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Improving Power-Conversion Efficiency via a Hybrid MPPT Approach for Photovoltaic Systems

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Abstract—**This paper presents a hybrid Maximum Power Point Tracking (MPPT) method for improving the power –conversion efficiency of Photovoltaic (PV) generators. By detecting the output power changes caused by environmental reasons, the proposed method performs variable-step online search process with an accurate estimation of the Maximum Power Point (MPP) locus. A PV generator with a Single Ended Primary Inductance Converter (SEPIC) is developed in PSIM to verify the feasibility and suitability of the proposed method. Simulation results show that it can not only deliver a stable reference operating voltage for MPPs at steady state, but also can speed up the searching process under rapidly changing environment conditions.**

Index Terms—**Photovoltaic effects, power conversion, search methods, estimation.**

I. INTRODUCTION

Since the availability of fossil fuels is declining, efforts have been made to popularize the solar energy. Photovoltaic (PV) generating systems, providing extra electrical power from solar energy, are becoming increasingly common and necessary component of daily life. Recent studies have shown that the PV panels exhibit non-linear electrical characteristics and the Maximum Power Point (MPP), at which PV generators deliver the maximum output power, is heavily dependent on ambient irradiance (G), temperature (T), and load profile [1], [2]. The task of Maximum Power Point Tracking (MPPT) at various environmental conditions therefore is sometimes considered to be interesting and challenging.

In recent years, a number of MPPT methods have been developed and implemented to improve the power-conversion efficiency of PV systems. These methods vary in complexity, sensors required, convergence speed and cost and [3]–[9]. In the literature [5], MPPT methods are classified into online and offline depending on the function of tracking methods or control strategies. The former normally uses measured operating power (W), voltage (V) or current (I) along with an online algorithm to search MPPs of PV generators. The most popular online methods are perhaps Perturbation and Observation (P&O) [6] and Incremental Conductance (IncCond) [7]. These approaches, although robust, usually produce slow response to the sudden changes of environment conditions (e.g. T and G). In addition, the fixed-size perturbation causes inevitable oscillations of output power, resulting in extra energy loss. Offline methods typically predict the MPP based on equations with the mathematical expression of the electrical characteristics of a PV panel, or on the algorithms obtained from empirical data. Curve fitting [8], fractional open voltage and short circuit [9] methods all fall into this category. Their performance is directly affected by the precision of the sensors used for measuring T and G, as well as the open voltage (V_{oc}) and the short current (I_{sc}). As reported by Salas [4], few offline MPPT methods are able to obtain the MPP exactly and thus are known as "quasi seeks".

This paper proposes a hybrid MPPT approach to overcome the inherit shortages of online and offline methods. Improving the conversion efficiency by means of this method only requires a cheap thermometer besides the essential sensing tools of P&O. The advantages of the proposed method are threefold as follows:

1) The variable search approach acclerates the convergence speed of the online MPPT process.
2) The number of online searching iterations can be decreased dramatically by using the initial reference voltage value delivered by a simple and accurate Maximum Power Point Estimation (MPPE) method.
3) Power oscillation, which is considered as an inherent drawback of P&O and IncCond methods, can be eliminated by the proposed hybrid method.

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II. PROPOSED HYBRID MPPT METHOD

A. *Variable-step online MPPT algorithm*

The conventional fixed step algorithms (e.g. P&O, IncCond) suffer an irreparable weakness: large perturbation step increases the oscillation magnitude at steady state while small perturbation step reduces the convergence speed. The dilemma can be overcome by the variable step searching approach [10], which starts with a large perturbation step and ends by acknowledging the achievement of tolerance. Secant Method (SM) [10], [11] is such an algorithm developed to find a root for function *f(x)*. With the two initial estimates of x, SM approximates the root iteratively by

$$x_{i+1} = x_i - \frac{f(x_i)\cdot(x_{i-1}-x_i)}{f(x_{i-1})-f(x_i)}, \quad i = 0,1,2\ldots \tag{1}$$

SM takes the name because the new value x_{i+1} is the root for a secant line passing through two distinct points, namely $(x_i, f(x_i))$ and $(x_{i-1}, f(x_{i-1}))$.

Since the *I-V* characteristic of PV modules exhibits a continuous derivative function [1], MPPT issues can also be reduced to a root-finding problem which is based on the fact that the derivative of the output power with respect to the output voltage *dP/dV* approaches zero at MPPs. In digital implementation, *dP/dV* of an arbitrary operating point *A* can be approximated by a backward finite divided difference [11]

$$\left.\frac{dP}{dV}\right|_{V=V_A} \approx \frac{\Delta P}{\Delta V} = \frac{V_A\cdot I_A - V_{A'}\cdot I_{A'}}{V_A - V_{A'}}, \tag{2}$$

where *A'* is an operating point sampled immediately after *A*. The difference between V_A and V' is ΔV. V_A, I_A and $V_{A'}$, $I_{A'}$ represent the voltage and current values at the points *A* and *A'*, respectively.

