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Extremum Seeking Control-based Global Maximum Power Point Tracking algorithm for PV array under partial shading conditions

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Abstract— **The aim of this paper is to present a general description about the method called Extremum Seeking Control (ESC), and its applications in the nonlinear systems, which have an unknown dynamics. The system we are interested in is the photovoltaic system. This technique presents a solution on real time optimization control problems.**

When a photovoltaic panel is exposed to the same irradiation range, the power-voltage characteristic has a single maximum point. However if a portion is shaded or covered by the clouds, this characteristic will have several maximum points. Hence in the first case, it is possible to track the maximum by a conventional maximum power point tracking (MPPT) method but in the second case a simple MPPT may fall into the local MPP (LMPP), that why ESC algorithm is implemented (to track global MPP).

The Photovoltaic panel is modeled and the ESC algorithm is designed using Matlab/Simulink Software.

Keywords—Extremum seeking control; Photovoltaic cell; GMPPT; optimization; adaptive control; photovoltaic system; Maximum power point tracking; partial shading condition.

I. INTRODUCTION

Traditional control system design deals with the problem of stabilization of a system where the reference is known-easily determined or generated- while reaching certain design criteria. However, in some cases it can be very difficult to find an appropriate reference value. For illustration, the energy efficiency of photovoltaic system depends on the irradiation, the temperature and the other climatic changes. If one desires to maintain optimal efficiency, it is necessary to change one of these variables. Extremum seeking control is a family of control design approaches whose purpose is to autonomously find optimal system behavior for the closed-loop system and for nonlinear map, while at the same time maintaining stability of signals. Extremum seeking control is therefore largely used to realize real-time optimization for dynamic systems and tracking a varying maximum or minimum (extremum, or optimum value) of a performance function. It is a very interesting methodology in practice because it does not necessitate any knowledge of the process dynamics or model of the system.

As it is known, the power characteristic of a photovoltaic (PV) array is nonlinear. The PV system exhibits only one maximum power point (MPP) on the power-voltage (P-V) curve which varies apparently with irradiance, temperature and other environmental condition. Due to this nonlinearity on this curve a Maximum Power Point Tracking (MPPT) must be applied.

The researchers have proposed many algorithms in this case that demonstrate good performance such as the searching resolution, tracking accuracy and searching speed. Some of those algorithms are: perturb and observe (P&O) [1], Incremental Conductance (IC) [2-4], and Hill Climbing (HC) [5].

The performances of a photovoltaic panel can be reduced considerably when a small portion of the panel is touched by the shadow or when more than one PV module are connected and one of them is partially shaded.

Consequently this paper is organized as follows: Section 2 discusses mathematical modeling of PV cell and PV generator. Section 3 will be reserved to show the influence of the shadow on the PV performances. ESC algorithm will be discussed and the performance indicators such as, the searching resolution and tracking accuracy are exposed in section 4. The results obtained for the performance indicators are mentioned in Section 5. Finally, last section concludes the paper.

II. PHOTOVOLTAIC SYSTEM MODELING

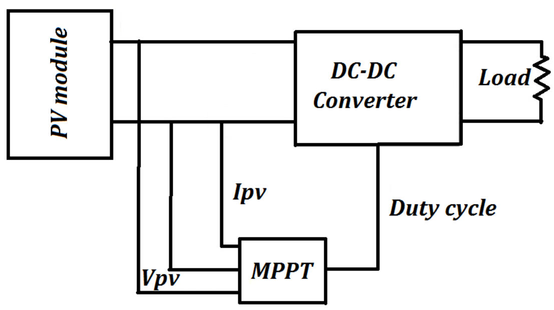

Fig. 1. block diagram of a photovoltaic system

A basic photovoltaic system includes generally three main components; a PV generator, a DC-DC converter with MPPT control and a load which could be a battery (Fig.1).

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A photovoltaic generator is constituted by several cells connected in series and/or parallels thus, a cell presents the elementary component of a photovoltaic array, and consequently the study can be limited to model one cell.

