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An Adaptive Predictive Control Strategy for RMPPT under Partially Shaded Conditions

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Abstract: As one of key technologies in photovoltaic converter control, Maximum Power Point Tracking (MPPT) methods can keep the power conversion efficiency as high as nearly 99% under the uniform solar irradiance condition. However, these methods may fail when shading conditions occur and the power loss can over as much as 70% due to the multiple maxima in $I-P$ curve in shading conditions v.s. single maximum point in uniformly solar irradiance. In this paper, a Real Maximum Power Point Tracking (RMPPT) strategy under Partially Shaded Conditions (PSCs) is introduced to deal with this kind of problems. An optimization problem, based on a predictive model which will change adaptively with environment, is developed to tracking the global maxima and corresponding adaptive control strategy is presented. No additional circuits are required to obtain the environment uncertainties. Finally, simulations show the effectiveness of proposed method.

Keywords: Photovoltaic systems, RMPPT, Partial shading, Adaptive predictive control

1. INTRODUCTION

Photovoltaic (PV) energy has gained great popularity in electricity generation, due to its clean and sustainable nature. A number of achievements have been made in academia and industry (Ching et al. (2010), Ribrant et al. (2007), Sachin et al. (2008), Chen et al. (2011)), where many researchers put their efforts on maximization of power extracted from solar penal, which is commonly referred to as Maximum Power Point Tracking (MPPT). Conventional MPPT methods, like Perturbation and Observation (P&O) method, Incremental Conductance, and Ripple Correlation Control, are very useful when the PV receives uniform solar irradiation. However, solar irradiance applied on entire PV array cannot guarantee uniform density continuously. That's because part of PV panel may be shielded by trees, clouds or buildings. In this case, the nonlinearity of the PV characteristic curve has been changed from a unique maximum to multiple local maxima, which make the traditional MPPT methods without considering PSCs cannot be applied directly. Therefore, a lot of researchers are interested in finding effective MPPT algorithms with stronger adaptability under PSCs.

Existing schemes working on this issue have been reported in the literature, for example, a new tracking method based on the combination of two loops for MPP at the PV array was presented (Mohammad et al. (2011)). The first loop was off-line set point calculation, which is fixed and cannot change with environment. The second loop was online tuning loop, which was used to tracking the derived fixed set point. Chin et al. (2011) introduced parallel off-line tracking function to assist an on-line fuzzy logic P&O method to enhance RMPPT performance, which can continuously search the absolute MPP beyond the trapped maxima. The information of operating voltage and the corresponding generation current is required to store in a database, which means an additional circuit for the measurement is needed. Patel et al. (2008) and Ishaque et al. (2012) discussed a modified P&O with global maxima tracking subroutine method, which was based on particle swarm optimization algorithm. However, many parameters are required to be adjusted, which is not easy to be applied in commercial PV systems. Methods mentioned above have some drawbacks with respect to fixed setting-point loop, additional circuit, and difficulties to apply in already installed systems, especially invalid when there is a large difference on solar irradiation level. Young-Hyok Ji et al. (2011) proposed a MPPT method with a simple linear function to moving the operating point toward the lower voltage level, by which the maxima can be tracked under PSCs without any additional circuits. Three special cases were discussed to illustrate the effectiveness of the linear function. However, whether the lower voltage level found by the designed linear function is close to the global maxima or not is not be discussed, which may result a local maxima be tracked instead.

