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A Hybrid MPPT Method for Photovoltaic Systems via Estimation and Revision Method

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Abstract—Maximum Power Point Tracking (MPPT) methods can be classified into direct and indirect approaches. They are used to improve the efficiency of power conversion in Photovoltaic (PV) systems. However, a review of recent literature implies that the indirect methods never produce accurate results. Meanwhile, the conventional direct Perturb and Observe (P&O) method has two problems: oscillations at steady state and slow dynamic response under changing environment conditions. Estimation and Revision (ER) method is proposed in this paper to overcome these limitations by the alternative use of MPP estimation and MPP revision process. The efficiency of the ER method is verified in an MPPT system implemented with a specific DC-DC converter and an adopted PV module.

I. INTRODUCTION

Photovoltaic (PV) generation, known as one of the green alternative energy sources, is becoming increasingly common and necessary component of daily life. Recent research has shown that the output power of a PV module varies as a function of operation points which exhibits the nonlinear current-voltage (I-V) characteristic [1]. For addressing these problems with the utilization of PV generation, the techniques on Maximum Power Point Tracking (MPPT) therefore become attractive in the field of PV generation. Over the past two decades, numerous MPPT algorithms have been proposed in literature. Based on the control strategies, they can be classified into two groups [2]:

1) “Indirect control” – Maximum Power Points (MPPs) are predicted offline by a variety of algorithms or equations with the mathematical expressions of the I-V characteristics of a PV panel.

2) “Direct control” – By detection of the operating point of PV modules, an online search algorithm is used to locate the MPPs regardless of any atmospheric conditions.

Open Circuit method is a typical indirect control approach and is widely used for its simplicity. On the basis of an approximated ratio between the Open Circuit Voltage \(V_{oc}\) and the Maximum Power Point Voltage \(V_{mp}\), it delivers an estimated MPP offline. Despite the ease of implementation, open circuit method may never achieve an accurate MPP and the approximated ratio varies with different PV materials. Direct methods are independent of priori knowledge of the PV generator characteristics and are considered to have robust performance [2]. Perturb and Observe (P&O) [3] may be the most widely used direct method in MPPT. It measures the PV characteristics and perturbs the operation point by using a hill climbing approach. On account of the fixed perturbation step, P&O performs steady-state oscillations and thus leads to energy losses. As shown in [4], another disadvantage of P&O is that it fails to track MPPs under fast changing environment conditions.

In view of the inherent defects in both direct and indirect methods, this paper proposes an Estimation and Revision (ER) approach which alternatively uses offline MPP estimation and online MPP revision algorithms to the dynamic behaviour of the MPPT system composed of a specific converter and an adopted PV module. Improving the conversion efficiency by means of this method only requires a cheap thermometer besides the essential sensing tools of P&O. It has been shown that the proposed ER method ensures a fast convergence speed in response to the rapidly changing atmospheric conditions. The variable perturbation step searching applied in ER not only accelerates the tracking speed, but also provides a way for eliminating the oscillations in steady state.

II. PROPOSED ER MPPT METHOD

A. Variable-step MPP revision algorithm

Conventional fixed step algorithms suffers an inherent and irreparable weakness: large perturbation step increases the oscillation magnitude at steady state while small perturbation step decreases the convergence speed. The dilemma can be overcome by the variable step searching approaches [5], which start with a large perturbation step and end by acknowledging the achievement of tolerance. A case in point is Secant Method (SM) [6] developed to find a root for function \(f(x)\). With the two initial estimates of \(x\), SM approximates the root iteratively by

\[
x_{i+1} = x_i - \frac{f(x_i)(x_{i-1} - x_i)}{f(x_{i-1}) - f(x_i)} \quad i = 0, 1, 2, ...
\]

SM takes the name because the new value \(x_{i+1}\) is the root for a secant line passing through two distinct points, namely
The derivative of the output power with respect to the voltage can be approximated by a backward finite divided difference [5]:

\[
\frac{dP}{dV} \approx \frac{\Delta P}{\Delta V} = \frac{V_A \cdot I_A - V_{A'} \cdot I_{A'}}{V_A - V_{A'}}
\]

(2)

where \(A'\) is an operating point sampled immediately after \(A\). The difference between \(V_A\) and \(V_{A'}\) is \(\Delta V\). \(V_A, I_A,\) and \(V_{A'}, I_{A'}\) represent the voltage and current values at \(A\) and \(A'\) respectively.