In the literature several models are proposed. The famous one called L5P (Lumped, 1 Mechanism, Parameters) [6- 13].

The photovoltaic cell is represented in the figure 2 by the electrical equivalent circuit, which consists of a current source modeling the luminous flux; the losses in the cell are modeled by two resistors, a shunt resistor and a series resistor. The model involves the following five unknown parameters: n, Iph, Rs, Rsh and Is.

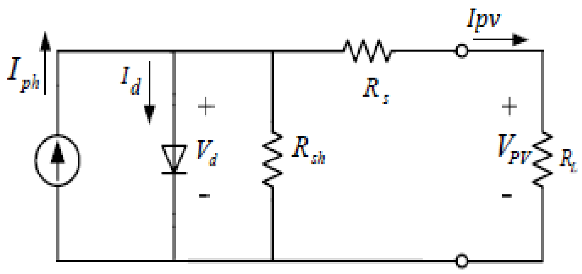

Fig. 2. Equivalent circuit of PV module.

The characteristic equation is deduced directly from Kirchhoff's law:

$$Ipv = Iph - Id - Ish \quad (1)$$

The final equation for the model of the photovoltaic cell based in the relationship between the output voltage, Vpv , and the current, I through the equation :

$$Ipv = Iph - Is\left(exp\left(\frac{Vpv + Ipv*Rs}{Vt} - 1\right) - (Vpv + Ipv*Rs)/Rsh\right) \quad (2)$$

Where:

- I_{ph} is the light current,
- I_s is the reverse saturation current of diode,
- Rs is the series resistance,
- Rsh is the shunt resistance,
- V_t is thermic voltage.

Characteristic of cell model

The power-voltage and current-voltage characteristics for different values of temperature are obtained from the simulation, under Matlab/Simulink software, of one cell keeping the irradiation value constant at 1000 W/m^2:

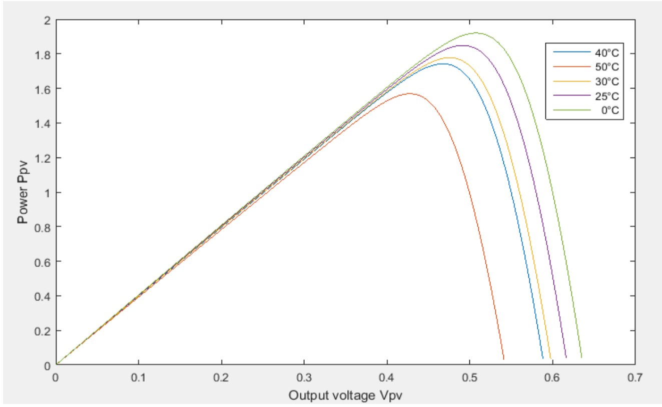

Fig. 3. Power characteristic for different value of temperature

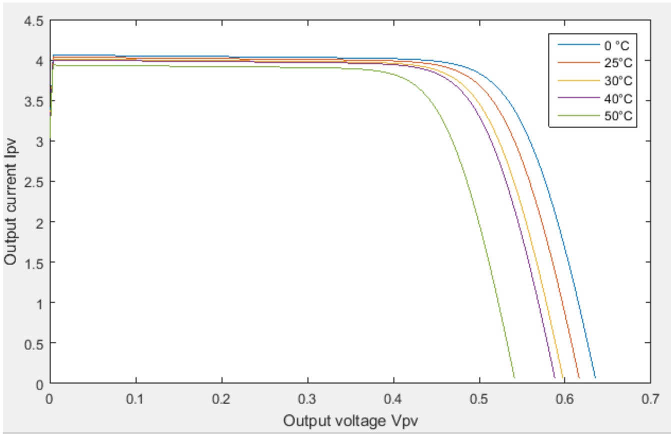

Fig. 4. Current characteristic for different value of temperature

As it is shown in these two figures above, when temperature increases both of the maximum power and the open circuit voltage decrease.

