A Hybrid Simulated Annealing and Perturb and Observe Method for Maximum Power Point Tracking in PV Systems under Partial Shading Conditions

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***Abstract*—This paper presents a hybrid method for Maximum Power Point Tracking (MPPT) of a Photovoltaic (PV) system which experiences non-uniform environmental conditions or partial shading conditions. The hybrid method combines two simple techniques with complementary strengths in achieving Global MPPT. Simulated Annealing (SA) has only recently been applied to PV MPPT and is very effective at locating global maxima with limited implementation complexity. Perturb and Observe (P&O) is a very common technique which provides continuous tracking of the MPP in a simple and easy to implement manner. The P&O method is generally incapable of locating global maxima, and the SA based method is unable to perform continuous searching. By merging these techniques in a hybrid MPPT method consisting of a global searching stage and a local searching stage, the tracking performance is improved compared to what each technique could achieve independently. Simulation results are presented to demonstrate the effectiveness of the proposed hybrid technique.**

***Index Terms*—Maximum Power Point Tracking, Photovoltaic, Simulated Annealing.**

I. INTRODUCTION

Maximum Power Point Tracking (MPPT) is a key consideration in the design of Photovoltaic (PV) systems. A PV system, due to the inherent non-linearity of the Power-Voltage (P-V) characteristics, has an optimal operating point which corresponds to the maximum power available. Installing a PV system represents a considerable investment, so it is essential that PV systems are operated at the MPP at all times during operation.

The non-linearity in the P-V characteristics is further complicated when the PV system is placed in a 'real' environment, rather than in a laboratory testing setting. In the outdoor environment, a PV system is exposed to non-uniform environmental conditions, which arise due to shading from objects in the environment, manufacturing mismatch between the modules, or physical damage and uneven aging effects on the modules over time. These 'real' conditions lead to multiple maxima being present in the P-V characteristics. Operating at local maxima can have a significant effect on the power available from a PV system. The challenge then becomes how to identify the Global MPP (GMPP) and continuously track this during system operation.

Many different approaches to MPPT have been proposed [1]–[5]. These techniques may be quite effective for tracking a local MPP, such as the Perturb and Observe (P&O) and Incremental Conductance (IncCond) methods, or may be designed to determine the global maxima such as the Particle Swarm Optimisation (PSO) [6]–[8] and Simulated Annealing (SA) [9]–[11] methods. Other techniques which provide accurate tracking and effective determination of the GMPP include DIRECT [12] and Fibonacci Search methods [13], [14], Chaos search [15] and power electronics based approaches [16]–[22]. These techniques however increase the complexity of the algorithm implementation and may also increase the cost due to a higher capability processor or additionally circuitry being required.

The purpose of the method proposed in this paper is to balance the need for continuous tracking (such as that required under an irradiance transient), and the need to perform this continuous tracking in the neighbourhood of the GMPP. To achieve these goals, the SA and P&O methods are presented in a hybrid implementation in this paper.

SA based MPPT methods are based on the process of annealing in metallurgy [23]. The search process uses a guided random search, where a prospective operating point may be selected as the new best operating point if it is greater in power than the previous best operating point or if it leads to a particular acceptance probability. A worse operating point may be selected as the new best operating point if the acceptance probability is high enough [24], [25]. This enables the method to fully search the solution space and to escape from local maxima if neighbourhood restriction is applied. An artificial temperature parameter is used to control the search and decreases based on some cooling schedule as the search progresses. As the

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temperature reduces, the probability of accepting a worse operating point also reduces. The acceptance probability is given by (1) [26], [27].

$$\Pr = \exp\left(\frac{P(k) - P(k-1)}{T(k)}\right) \tag{1}$$

Where, $P(k)$ is the power of the sampled operating point, $P(k-1)$ is the power of the best operating point selected so far and $T(k)$ is the current temperature of the search process.

The temperature can be reduced using a number of different functions. Common temperature reduction functions include the geometric cooling function [28]–[30] and Lundy [31] cooling schedule given in (2) and (3), respectively.

$$T(k) = \alpha T(k-1) \tag{2}$$

Where, $\alpha < 1$, is the geometric cooling constant.

$$T(k) = \frac{T(k-1)}{1 + \beta T(k-1)} \tag{3}$$

Where, the parameter β controls the Lundy cooling schedule.

