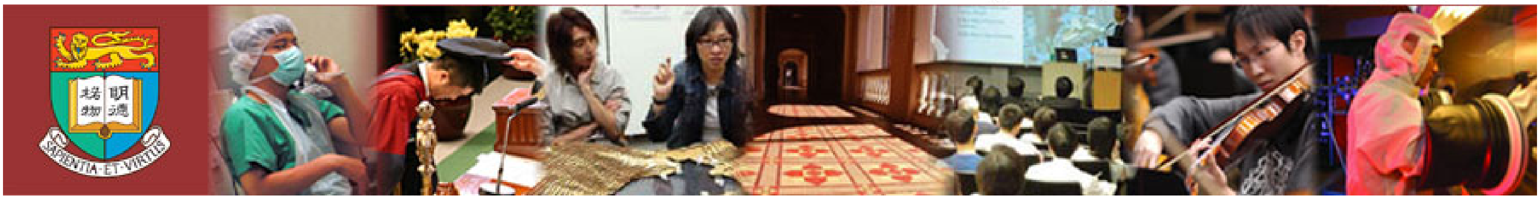

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Low-Cost Global MPPT Scheme for Photovoltaic Systems under Partially Shaded Conditions

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***Abstract*—Maximum Power Point Tracking (MPPT) is a technique applied to improve the efficiency of power conversion in Photovoltaic (PV) systems. Under partially shadowed conditions, the Power-Voltage (P-V) characteristic exhibits multiple peaks and the existing MPPT methods such as the Perturb and Observe (P&O) are incapable of searching for the Global Maximum Power Point (GMPP). This paper proposes a low-cost on-line MPPT scheme to overcome this drawback. By using hybrid numerical searching process, the operating point approaches Local Maximum Power Points (LMPPs) gradually and the GMPP is caught by comparing all the LMPPs. Simulation results prove the effectiveness and correctness of the proposed method.**

I. Introduction

The growing worldwide demand for electricity and the willingness to prevent hydrocarbons resources addresses the need for promoting the development and utilization of renewable energy. Photovoltaic (PV) generation is a green source which not only can help power producers meet the future energy needs, also can do so without incurring any noise, toxic-gas emissions, or greenhouse gases.

A major challenge in the utilization of PV generation is posed by its nonlinear Current-Voltage (I-V) characteristic, which results in an unique Maximum Power Point (MPP) varying with different atmospheric conditions in its Power-Voltage (P-V) curve (e.g. temperature, insolation) [1]. Over the past two decades, numerous efficient Maximum Power Point Tracking (MPPT) algorithms have been proposed to track MPPs to improve the conversion efficiency of a PV array under uniform solar insolation [2]. Perturb & Observe (P&O) method [3] may be the most common scheme in PV generation. It is based on the principle of "hill-climbing" that the operating point is moved in the direction in which the output power increases. In light of the fact that the derivative of output power with respect to the output voltage dP/dV is zero, Chun *et al.* [4] introduced a method to search MPPs by classical root-finding methods. Despite the effectiveness of these algorithms, they fail to track MPPs under partially shadowed conditions, on which P-V characteristic of a PV array exhibits multiple peaks: only one of which is the Global Maximum Power Point (GMPP) and the others are Local Maximum Power Points (LMPPs). In recent years, Particle Swarm Optimization (PSO) [5] has been applied to address the global MPPT issues. The evolutionary optimization approach prevents the operating point from concentrating at LMPPs, but its accuracy is mainly affected by the precision of sensors, particularly the light radiation sensor (pyranometer) which significantly increases the cost. A dividing rectangle (DIRECT) algorithm in conjunction with P&O method is applied to PV systems in [6]. The online search method improves the reliability. However, the DIRECT algorithm increases the computing effort and the output power suffers oscillations at steady state.

In this paper, an online global MPPT algorithm is proposed for PV systems with multiple-peak P-V characteristics. It capitalizes on the observation by locating the intervals where dP/dV changes sign. The GMPP is derived by a variable-step bracketing method, which not only accelerates the convergence speed, but also ensures the stable output power in steady state. The proposed method is independent of priori knowledge of the electrical characteristics of a PV array, and therefore the meters for measuring atmospheric conditions can be eliminated to achieve a lower lost.