Now we present the power-voltage and the current-voltage characteristics for different values of irradiance keeping the temperature value constant at 25°C:

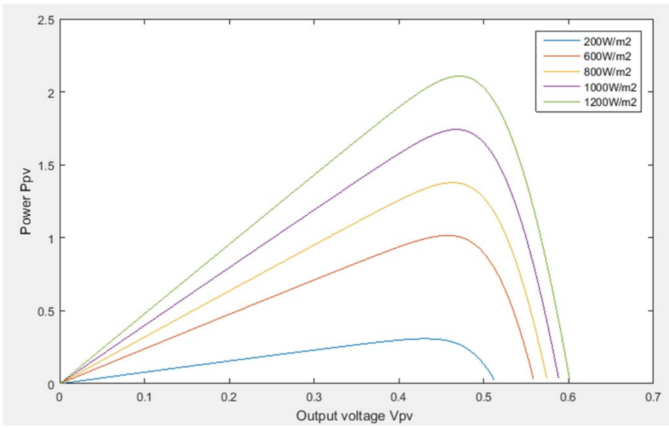

Fig. 5. Power characteristic for different values of irradiance

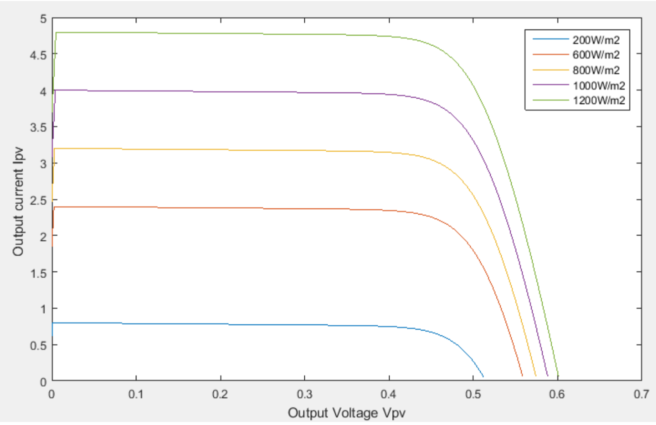

Fig. 6. Current characteristic for different value of irradiance

The characteristic of a PV cell is directly dependent on irradiance and temperature.

The variations of current and power as a function of voltage for different values of irradiance at constant temperature 25 ° C (Fig. 5 and Fig. 6), attest that the output current I_{pv} is considerably influenced by the change in irradiance. While the output voltage V_{pv} remains approximately constant and clearly show the existence of maximum on the power curves corresponding to the Maximum Power Points P_{max}.

Temperature is a very important parameter in the behavior of solar cells. The temperature also has an influence on the characteristic of a PV cell. Fig. 3 and Fig. 4 show the variation of the characteristics of a PV cell as a function of the temperature at a given irradiance. On the other hand, for a changing temperature, it can be seen that the voltage changes considerably while the current remains constant.

III. PV GENERATOR UNDER PARTIAL SHADING CONDITION

Each photovoltaic generator has a unique operating point at which it can provide the maximum power and this power depends mainly on the radiation intensity. If some module of a string within a PV generator is in the shade, their electrical property will be changed.

It is not possible to have uniform irradiance of PV panel all the time because of buildings or trees shades, atmosphere fluctuation, existence of clouds and daily sun angle changes [14] as shown in Fig. 7.

Fig. 7. Partial shading on the PV Panel

Several studies can be found in the literature on this topic: the effects and the examination of partial shading on the characteristics of PV array [15–19].

