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Design of a Global Maximum Power Point Tracking (GMPPT) for PV array based on precise PV shadow model

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***Abstract*—This paper presents the modeling of a photovoltaic system under complex shading conditions. The approach integrates a complete PV array with each cell modeled separately including shadow coefficients depending on a percentage of area impacted and the level of irradiance (named shaded opacity). A dedicated global maximum power point tracking algorithm is developed taking into account all behavior of the system, in particular, under compound shading conditions. The Hybrid Bond-Graph tool is chosen to facilitate the modeling of the energy flows of the inner of PV cell, between the cells, panels and boost converters in the aim of future work in complex micro-grid and energy conversion.**

***Index Terms*—MPPT, shading, PV model, shadow area, PV power losses.**

I. Introduction

In the last few years, solar or photovoltaic (PV) systems has received much attention, especially for the ease of implementation and for its applications in rural and urban areas. A PV system is composed commonly of an arrangement of several components as: a) solar panels, b) MPPTs, c) DC-DC converters, and d) DC-AC inverters. Main factors that affect the conversion of solar energy to electricity (energy losses) are: 1) climatic and environmental factors (presence of obstacles between sunlight and solar panels, temperature increases), 2) inefficiency associated with properties of conversion of the semiconductors used in the manufacture (e.g: Crystalline-Si cells 25.6%), and c) operating factors (work points of system devices). In this paper, we will address the problem of finding the ideal working point of one or several solar panels. This is an open problem in this area, for which we propose an algorithm based on the development of a high precision model of solar panels. That allows us to make increments of variable size of the load resistance thus achieving small variations of the slope $1/R$. This allows us to compare very close points of the I-V curve. Inevitably, allow us to evaluate the power produced by the system, and finding also the points of slope 0 where are the local maximum power point (LMPP) and the global maximum power point (GMPP).

It exists several causes of PV efficiency losses related for example to the shading such as trees, adjacent buildings or soiling [1], [2]. This problem cause low efficiency-per-m^2 in the installed system. However, the use of this energy is affected by shadows. PV array is a difficult forecasting source of power highly depending on the temperature and the irradiation level. Today, maximum power point tracking (MPPT) is included in main converters dedicated to maximize the efficiency of PV panels. In the literature, it exists many methods to track the maximum power point (MPP) of PV generator [3], [4] with high efficiency in homogeneous shadow. Nevertheless, under a partially shading condition, multiple MPP are visible on the I-V characteristic of the PV module. The conventional MPPT techniques may lead to the operation at a local maximum power point not exactly the global maximum power point. In [5]–[7], a suitable GMPP algorithm has been developed to extract the MPP of the PV array under partial shading conditions. Even with bypass diode protection and a MPPT control, PV array generates low efficiency production, and failures linked to effectiveness non-homogeneous irradiation.

The presence of the complex partial shadows affects drastically the efficiency and operating state of the PV modules. Several authors have developed modeling approaches to understand the impact of the shadows on the PV module performances [8]. In [9] is presented a shadow coefficient PV model. It is important to quantify and to improve the shadow impact on the electric conditions of PV arrays [10]. In [11] Mohapatra has suggested that it was necessary to develop an accurate mathematical model under shading condition that allows the track of maximum power at partially shaded PV array. Its properties can easily be used for complex system such as multi-scale and multi-energy (i.e, electrical, mechanical, thermal, etc).

The purpose of this study consists in designing a new MPPT algorithm using a precise PV model including the equivalent shadow area and the level of shadow opacity. The Bond-Graph (BG) is chosen to implement the precise PV model of each PV cell. The BG is a graphical representation of a physical

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dynamic system allowing the conversion of the system into a state-space representation. It can incorporate multiple domains seamlessly and can use power variables composed of flow and effort.

This paper is organized as follows: Section II show the GMPP algorithm proposed. Section III shows the model and the simulation of PV model and the MPPT proposed. Section VI show the conclusions of paper.