II. P-V Characteristics of a PV Array under Partially Shaded Conditions

PV modules are normally connected in series to scale up the voltage because their open circuit voltage is independent of the module area and is limited by the semiconductor properties [7]. However, the electrical output of the series connected PV array is relatively sensitive to the partial shadowing conditions which may be caused by trees, passing clouds, neighbouring buildings, etc. PV modules are actually photodiodes. As a

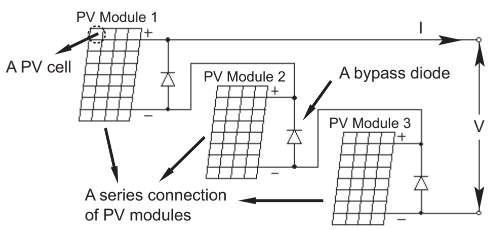

Fig. 1. MPP seeking process with SM under STC

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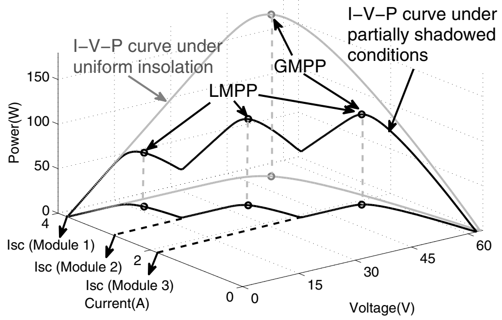


Fig. 2. The series array of 3 PV modules with bypass diodes

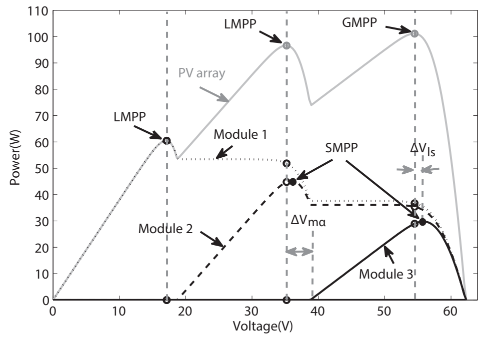


Fig. 3. P-V curves of the modules in Fig. 1

shaded module is driven with a high current, internal “short-circuiting” (the electrons reversing course through the p-n junction) occurs and the shaded module consumes power instead of producing power. This phenomenon, referred to as “hot-spot” in literature, may cause a security risk as the shadowed module heats up. The bypass diodes are a standard addition to PV modules and are used to eliminate the “hot-spot” effect.

Fig. 1 shows a typical PV array with bypass diodes under the following environment set:

PV Module 1: $G = 1000\ W/m^2,\ T = 25°C$
PV Module 2: $G =\ 750\ W/m^2,\ T = 25°C$
PV Module 3: $G =\ 500\ W/m^2,\ T = 25°C$

where G represents the solar insolation and T denotes the temperature. PV module 1, 2, and 3 are connected in series and form an “assembly”. Each module, with a different level of irradiance, is named “subassembly” [1].

The Current-Voltage-Power (I-V-P) characteristics of the corresponding PV array are designated by a black line in Fig. 2, and the I-V characteristics can be represented by their projections in the base. It is observed that three local peaks located at 17 V, 35 V, 54 V respectively, among which the point at 54V delivers the maximum output power, namely the GMPP. The I-V-P curve of the PV array under the uniform insolation ($G = 1000\ W/m^2,\ T = 25°C$) are drawn in grey for reference. It exhibits one peak in this case.

