stage MPPT controller to track the global maximum by moving the operating point to the vicinity of the real MPP at the first stage and, thereafter, shifting this point to the real MPP using the traditional IncCond algorithm. The advantage of this method is that the algorithm is capable of tracking the global MPP in most cases. However, the additional circuits for measuring the short circuit current and

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http://dx.doi.org/10.1016/j.enbuild.2012.12.001

open circuit voltage online add complexity to the system, and it requires a large amount of storage. Patel and Agarwal [5] proposed an observation method to track the global MPP under partially shaded conditions by searching two sides of the local MPP with disturbance step ΔV_{large}, which is less than the minimum possible displacement between the two successive peaks. This method can find the global MPP, but the MPP tracking speed is limited because all the local MPPs are required to be checked in order to get the global MPP. In addition, when the irradiance is non-uniform, with a complex distribution, the multiple local maximum points (which tend to be close to each other) make the selection of the step size for voltage perturbation quite difficult. Another method associated with the MPPT under partially shaded conditions was proposed in [6]. The basic idea of this algorithm is to move the operation point decided by a linear function ($V_{pv} = (V_o/I_o) \times I_{pv}$, where V_{pv} is the reference voltage at the next perturbation step, V_o is the open circuit voltage and I_o is the short circuit current), and then, use the traditional MPPT algorithms, such as P&O or IncCond, to track the global MPP. The advantage of this method is that it works very well under both uniform irradiance and non-uniform irradiance with slow irradiance changes. However, under non-uniform irradiance with rapidly changing conditions, the traditional MPPT algorithm works better than the proposed algorithm. Miyatake et al. [7] propose another MPPT method based on the Fibonacci search algorithm. The main principle is to iteratively restrict and shift the search range to contain the optimal point in the range by using the line search algorithm with an improved Fibonacci sequence. This algorithm can be used under partially shaded or rapidly changing irradiance conditions, but does not guarantee to find the global MPP under all conditions. A dividing rectangle (DIRECT) search method in conjunction with the P&O method has also been proposed in [8]. The algorithm searches the Lipschitz function, which describes the PV power and voltage relationship in an interval. However, the selection of the initial operating point heavily influences performance in finding the global MPP. In addition, since the P&O algorithm is used under uniform conditions, the oscillation around the MPP reduces the efficiency of the system.

Some other methods are also proposed [9–11]. For instance, the fractional-order incremental conductance method shortens the tracking time [9]. However, it is only suitable for small-scale PV systems. When applying this method to large-scale PV systems under partially shaded conditions, it fails to find the global MPP. The power or voltage compensation method improves the efficiency of the system [10,11], but requires additional devices which increase the complexity and cost of the system.

Compared to these direct search methods, computational intelligence based methods, such as fuzzy logic (FL) [12], artificial neural network (ANN) [13–15], particle swarm optimization (PSO) [16] and so forth, offer significant benefits. These can include: no requirement for knowledge of internal system parameters, reduced computational effort and a compact solution for multivariable problems. However, for fuzzy logic based methods, the fuzzy rule base, which is dependent on the experience of algorithm developers, significantly influences the performance of MPPT. For ANN based methods, it is only suitable for the system that can get sufficient training data. The PSO based method is efficient for non-uniform weather conditions. However, its convergence significantly depends on the initial place of the agents [16].

At present, ant colony optimization (ACO) has been widely used in scheduling [17], image processing [18], power electronic circuit design [19], and many other fields. In this paper, we propose a novel ACO-based MPPT to track the MPP for a large-scale PV system under partially shaded conditions. We also design a PV array configuration structure along with this new MPPT algorithm. With this MPPT control scheme, only one pair of current and voltage sensors are required which simplifies the PV system and reduces the system cost. It also guarantees to find the global MPP under various partially shaded conditions. In addition, it features fast convergence speed, convergence independent of the initial conditions, and no requirement of knowledge about the characteristic of PV array.

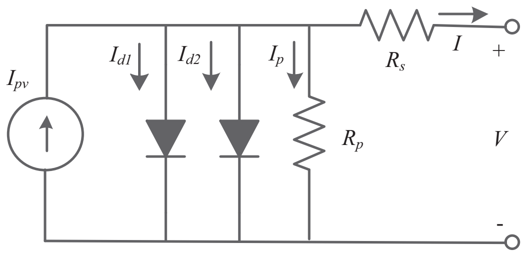

Fig. 1. Equivalent circuit for two-diode model.

The reminder of the paper is organized as follows. Section 2 introduces the PV system and our proposed configuration structure that we investigated. Section 3 briefly presents the main principle of the ACO algorithm and how it is applied to MPPT for PV systems. Section 4 provides experimental results and a discussion of the proposed approach. Comparisons with other methods are also presented in this section. Finally, Section 5 presents the conclusions and directions for future work.

2. Photovoltaic system

2.1. PV array models

In order to test our proposed MPPT method, a two-diode model [20] is used to model the characteristics of the PV arrays. It reduces the computational time and improves the accuracy of the performance especially under low irradiance. The equivalent circuit of the two-diode model for a solar cell is shown in Fig. 1.

Suppose that the PV array contains N_{ss} PV modules in series and N_{pp} PV strings in parallel, the output current of the PV array is given by the equation [20]

$$I = I_{pv}N_{pp} - I_{01}N_{pp}\left[\exp\left(\frac{V+\lambda I R_s}{a_1 V_t N_{ss}}\right)-1\right] - I_{02}N_{pp}\left[\exp\left(\frac{V+\lambda I R_s}{a_2 V_t N_{ss}}\right)-1\right] - \frac{V+\lambda I R_s}{\lambda R_p} \quad (1)$$

where I is the photovoltaic output current, V is the photovoltaic output voltage, $\lambda = N_{ss}/N_{pp}$, R_s and R_p are the series and parallel resistances, respectively, V_t is the thermal voltage of the two diodes ($V_t = N_s\, k\, T/q$), N_s is the number of solar cells connected in series in each PV module, k is the Boltzman constant, q is the electron charge, and a_1, a_2 are the diode ideal constants. The light generated current is given by

$$I_{pv} = (I_{pv\_STC} + K_i(T - T_{STC}))\frac{G}{G_{STC}} \quad (2)$$

where I_{pv_STC} represents the light generated current under standard test conditions (STC) with temperature $T_{STC} = 25\,°\mathrm{C}$, and irradiance $G_{STC} = 1000\,\mathrm{W/m^2}$, and the constant K_i is the short circuit current coefficient. The reverse saturation current of the diode is given by

$$I_{01} = I_{02} = \frac{I_{sc\_STC} + K_i\Delta T}{\exp((V_{oc\_STC} + K_v\Delta T)/V_t) - 1} \quad (3)$$

where the constant K_v is the open circuit voltage coefficient, I_{pv_STC} is the short circuit current under STC, and V_{oc_STC} is the open circuit voltage under the STC. In fact, Eq. (1) can be represented as $I = f(I, V)$. Therefore, for a given current value, this nonlinear equation can be solved using the standard Newton–Raphson method. The