II. Maximum power point tracking (MPPT)

Aim of the MPPT is optimize the use of the PV systems, specifically to maximize the module or sting or array photovoltaic efficiency to guarantee maximum production. The characteristics of the non-linear curve P-V are affected for the continuous variations of environmental conditions (irradiance, temperature, and shadows). When the PV module receives uniform irradiation from the sun in all the cells, the power-voltage (P-V) curve shows a unique peak [12]. But when PV module receives partial shading, it shows multiple peaks on the P-V curve [13]. Each peak receive the name of LMPP, and the GMPP. In Fig(1) can see two panels, one without shadows that produce a P-V curve with a single maximum, and the other a panel with non-homogeneous shadows that produces three local maximum, and a global maximum.

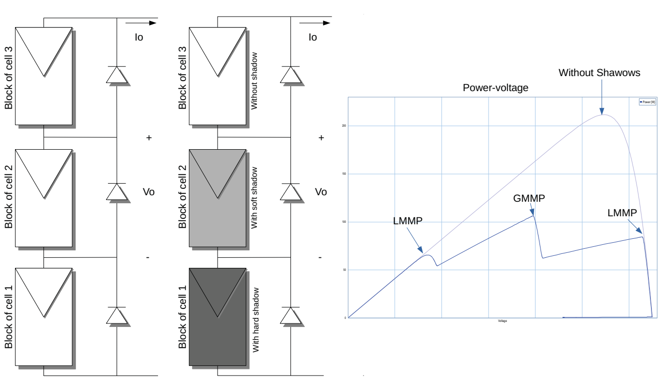


Figure 1. Shadow and its influence on P-V curve

Conventional algorithms fail to find the GMPP among the local point, which lead to reducing the overall efficiency of the system [1]. In fact, to improve the global point tracking capability, the literature proposes various techniques that can be classified on conventional, non-conventional, and hybrid (mixture between conventional and no-conventional algorithms). In [14] are discussed MPPT methods of PV system for normal and partial shading conditions. In [15] the most popular and used MPPT techniques, PV array configurations, system architectures and circuit topologies are discussed.

1) State of art in MPPT in ideal condition: In [16] are shown a resume of MPPT algorithms in normal operating conditions (i.e., without shadow). In [17] are compared the performance quantitatively for different working conditions: fixed step size P&O method, variable step size incremental conductance method, and hybrid step size Beta method. The traditional algorithms to find MPPT in a PV system without shadow are the following:

- Perturb & observe (P&O)
- Incremental conductance (IC)
- Fractional Open Circuit Voltage (FOCV)
- Hill Climbing (HC)

2) State of art in MPPT in partial shading condition:

a) Conventional algorithms: In [17] is proposed a conventional MPPT method and it is compared with Perturb and Observe (P&O) and Incremental Conductance (INC) MPPT method. In [18] is proposed a algorithm, and it is compare with others two algorithms: Particle Swarm Optimization (PSO) and Cuckoo Search (CS). In [19] is also presented ones tests the most commonly used MPPT methods at long term environmental conditions and evaluated their performance. In [20] are compared the methods: perturb and observe (PO), incremental conductance (IC), sliding mode (SM), and fuzzy logic (FL) tracker.

b) Meta-heuristic algorithms: In [11], [21] are presented a review of various MPPT algorithms under partial shading condition. The main no-conventional (meta-heuristic) algorithms for PV system without shadow are the following:

- Ant colony system
- Cuckoo Search Algorithm
- Cat Swarm Optimization algorithm
- Bats algorithm
- Particle Swarm optimization
- Genetic algorithm [22]

c) Hybrid Algorithms: These algorithms mix the advantages of methods that use conventional algorithms with the advantages of methods that use meta-heuristic algorithms. In [23] a algorithm including an artificial neural network and a hill climbing method is proposed. In this perspective, in [5] and [24] are proposed hybrid algorithm, compared with others algorithms.

A. MPPT algorithm based on the modeling of the photovoltaic system

Our proposal differs completely from those mentioned in the state of the art. For example, in [25] describes that all the cells of the panel have the same irradiation, temperature and shade and therefore all produce energy in a uniform way. Our proposal is based on the knowledge of the model that describes the behavior of each cell of each photovoltaic panel getting one accurate PV model. With help of Bishop model, we incorporates to the model the avalanche effect as shown Eq(1) and Fig(2).:

$$I = I_{ph} - I_o \left[e^{\frac{V_c + IR_s}{V_t}} - 1 \right] - \frac{V_c + IR_s}{R_{sh}} \left[1 + k \left(1 - \frac{V_c + IRs}{V_{br}} \right)^{-n} \right] \quad (1)$$

where I_{ph} is the generated photo-current (A), I_o is the reverse saturation current (A), R_s is the series resistance (Ω),

R_{sh} is the shunt resistances (Ω), V_{br} is the breakdown voltage (V), k and n are constants.