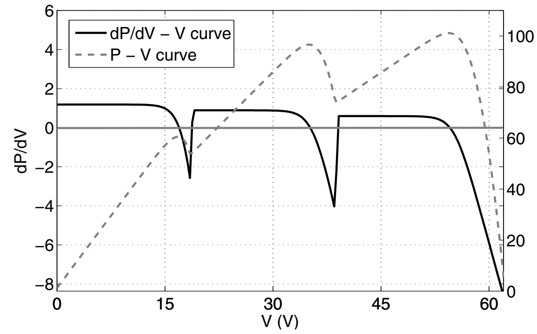


Fig. 4. MPP seeking process with SM under STC

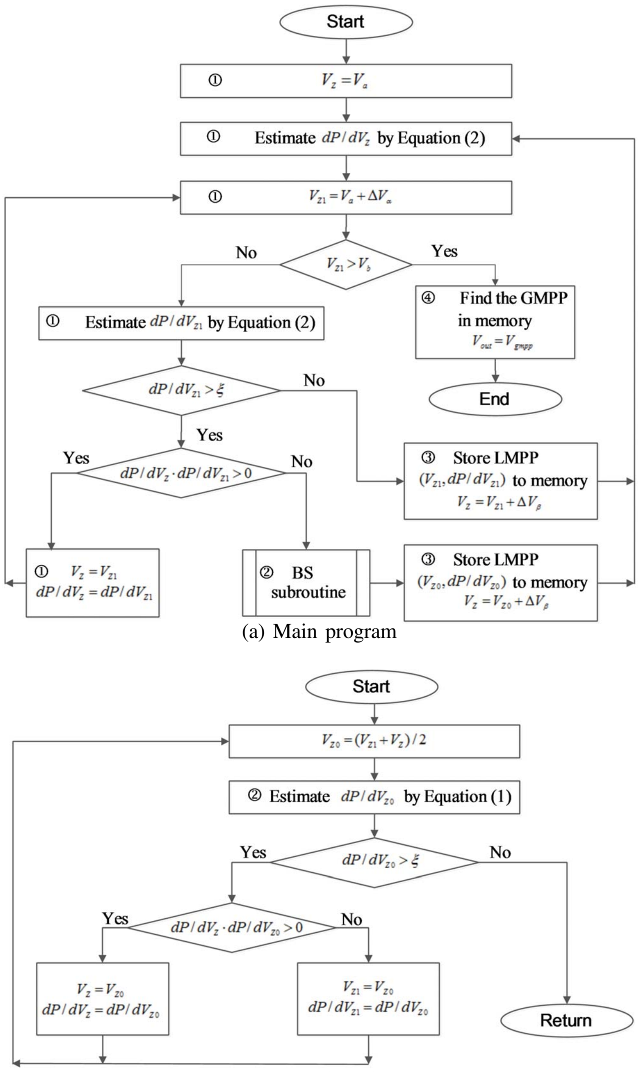
Fig. 3 shows the P-V curves of the three subassemblies. The output power of the array is the sum of the power generated by these subassemblies. In the interval between 0 V and 19 V, only the module at full irradiance of $1000\ W/m^2$ generates power. It then sinks in the current generated in PV module 2 and its output power becomes flatten. All the three modules deliver positive power at the valid operating points whose voltage is larger than 39 V.

Some of the critical observations from the study of I-V-P curves of a partially shadowed array are listed as follows:

1) A PV array has the unique peak in its P-V curve under uniform insolation. The P-V characteristics exhibit multiple peaks on the condition that the modules receive different level of insolation.
2) Under partial shadowed conditions, the maximum number of the LMPPs in the P-V curve is equal to the number of the series connected modules in the PV array.
3) The voltage of LMPPs are extremely closed to the places where the Maximum Power Points of Subassemblies (SMPPs) locate at P-V curves, yet a voltage deviation between LMPPs and SMPPs ΔV_{ls} is observed in Fig. 3.
4) The shadowed subassembly is activated as the operating current drops to the magnitude that equals to its Short-Circuit Current I_{sc}.
5) A voltage difference $\Delta V_{m\alpha}$ exists between the LMPP and the operating point at which the shadowed subassembly starts to generate power. The value of $\Delta V_{m\alpha}$ is dependent on the difference of the received insoluation of subassemblies.
6) $\Delta V_{m\alpha}$ is usually far larger than ΔV_{ls}. The minimum displacement between successive peaks $\Delta V_{m\beta}$ therefore can be considered larger than 74% of the Open-Circuit Voltage V_{oc}, which is the lower bound of the magnitude of V_{mpp} [8].

