A New Algorithm for Rapid Tracking of Approximate Maximum Power Point in Photovoltaic Systems

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***Abstract*—This paper presents a new algorithm for tracking maximum power point in photovoltaic systems. This is a fast tracking algorithm, where an initial approximation of maximum power point is (MPP) quickly achieved using a variable step-size. Subsequently, the exact maximum power point can be targeted using any conventional method like the hill-climbing or incremental conductance method. Thus, the drawback of a fixed small step-size over the entire tracking range is removed, resulting in reduced number of iterations and much faster tracking compared to conventional methods. The strength of the algorithm comes from the fact that instead of tracking power, which does not have a one-to-one relationship with duty cycle, it tracks an intermediate variable β, which has a monotonically increasing, one-to-one relationship. The algorithm has been verified on a photovoltaic system modeled in Matlab–Simulink software. The algorithm significantly improves the efficiency during the tracking phase as compared to a conventional algorithm. It is especially suitable for fast changing environmental conditions. The proposed algorithm can be implemented on any fast controller such as the digital signal processor. All the details of this study are presented.**

***Index Terms*—Maximum power point (MPP) tracking, photovoltaic.**

I. INTRODUCTION

THE PHOTOVOLTAIC (PV) systems display an inherently nonlinear current-voltage relationship, requiring an online identification of the optimal operating point for maximum power extraction. Continuous tracking of this operating point, called the maximum power point (MPP), is necessary to maximize the utilization of the solar array for a given insolation and temperature. Several approaches have been devised for tracking MPP accurately for PV cells. Some of the popular ones are the perturb-and-observe (or hill-climbing) method [1], the incremental conductance method [2] and the ripple-based method [3].

The hill-climbing method is based on the principle of perturbation and observation. Small perturbations are introduced in the system in order to vary the operating point such that the maximum power point is achieved. However, this method has several drawbacks such as slow tracking speed and oscillations about MPP, making it less favorable for rapidly changing environmental conditions. Hussain *et al.* [2] have proposed another algorithm for matching the panel and converter impedance, which improves the tracking direction movement for rapidly changing environmental conditions. Another method [3] uses the ripple in the array output to maximize the power by dynamically extrapolating the characteristics of the PV array. A phase relationship between power ripple and array voltage ripple decides the correction to be made.

It must be pointed out that all the conventional tracking methods use fixed, small iteration steps, determined by the accuracy and tracking speed requirements. If the step-size is increased to speed up the tracking, the accuracy of tracking suffers and vice versa. This algorithm works in two stages. The first stage takes the operating point (OP) quickly within a close range of the actual MPP. The second stage consisting of a conventional scheme (such as the ones mentioned above) is then used to bring the OP to the exact MPP. The proposed scheme offers the following advantages over the existing schemes.

1) In the first stage, the scheme tracks an intermediate variable, β, that appears in the analysis, rather than tracking power. This overcomes the limitation of the conventional schemes where there is no way to predict the iteration step size and the duty cycle needed to track the MPP. It will be shown subsequently that tracking β facilitates fast tracking, with a relatively larger and variable iteration step size. Thus the proposed algorithm is more efficient, as losses due to small steps, when the operating point is away from MPP, are eliminated.
2) The fast tracking of the first stage does not compromise the accuracy of the tracking because it is followed by a conventional scheme in the second stage, which tracks power with fine steps. But since the first stage brings the OP within a close proximity of MPP, the second stage does not require a long time.
3) In view of (1) and (2), the proposed algorithm is especially suitable for fast-changing environmental conditions.

II. THEORY OF PROPOSED TECHNIQUE

Considering the dotted portion of Fig. 1, and taking the derivative of p_{pv} with respect to v_{pv}, we get

$$\frac{dp_{\rm pv}}{dv_{\rm pv}} = i_{\rm pv} + v_{\rm pv} \times \frac{\partial i_{\rm pv}}{\partial v_{\rm pv}} \tag{1}$$

where p_{pv}, $v_{\rm pv}$, $i_{\rm pv}$ are the PV array output power, output voltage, and output current, respectively. It is known that

$$i_{\rm pv} = I_{\rm ph} - I_o \times \left(e^{c\times(i_{\rm pv}\times R_s + v_{\rm pv})} - 1\right) \tag{2}$$

where I_{ph} is photo generated current, I_o is reverse saturation current, $c = q/(k \times T \times \eta)$, where q is electronic charge, k is

