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A novel technique to extract the maximum power of photovoltaic array in partial shading conditions

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ABSTRACT

Photovoltaic (PV) arrays are composed of PV cells which have a nonlinear power-voltage characteristic. To extract maximum amount of energy from a PV array, it is essential to track maximum power point (MPP). When all PV cells are subject to the same solar energy, MPP is found easily. However, in some ambient conditions, PV cells are partially or completely shadowed. Under partial shading conditions (PSCs), overall power-voltage curve will have several peaks. This paper presents a novel approach for MPP tracking, utilizing configuration of PV cells in series and parallel that may deliver maximum power in shading conditions. As such, instead of blindly searching for the global MPP among local MPPs, the proposed method limits the search space by calculating the required combination of series and parallel PV cells that can deliver global MPP. This efficient technique leads to a faster dynamic response when partial shadowing is encountered, while maintaining the conventional MPP tracking in normal condition. Moreover, the method does not require any additional hardware. Rather, the existing MPP tracking algorithm should be modified to accommodate PSCs. The efficiency of proposed technique is investigated via time-domain studies, where results verify the superiority of proposed method compared to other approaches.

1. Introduction

Because of exhaustible nature of fossil fuels, many countries will face numerous energy problems at the upcoming decades. In addition, exorbitant usage of fossil fuels causes a lot of environmental problems such as global warming. One of the most reasonable solutions suggested to solve the mentioned problems is the exploiting renewable energy sources. Solar energy has experienced improved efficiency and price decline in the past two decades. In addition, due to the numerous advantages of PV arrays such as incurring no fuel costs, no environmental pollution, emitting no noise, and requiring little maintenance, utilization of this source of energy at different situations such as distributed power generation and stand-alone systems has grown dramatically [1–3].

In spite of foregoing advantages, energy conversion from solar radiation to electrical energy in PV cells suffers low efficiency. Moreover, the power-voltage (P-V) characteristics curve of a PV cell shows that its output power varies with the magnitude of its DC output voltage. In this curve, there is an exclusive point in which the PV cell delivers maximum power to the power network. To extract maximum amount of electrical energy, PV cells should operate in maximum power point (MPP). PV arrays, consisting of series and parallel interconnection of PV cells, employ MPP tracking (MPPT) strategies to this end. Most of these search methods use direct scanning algorithm to find the GMPP. It means that, they vary set-point voltage with a constant or variable step to find the GMPP [4–10]. Some works utilize curve fitting or parabolic prediction methods to find the maximum power point. These methods have lower computational complexity than direct search methods due to less scanning steps [11,12].

Most of the existing MPPT algorithms can operate correctly only in normal conditions, when all PV cells are subject to the same solar radiation. It means that MPPT strategies can pursue MPP in P-V characteristic curves which contain only one peak. There are however situations where P-V curve of a array consists of several peaks. One of the prevalent situations which causes this problem is partial shading condition (PSC) , where different cells of a PV array receive different amount of solar energy. This translates into extracting less electrical output power on the one hand and several local peaks and one global

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peak in the P-V curve of the array on the other hand. As such, conventional MPPT algorithms reach a local MPP in the vicinity of the previous operating point, as the global MPP may have moved far away on the P-V curve. This considerably reduces the efficiency of the PV array, in particular when partial shadowing is experienced frequently. Hence, different methods have been proposed to alleviate the impact of partial shading in PV systems [13–19]. These methods can be generally categorized into hardware and software solutions [20]. Hardware solutions include utilizing PV array reconfiguration [21], different PV array architectures [22] and different converter topologies [23]. Software solutions aim at achieving a more efficient MPPT algorithm for PSCs. These solutions are more favorable, as they only modify the control strategy for finding MPP, without the need for hardware changes. In [24] a linear equation is used to reach the vicinity of the global MPP and next track MPP. Despite easy implementation, this algorithm may find a suboptimal solution, depending on the shading condition. Similar to conventional hill climbing [25] and perturb-and-observe [26] methods, a variable step-size is used in [27] to track MPP in shading conditions. However, it is also prone to be trapped in local maxima. The method in [16] needs additional measurements for PV modules, incurring additional cost, to detect PSCs. Evolutionary techniques have also been employed to find the global MPP in shading conditions [28–30]. Evolutionary techniques, however, take more time to find the global MPP if not trapped in local maxima.

There are several works that try to find GMPP by reducing the searching area. Hu et al. in [31] expressed that under the partial shading condition, the current of faulted cell or module increases and it cause overheating some faulted cell or modules. Hence there are multiple local maximum power points. They propose usage of thermal camera to recognize partial shading condition. This method not only determines partial shading but also could specify the cell or module faults. [32] utilized the thermo-graphical data of panels to separate the PV array into healthy and unhealthy sections. Afterwards, a virtual MPPT is estimated to reduce the computational time of global MPPT tracing.