The P&O method is one of the most commonly implemented MPPT methods due to its simplicity and ease of application [32]–[35]. As the method relies on perturbing the operating point and then observing if this improves the power from the system, the method will continuously search for the MPP. Unfortunately, if a large step size is used, such as when the method is searching a large potential operating range, oscillations in the power are observed at the MPP [33], [34]. Additionally, as the P&O method is based on finding the point where $\frac{dP}{dV} = 0$, and this condition exists at all MPPs, the method will remain stuck in the first maxima it locates, which may not necessarily be the GMPP.

Enhanced applications of the P&O method have included using a variable step size which allows large steps in the operating point to occur when it is far from the MPP, and smaller steps as the MPP is reached [32], [36], [37], or applying the P&O method as the second stage in two stage GMPPT strategy [38]–[42]. Typically, the applications where the P&O method is used in a two stage approach, rely on using a load line definition to move to an appropriate operating point before starting to search [39]–[42], or combining the P&O method with the PSO method [43] or fractional open-circuit voltage method [38].

The approach presented in this paper is unique as it combines the SA method in the first global searching stage with the P&O method in the second local searching stage. These techniques are complementary and lead to improved performance compared with when each technique is applied independently.

In Section II, the proposed hybrid method is described. Section III, presents simulation results demonstrating the overall performance of the proposed method and the performance after each stage of the method, on a PV system which experiences Partial Shading Conditions (PSC). In Section IV, conclusions are presented.

II. Proposed Hybrid MPPT Method

The proposed method is described in this section showing how the two techniques are complementary. The proposed hybrid method combines the SA method as a global searching mechanism with the P&O method for continuous local searching. Additionally, a global search is triggered by monitoring any significant changes in power as the P&O method is executed. Other potential reset conditions which could be incorporated in future implementations of the method include periodically sampling a point approximately one MPP above and below the GMPP to indicate if a change in conditions may have occurred. The results from [44] indicate that the spacing of the MPPs is about 80% of the open-circuit voltage and that the MPPs successively decline in magnitude as the voltage moves away from the GMPP. This result could be used to sample at a point approximately one MPP above and one MPP below the current operating point to provide an indication of if a change in conditions may have occurred. If the two sampled points have a power less than the power at the previous best operating point, then the method will return to the previous best operating point and continue searching with the P&O method. If a disproportionally large change in the power occurs for a step in voltage of the P&O method, the global search will also be initiated.

The algorithm operates by firstly performing the SA method to locate the neighbourhood of the global maxima. Then the P&O method with a small step size of 0.1 V is applied to perform fine tracking to the GMPP. After each perturbation in the P&O method, the decision criterion is applied to determine if a new global search is required. This decision criterion determines the percentage of power change since the last measurement, and if this is greater than some threshold, a global search is initiated. In general, when the P&O method is tracking around a MPP, only a small change in power should occur for each small step, so any large power variations observed are most likely due to the change in the conditions or the method having deviated from near the MPP.

The reset condition is given in (4) [8], where $P_{pv,new}$ is the current measured PV power at the operating point, and $P_{pv,last}$ is the previous PV power measurement. The threshold value applied in this particular case is 2%.

$$\frac{|P_{pv,new} - P_{pv,last}|}{P_{pv,last}} > threshold \tag{4}$$

The flowchart of the proposed method is shown in Fig. 1 and Fig. 2. Figure 1 details the overall algorithm and Fig. 2 shows the global MPPT routine.

III. Simulation Results

The simulation results are described in this section showing how the model is formulated and the key results obtained. Two types of simulations have been studied. In the first case, the proposed method is applied from an initial condition each time a known change in the environmental conditions occurs and in the second case the reset condition given in (4) is incorporated into the proposed hybrid MPPT technique.