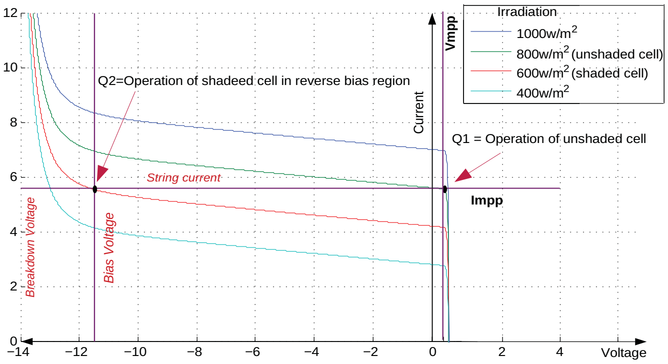


Figure 2. Current -Voltage characteristic of PV cell of TENESOL 2200 during reverse biased region

1) Proposed model: The proposed model takes into account the electrical and thermal behaviour of each PV cell of a PV module. The configuration of a cell interconnection circuit suitable for powering a given application is obtained by calculating the number of cells in series needed to generate a convenient voltage $V_o(t)$, and the number of strings in parallel needed to produce sufficient current $I_o(t)$. Normally, a PV panel is composed on a set of cells (e.g., 36, 60, 72), and a set of bypass-diodes.

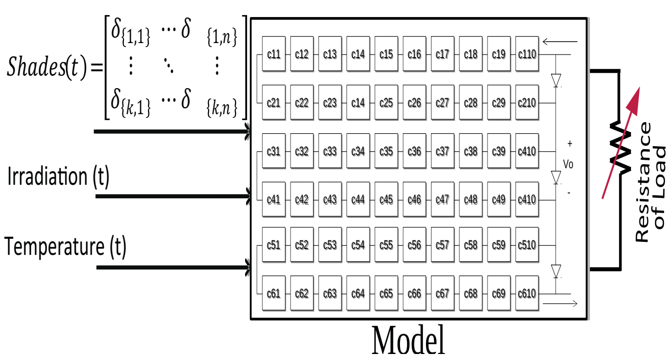


Figure 3. General schematic of the proposed PV-module model

In Fig. (3), we shows the general schematic proposed. The model inputs represents the environmental variables such as solar irradiation, temperature, matrix of shadow and the electrical parameters of PV cells. The model outputs are PV module voltage and PV module current, done variations on the load resistance.

III. Implementation PV model

The problem of obtaining a continuous simulation (24/7) of the photovoltaic production from the bishop model is solved using cosimulation. The model is able to emulate the behavior of panel, string or array from the environmental information, characteristics of the panels and its connections.

- Model of interchange of energy (bondgraph) that described the behaviour of PV system is to do in the software 20sim,
- Matlab is in charge of making changes in the value of the input variables (temperature, irradiation, shadow factor) that allows us to have 1440 simulations (24hx60min).

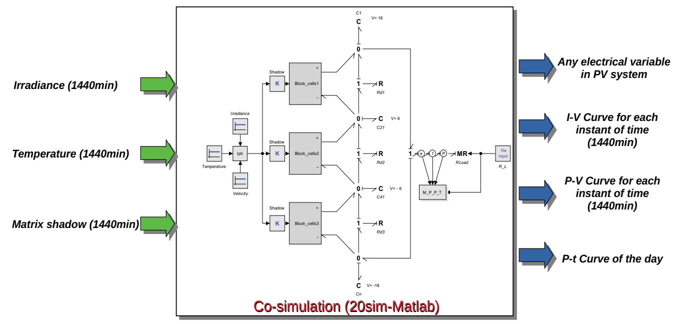


Figure 4. Cosimulation 20sim-matlab

2) Experimentation and validation PV model: In the laboratory of the LAAS-CNRS located in Toulouse-France. For the validation of the model of the photovoltaic panel under a scenario of shadows. In Fig. 5 can see some sheets of paper are placed in front of a PV module (Tenesol 2200) during the March, 22nd, 2018.

