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# Probability distribution of GMPP under different temperatures and irradiation conditions

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**Abstract**—A photovoltaic (PV) array having multiple cells in series with bypass diodes may exhibit multiple power peaks under uneven irradiation, and an algorithm is required to reach the global maximum power point (GMPP). While a lot of methods have been proposed in the literature, they are either complex or not fast enough for systems around 1-100W operating under fast-varying irradiation conditions of around 100ms. This paper highlights a rapid and efficient characterization of the PV array using MATLAB to find the probability distribution of GMPP under multiple irradiation conditions and different temperatures. The resulting distribution result for an example of 3 PV macro cells with 3 bypass diodes will be presented and from the obtained result, we simulated a simple algorithm capable of predicting in which zone GMPP is located up to 96% of the time.

## I. INTRODUCTION

The scope of this study is a solar harvester system of around 1-100W, working under fast-varying and uneven irradiation. It consists of 3 macro cells in series with 3 bypass diodes as shown in Figure 1. This configuration when receiving uneven irradiation may exhibit multiple power peaks as shown in Figure 2. When we take for example the case where the 3 macro cells received respectively 1000W/m<sup>2</sup>, 800W/m<sup>2</sup> and 400W/m<sup>2</sup>, the GMPP voltage substantially deviates from the case where all 3 macro cells are under the same irradiation of 1000W/m<sup>2</sup>. Therefore, there is a need for a simple and fast converging GMPP algorithm if the system is to work optimally under very fast varying irradiation of around 100ms. Even though a lot of innovative and sophisticated methods have been proposed in the literature to tackle this problem, they either require too much computing resources or is slow for our use case [1]. Sweeping the entire voltage and measure the power extracted would be the simplest method, but it is limited by system dynamics and potential operating points that GMPP may never be found.

In this paper, we will start with a method to solve for the power output of a solar array and quickly sweep a lot of irradiation conditions to register the distribution of GMPP in MATLAB. The distribution result will then be presented and used to implement a simple simulated GMPP algorithm. Finally, we will be discussing the eventual applications or improvements that can be made to this study.

## II. METHODS

Due to the sheer amount of simulation passes needed, we decided to solve mathematically for the output power of the solar array to optimize MATLAB run time. We model our macro cell using the single diode model as in Figure 3.

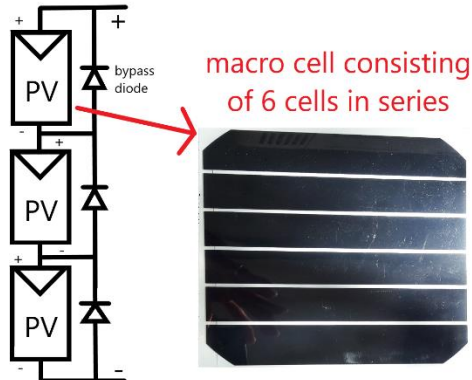


Figure 1 Example of 3 PV macro cells in series with bypass diodes

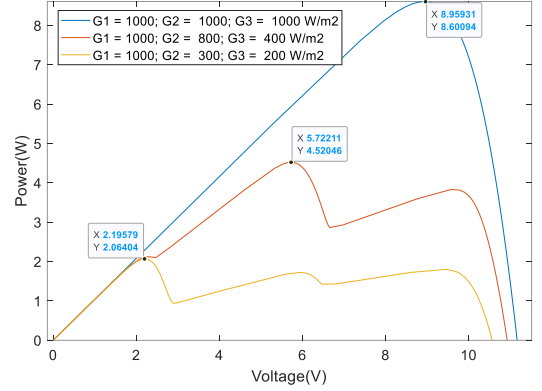


Figure 2 Power curves of 3 PV macro cells in series with bypass diodes under 3 irradiation conditions in W/m<sup>2</sup> to illustrate the effects of partial shading. This is reflected in the irradiation received by each cell.