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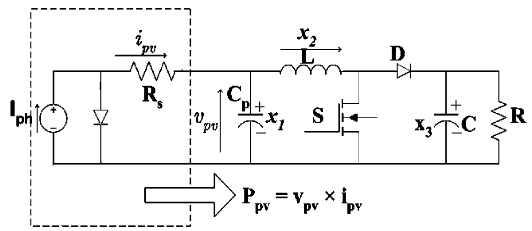

Fig. 1. PV converter system used in this study. A 60 W solarex MS ×60 solar array was considered. p_{pv} denotes the power output of the array. The states of the system are also marked.

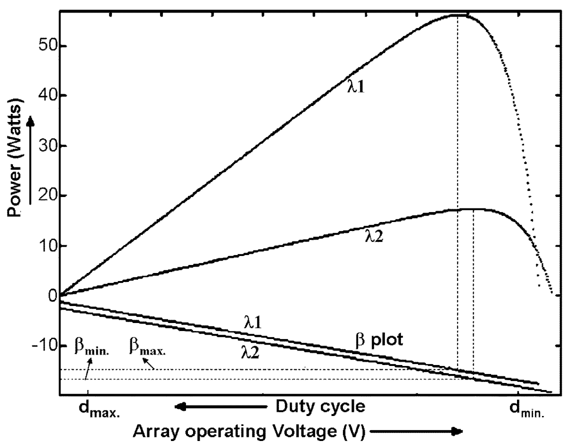

Fig. 2. Variation of power and β with duty cycle at different insolation and different temperature ($\lambda 1 = 1$ sun and temperature $= 55\,^{\circ}\mathrm{C}$, $\lambda 2 = 0.3$ suns and temperature $= 30\,^{\circ}\mathrm{C}$).

Boltzmann's constant, η is diode quality factor, T is ambient temperature in Kelvin and R_s is the cell series resistance in Ohms. Differentiating (2) with respect to v_{pv}, solving and substituting in (1), and applying the MPP condition yields

$$\frac{dp_{\rm pv}}{dv_{pv}} = 0 = i_{pv} + v_{\rm pv} \times \frac{-I_o \times \left(e^{c\times(i_{\rm pv}\times R_s + v_{\rm pv})}\right) \times c}{1 + I_o \times \left(e^{c\times(i_{\rm pv}\times R_s + v_{\rm pv})}\right) \times R_s \times c}. \quad (3)$$

Solving (3) for $i_{\rm pv}/v_{\rm pv}$ and taking the natural log on both sides of the resulting equation

$$\ln\left(\frac{i_{pv}}{v_{pv}}\right) - c \times v_{pv} = \ln(I_o \times c) + R_s \times c \times i_{pv} - \ln\left(1 + I_o \times \left(e^{c\times(i_{pv}\times R_s + v_{pv})}\right) \times R_s \times c\right). \quad (4)$$

The left-hand side quantity of (4) is denoted by β. The crux of the proposed scheme lies in the fact that instead of tracking power which does not have an injective relationship with the duty cycle of the boost converter (e.g., two different values of the duty cycle may yield the same power), we track β, which offers a monotonically increasing and injective relationship with the duty cycle (see Fig. 2). Hence, tracking β is simpler and faster than tracking power.

III. Proposed Algorithm for MPPT

To analyze the variation of the magnitude of β with change in temperature and insolation, let them initially be considered as independent parameters. Now, consider the diode model of a single solar cell with negligible Rs. Equation (4) can be simplified to

$$\ln\left(\frac{i_{\rm pv}}{v_{\rm pv}}\right) - c \times v_{\rm pv} = \ln(I_o \times c) = \beta. \quad (5)$$

It may be noted from (5) that β is independent of insolation but depends on temperature. The issue related to the fact that temperature and insolation are, after all, not independent of each other, was resolved in the following manner. Taking the worst and best conditions of temperature and insolation, magnitude variation of β at MPP was observed for four extreme conditions (C1, C2, C3, and C4) with the help of preliminary simulations carried out on a 60 W Solarex MS ×60 solar array [4] based converter system (Fig. 1). The observations are shown in Table I. The four conditions are the following:

- C1: Varying insolation with minimum constant temperature (Table I, S. no. 1,4,7);
- C2: Varying insolation with maximum constant temperature (Table I, S. no. 3,6,9);
- C3: Varying temperature with minimum constant insolation (Table I, S. no. 1,2,3);
- C4: Varying temperature with maximum constant insolation (Table I, S. no. 7,8,9).