III. The proposed global MPPT method

The dP/dV–V and P–V curves of the PV array in Fig. 1 are shown in Fig. 3 . These electrical characteristics with partially shadowed conditions are normally modelled by continuous derivative functions [9] and the dP/dV of an operating point



(a) Main program

(b) BS subroutine

Fig. 5. Flowchart of the proposed algorithm

can be approximated by a backward finite divided difference [4]:

$$\left.\frac{dP}{dV}\right|_{V=V_A} \approx \frac{\Delta P}{\Delta V} = \frac{V_A \cdot I_A - V_{A'} \cdot I_{A'}}{V_A - V_{A'}} \qquad (1)$$

where A' is an operating point sampled immediately after A and their voltage difference is ΔV_β. V_A, I_A. and $V_{A'}$, $I_{A'}$ represent the voltage and current values at A and A' respectively.

Based on the the fact that the derivative at LMPPs is approaching zero, this paper proposes a global search scheme that transfers the MPPT issue into a root-finding problem. Basically, the searching procedures can be divided into four states:

① Incremental Search: the algorithm is to determine the range where LMPPs locate. Starting with the operating voltage V_z, it evaluates the intervals that obtain different signs of dP/dV, indicating the existence of LMPPs. To ensure the correctness, the increment length ΔV_α should be less than $\Delta V_{m\alpha}$ according to the observations in section 2.

② Bisection Search: Bisection Method (BS) [10] is activated as long as incremental search successfully detects the voltage interval of LMPPs. By comparing the signs of dP/dV at midpoint V_0 and each end of the interval, BS determines the subinterval where the LMPP locates. The interval is narrowed by half in the next iteration.

③ Storing LMPPs: as long as dP/dV is small enough and achieves the tolerance ξ, it indicates the LMPP is caught and the corresponding operating point is stored. The operating voltage is then given an incremental V_β, which is set to larger than $V_{m\beta}$ to approach the successive LMPP.

④ Locating GMPP: V_a and V_b represent the upper and lower limit respectively. If the operating voltage exceeds V_b, searching state 1-3 are terminated and the operating point keeps at the LMPP which delivers the maximum output power.

The flow chart of the proposed MPPT algorithm is shown in Fig. 5 while all the states are denoted by circled numbers. It is worth pointing out that either state 1 or state 2 can initiate state 3. Not only bisection searching is capable of forcing the operating point closed to LMPPs, but incremental searching may also point to local peaks directly.

IV. Results and Discussions

A. Construction of MPPT system

The operation of the proposed MPPT algorithm has been verified by a PV-supplied Single Ended Primary Inductance Converter (SEPIC) in PSIM [11]. The prototype of the MPPT system, which used a 10 KHz switching frequency, was shown in Fig. 6. Aiming to keep a stable output voltage of SEPIC V_l, a 30V-battery was connected to the load. Since the duty cycle of the SEPIC D has a relationship with the output voltage of the PV module V_{out} and V_l [12]:

$$D = \frac{V_l}{V_l + V_{out}} \qquad (2)$$

D can control the operating point as long as V_{out} is measured. According to the design guideline in [12], the parameters of