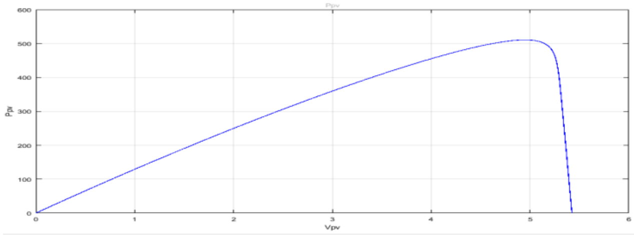

Fig. 8. Power characteristic of PV Panel without partial shading

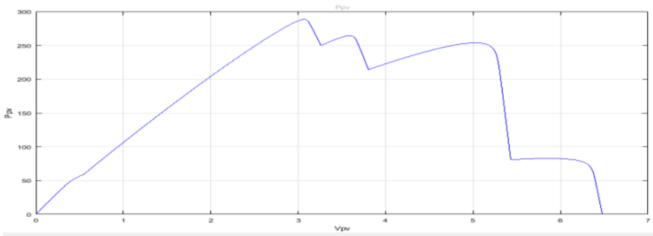

Fig. 9. Power characteristic of PV Panel with partial shading

Figure 8 shows the presence of one maximum on the power curves when the panel is not covered by clouds or generally does not be under shade (PV have uniform distribution of irradiance). However, when a portion of the panel is shaded, then the power characteristic has several peaks and presents a lot of local MPP, as it is shown on Fig. 9. One of these peaks presents the Global maximum power point. For the simulation, temperature was fixed at 25°C and irradiance has different values.

IV. GMPPT BASED ON EXTREMUM SEEKING CONTROL ALGORITHM

Extremum Seeking Control (ESC) is real-time optimization algorithm and adaptive control tool [21], which resolves the problem of tracking a varying maximum or minimum of a performance function; generally, it attempts to determine the extremum value of an unknown nonlinear performance function. [20].

As it is known conventional control algorithm deals with the problem of equilibrium of a system about a known reference trajectory or easily determined, while reaching certain design criteria. However, in some cases it can be very difficult to find a reference value.

Between the various applications of ESC we can found Global Maximum Power Point Tracking which can seek and track the MPP.

There are a lot of methods to implement Maximum power Point Tracking in PV field. Researchers have proposed different approaches that have the objective of extracting the operating point of power under varying conditions of weather (temperature and irradiance), the famous traditional algorithms are: Perturb and observe (P_O), Incremental Conductance (IC) and the Hill Climbing (HC) [22–31]. In the literature there are also methods based on Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN) [31–34].

The performance of a PV array is nonlinear and the power characteristic presents several peaks especially when the PV panel is in the partial shading conditions that why it is necessary to find the global MPP. By using conventional MPPT, we may fall on one of these peaks, not obligatory on the highest one, which refer to Global MPP. ESC algorithm resolves this problem without knowing the internal parameters of the system.

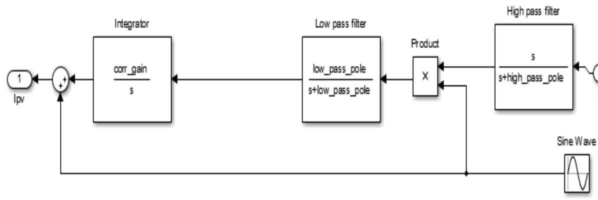

Fig. 10. Proposed ESC scheme.

The scheme employs a sinusoidal perturbation sine wave which additively enters the system. The measured output Ppv is then passed through a high pass filter and multiplied by the same perturbation signal, sine wave generating an estimate of the derivative at the input of the integrator. The Low-Pass Filter (LPF) used after the demodulation block is not necessary but it is helpful in filtering out the effect of dither signal. The High pass filter is just more effective in eliminating the DC component of the system. The gain parameter of integrator controls the speed of convergence.