TABLE I
Variation of β With Temperature and Insolation at MPP

S.No.	Insolation λ (Sun)	Temperature(°C)	β at MPP
1	0.3	30	-16.9
2	0.3	40	-16
3	0.3	55	-14.85
4	0.6	30	-16.4
5	0.6	40	-15.8
6	0.6	55	-14.7
7	1.0	30	-16.2
8	1.0	40	-15.7
9	1.0	55	-14.5

The following two important inferences can be made from Table I.

1) For a given, fixed temperature, variation in the magnitude of β at MPP is small even as the insolation is varied over a wide range.
2) There is an inverse variation of magnitude of β with temperature.

With these observations, it can be concluded that if the panel temperature varies in between a fixed range, the magnitude of β at MPP also lies within a small, fixed range ($\beta_{\min}$ to $\beta_{\max}$). This range of β is guided by temperature variation and other constant parameters. An appropriate range of β can be specified for a given PV system for use with the proposed algorithm. The upper limit of $\beta_{\max}$ at MPP corresponds to maximum insolation and maximum temperature (see Table I, S. no. 9). The lower limit of

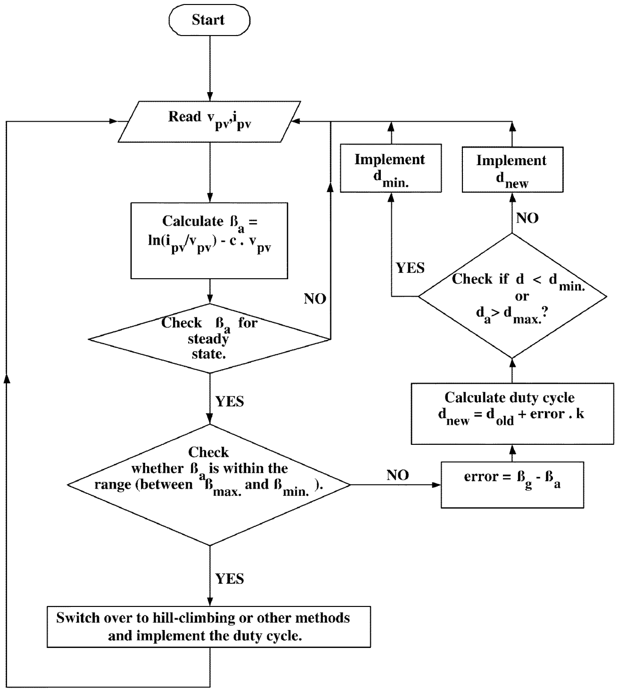

Fig. 3. Flow-chart corresponding to the proposed MPPT technique.

$\beta_{\min}$ at MPP corresponds to minimum insolation and minimum temperature (see Table I, S. no. 1). While implementing the first stage of the algorithm, β_g, the value of β corresponding to the most probable array temperature is used as the guiding value for calculating the duty correction as given as follows:

$$\text{error} = \beta_g - \beta_a \text{ and } d_{\text{new}} = d_{\text{old}} + \text{error} \times k \tag{6}$$

where, β_a is the actual value of β at a given instant, d_{old} is the previous duty cycle, d_{new} is new duty cycle and k is a constant corresponding to the β plot. If d_{new} is less than $d_{\min}$ or greater than $d_{\max}$(see Fig. 2), then change d_{new} to $d_{\min}$ to utilize the fact that MPP is close to the $d_{\min}$ point. The flowchart for the proposed MPP tracking algorithm is shown in Fig. 3.