Fig. 1 shows the MPP revision process for a PV module under the Standard Testing Condition (STC) (Temperature \(25^\circ C\), Irradiance \(G = 1000 \text{W/m}^2\)). \(dP/dV\)-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 Equation (1) and \(P3\) is the corresponding \(dP/dV\). New iteration is released by replacing \(P2\) with \(P3\). The searching process continues until \(dP/dV\) is within the control tolerance \(\xi\).

B. MPP Estimation

A PV module under the uniform environment condition exhibits a I-V characteristic with a unique MPP [8]. The conventional perturbation MPPT algorithms (e.g. P&O, IncCond [4]), although their tracking speed is limited, are capable of tracking the actual MPPs gradually in the steady state. However, the electrical response of PV modules and the location of MPPs are significantly affected by the operating temperature and solar irradiation. Fig. 2 sketches the Current-Voltage-Power (I-V-P) curves of a classical multi-crystalline PV module (MSX60 [9]) under different temperature and irradiance. The circles denote the theoretical MPPs of the PV module. It can be observed that the changes in temperature mainly influence the location of MPPs, while irradiance changes mainly affect the output power of MPPs. This kind of MPP variations may cause the conventional direct MPPT algorithms to fail in tracking. MPP estimation provides an optimization scheme allowing the SM to start with an optimal initial point under a specific environment. Its significance lies not only in the demands for increasing the convergence speed, but also in the effects on the the prevention of MPP divergence.

As has been introduced in [7], [10], the power at any point of the PV characteristic is given by the following equations:

\[
P = V \times I = V[I_{pv} - I_o(e^{\frac{V}{Vmp}} - 1)]
\]

(3)

\[
V_t = \frac{kT}{q}
\]

(4)

\[
I_o = \frac{(I_{oc} + K_s \Delta T)}{e^{(V_{oc} + K_s \Delta T)/(nN_s V_t)}} - 1
\]

(5)

\[
I_{pv} = (I_{oc} + K_s \Delta T) G G_{stc}
\]

(6)

where \(I_{pv}\) is the photocurrent, \(I_{oc}\) is the photocurrent at STC, \(I_o\) is the saturation current, \(V_t\) is the thermal voltage, \(K_s\) is short circuit current coefficient, \(K_v\) is open circuit voltage coefficient, \(n\) is the diode ideality constant, \(N_s\) is the number of series connected cells in the module, \(k\) is the Boltzmann constant \((1.380650 \times 10^{-23} \text{ J/K})\), \(q\) is the electron charge \((1.602176 \times 10^{-19} \text{ C})\) and \(\Delta T\) is the difference between the operating temperature and the nominal temperature.

By applying derivative to Equation (3), \(dP/dV\) satisfies the following relationship at MPPs:

\[
\frac{dP}{dV} \bigg|_{V=V_{mp}} = 0 = I_{pv} - I_o(e^{\frac{V_{mp}}{Vmp}} - 1) - \frac{V_{mp}}{nN_s V_t} I_o e^{\frac{V_{mp}}{Vmp}}
\]

(7)

Considering the fact that irradiance has a minor effect on \(V_{mp}\), light meters are eliminated and the irradiance is assumed on STC to address a low cost solution. Equation (7) is therefore modified as:
I\[pvn\]−I\[io\](e\[V_{mp}\]nNsVt−1)−V_{mp}nNsVtI\[io\]e\[V_{mp}\]nNsVt=0 \tag{8}

At a specific time point, \(I_{io}, V_t\) and \(I_{pv}\) are known as a constant calculated by Equation (4), (5) and (6) respectively. The root of Equation (8), namely the estimated voltage of MPPs \(V_{emp}\), can be solved directly by Newton-Raphson algorithm, whose time complexity of is \(O(n)\) \[11\].

C. Control process of the proposed ER method

ER basically contains three operating states: MPP estimation, MPP revision, and steady state. After computing an approximate MPP, the online searching process is activated instantly. The tracking process keeps tracking MPPs by varying perturbation steps until it achieves process control tolerance \(\xi\). The operating state then transfers to 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 power varies exceeding the predetermined tolerance \(\tau\), which indicates the changes of I-V characteristic, MPP estimation process is reactivated and a new searching iteration begins.

The flow chart of the proposed ER method is shown in Fig. 3.