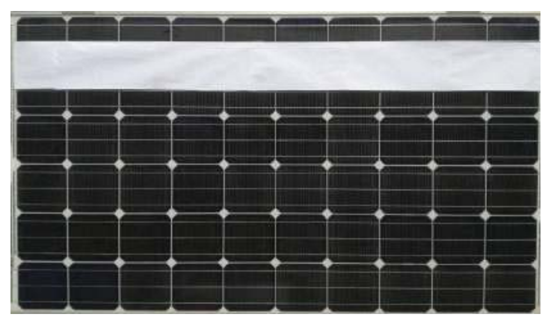


Figure 5. Photo of module Tenesol 2200 with shadows 22-03-2018

With the help of a meteorological station, a pyranometer and a pair of thermocouples placed on the panel, solar radiation and temperature are measured. In Fig(6) can be seen the irradiation and temperature of the day 22-03-2018.

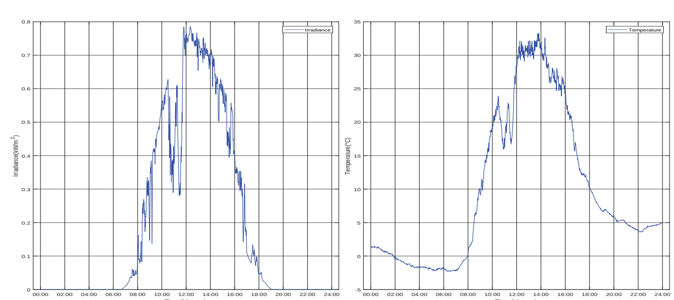
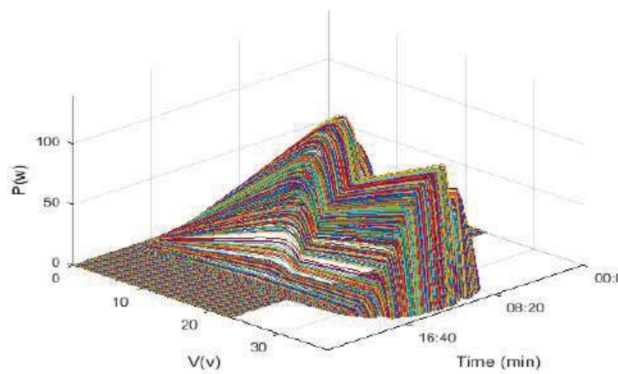
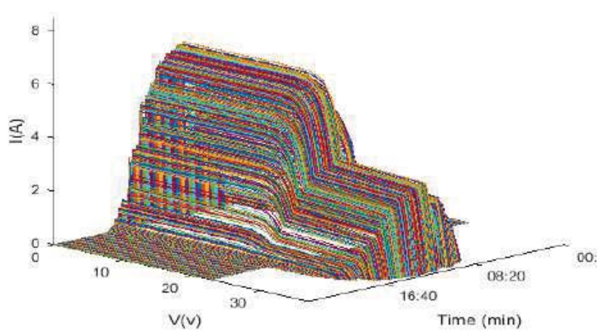


Figure 6. a) Irradiance b) Temperature

In fig(7) can be see the results of the co-simulation. These are 1440 lines of different color that form a 3D surface. The impact produced by the shadow on the photovoltaic panel can be seen on the curve voltage-time-power in fig(7(a)) and voltage-time-current infig(7(a)).



(a)



(b)

Figure 7. (a)Simulation of the curve P versus V of one day (b)Simulation of the curve I versus V of one day

A. MPPT algorithm based on model

The algorithm that we propose is based on the precise modeling of the photovoltaic cell, photovoltaic panel, bypass diodes, and anti-return diodes. The PV model with shadows properties is integrated into the system to see the electrical behavior of the whole system in complex shading conditions. In Fig(8), we show the algorithm propose to find the GMPPT.