Jain and Agarwal in [33] the maximum power point approximate quickly by using variable iteration step-size. They utilize an intermediate variable, instead of power. This method that known as beta algorithm, track the maximum power point very close to global MPP in few seconds. In [34] a novel two-step MPPT method was proposed by improving the conventional beta algorithm. This method improved the accuracy and tracking speed of beta algorithm by obtaining an equivalent PV string model.

Furtado et al. in [35] propose a novel efficient and reliable GMPP algorithm that uses trapezoidal area in the PV curve. In this paper, the analytical information of all possible local MPP is estimated base on PV string mathematical model and utilized to reduce the searching area and tracking time. In [36], two other methods that limit the searching area have been presented. The proposed search based method limit the searching voltage range based on the detailed study of IV and PV characteristics of PV array. They restrict the searching area based on the measured array current and the highest sampled power. Although the accuracy of this methods is high, its tracking speed is low due to small steps. Ghasemi et al. in [37] searching region is reduced by dividing the searching area into several small sub-regions. In the proposed method, the upper limit of array power in each sub-region estimated by using some sample point of I-V curve.

In this paper, at the first step, the circuit model of a PV array [38] is presented. The simulated PV array is a standard model and all factors that affect the performance of PV arrays have been considered. Then, the P-V characteristic curve of the simulated PV array in normal condition is obtained and it is shown that it contains only one peak. In the second step, the phenomenon of partial shading in a PV array is modeled. In addition, it is shown how PSCs increases the number of peaks in the P-V characteristic curve of a PV array and why conventional MPPT algorithm cannot operate correctly.

In the next step, by introducing a novel technique based on the maximum power that the series and parallel configuration of PV cells are able to deliver, global MPP is found, with the least computational burden. The proposed techniques does not require any additional measurements or hardware modification. It is only sufficient to modify the software code for MPPT to overcome PSCs. Finally, the dynamic response of the proposed MPPT algorithm is examined again via simulation tests. Simulation results show that the proposed technique can set the operational point of PV array in the global MPP with an acceptable dynamic performance in all normal and partial/complete shading conditions.

2. PV array modeling

2.1. Basic concepts

The basic components of a PV array are solar cells constructed from the P-N semiconductor junctions [38]. Based on the semiconductor theory, the current-voltage relation of a solar cell is as below [39]:

$$I_{PV} = I_{ph} - I_s\left(\exp\left(\frac{q}{AKT}(V_{PV} + I_{PV}R_s) - 1\right)\right) - \frac{V_{PV} + I_{PV}R_s}{R_p}, \tag{1}$$

where I_{PV}, and V_{PV} are the output current and voltage of the solar cell, respectively. Moreover, I_{ph} is the photocurrent resulted form solar radiation and I_s is the short-circuit current of the cell. These two parameters are calculated as follows:

$$I_s = I_r\left(\frac{T}{T_r}\right)^3 \exp\left(\frac{q.\,E_{go}}{BK}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right), \tag{2}$$

$$I_{ph} = (I_{SRC} + K_I(T - T_r)) \times \frac{\Sigma}{1000}, \tag{3}$$

where q is the electron charge ($1.30217646 \times 10^{-29}$ C), K is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K); Σ is the radiation in W/m^2; T_r is the reference temperature in K; T is the temperature of the cell in K; E_{go} is the silicon forbidden band width; R_s is the series resistor; R_p is the parallel resistor; A and B are the fitting constant ($A = B$); I_r is the inverse current of the diode; I_{SRC} is the light-generated current; and K_I is the temperature coefficient. Based on (1), it can be concluded that the equivalent electrical circuit of a PV cell can be modeled as an electrical current source in parallel with a diode and resistor R_p. In addition, the resistor R_s should be connected in series with the mentioned elements. It should be mentioned that the resistors R_s and R_p do not exist in the ideal PV cell models. To simplify the above equations, the parameter of $\Sigma/1000$ is denoted by λ called the sun radiation factor. The equivalent circuit of a PV cell is shown in Fig. 1(a).

There are different types of PV cells, each of which has its own parameters. In this paper, the ploy-crystalline type, whose parameters are tabulated at Table 1, has been considered for simulations. It should be mentioned that proposed model has two parameters as inputs, namely ambient temperature and solar radiation. In the next step, one exterior resistor is connected to the output port of the PV cell. Then by increasing the resistance of this load from negligible values (short circuit condition) to extremely great values (open circuit condition), the output power and voltage of the PV cell are measured. The power-voltage characteristic curve of the simulated PV cell has been shown in Fig. 1(b). It should be mentioned that during this process, the amount of the solar radiation factor (λ) and ambient temperature (T) have been considered as constant values. As Fig. 1(b) shows, at various values of the output voltage, different amounts of electrical power can be extracted from solar cell. In addition, the results show that at a special point, i.e. MPP (point A), the maximum amount of electrical power is delivered to the load. As the PV array is formed by connecting multiple solar cells in parallel and series pattern, the power-voltage characteristic curve of a PV array resembles that of a PV cell.