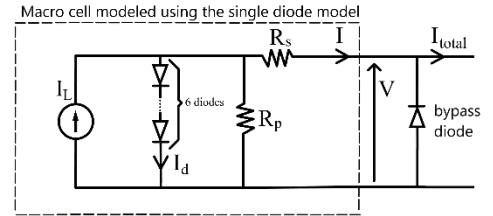


Figure 3 Single diode model of the PV macro cell

Let us first discuss how to solve for the output current of the macro cell, whose equation can be written as (1) [2].

$$I = I_L - I_d - \frac{V + IR_s}{R_p} \quad (1)$$

with  $I_L = \frac{G}{G_{ref}} (I_{scn} (1 + \frac{R_s}{R_p}) + k_i (T - T_{ref}))$

$$I_d = \frac{I_{scn} + k_i (T - T_{ref})}{e^{\frac{q}{kT} (V_{ocn} + k_v (T - T_{ref}))} - 1} (e^{\frac{q}{kT} (V + IR_s)} - 1) = I_0 (e^{\frac{q}{kT} (V + IR_s)} - 1)$$

with  $G$  the PV macro cell irradiation,  $G_{ref}$  the standard irradiation condition,  $T$  the PV cell temperature,  $T_{ref}$  the reference temperature,  $V_{ocn}$  and  $I_{scn}$  the nominal open circuit voltage and short circuit current respectively at standard test condition,  $k_v$  and  $k_i$  the voltage and current temperature coefficient respectively,  $A$  the diode ideality factor,  $q$  the electron charge and finally  $k$  the Boltzmann constant.

Inspired by the work in [3], we use the Lambert function to solve  $I$

for a given  $V$ ,  $G$  and  $T$ . Let  $X = \frac{I_L + I_0 \frac{V}{R_p}}{(1 + \frac{R_s}{R_p})}$ ,  $Y = \frac{I_0 e^{KV}}{(1 + \frac{R_s}{R_p})}$  and  $K = \frac{q}{kT}$ ,

we can transform (1) into (2).

$$I = X - \frac{\text{Lambert}(KYR_s e^{KXR_s})}{KR_s} \quad (2)$$

With the bypass diode added in parallel with the macro cell, the output current of the module becomes (3).

$$I_{total} = X - \frac{\text{Lambert}(KYR_s e^{KXR_s})}{KR_s} + I_r e^{\frac{-V}{V_{th}}} \quad (3)$$

with  $I_r$  the diode reverse saturation current and  $V_{th}$  the diode thermal voltage. For simplicity,  $I_r = 50\text{nA}$  and  $V_{th} = 26\text{mV}$  were applied for this study.

The global voltage of a series of macro cells with bypass diodes is obtained by adding their respective voltage for a given current. The result should look like Figure 4. We can then multiply the current and voltage to obtain the total output power of the array.

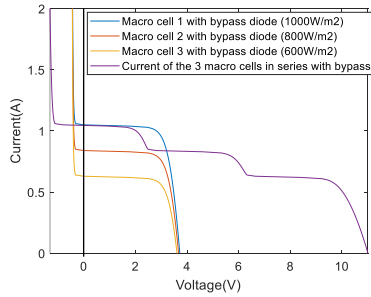


Figure 4 I/V of 3 PV macro cells with bypass diodes at 25°C.

### III. RESULTS

#### A. Distribution results

The following parameters were extracted from experiments and applied to the simulation of our PV macro cells in MATLAB:  $I_{scn}=1.05A$ ,  $V_{ocn}=3.725V$ ,  $k_i=0.0023A/K$ ,  $k_v=-0.0026V/K$ ,  $R_s=0.34\Omega$ ,  $R_p=180\Omega$  and  $A=5.2$ .

By first fixing macro cell 1 to 1000W/m<sup>2</sup> and varying the other two from 0 to 1000W/m<sup>2</sup>, we can visualize the amount of power generated by the array using a color map in Figure 5 and the GMPP zoning on the voltage range using a contour map in Figure 6.

While these methods give us a good visualization of how GMPP are distributed, it is not easily scalable to bigger arrays of solar cells with more bypass diodes. By varying the irradiation of all macro cells between 0 and 1000 W/m<sup>2</sup> in steps of 20 W/m<sup>2</sup> and registering how often a given voltage is GMPP while assuming all irradiation conditions are equally probable, we have the distribution graph in Figure 7. This method could be scaled up for many more PV cells with more bypass diodes. As expected, the GMPP falls into 3 distinct zones, [2V, 2.7V], [5.1V, 6.5V] and [8.4V, 10.6V], on the voltage range. We also observe the temperature impact where higher temperatures shift the peaks toward lower voltage values, indicating a drop in performance.