Fig. 1 shows the MPP revision process for a PV module under the Standard Testing Condition (STC) (T = 25°C, G = 1000W/m^2). *dP/dV-V* and *P-V* curves prove that the MPP locates the place where *dP/dV* is zero. Initialized by the points *P1* and *P2*, the new estimate for the root is computed by (1) and *P3* is the corresponding *dP/dV*. The new iteration is released by replacing *P2* with *P3*. The searching process continues until *dP/dV* is within the tolerance ξ.

B. *MPPE method*

The conventional PV models are generally analytical equations based on a physical description formulating *I* with *V*, *T* and *G* [12], [13]. Considering the effects of series and shunt resistance, [1] introduced an accurate single-diode PV model:

$$\begin{cases} I = I_{pv} - I_o\left(e^{\frac{V+I\cdot R_s}{n\cdot N_s\cdot V_t}} - 1\right) - \dfrac{V+IR_s}{R_p}, \\ V_t = \dfrac{kT}{q}, \\ I_o = \dfrac{Iscn + K_i\Delta T}{e^{(V_{ocn}+K_v\Delta T)/(nN_sV_t)} - 1}, \\ I_{pv} = (I_{pvn} + K_i\Delta T)\dfrac{G}{G_n}, \end{cases} \tag{3}$$

where I_{pv} is the photocurrent, I_{pvn} is the photocurrent at STC, I_{scn} is the short circuit current at STC, I_o is the saturation current, V_t is the thermal voltage, K_i is short circuit current coefficient, K_v is open circuit voltage coefficient, R_s is the series resistance, R_p is the shunt resistance, k is the Boltzmann constant (1.38065 × 10^{-23} J/K), q is the electron charge (1.60218 × 10^{-19} C), n is the diode ideality constant, N_s is the number of series connected cells in the module, and ΔT is the difference between the operating temperature and 25°C.

With the aim of finding MPPs, a necessary condition should be considered as below

$$\frac{dP}{dI} = \frac{d(VI)}{dI} = V + I\frac{dV}{dI} = 0. \tag{4}$$

After differentiating (3), Alghuwainem [14] derived a simplified mathematical expression for *dV/dI* with the assumption $V/R_p \rightarrow 0$ as follows:

$$\frac{dV}{dI} = \frac{1}{A}\left(\frac{-\beta}{I_{pha} - \beta I + I_o}\right) - R_s, \tag{5}$$

where $I_{pha} = I_{pv} + I_o$, $A = \dfrac{q}{nV_tN_s}$, $\beta = 1 + \dfrac{R_s}{R_p}$.

Therefore, (4) becomes

$$\underbrace{\ln\left(\frac{I_{pha} - \beta I}{I_o}\right)}_{F_1} - \underbrace{\frac{\beta I}{I_{pha} - \beta I}}_{F_2} - 2AIR_s = 0. \tag{6}$$

Taking the first term of Taylor expansion $\ln(1+x) \approx x$ (for $x \approx 0$), F_1 can be approximated as

$$F_1 = \ln\left(\frac{I_{pha}}{I_o}\right) + \ln\left(1 - \frac{\beta I}{I_{pha}}\right) \approx \ln\left(\frac{I_{pha}}{I_o}\right) - \frac{\beta I_o}{I_{pha}} \tag{7}$$

According to the simulation results, a more accurate approximation expression of F_1 was found in [14]

$$F_1 \approx \ln\left(\frac{I_{pha}}{I_o}\right) - 2\frac{\beta I_o}{I_{pha}}. \tag{8}$$

Alghuwainem then transferred (6) into a standard form of the second order equation, which gives

$$aI^2 + bI + c = 0, \tag{9}$$

$$a = 2\beta + 2A\beta I_{pha}R_s, \quad b = -\beta I_{pha}\ln\left(\frac{I_{pha}}{I_o}\right) - 3\beta I_{pha} -$$

$$-2AI_{pha}^2R_s, \quad c = I_{pha}^2\ln\left(\frac{I_{pha}}{I_o}\right).$$

By recognizing the condition that $I < I_{pha}$, the operating current of the corresponding MPP (I_{mp}) can be calculated by [14]

$$I_{mp} = \frac{1}{2a}\left(-b - \sqrt{b^2 - 4ac}\right). \tag{10}$$

With the assumption $V/R_p \rightarrow 0$, we may obtain the operating voltage of the MPP (V_{mp}) after substituting (10) into (3)

$$V_{mp} = \frac{1}{A}\ln\left(\frac{I_{pha} - \beta I + I_o}{I_o}\right) - IR_s \,. \tag{11}$$