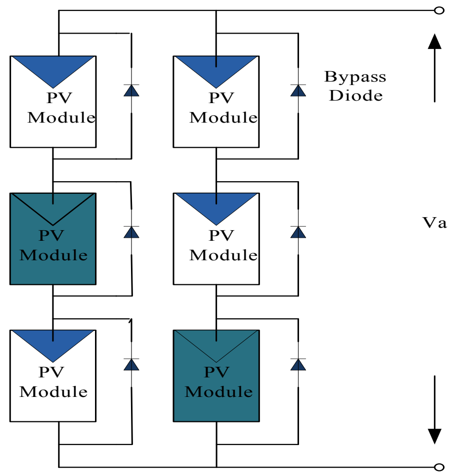

Fig.1 PV modules in series-parallel with bypass diode

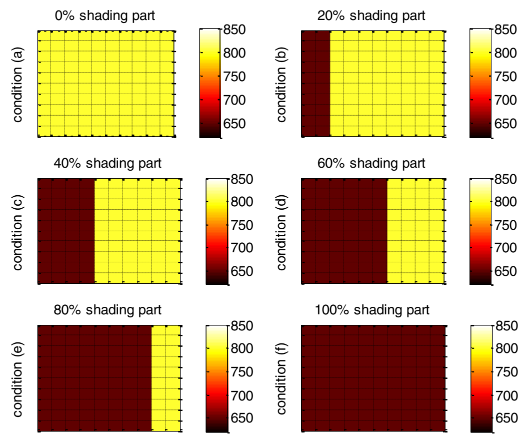

Fig.2 Different partial shading conditions of PV array

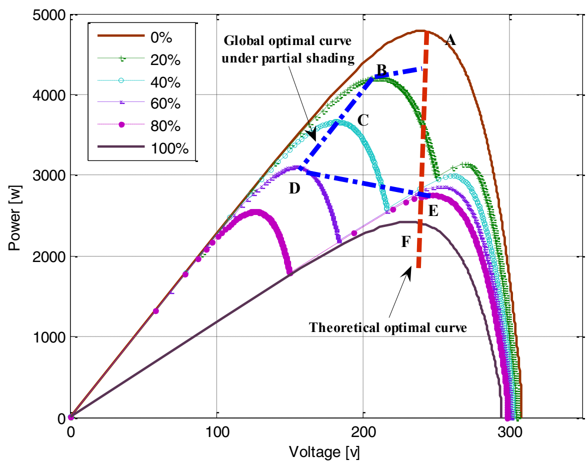

Fig.3 V-P curves under different partial shading conditions

In this paper, an adaptive predictive control principle is presented to overcome the environment uncertainties. No additional circuit is required to measure operating voltage. An RMPPT optimization problem with constraints is defined, where the change rate of duty cycle is also considered to prevent power switches damages and reduce unnecessary energy losses. Moreover, the corresponding adaptive control strategy is developed under PSCs, which can cope with the varying operating conditions and change model parameters according to temperate and radiation. The rest of this paper is organized as follows: Firstly, the characteristics of PV system under PSCs are analysed in Section 2. Secondly, a predictive output power model and the optimal problem are designed in Section 3. Then, simulations are presented in Section 4 to illustrate the effectiveness of the proposed control method. Finally, a conclusion is made in Section 5.

2. PV CHARACTERISTICS UNDER PSCs

A general Photovoltaic system consists of four parts, namely the photovoltaic array, power converter, controller with environment sensor, and grid, where its major technical issues include improving the energy conversion efficiency, enhancing stability of power grid, and reducing components cost. A suitable control technology for the power electronic devices is one of the keys to improve the efficiency of grid-connected PV systems, that is, how to keep the PV system working on its maximum power point to maximize the power conversion regardless of weather situation. However, unlike the uniform irradiation condition, the same string may be exposed to different irradiation. The bypass diode in PV array will divert the current from the module, showed in Fig.1, producing multiple peaks in P-V curve of the panel, which make the traditional MPPT methods not applicable.

To illustrate clearly, a 10×10 PV panel under PSCs is given as an example. Fig.2 (a) shows no shading in the panel when the whole panel exposure under $800W/M^2$. The $V-P$ curve is shown as solid grey line in Fig.3. Fig.2 (b) to Fig.2 (e) expresses different shading cases whose area extend from 20% to 80%. It means the shaded part of the panel receives a partial solar irradiation, say $600W/M^2$, and the rest is under full irradiation, which makes the panel under PSCs be looked as a load instead of a generator. Note that in these partial shading conditions, the $V-P$ curve emerges multiple peaks and the PV array should work on the global optimal curve to get maximum power instead of theoretical optimal curve for a lager power output, see dotted lines in Fig.3. Fig.2 (f) shows a 100% shading case and the corresponding MPP returns to the theoretical optimal curve in Fig. 3. By this example, it is easy to see that the traditional MPPT methods without considering PSCs will follow the theoretical curve instead of the global optimal curve, which will miss the real global maxima. Hence, a new method with adaptive capacity in finding the global maxima under PSCs is studied. Before we continue, the model of PV array is introduced.