Algorithm is divided on two parts:

- First part is the algorithm of PV model with shadow, based on the evaluation of the set equations that describe the behavior I-V and P-V of the system with steps of current no-nonuniform. The panel model produces 61 equation differentials (ED). It is necessary to carry out a variation of the Resistance of Load (RL) from an initial value RL=$\infty\Omega$ to RL=0 Ω for to get the I-V curve. For the set of ED is impossible to find a response analytically. Therefore, it is necessary to find a solution using numerical methods. We used a method called backward differentiation formula (BDF) to address the above issue. Its methods approximate the derivative of that function using information from already computed times. A BDF is used to solve the initial value problem $y' = f(t, y), y(t_0) = y_0$ and to solve the I-V curve $\sum_{n=0}^{s} a_k y_{n+k} = h\beta f(t_{n+s}, y_{n+s})$, where h is the step size, t_n is $to + nh$.
- and second part the algorithm of MPPT, consists in that with the information of the power curve in each instant of the time P(t). We can obtain the sequence of value $P(t) = P(0), P(1)...P(n)$. Thereupon, we can find the value maximum of P(t).

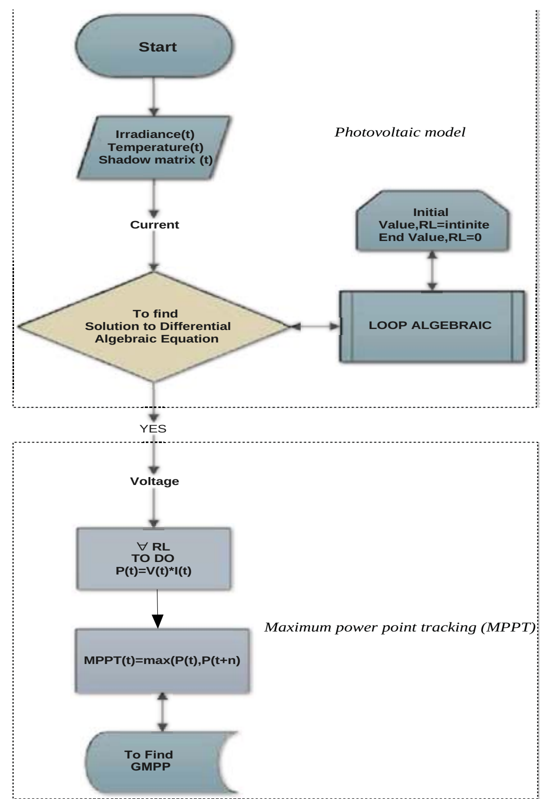
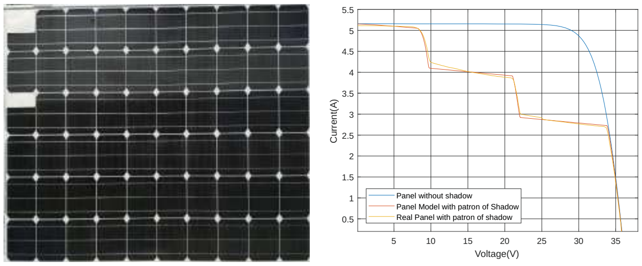


Figure 8. MPPT algorithm based on precise PV model

IV. Experimentation and results of MPPT

To show the application of the MPPT model, a different shadow pattern is chosen. In Fig(9(a)) is showed a photography of a PV panel (Tenesol 2200) with two shadows which produces three peaks. The area of shadow of one PV cell is 50% and the other 23%. The experimentation tests are performed during the February, 9th, 2018 at 12:06PM with a solar irradiation of 387.80W/m^2 and a cell temperature of 19°C. Fig. (9(b)) shows the I-V curve in normal operating and the I-V curves comparison between the experimental test under complex shading and the I-V model. In this case the *MSE* is equal to 3%.



(a) (b)

Figure 9. (a) Photo of a PV panel with shadow, (b) Validation Curve I-V

In Fig(10) is showed the results of the algorithm proposed. In Fig(10 (a)) can seen the current-voltage curve, with three peaks of V-I. In Fig(10 (b)) can been the three peaks of the power-voltage curve; two are LMPP and one is GMPP. In third curve. In Fig(10 (c)) can seen the evolution on time of the MPPT algorithm; first it find a LMPP and to next the GMPP. In Fig(10 (d) can be seen the delta dirac signal indicating that the δ P value increased. The point of GMPP is V_{gmpp} = 21.28V, I_{gmpp} = 5.61A.