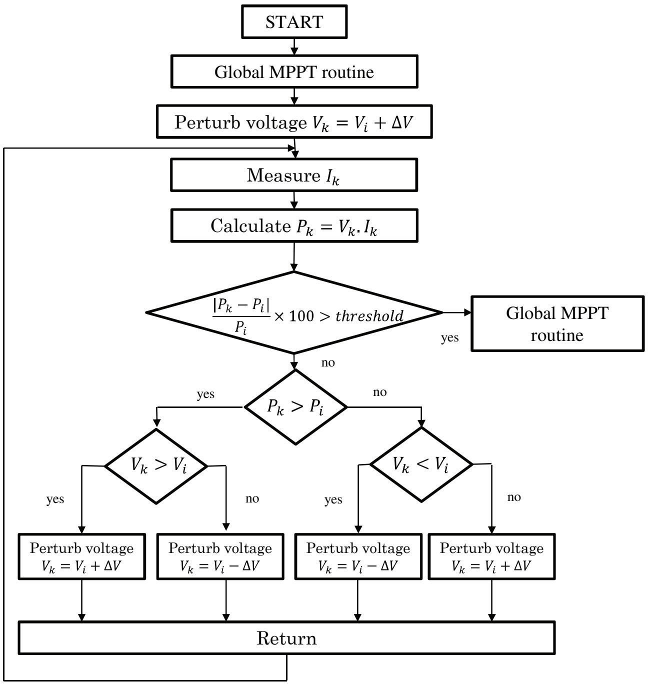

Figure 1. Flowchart of Proposed Hybrid MPPT method.

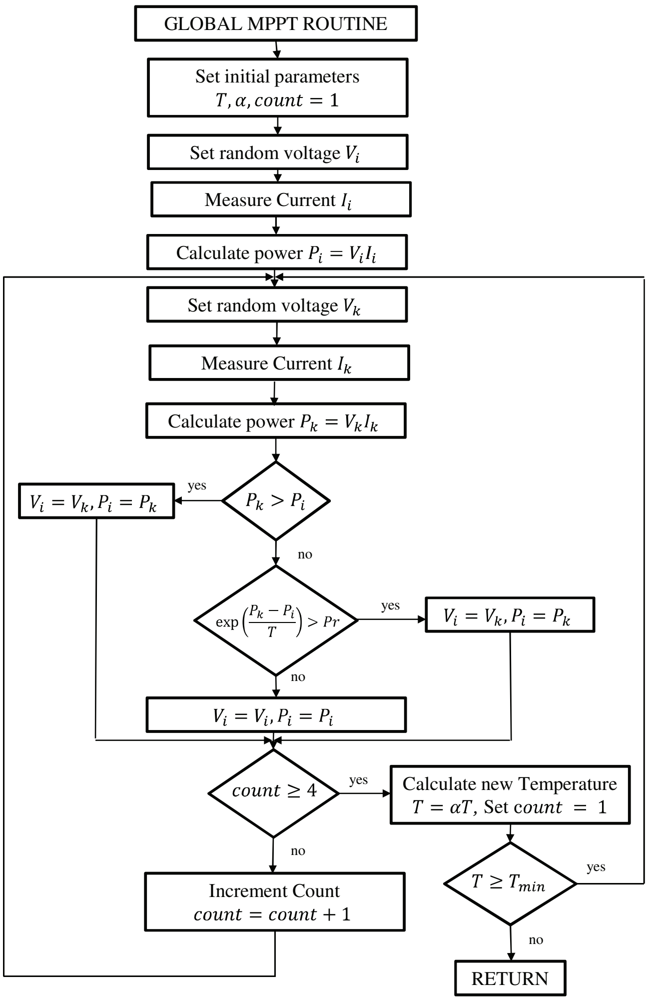

Figure 2. Flowchart of Global MPPT routine of hybrid MPPT method.

A. *Performance from initial condition*

For each different environmental condition which is applied to the system, the SA method is applied until it converges to a final operating neighbourhood and then the local search using the P&O method commences. The SA method is applied with a temperature update constant of 0.8, initial temperature of 25°C, final temperature of 0.2°C, and with temperature update being applied every four samples. This enables the SA method to have 56 samples to search the P-V curve to locate the neighbourhood of the global maxima. Once the SA method reaches its final temperature, the P&O method will continually search for the GMPP with a step size of 0.1 V. The results detailed in Table I, show the performance enhancement that the hybrid method has over just applying the SA method for GMPPT for a clear day irradiance profile. Table II shows the performance with a variable day irradiance profile. For Table I and Table II, the numbers of cases that converge under each convergence criterion are given for each stage of the method. Accompanying each irradiance profile is an obstacle placed in the environment which leads to shading on some of the panels resulting in a PSC P-V characteristic. Only the time when PSC has occurred is of interest in this study, which leads to a data set of 17 minutes of shading for the clear day profile and 64 minutes of shading for the variable day profile. The irradiance profiles are obtained from one minute solar irradiance data provided by the Australian Bureau of Meteorology [45] at the Cape Grim weather monitoring site in Northern Tasmania.