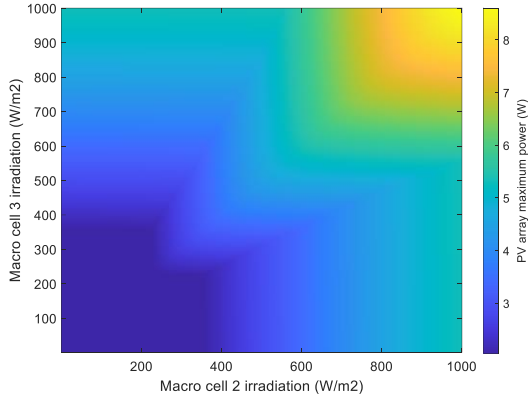


Figure 5 Power distribution map measured in W at 25°C

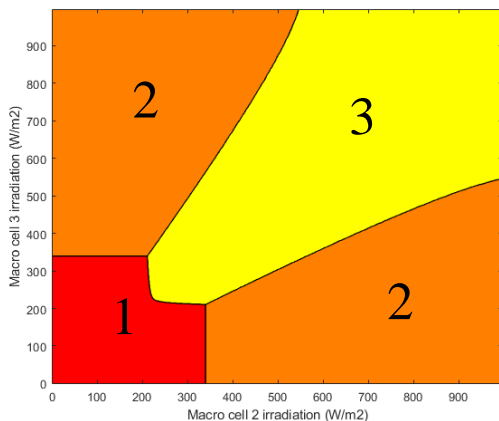


Figure 6 Voltage at peak power distribution map at 25°C. Zone 1 = [0,  $V_{ocn}$ ], zone 2 = [ $V_{ocn}$ ,  $2V_{ocn}$ ] and zone 3 = [ $2V_{ocn}$ ,  $3V_{ocn}$ ]

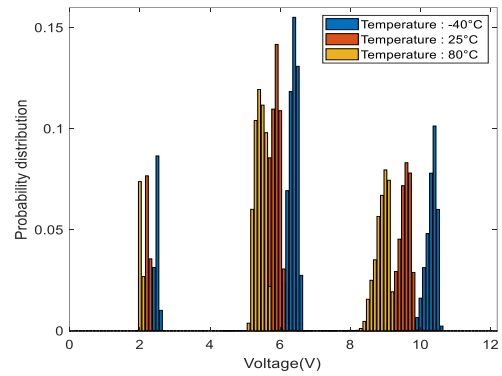


Figure 7 Probability density of voltage points where GMPP is located for 3 different temperature conditions.

#### B. Simulated algorithm

With the 3 zones of GMPP clearly delimited, our proposed algorithm is to take one fixed voltage value in each zone, evaluate its power, and the one with the highest power will be chosen as the starting point to apply a perturb and observe (P&O) to reach true MPP. To maximize this probability, we chose the voltage point with highest MPP probability at 25°C in each zone, which are 2.2V, 5.9V and 9.6V. This is chosen because 25°C is the closest to potential deployment situation. Our criterion for a successful prediction is when the chosen starting point falls into the same zone as true MPP, which we have defined to be at most 1.2V away from true MPP seeing how the peaks are distributed. By simulating this algorithm when performing the sweep, we achieved 361379 successful predictions over 375000 conditions checked, netting 96.4% success rate. This is impressive given that only a limited voltage range was checked, and the convergence time would mostly depend on the P&O, which at this point is very well optimized in the literature as can be shown in [4] and [5].

### IV. CONCLUSION & PERSPECTIVE

This paper primarily aims at presenting a method to visualize the GMPP distribution and a simulated algorithm based on this result. We will follow up with another paper with its implementation and experimental results. By visualizing the distribution of GMPP under a wide range of irradiation conditions, we can observe the clear limits of MPP zones and implement a simple yet fast algorithm that might drastically reduce the convergence time toward GMPP. However, this result still implies equal probability of all irradiation conditions which may not correctly represent the real-world use case and the probability of some GMPP zones may be heavily skewed compared to others. To improve on this, we are working on a field study and registering how much light the cells receive. For example, in a target use case like a cyclist, a test ride with pyranometers to measure the amount of daylight around a popular cycling route could be useful information to incorporate as probability weight to improve the accuracy of the probability distribution.

#### ACKNOWLEDGEMENT

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