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Probability distribution of GMPP under different irradiation and temperature conditions for GMPP tracking algorithm

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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, therefore an algorithm is required to reach the global maximum power point (GMPP). While a lot of methods for GMPP tracking have been proposed in the literature, they are too complex for a system around 1-100W operating under partial shading and fast-varying irradiation conditions of around 100ms. This paper first highlights a rapid and efficient mathematical simulation of the PV array using MATLAB to find the probability distribution of GMPP under multiple irradiation conditions and different temperatures. The resulting GMPP distribution for an example of 4 PV macro cells with 4 bypass diodes in series is presented, both under the assumption of equal probability as well as a real-world operating condition. From the obtained result, we simulated a simple GMPPT algorithm capable of predicting which zone GMPP is located up to 96% of the time for both distributions.

Keywords—photovoltaic, global maximum power point, GMPPT algorithm, probability distribution of GMPP, MATLAB, Lambert function

I. INTRODUCTION

The scope of this study is a solar harvesting system of around 1-100W, working under fast-varying and uneven irradiation. It consists of 4 PV macro cells in series with 4 bypass diodes as shown in Figure 1. This configuration when receiving uneven irradiation may exhibit multiple power peaks as shown in Figure 2 and for each condition in this example, we can see that the maximum power point is located at a different voltage value. 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. This criterion is estimated for a hypothetical use case where a 1m shadow covers our solar panels moving at around 5m/s. It also considers the capabilities of our system, notably the response time of the solar panels and converter. While there are a lot of innovative and sophisticated methods proposed in the literature to tackle fast-varying solar irradiation [1] or partial shading problems [2] [3], there are none that can satisfy both of these criteria while being simple and efficient for our target application. 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 where GMPP may never be found. The logical increment is to limit the search down to only zones where there are potential GMPP, such as the methods proposed in [4]. For this purpose, we need an overall view of how the system behaves under a lot of different conditions to zone the voltage range effectively.

In this paper, we will start with a method to solve for the power output of a solar array enabling us to quickly check a lot of irradiation conditions and register the distribution of

GMPP in MATLAB. A set of experimental data would be provided to verify the validity of the mathematical simulation. The distribution result will then be presented, both under assumption of equal probability of all irradiation conditions as well as one from experimental measurements. We will then use it to propose a simple simulated GMPP algorithm. Finally, we will be discussing the eventual applications or improvements that can be made to this study.

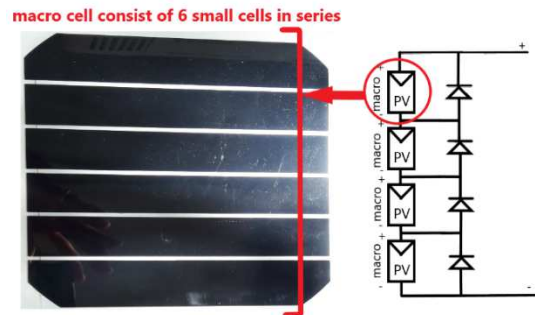


Figure 1 Example of 4 macro cells with bypass diodes in series

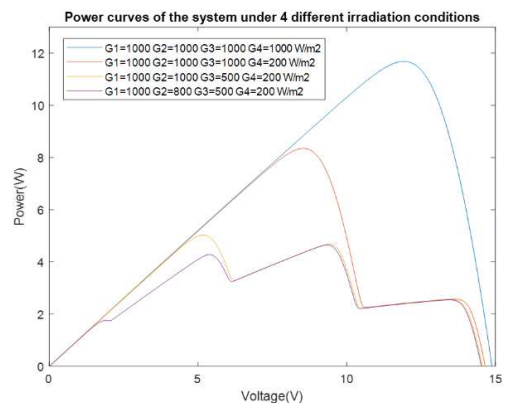


Figure 2 Power curves of 4 PV macro cells in series with bypass diodes under 4 irradiation conditions in W/m² to illustrate the effects of partial shading. This is reflected in the irradiation received by each cell.