A variety of convergence measures are defined where a 1% convergence rating indicates that the final operating point of the method has converged to within 1% of the known GMPP voltage and power. The other convergence measures are defined similarly.

For the clear day profile, of the 17 test cases considered, 14 cases converged to the GMPP location. Of the three cases that did not converge, 2 converged to a local MPP with similar power to the GMPP and the third converged to a local MPP with considerably less power than the GMPP.

For the variable day profile of the 64 test cases, 63 converged to the GMPP. In the other case the method converged to a local MPP with less power than the GMPP.

In each case it can be seen that the performance of the method in converging to the GMPP under all convergence measures improves once the local searching stage has been applied. This highlights the key feature of the SA method which is to converge to the neighbourhood of the GMPP, but not necessarily exactly to the best operating point.

TABLE I. PERFORMANCE IN CONVERGING TO GMPP UNDER CLEAR DAY IRRADIANCE PROFILE

	After first stage (SA) (number of cases that converge)	**After second stage (P&O)** (number of cases that converge)
1% convergence	4	14
2% convergence	9	14
3% convergence	12	14
4% convergence	13	14
5% convergence	13	14

TABLE II. PERFORMANCE IN CONVERGING TO GMPP UNDER VARIABLE DAY IRRADIANCE PROFILE

	After first stage (SA) (number of cases that converge)	After second stage (P&O) (number of cases that converge)
1% convergence	20	63
2% convergence	34	63
3% convergence	40	63
4% convergence	44	63
5% convergence	50	63

B. *Performance with reset condition*

The reset condition and full implementation of the hybrid MPPT method, as detailed in Fig. 1 and Fig. 2, is considered in this section. The method is implemented with the same parameters outlined in Section III.A, but now a change in environmental conditions is determined by the algorithm using the reset condition given in (4). A threshold value of 2% is used with the reset condition to determine when a global search may be required.

The full implementation is applied to the variable day irradiance profile with a single obstacle placed in the environment as outlined in Section III.A.

The number of times that the reset condition is not applied when a slight change in the environmental conditions occurs is in 12 of the 64 cases. In most of these cases, only a slight change in the voltage at the GMPP occurred and only a small change in the power at the GMPP occurred. In 19 cases, a global search was initiated even though the GMPP voltage did not change significantly (<1.5V change) which suggests that perhaps a larger threshold should be applied in (4). The convergence of the method after the SA stage and P&O stage of the method for the 52 cases where the global search is initiated are outlined in Table III. The results show similar convergence to the GMPP in the full hybrid method as in the test cases considered in Section III.A. In only one case the method converged to a local MPP. In cases where the global search was not initiated, the P&O method ensured continuous tracking within the 1% convergence rating for all 12 test cases.

Examples of the voltage and power tracking under the different conditions are detailed in Fig. 3-6. In Fig. 3 and Fig. 4, the voltage and power tracking, respectively, are shown when the global search is initiated. In Fig. 5 and Fig. 6, the voltage and power tracking, respectively, when two changes in the environmental conditions occur and do not trigger a global search, are shown. In the simulation, each shading and environmental condition is applied for 10 seconds of simulation time. The solid line shows the GMPP voltage and power and the dashed line shows the voltage and power tracking of the algorithm.

TABLE III. PERFORMANCE IN CONVERGING TO GMPP UNDER VARIABLE DAY IRRADIANCE PROFILE WITH RESET CONDITION

	After first stage (SA) (number of cases that converge)	After second stage (P&O) (number of cases that converge)
1% convergence	18	51
2% convergence	30	51
3% convergence	37	51
4% convergence	38	51
5% convergence	40	51

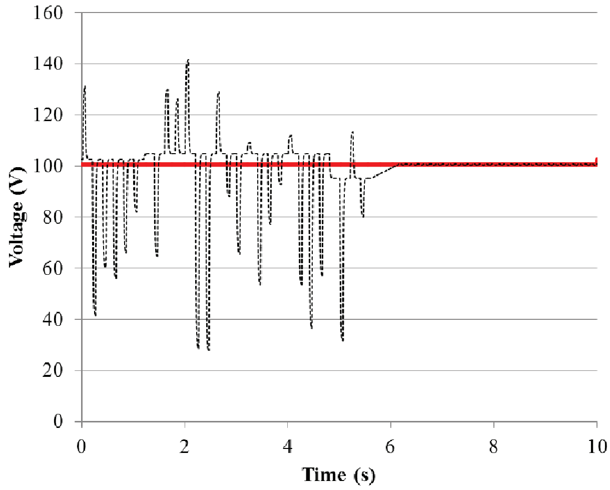

Figure 3. Voltage tracking using hybrid method when a global search is initiated.