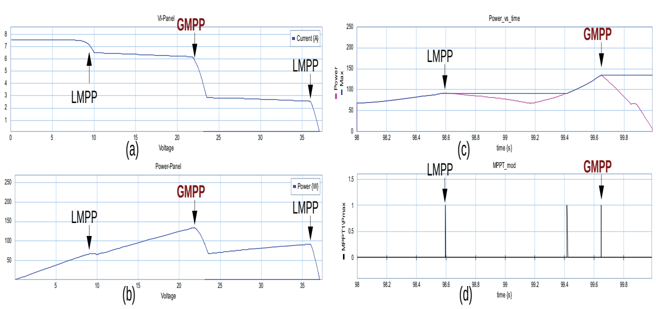


Figure 10. a) I-V curve, b) P-V curve, c) Evolution over time of the MPPT algorithm, d) Detection of GMPP

The simulation of the MPPT was probed also connected to a boost converter under complex shading conditions. The system was composed of inputs parameters, PV panel, MPPT, boost-converter, and load. The voltage of MPPT is V_{gmpp} = 21.28V, I_{gmpp} = 5.61A, voltage of output 41.6v. Parameters of the boost converter are : L_{in}=47μH, C=10μC. therefore, the duty cycle of boost converter D=$\frac{Vo}{Vo-Vi}$= 50%.

V. Evolution of the MPPT on time

As the model shown in the previous section works properly for a moment of time, we decided to check that it works in the same way for an entire day. The shadow is the same that the Fig(fig:model). In Fig(11) and Fig(12) can be seen, compared the 3D surface obtained in the real system and the model:

- the surfaces 3D (Voltage,time and power) obtained by MPPT EKO-M160 are the figures (a) and the surface obtained by model are the figures (a).
- the evolution of the red line, which shows how the maximum power transfer point changes during the day due to changes in solar radiation, temperature and shadows.

VI. Conclusion and perspectives

A precise model of each cell was performed integrating shadow properties to see its electric behavior. We obtained a precise model of a photovoltaic array that allows us to obtain valuable information from the system. The algorithm MPPT was tested and its efficiency is validated for different shadow conditions. We solve the problem of how to find the appropriate size of the voltage step in the P-V curve. In the section of results we can corroborate the correct detection of our MPPT. A boost converter was used with the MPPT to validate the correct performance of the strategy. This methodology will allow us to use it for the design of photovoltaic systems as converter and inverters; and in general of the PV conversion chain. Also, it will be used in new research that take into account the impact of shadows on photovoltaic production. This methodology can be used in the detection and diagnostic of faults in photovoltaic systems. This can help in the improvement of the lifetime of PV systems. It can be employed in real time simulations.

References

[1] C. Cabal, C. Alonso, A. Cid-Pastor, B. Estibals, L. Seguier, R. Leyva, G. Schweitz, and J. Alzieu, "Adaptive digital mppt control for photovoltaic applications," in *Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on*. IEEE, 2007, pp. 2414–2419.

[2] "Experimental study of mismatch and shading effects in the iv characteristic of a photovoltaic module," *Solar Energy Materials and Solar Cells*, vol. 90, no. 3, pp. 329 – 340, 2006.

[3] R. Leyva, C. Alonso, I. Queinnec, A. Cid-Pastor, D. Lagrange, and L. Martinez-Salamero, "Mppt of photovoltaic systems using extremum - seeking control," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 42, no. 1, pp. 249–258, Jan 2006.

[4] N. Karami, N. Moubayed, and R. Outbib, "General review and classification of different mppt techniques," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 1 – 18, 2017.

[5] H. M. El-Helw, A. Magdy, and M. I. Marei, "A hybrid maximum power point tracking technique for partially shaded photovoltaic arrays," *IEEE Access*, vol. 5, pp. 11 900–11 908, 2017.