Photovoltaic cells can be seen as photo-generated current sources which have the same basic characteristics as a diode. These cells are combined into a photovoltaic array in series and/or parallel connection. Mathematic model of output current of the photovoltaic cell can be expressed as follows (see Pandey et al. (2010) and Mutoh et al. (2006)):

$$I = I_p - I_o\left[\exp\frac{q(V+IR_{se})}{aBT} - 1\right] - \frac{V+IR_{se}}{R_{pa}} \tag{1}$$

where I and V are output current and voltage respectively; I_p is the photo-generated current; I_o indicates the reverse current of equivalent diode; a is idealized factor of the diode values; R_{se} and R_{pa} are equivalent series resistance and equivalent parallel resistance; q is electron charge; B is Boltzmann constant; T is temperature. Photo-generated current I_p and reverse saturation current I_o can be expressed as:

$$I_p G_n = (I_{sc} + \kappa \Delta T)G \tag{2}$$

$$\frac{I_o}{I_{on}} = \left(\frac{T}{T_n}\right)^{3/a} \exp\left[\frac{qV_g}{aB}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{3}$$

in which G is an actual light intensity while G_n is a standard light intensity; κ is the temperature coefficient; ΔT stands for temperature difference; T_n is the standard temperature; V_g is the band of energy gap of semiconductor material. N_s represents series modules, when part of the PV array, see N_d in *xth* string, is shaded, the bypass diode will divert current, leading the output current as:

$$I_s = \sum_{x=1}^{N_p} I_x = \sum_{x=1}^{N_p} I_{scx}\alpha \tag{4}$$

in which where N_p is the parallel modules; I_{scx} is short circuit current in *xth* string; the adaptive factor α which contains shading information N_{dx} ($N_{dx} \prec N_s$) can be expressed as:

$$\alpha = 1 - \exp\left(\frac{q(V_a + R_s I_{scx} - V_{ocx})}{AkTN_s(N_s - N_{dx})}\right) \tag{5}$$

where N_s is series modules; V_a is parallel voltage of entire array; V_{ocx} means open circuit voltage of shading modules in *xth* string. The existing of shading parameter N_{dx} leads string current I_x different, so the PV $I-P$ curve will be multiple peaks.

REMARK 1: When shading modules N_{dx} values zero, then $V_{ocx} = 0$ and the adaptive factor α converts to:

$$\alpha = 1 - \exp\left(\frac{q(V_a + R_s I_{sc})}{AkTN_s^2}\right) \tag{6}$$

which means uniform solar irradiance is applied on the entire PV array, then parameters of each string is the same, the output current can be represented as:

$$I_s = N_p I_{sc}\left(1 + \exp\left(\frac{qV_{oc}}{N_s kT}\right) \cdot \alpha\right) \tag{7}$$

in this case, only one maxima will appear in $I-P$ curve, same as $N_{dx} = N_s$, which means the array is under another solar irradiance degree.

3. ADAPTIVE PREDICTIVE CONTROL FOR RMPPT

The main control objective of RMPPT in this paper is to operate the switch with a properly optimized duty cycle to make the PV output current track its reference accurately. The reference will change with the environment. So we design an adaptive controller to overcome this uncertainty and track the real reference with considering PSCs. Fig.4 shows control diagram with Support Vector Machine (SVM) module as reference power producer. After training process in database and construct the fitting function ahead, output power and optimal current can be obtained by measuring the inputs parameters. Then the reference value of inductor current, together with the outputs of the predictive model will be inputted to the cost function. The optimal solution-duty cycle, will be inputted into converter to regulating the operating current and load voltage.