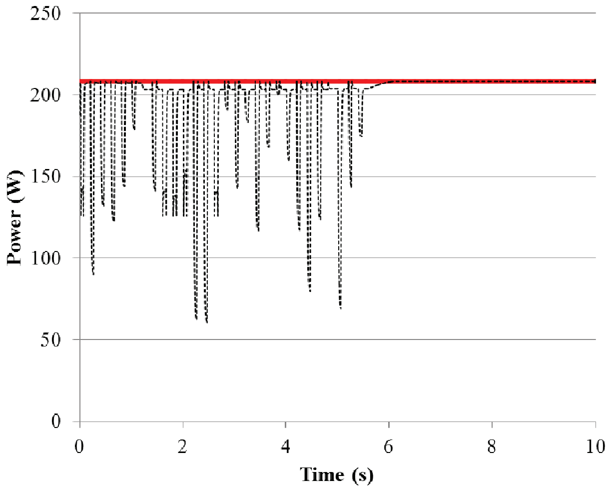

Figure 4. Power tracking using hybrid method when a global search is initiated.

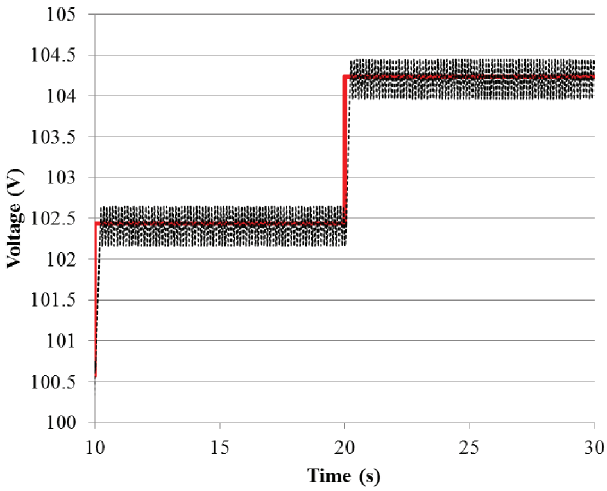

Figure 5. Voltage tracking using hybrid method when a change in conditions occurs and a global search is not initiated.

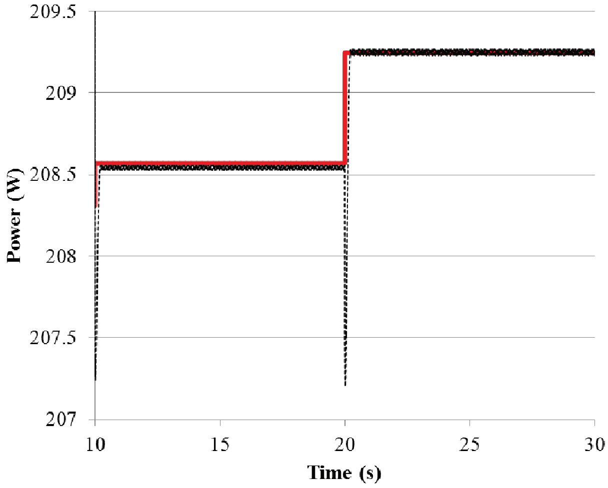

Figure 6. Power tracking using hybrid method when a change in conditions occurs and a global search is not initiated.

IV. Conclusions

The proposed hybrid SA and P&O method performs well in achieving GMPP identification and continuous tracking. By combining the two techniques, some of their key limitations are overcome including the inability of the SA method to continually track and the limited capability of the P&O method to locate global maxima. The presented simulation results show that the combination of the techniques presents a simple yet robust method for GMPPT. Future work will include optimising the parameters of the SA method, and hybrid method, and further development of a suitable threshold to detect when a change in the environmental conditions has occurred.

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