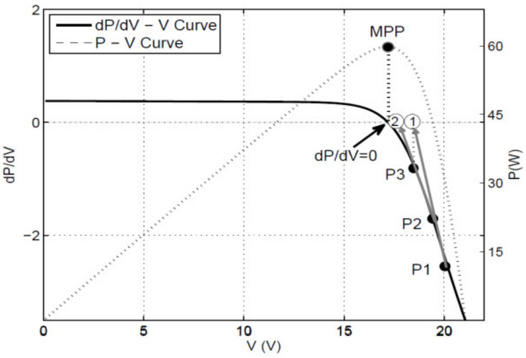


Fig. 1. MPP Seeking process with SM under STC.

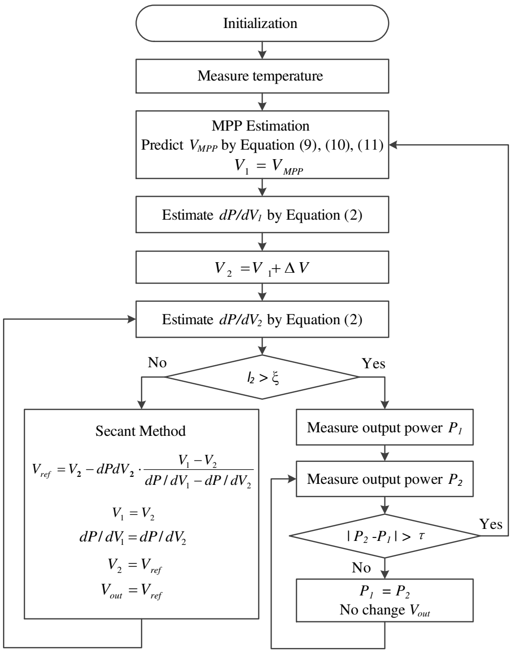


Fig. 2. Flowchart of the proposed hybrid method.

Table I proves the MPPE method is able to give an approximation V_{mp} for different PV modules. However, it cannot obtain the exact MPP. The reasons are twofold:

1) The accuracy of MPPE is strongly dependent on the methods of measuring the environment factors (e.g. T and G).

2) The approximation results are on the basis of many assumptions, simplification methods and numerical calculations, which lead to the estimation error.

C. Proposed hybrid method

The proposed hybrid method basically consists of three operating states: MPPE, SM searching and steady state. The method is initiated by estimation process. Considering the fact that irradiance has a minor effect on V_{mp}, light meters can be eliminated; and the irradiance is assumed on STC to address a low cost solution. The exact MPP can be found by SM method with an initial V_{mp} provided by MPPE. It keeps tracking MPPs by varying perturbation steps until it achieves process control tolerance ξ. The operating state then transfers to the steady state which delivers a stationary optimized operating voltage to control system and the sensors start to monitor the output power. As long as the output power varies exceeding the predetermined tolerance τ, which indicates the changes of I-V characteristic caused by environmental reasons, MPPE process is reactivated and a new searching iteration begins. The flow chart of the proposed method is shown in Fig. 2.

TABLE I. V_{MP} OF DIFFERENT MODULE MODELS UNDER STC.

Module Type	Module	Vmp (V)		Relative Error
		Measured	Estimated	
Multi-crystal	MSX60	17. 1	16.8213	1.63%
	SM55	17. 4	17.4234	0.13%
	KG200GT	26. 3	26.2094	0.34%
Mono-crystal	SP-70	16. 5	16.5100	0.06%
Thin-film	ST-40	16. 9	16.5760	1.92%

III. RESULTS AND DISCUSSIONS

A. Construction of MPPT system

To verify the feasibility and suitability of proposed hybrid MPPT method, a MPPT system, consisting of a MSX60 model, a Single Ended Primary Inductance Converter (SEPIC), a MPPT function model and a 30-V battery, is constructed under the simulation environment PSIM [15]. Compared to a traditional buck-boost converter, the SEPIC, allowing the voltage at its output to be greater than, less than, or equal to that at its input, has advantages of having non-inverted output. Thus, the SEPIC supplied by the PSIM Renewable Energy Package is applied in this paper and its switching frequency and sampling rate are set to 10 KHz and 10 Hz respectively. According to the design guideline in [16], the parameters of SEPIC are specified as follows: $L1 = L2 =$ 0.40 mH, $C1$ = 100 uF and $C2$ = 480 uF. The duty cycle (D) is capable of controlling the operating point. In [16], D was mathematically expressed as a function of the reference operating voltage (V_{out}) and the output voltage of the converter (V_l)