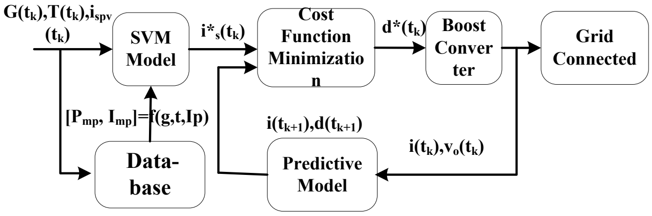

Fig.4 Control diagram of proposed current control method

3.1 *Adaptive Model for Output Power and Optimal Current*

We choose support vector machine as a useful tool for data classification and pattern recognition (Jiang et al. (2009), Yu et al. (2009), Ahemed et al. (2010)). This method can obtain estimated measurements by finding regression coefficients which can best fit with residual. Besides the solar intendancy and temperature, the photo-generated current also has a mapping relationship with current at the real maximum power point. When the solar panel work under the shading condition, the photo-generated current reflects the shading information and can be measured in the confluence box. The shading percentage can be expressed as follows:

$$I_p = \frac{(1-S)G_{normal}}{G_s} \cdot I_{ps}, S = \frac{G_{shading}}{G_{mormal}} \tag{8}$$

$$[P_{mp}, I_{mp}] = f(x) = f(g, t, I_p) \tag{9}$$

$$f(x) = \sum_{n=1}^{m}\left(\alpha_n - \alpha_n^*\right)k\left(x, x_n\right) + b \tag{10}$$

where I_{ps} is photo-generated current under standard condition. Optimal current I_{mp} is corresponding with maximum power P_{mp}, these parameters serve as output pair. SVM method is used to find the fit equation to observed variables and I_{mp} will be used as reference signal I^*.

In order to construct the fitting function $f(x)$ with residual less than ε, we have the following steps:

Step1. Collecting input data: light intensity g, temperature t, and photo-generated current I_p on $(n-1)_{th}$ and n_{th} days, scoping fitting trade-off- C and insensitive loss function- ε to minimize the training error. The trade-off should be a small value to avoid over fitting phenomenon.

Step2. Selecting a kernel function $k(x, x_n)$: using lagrangian multiplier method and the selected kernel function $k(x, x_n)$ to work out the lagrangian multiplier- α, α^* and bias- b. Then the fitting function in Eq. (10) can be obtained.

Step3. Finding the reference current: measuring g, t, and I_p on $(n+1)_{th}$ day, substituting these three parameters to the fitting functions in Eq. (10), and by Eq. (9), the output power and optimal current can be calculated. The optimal current obtained is used as the reference input.

3.2 *RMPPT Adaptive Predictive Control Algorithm*

With the consideration of external parameter uncertainties, we design an adaptive controller based on mathematic model of boost converter (Giovanni et al. (2005)),which produce an optimized duty cycle to regulate the output current and then track its reference. The cost function we used is defined as follows:

$$\min_{D,x,d} J = \sum_{j=0}^{P} \left\| i(k+j/k) - i^*(j) \right\|_{Qy}^2 + \sum_{j=0}^{M} \left\| \Delta d(k+j-1/k) \right\|_{Qm}^2 \quad (11)$$

where P is prediction horizon, M is control horizon, $i(k+j/k)$ is the predicted output current at instant k, i^* is reference current, Q_y is a weighting coefficient to penalize output signal error and Q_m is a weighting coefficient to penalize big changes in input signal. The cost function in Eq. (11) means that the derivation between output current and reference current will be minimized and that the fluctuation of duty cycle will be reduced, which can avoid the energy loss caused by frequent switching.

The predictive output is expressed as follows:

$$i(k+j/k) = \zeta \cdot x(k) + \Omega \cdot \gamma(k+j/k) \quad (12)$$

where

$$\gamma(k+j/k) = \left(d(i), \delta(i), z(i)\right)^T, \quad i \in \{k, \ldots, k+M-1\},$$

$$\zeta = c \cdot \left(A', A'^2, \ldots, A'^P\right)^T, \Omega = c \cdot \left(P_1 \quad P_2 \quad P_3\right),$$

$$P_1 = \begin{pmatrix} B' & 0 & \cdots & 0 \\ A'B' & B' & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ A'^{P-1}B' & A'^{P-2}B' & \cdots & A'^{P-M}B' \end{pmatrix},$$

$$P_2 = \begin{pmatrix} R & 0 & \cdots & 0 \\ A'R & R & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ A'^{P-1}R & A'^{P-2}R & \cdots & A'^{P-M}R \end{pmatrix},$$

$$P_3 = \begin{pmatrix} G & 0 & \cdots & 0 \\ A'G & G & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ A'^{P-1}G & A'^{P-2}G & \cdots & A'^{P-M}G \end{pmatrix},$$