IV. Simulation of the Proposed Algorithm

The entire solar array converter system of Fig. 1 has been simulated in MATLAB–SIMULINK [5], [6]. The built-in MATLAB function is used to model the solar array [4] with a provision to feed the insolation, temperature, and output array voltage (v_{pv}) as input parameters and calculate the corresponding output array current with the help of M-file. The PV array system is simulated in terms of its various state equations given below. When the switch "S" is ON, the relevant state equations are

$$i_{\text{pv}} = C_p x_1' + x_2; \quad x_1 = L x_2'; \quad \frac{x_3}{R} + C x_3' = 0. \tag{7}$$

When switch "S" is OFF and diode "D" is conducting, the corresponding state equations are

$$i_{pv} = C_p x_1' + x_2; \quad x_1 = L x_2' + x_3; \quad \frac{x_3}{R} + C x_3' = x_2. \tag{8}$$

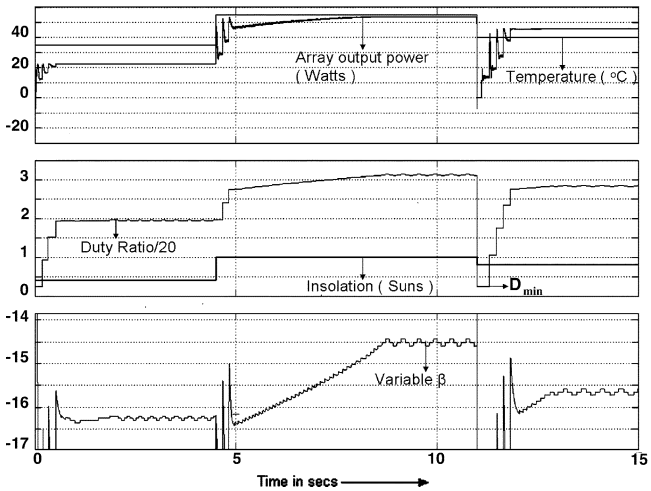

Fig. 4. PV converter system for different MPP at varying environmental conditions of temperature and insolation.

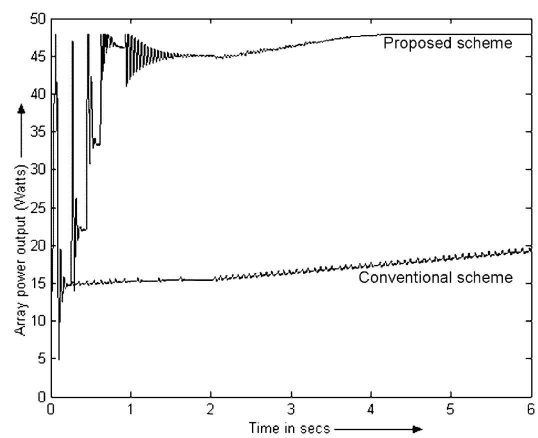

Fig. 5. Simulation plots for comparison of proposed MPPT technique with conventional hill climbing technique. In a conventional scheme, as well as in stage-2 of proposed scheme, a very fine step size has been used for accurate tracking.

When switch "S" is OFF and diode "D" is not conducting, the corresponding state equations are

$$i_{pv} = C_p x_1'; \quad x_2 = 0; \quad \frac{x_3}{R} + C x_3' = 0. \tag{9}$$

Simulation runs switch back and forth between the different sets of state equations given above depending on the state of the system. The proposed algorithm is applied to the Simulink model at different environmental conditions and MPP tracking is recorded (see Fig. 4). A notable observation is made with respect to Fig. 4, when the insolation suddenly changes downwards. The energy storage element across the solar panel terminals (capacitor C_p), has an influence on the controller action during this transient condition, and this tends to disturb the β versus duty cycle relationship. But this can be handled by putting appropriate limits on the duty cycle variation (e.g., $D_{\min}$) as marked in Fig. 4, so that the solution does not diverge. Further, it may be noted that the temperature and insolation were changed quite abruptly in the simulation studies. This is not the case in reality as these parameters will rise and fall with definite time constants, giving more time for the controller to adjust.

V. Conclusion

A new algorithm has been presented which is capable of rapid tracking of the maximum power point in PV systems by using a variable iteration step-size. The algorithm brings the operating point very close to the actual MPP with a few iterations. Hill-climbing or incremental conductance methods with finer steps can, then, be used to track the exact MPP. The proposed algorithm has the advantage of very fast convergence and accurate tracking of MPP as seen in Fig. 5. It is quite efficient during the transient tracking phase, as compared to conventional methods and is especially suitable for fast changing environmental conditions. But care should be taken to limit the duty cycle of the converter within safe limits. The scheme is quite robust and can be implemented on any fast controller such as the DSP.

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