V. SIMULATION AND DISCUSSION

In this section, we will present the result of simulation, where we use a PV module model based on module data-sheet parameters of six PV panels in series. This model has Ipv input, which is suitable for series connections. Each pannel model has no temperature dependence, static model, and has these characteristics:

- Short-circuit current = 5.45 A
- Open-circuit voltage = 22.2 V
- Current at maximum power = 4.95 A
- Voltage at maximum power = 17.2 V

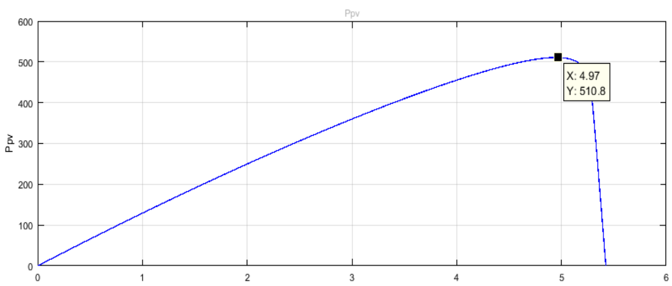

Fig. 11. Power characteristic of PV Panel at uniform irradiance

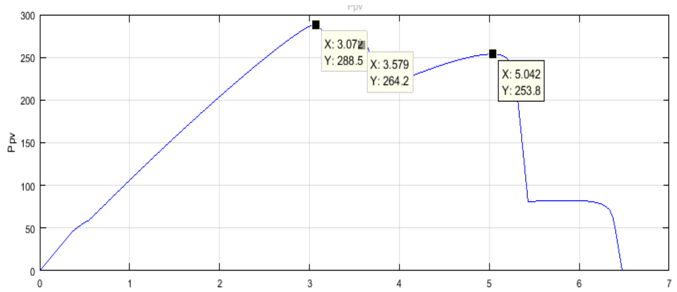

Fig. 12. Power characteristic of PV Panel under partial shading conditions

By applying the proposed ESC algorithm (Fig. 10) to the PV panel with and without partial shading conditions, we obtained this result for different values of parameters in function of time.

- Case 1:

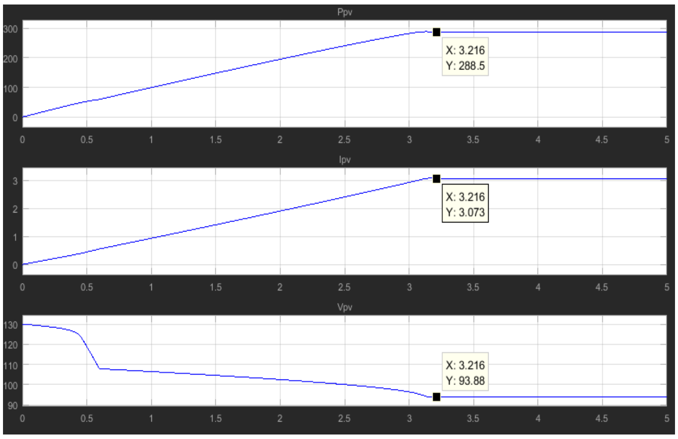

Fig. 13. Tracking the GMPP and optimal values of voltage, current of PV Panel under partial shading conditions

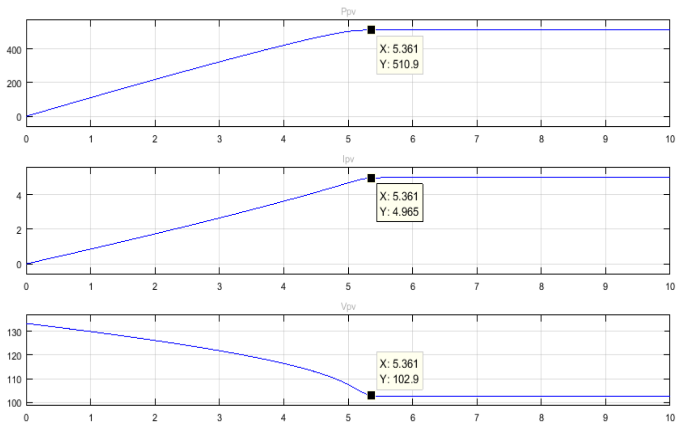

Fig. 14. Tracking the GMPP and optimal values of voltage and current of PV Panel without partial shading condition