A', B', R and G are matrices of state-space model of boost converter; $c = (1 \quad 0)$; $\gamma(k)$ is the combination of $d(k)$, $\delta(k)$ and $z(k)$; $x(k)$ is the state variable at time t_k. By substituting $i(k+j/k)$ into the cost function J in Eq. (11), a general form of the optimization problem is obtained:

$$\begin{aligned} &\min_{\gamma} && \gamma^T H \gamma + 2 f^T \gamma \\ &subject \quad to: && F_1 \gamma \le F_2 + F_3 \cdot x_o \end{aligned} \quad (13)$$

where $H = \Omega^T Q_y \Omega + Q_m$, $f = 2 \cdot \zeta^T Q_y \zeta - 2 \cdot d_0^T Q_m$; γ is the solution sequence; d_o is initial value of duty cycle in each computation period; $d(k)$ is valued between 0 and 1; x_o is the initial state; F_i, $i = 1,2,3$ are constraint matrices. Thus, the optimal control problem has been converted to solving a corresponding Mixed Integer Quadratic Programming (MIQP) problem, which can be solved by *matlab* function *miqp.m*. Note that at step k, an optimal sequence γ^* are obtained but only the first solution $d^*(k|k)$ from sequence γ^* is applied.

4. SIMULATION RESULTS

To verify our proposed method, several simulations are carried out under different situations on the photovoltaic system, which is located at Shanghai Jiao Tong University as shown in Fig.5.

Fig.5 PV system in Department of Automation, SJTU

The data were collected from May 6 to May 20, 2013. On these days, the photovoltaic array were partial covered from 10:20 to 13:15, and the corresponding photo-generated current which reflects shading information was measured by electricity meters. The performance of output current tracking the reference is presented in Fig.6. It is obvious that the output current (red) closely track the reference (blue) from 7 a.m. to 17p.m. Fig.7 shows the working voltage of PV arrays with PSCs, from which we can see the voltage will change its working region to track the RMPPT.

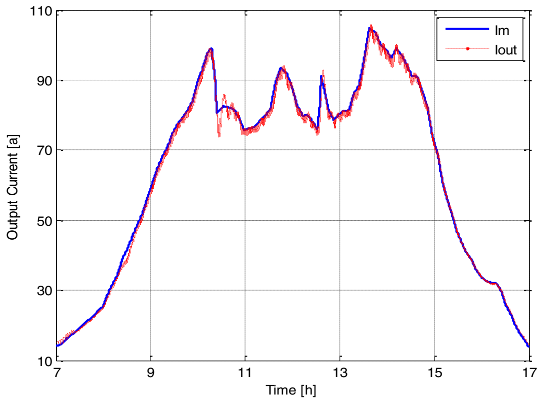

Fig.6 Output current tracking reference with PSCs

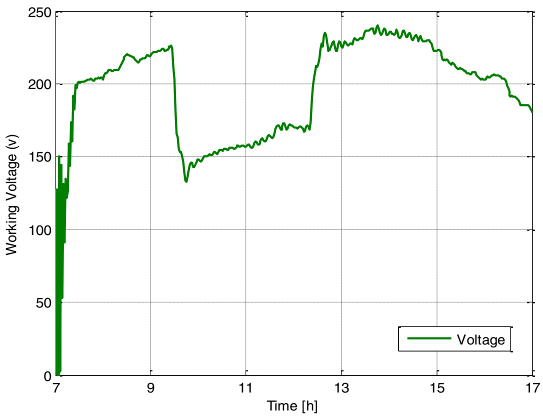

Fig.7 working voltage of PV arrays with PSCs

Moreover, the comparison of RMPPT performance between our proposed method and conventional P&O method is showed in Fig.8. By Fig. 8, we can see the conventional method miss tracking the MPP during the partial shading period. The peak value of output power is around 13.2KW and the efficiency of the whole produce is 90.29%, while our proposed method can track the reference with peak value as 17.8KW and efficiency as 99.6%.