[6] K. Chen, S. Tian, Y. Cheng, and L. Bai, "An improved mppt controller for photovoltaic system under partial shading condition," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 3, pp. 978–985, July 2014.

[7] A. Dolara, S. Leva, G. Magistrati, M. Mussetta, E. Ogliari, and R. V. Arvind, "A novel mppt algorithm for photovoltie systems under dynamic partial shading recurrent scan and track method," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Nov 2016, pp. 1122–1127.

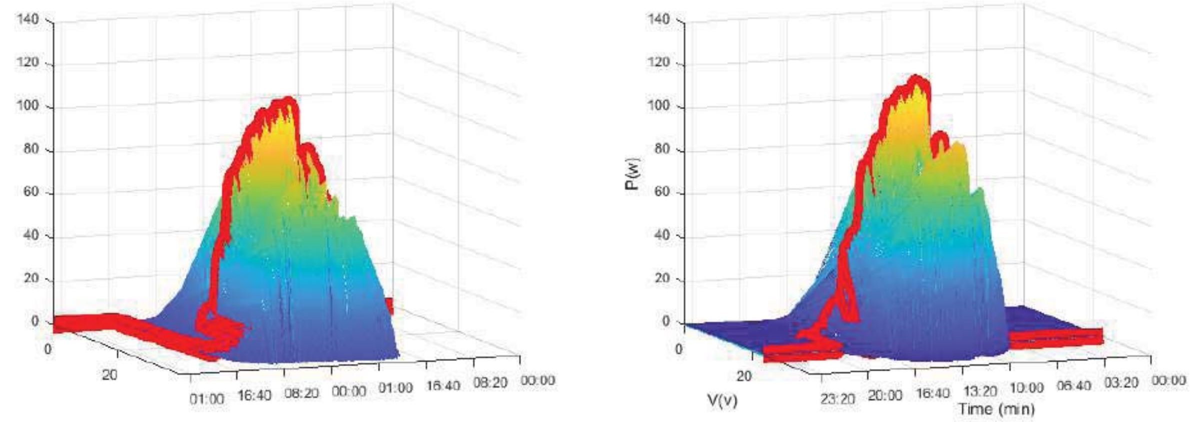
[8] E. I. Batzelis, P. S. Georgilakis, and S. A. Papathanassiou, "Energy models for photovoltaic systems under partial shading conditions: a comprehensive review," *IET Renewable Power Generation*, vol. 9, no. 4, pp. 340–349, 2015.

[9] M. Bressan, A. Gutierrez, L. G. Gutierrez, and C. Alonso, "Development of a real-time hot-spot prevention using an emulator of partially shaded pv systems," *Renewable Energy*, vol. 127, pp. 334–343, 2018.

[10] S.Daliento, A. Chouder, P. Guerriero, A. M. Pavan, A. Mellit, R. Moeini, and P. Tricoli, "Monitoring, diagnosis, and power forecasting for photovoltaic fields: A review," *IET Renewable Power Generation*, vol. 2017, 2017.

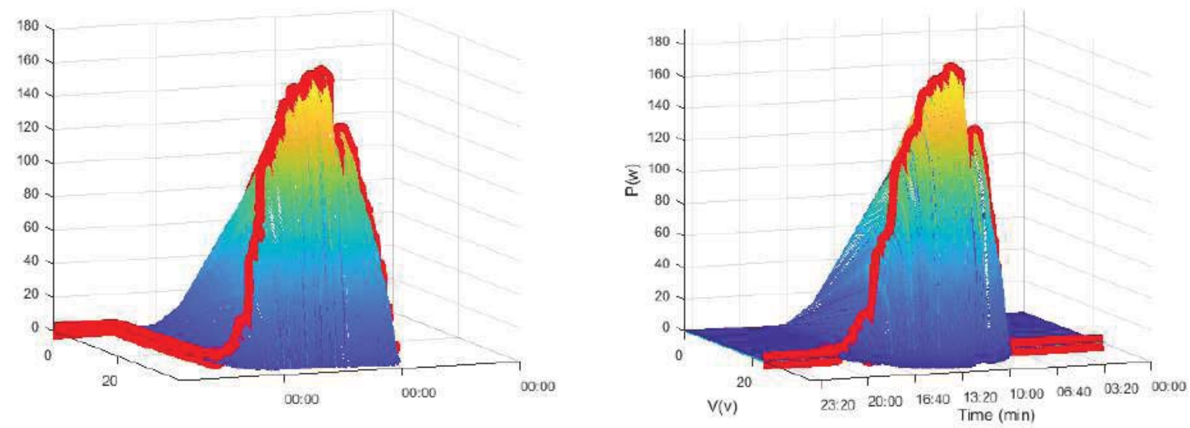
[11] A. Mohapatra, B. Nayak, P. Das, and K. B. Mohanty, "A review on mppt techniques of pv system under partial shading condition," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 854 – 867, 2017.