III. RESULTS AND DISCUSSIONS

A. Construction of MPPT system

In the aim of verifying the proposed ER method and its suitability in the system studies, a PV-supplied Single Ended Primary Inductance Converter (SEPIC) with the MPPT algorithm is constructed in the PSIM \[12\] simulator as shown in Fig. 4. The output current and voltage of MSX60 module are provided by the Renewable Energy Package of PSIM. According to the design guideline in \[13\], the parameters of SEPIC are specified as follows: \(L1 = L2 = 0.4018 \text{ mH}, C1 = 100 \text{ uF}, C2 = 480 \text{ uF}\). The switching frequency and sampling rate is chosen to 10 KHz and 10 Hz respectively. A 30V-battery is applied to keep a stable output voltage of SEPIC \(V_t\). By measuring the output voltage of PV module \(V_{out}\), the duty cycle of SEPIC \(D\) can be calculated via \[13\]:

\[D = \frac{V_t}{V_t + V_{out}} \tag{9}\]

Equation (9) implies that the operating points of the adopted PV modules are controlled by the duty cycle delivered by MPPT block. For the reason that Proportional plus Integral (PI) controllers do not work efficiently in nonlinear applications \[14\], this work eliminates them and the duty cycle is adjusted directly by MPPT algorithms. PSIM provides an interface linking the function model to its schematic program and thus MPPT algorithms are written in C using “dynamic link library (DLL)”. By comparing the reference duty cycle with a triangular signal, the switching signal can be generated.

B. Performance verification and comparison

The proposed ER approach is compared with the classical standard P&O and SM in the above-mentioned MPPT system. Tests are designed to investigate the MPPT performance in steady and dynamic states by varying atmospheric conditions at different time points:

\[\begin{align*}
0 \sim 1s: & \ G = 1000 \text{ W/m}^2, \ T = 32^\circ \text{C} \\
1 \sim 2s: & \ G = 1000 \text{ W/m}^2, \ T = 0^\circ \text{C} \\
2 \sim 3s: & \ G = 500 \text{ W/m}^2, \ T = 32^\circ \text{C} \\
3 \sim 4s: & \ G = 500 \text{ W/m}^2, \ T = 0^\circ \text{C}
\end{align*}\]

Fig. 5 (a) shows the PV output power obtained with P&O method. Initialized with a 12V initial reference voltage, P&O takes time to force the operating point closed to MPPs by stationary increments. A slight power decrease caused by the failure of P&O under changing environment conditions is seen at the beginning of the third and fourth seconds.
Although the output power approaches the theoretical MPPs, the output power keeps oscillating at steady state. Fig. 5 (b) proves SM can constrain the PV module to deliver a stable output after the searching process. However, an initial point far distant from the actual MPP may lead to an inefficient tracking process and thus the conventional SM based MPPT method does not show a steady performance. The proposed ER method deals with the problem of the standard SM by assigning an estimated MPP derived from the mathematical expression of output power. The output power of the applied PV module and the reference duty cycle are shown in Fig. 5 (c) and 6 respectively. They depict that the direct MPP estimation accelerates the indirect MPP revision process while the variable-step searching approach wards off oscillation at steady state.

The performance of MPPT algorithms is normally evaluated by the MPPT efficiency $\eta$ defined in [4], and it can be expressed as:

$$\eta = \frac{\int_{t_1}^{t_2} P \, dt}{\int_{t_1}^{t_2} P_{\text{max}} \, dt}$$  \hspace{1cm} (10)

where $t_1$ and $t_2$ are the start-up and shut-down time of the PV system, $P$ and $P_{\text{max}}$ denote the PV output power and the theoretical maximum PV power respectively. The MPPT efficiency of P&O, SM and ER toward the test set in this work is summarised as follows:

- i) $\eta_{\text{P}&O} = 93\%$, ii) $\eta_{\text{SM}} = 90\%$, and iii) $\eta_{\text{ER}} = 98\%$.

**IV. CONCLUSION**

An MPPT method has been proposed to improve the efficiency of PV systems by means of alternative use of MPP estimation and direct search algorithms. It is set up to combine the merits of both the approaches and to address the main problem of transient and steady state in the conventional direct and indirect approaches. An MPPT system composed of a SEPIC and PV generator is implemented in PSIM to verify the efficiency of the proposed method. The results show that the dynamic response of ER is quicker than that of SM while the output power of ER is more stable than that of P&O.

**REFERENCES**