$$D = \frac{V_l}{V_l + V_{out}} \,. \tag{12}$$

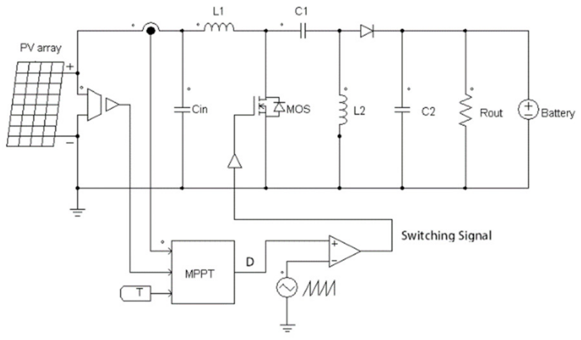
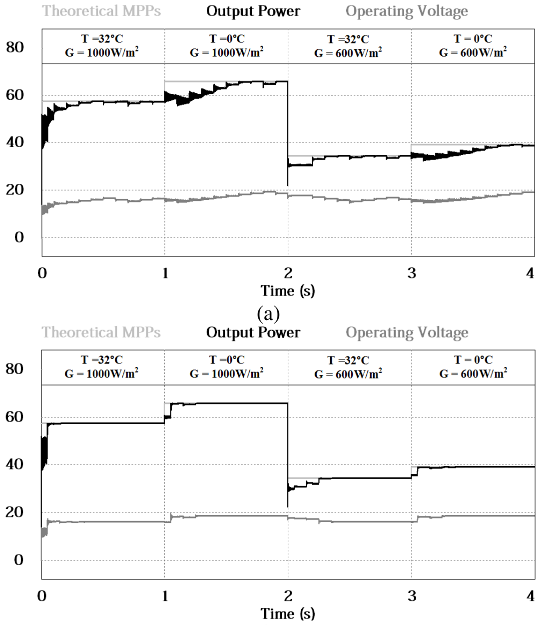


Fig. 3. Simulation Model for PV array with the hybrid MPPT method.

The MPPT function model, which uses Dynamic Link Library (DLL) blocks to link C/C++ code with PSIM, is applied to calculate D. It is worthwhile to remark that this work eliminates Proportional plus Integral (PI) controllers since they do not work efficiently in nonlinear application [17]. The switching signal is generated by comparing the reference duty cycle with a triangular signal.

B. Performance verification and comparison

Simulation studies have been carried out with different operating environment sets to show the effectiveness of the proposed approach. Fig. 4(a) shows the output power and operating voltage of the PV generator with P&O method. It took many fixed increments to force the operating point closed to MPPs with a 12V initial reference voltage. The output power kept oscillating at steady state although it approached the theoretical MPPs. In Fig. 4(b), exact MPPs are found by the proposed hybrid method. The performance of MPPT algorithms were evaluated by the MPPT efficiency defined in [5]. Compared to P&O, the hybrid approach produced a 7 % of improvement toward the test set in Fig. 1.



(a)

(b)

Fig. 4. PSIM simulation results of different MPPT methods under changing atmospheric conditions: (a) P&O, (b) Hybrid method.

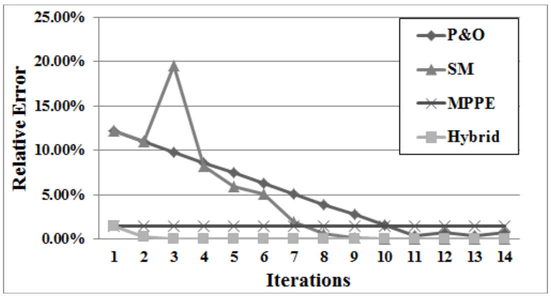


Fig. 5. Relative error of V_{mp} obtained from different MPPT methods. (Environment: STC; Initial operating voltage of P&O and SM: 15V).

Fig. 5 further studies the tracking efficiency by the relative error of V_{mp} obtained from different MPPT methods. A steady but slow decrease can be seen in the error curve of P&O. The relative error oscillates from the 13th iteration. SM, although effective, may produce poor prediction if the initial value is far from the theoretical V_{mp}. In the test, SM delivered an acceptable reference voltage fewer than 10 iterations with the initial value of 15V. MPPE is capable of computing an approximation V_{mp} from the early tracking state. However, the error rate could not be further improved. With the approximation V_{mp}, the hybrid method only requires 2 steps to achieve the predetermined tolerance. It showed the fastest tracking speed and its relative error is kept low.

IV. CONCLUSIONS

A hybrid MPPT method has been proposed to improve the efficiency of PV systems by means of the use of MPPE and online SM search methods. It is set up to combine the merits of both the approaches and to address the main problem of transient and steady state arisen in the utilization of conventional online and offline approaches. By varying the environment sets, simulation results have proven that the MPPE accelerates the online search process while the variable-step searching approach wards off oscillation at steady state.

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