[12] S. Gautam, D. B. Raut, P. Neupane, D. P. Ghale, and R. Dhakal, "Maximum power point tracker with solar prioritizer in photovoltaic application," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, Nov 2016, pp. 1051–1054.



(a) (b)

Figure 11. (a) MPPT with shadow real (b) MPPT without shadow simulate (Power Surface and MPPT with shadow 22/03/2018)



(a) (b)

Figure 12. (a) MPPT without shadow real (b) MPPT without shadow simulate (Power Surface and MPPT without shadow (22/03/2018)

[13] L. N. Rao and S. Gairola, "Pv system analysis under partial shading using a sine model," *International Journal of Renewable Energy Research (IJRER)*, vol. 8, no. 1, pp. 280–290, 2018.

[14] "A review on maximum power point tracking for photovoltaic systems with and without shading conditions," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 144 – 159, 2017.

[15] "A comprehensive overview of maximum power extraction methods for pv systems," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 93 – 112, 2017.

[16] D. Verma, S. Nema, A. Shandilya, and S. K. Dash, "Maximum power point tracking (mppt) techniques: Recapitulation in solar photovoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1018 – 1034, 2016.

[17] B. Veerasamy, A. R. Thelkar, G. Ramu, and T. Takeshita, "Efficient mppt control for fast irradiation changes and partial shading conditions on pv systems," in *Renewable Energy Research and Applications (ICRERA), 2016 IEEE International Conference on*. IEEE, 2016, pp. 358–363.

[18] "A comparison of different global mppt techniques based on meta-heuristic algorithms for photovoltaic system subjected to partial shading conditions," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 377 – 386, 2017.

[19] X. Li, H. Wen, and Y. Hu, "Evaluation of different maximum power point tracking (mppt) techniques based on practical meteorological data," in *Renewable Energy Research and Applications (ICRERA), 2016 IEEE International Conference on*. IEEE, 2016, pp. 696–701.

[20] A. Belkaid, U. Colak, and K. Kayisli, "A comprehensive study of different photovoltaic peak power tracking methods," in *Renewable Energy Research and Applications (ICRERA), 2017 IEEE 6th International Conference on*. IEEE, 2017, pp. 1073–1079.

[21] M. B. Smida and A. Sakly, "A comparative study of different mppt methods for grid-connected partially shaded photovoltaic systems," *International Journal of Renewable Energy Research (IJRER)*, vol. 6, no. 3, pp. 1082–1090, 2016.

[22] A. Badis, M. H. Boujmil, and M. N. Mansouri, "A comparison of global mppt techniques for partially shaded grid-connected photovoltaic system," *International Journal of Renewable Energy Research (IJRER)*, vol. 8, no. 3, pp. 1442–1453, 2018.

[23] S. A. Rizzo, N. Salerno, G. Scelba, and A. Sciacca, "Enhanced hybrid global mppt algorithm for pv systems operating under fast-changing partial shading conditions," *International Journal of Renewable Energy Research (IJRER)*, vol. 8, no. 1, pp. 221–229, 2018.

[24] "Experimental assessment of new fast mppt algorithm for pv systems under non-uniform irradiance conditions," *Applied Energy*, vol. 199, pp. 416 – 429, 2017.

[25] M. SAADSAOUD *et al.*, "Study of partial shading effects on photovoltaic arrays with comprehensive simulator for global mppt control," *International Journal of Renewable Energy Research (IJRER)*, vol. 6, no. 2, pp. 413–420, 2016.