- Case 2:

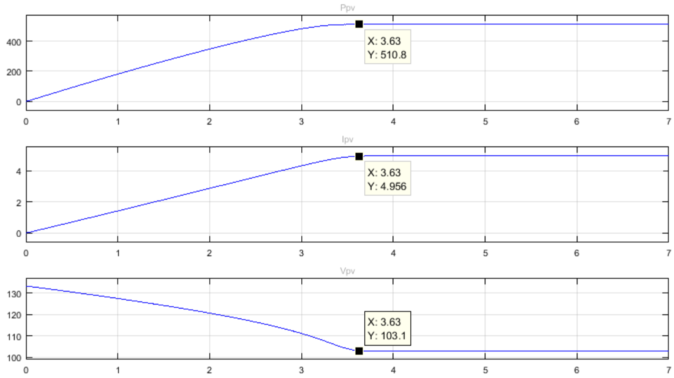

Fig. 15. Tracking the GMPP and optimal values of voltage, current of PV Panel without partial shading condition

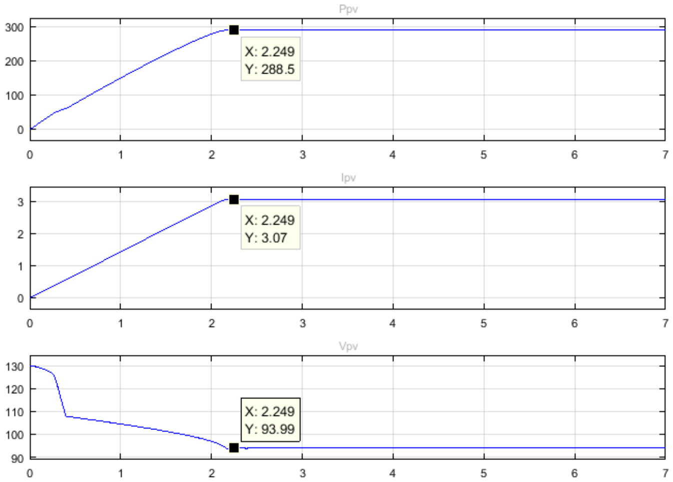

Fig. 16. Tracking the GMPP and optimal values of voltage, current of PV Panel under partial shading condition

For case 1: The dither frequency is Fd=1000Hz, the dither amplitude is Kd=0,001, the cut-off frequency of the HPF is Fh=800Hz, and the cut-off frequency of the LPF: Fl=60Hz. And in case 2: The dither frequency is Fd=1000Hz, the dither amplitude is Kd=0,001, the cut-off frequency of the HPF: Fh=900Hz, and the cut-off frequency of the LPF: Fl=30Hz. The simulation results are presented in Fig. 11, 12, 13, 14, 15, and 16. We can clearly show that ESC algorithm seek, and track the global MPP with maintaining its value. For example in fig. 11 the curve of Power present only one optimum value set on 510.8 W, this value is obtained by application of ESC method with different value of parameters (mentioned previously) on a PV array exposed to the same distribution of illumination.

If we look at Fig. 12, the power characteristic has several Local MPP because of exposition to different range of irradiation. The highest peak set at 288.5 W. By applying ESC algorithm in this distribution of illumination, we obtain Fig.16 and Fig.13. The main difference between these two cases is about time of tracking that is reduced considerably in both cases with and without partial shading condition. The value of tracking accuracy is 100%.

VI. CONCLUSION

In this paper, we presented a model of PV panel based on single diode model and we exposed the effect of partial shading condition. Studying the approach and the capability of the ESC algorithm to track the GMPP for PV array is shown also in this study as well.

The most challenging thing in the use of ESC sets in how to choose its parameters which guarantees searching resolution, tracking accuracy and other performances without changing the dynamic of the system.

The PV cell/array modeling and the ESC Global MPPT algorithm are simulated with MATLAB-SIMULINK software.

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