To demonstrate effectiveness and fast response of the proposed method in a deeper perspective, the trajectory of operating points is compared with voltage-power and voltage-current curves to test whether the PV system is working at the true RMPP. By Fig. 9 to Fig. 10, a detailed view of the RMPPT performance can be observed. When the shading appears, the working point follows the global optimum curve to jumping out of local optimum and the corresponding working voltage changes from 210V to 150V roughly. When the shading disappears, photovoltaic arrays receive uniform solar intensity again and the operating point move back to the theoretical optimal curve. These results show the feasibility of re-positioning and tracking the RMPPT among multiple local maxima exhibited.

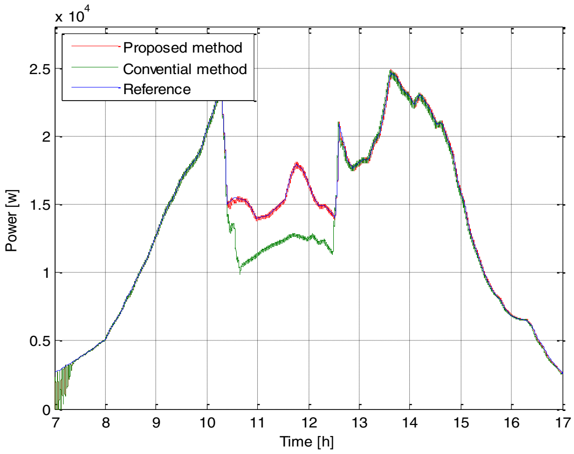

Fig.8 Comparison of RMPPT performance of proposed method and conventional method under PSCs

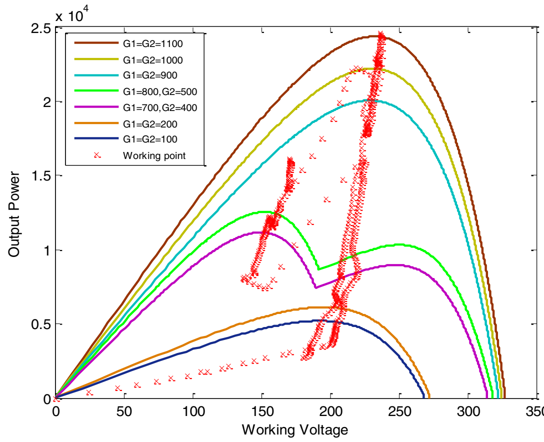

Fig.9 Operating points versus PV V-P curves under shading

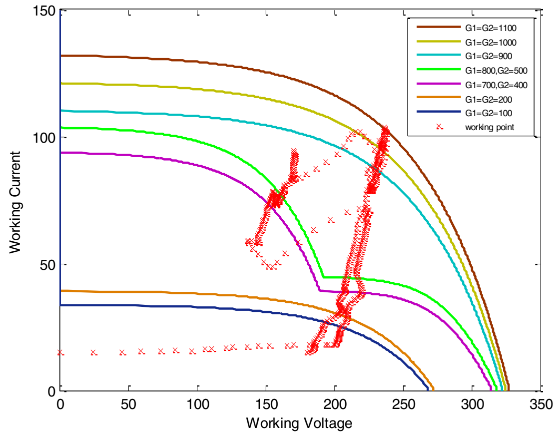

Fig.10 Operating points versus PV V-I curves under shading

5. CONCLUSION

In this paper, an adaptive controller for RMPPT under PSCs was developed with the consideration of uncertainties of solar radiation and temperature. The RMPPT was achieved by solving an adaptive optimization problem which was formulated based on a SVM nonlinear system model. Simulations carried out shown the effectiveness of our proposed method.

ACKNOWLEDGEMENT

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