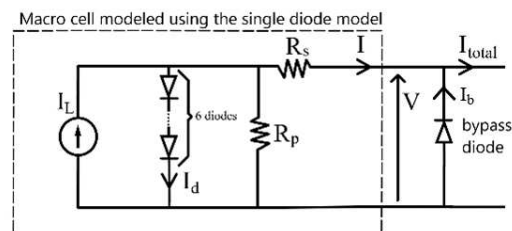


Figure 3 Single diode model of the PV macro cell and its respective bypass diode

II. MATHEMATICAL SIMULATION OF THE SYSTEM

While Simulink can be used to simulate a PV system with partial shading or fast-varying irradiances without much difficulty [5], our study necessitates a lot of simulation passes and Simulink is too inefficient for this task. Therefore, we need to solve mathematically for the output power of the solar array to optimize MATLAB run time. We model our macro cells using a modified single diode model as in Figure 3, as this offers a good compromise between simplicity and accuracy [6].

A. Mathematical 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) [6].

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

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

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

with G the PV macro cell irradiation, G_{ref} the standard irradiation condition, T the PV macro 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 k the Boltzmann constant.

B. Solve for the output current of the system

Inspired by the work in [7], 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 $K = \frac{q}{AkT}$, we arrive at equation (2).

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

The bypass diodes are modeled using a simplified version of the Shockley diode equation:

$$I_b = I_r e^{\frac{-qV}{NkT}} \quad (3)$$

with I_r the bypass diode reverse saturation current and N the bypass diode ideality factor.

Connecting the bypass diode added in parallel with the macro cell, the output current of the block is expressed as follows:

$$I_{total} = X - \frac{\text{Lambert}(KYR_s e^{KXR_s})}{KR_s} + I_r e^{\frac{-qV}{NkT}} \quad (4)$$

Equation (4) is used to determine the output current of the PV macro cell and its bypass diode for an array of input V , G and T in MATLAB.

To obtain the overall current output of the 4 PV macro cells in series with bypass diodes, we need to add their respective voltage for a given current value. However, because we are solving current for given voltage, the resulting current may not be evenly spaced to easily add their respective voltage points together. Therefore, we used the “*interp1()*” function in MATLAB to obtain an evenly spaced current array with their associated voltage value. The result of interpolation and addition is illustrated in Figure 4.

III. VALIDATING THE SIMULATION METHOD

To reliably simulate the system, we need to have a good estimation of the real-world system. The two important

elements in this work are the bypass diodes and the PV macro cells. In this section, we will be discussing the characterization and parameter estimation of these two components.

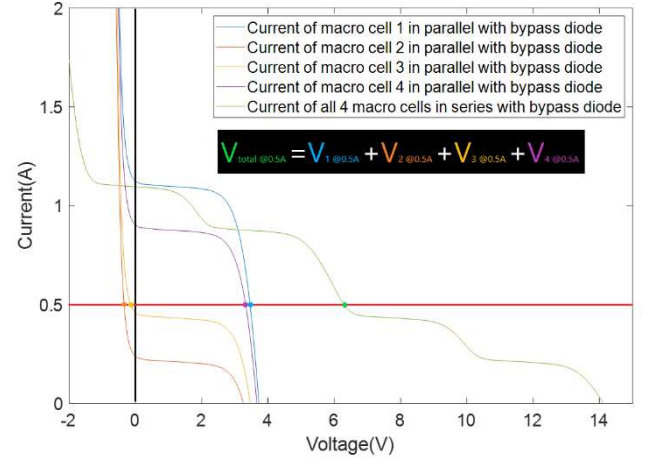


Figure 4 Resulting current output of 4 macro cells with bypass diodes in series constructed from interpolation and addition

A. Characterisation of the bypass diodes

The bypass diodes used are SL447, which are characterized using an Agilent N6705B and the results are then used to find the best estimation of the diode mathematically using the Shockley diode equation. The parameter fit is done using “*cftool()*” in MATLAB. We determined that $N = 4.23$ and $I_r = 0.017A$, and the resulting estimation is shown in Figure 5. This estimation although not perfect should be enough to give us a decent estimation of the diode’s behavior.

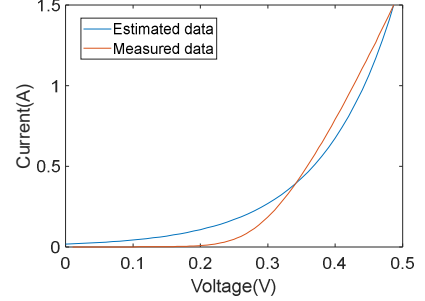


Figure 5 Experimental and simulated I-V curve of the bypass diode

B. Characterisation of PV macro cells



Figure 6 Test setup to simulate the effects of partial shading

The first step is to well characterize each of the 4 panels individually to identify their simulation parameters. This step is done under good daylight condition, measuring at $960W/m^2$

using a CMP3 pyranometer and the temperature is measured using a FLIR thermal imaging camera right after the I/V read. Following the method as described in [6], we arrived at the following parameters list that best fits the 4 panels:

- $V_{ocn} = 3.8V$
- $I_{scn} = 1A$
- $R_s = 0.2\Omega$
- $R_p = 120\Omega$
- $A = 9.5$

They are again measured using the same method but with the cardboard covers on (Figure 6) to confirm that the mathematical estimation holds across various irradiation values and Figure 7 shows good estimation by the model.