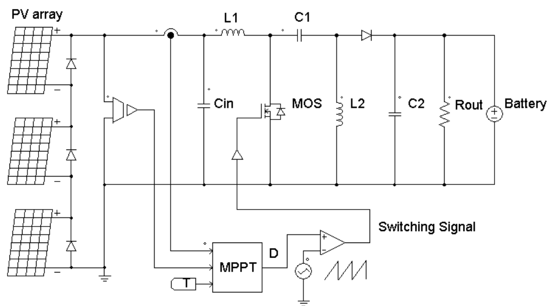
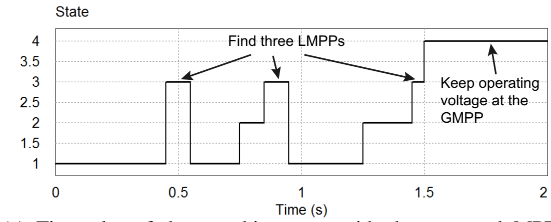
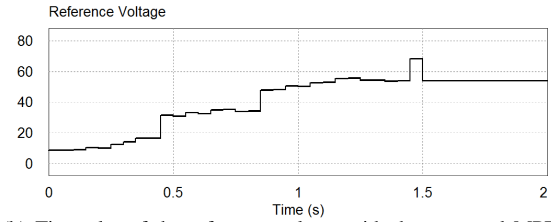


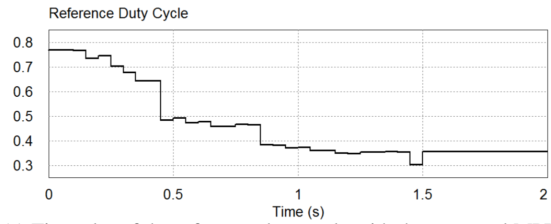
Fig. 6. Simulation Model for PV array with the proposed MPPT method



(a) Time plot of the searching state with the proposed MPPT method

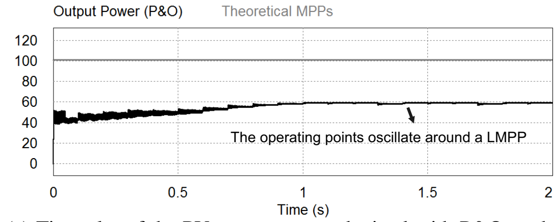


(b) Time plot of the reference voltage with the proposed MPPT method

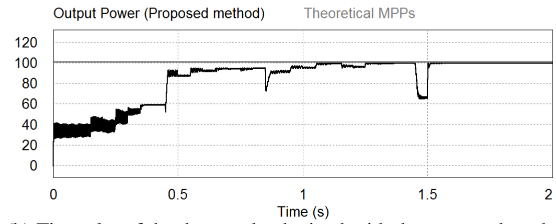


(c) Time plot of the reference duty cycle with the proposed MPPT method

Fig. 7. PSIM simulation results with the proposed MPPT method under partially shadowed conditions



(a) Time plot of the PV output power obtained with P&O method (perturbation step = 0.5 V)



(b) Time plot of the duty cycle obtained with the proposed method

Fig. 8. PSIM simulation results of different MPPT methods under partially shadowed conditions

SEPIC were specified as follows: $L1 = L2 = 0.4$ mH, $C1 = 100$ uF and $C2 = 480$ uF. The sampling rate was set to 10 Hz. The MPPT algorithm was written in C and was simulated together with the schematic program of PSIM.

B. Performance verification

With purpose of verifying the tracking performance of the proposed MPPT scheme, the three PV modules were set under 1000 W/m^2, 750 W/m^2, 500 W/m^2 respectively. Fig. 7 (a) is a time plot of the searching state. A LMPP was found by incremental searching within the first 0.5 s, while other LMPPs were tracked via BS. The MPPT process was ended by the initiation of state 4 and the operating point stayed at the GMPP then. Fig. 7 (b) and (c) illustrated the reference voltage and duty cycle for SEPIC respectively.

A comparison between the classical P&O and the proposed global MPPT scheme was given by Fig. 8. It was observed that P&O oscillated around a LMPP and failed to catch the GMPP. With variable steps, the proposed method delivered a stable output power which located close to the theoretical MPPs after 1.5 s.

V. Conclusion

An MPPT method has been proposed to improve the efficiency of PV systems under partially shadowed conditions, on which the P-V characteristics exhibit multiple peaks. With the detection of the ranges where LMPPs locate, the proposed scheme tracked accurate results by a classical BS algorithm. An MPPT system composed of the specific DC-DC converter and PV generator was implemented in PSIM to verify the efficiency of the proposed method. The simulation results proved the accuracy and stability of the proposed method.

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