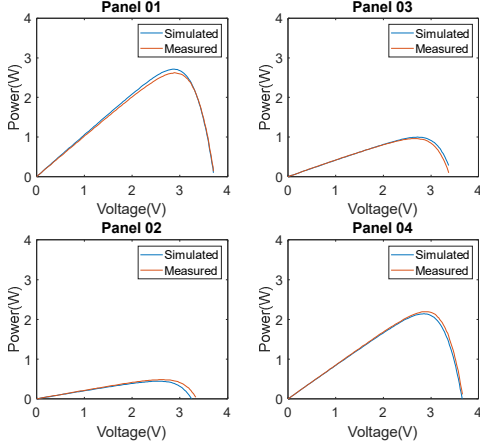


Figure 7 Comparison between the simulated and experimental output of the PV macro cells with cardboard covers

Finally, we connect the 4 solar panels in series with bypass diodes, with covers on to simulate the effect of partial shading and measure the entire system overall power output. This is compared to the output generated by the mathematical model as shown in Figure 8.

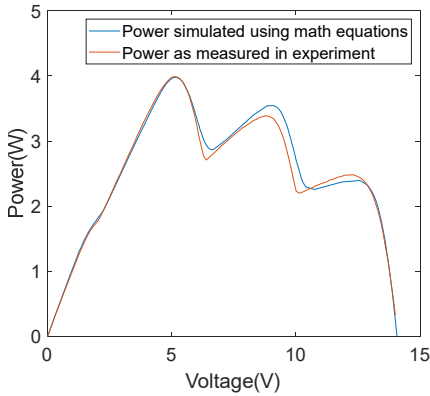


Figure 8 Output power generated by mathematical simulation compared to experimental data

Even though the mathematical estimation and the experimental result is not a perfect overlap, for the purpose of quickly finding GMPP under different conditions, we believe this level of precision should be sufficient.

IV. DISTRIBUTION OF THE GMPP

Using this mathematical method, we can simulate a lot of conditions in a reasonable amount of time. In this section, we will be discussing how the GMPP are distributed on the voltage range for two cases: one where we suppose all

irradiation conditions are equally probable and one where the irradiation conditions are from measurements during a bike ride.

A. Equal probability between irradiation conditions

By varying the irradiation of all macro cells between 0 and 1000 W/m² in steps of 25 W/m² and registering how often a given voltage is GMPP while assuming all irradiation conditions are equally probable, we have the distribution graph in Figure 9. The sweep is performed under 3 different temperatures: -40°C, 25°C and 80°C. As expected, the GMPP fall into 4 zones, [1.6V, 2.6V], [4.6V, 6.4V], [7.3V, 10.1V] and [10.1V, 13.7V] on the voltage range. Even though there is a slight overlap between the last two zones, it happens for 2 very different temperature conditions. The graph also shows that higher temperatures shift the peak distribution toward lower voltage values, indicating a drop in performance.

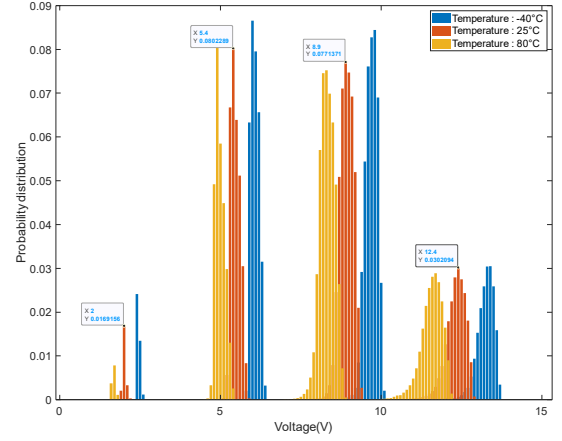


Figure 9 Probability density of GMPP location on the voltage range for 3 different temperature conditions, under equal probability assumption



Figure 10 Experiment to measure the potential irradiation as received by our system during a bike ride

B. Irradiation measured during bike ride

To improve on the previous distribution result, we used 4 pyranometers to measure the amount of light that our PV panels would likely receive during a potential deployment, in this case a bike ride around Toulouse, France (Figure 10). We used 4 SP Lite2 pyranometers, each acquired at 5kHz using a NI-6009 DAQ and a Labview program. For processing, we take the average of 50 consecutive values to filter out abrupt variations or errors. Therefore, the effective sampling time is 10ms. The resulting irradiation distribution is shown in Figure 11. These values are rounded to the nearest tens, and we count how many times each unique condition occurred. With this information, we arrived at the GMPP distribution

result for the bike ride as shown in Figure 12. We observe that the zones are not as clear cut as the ones in Figure 9 but we can still identify them. Moreover, we also see that the overall probability of each zone has changed.

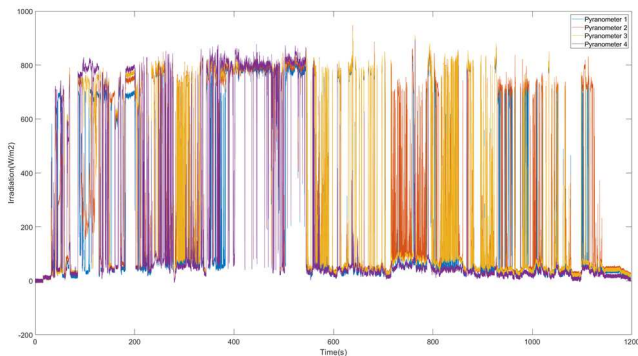


Figure 11 Irradiation measurement for 4 PV macro cells during bike ride, made from 10h34 to 11h22, 21/06/2021. Ambient temperature at 28°C

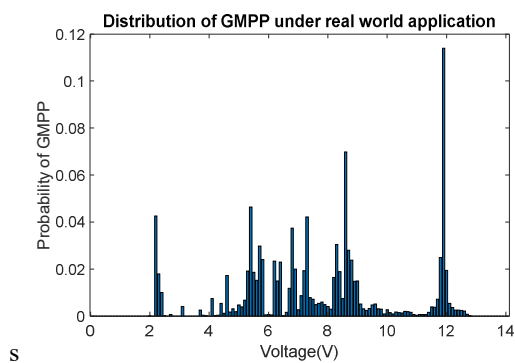


Figure 12 Probability density of GMPP location on the voltage range during the bike ride

V. GMPP TRACKING ALGORITHM

With the 4 zones of GMPP clearly identifiable, our proposed algorithm is to take one fixed voltage value in each zone, measure the available power, and choose the highest one as the starting point to apply a perturb and observe (P&O) algorithm 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 2V, 5.4V, 8.9V and 12.4V. This is because 25°C would be closest to our real-world deployment. We also assume that our P&O will converge toward the nearest local MPP. Therefore, our criterion for a successful prediction is when the power gradient between the starting point and the GMPP is only increasing or decreasing.

In the case of equal probability assumption of all irradiation conditions, the sweep was performed in step of 25 W/m² from 0 to 1000 W/m² for all 4 PV macro cells under 3 different temperatures, totaling 7680000 conditions. The simulated algorithm made 7387714 good predictions, netting 96.19 % success rate. In the second case of irradiation measured during a bike trip, there are a total of 38802 distinct irradiation conditions and the algorithm successfully pick a good starting point 37857 times, netting 97.56 % success rate. This is a very good result given that only 4 distinct operating points were checked. The convergence time can be improved by implementing a good P&O algorithm such as the ones put forward in [8] [9].

VI. CONCLUSION AND PERSPECTIVE

This paper primarily aims at presenting a method to visualize the GMPP distribution, under equal probability assumption as well as a real-world application. From this, we propose a simple algorithm that has a high probability of finding the true MPP after only 4 measurements. However, while this method is applicable for our target application which includes a small number of PV macro cells and our visualization result could be scaled up for bigger arrays, the authors of [10] have discussed in depth about its potential weakness, notably very long simulation times. Furthermore, this work is also dependent on the array configuration, limiting its portability to different PV arrays. Finally, while we have continued to simulate the proposed algorithm in Simulink with promising results, we have yet to properly test it out under an experimental context, which will be published in a future article.

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