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Fault-Tolerant Control of Photovoltaic Panels

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Abstract

In this work we present a fault-tolerant control strategy to extract the maximum power from photovoltaic (PV) Panels. The performance of PV panels is affected with different type of faults such as mismatch, shading, cell degradation, different type of panels, soiling… These faults result in multiple local maximum power points in the P-V characteristic where the classical P&O Maximum Power Point Tracking (MPPT) algorithm is unable to achieve the global maximum power point. The proposed method is based on the use of a hybrid Particle Swarm Optimization and a classical PI controller in order to achieve maximum performance in the presence of different type of faults.

*Keywords:*Fault-Tolerant Control FTC, Photovoltaic (PV) Panels, Partial Shading, Maximum Power Point Tracking (MPPT).

1. Introduction

Although the increasing interest in research to improve the performance of Photovoltaic (PV) systems, there is a little work done so far on fault diagnosis of PV arrays. Mismatch, shading effect and soiling are some of the faults that reduce the solar PV panels life. Such faults affect also the instant output power produced [3].

The ground fault is investigated in [1] on the AC side of the PV system and in [3] for the DC side. Line to Line fault is considered in [5]. Shading fault is studied in references [2], [7] and [10].

Many maximum power point tracking (MPPT) control methods were developed to achieve a maximum power output in real-time. The "Perturb and Observe" known as P&O is a well-known method that is widely used in commercial controllers due to its good performance and simple implementation. The principal drawback of this method is the loss of power caused by the oscillations and is unable to reach the maximum power point at low irradiations.

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In this work, an analysis of the performance of the MPPT method is developed. The different problems that occur when the control algorithm is running in the presence of different type of faults are detailed and some solutions are given.

The equivalent model of a PV panel is introduced in Section II. In Section III we discuss different faults and their effect on the *I-V* and *P-V* curve are detailed. Some possible solutions are presented in Section IV. Concluding remarks are given at the end.

2. Model of a PV Array

The equivalent circuit of a PV cell is given by **Fig.1**.

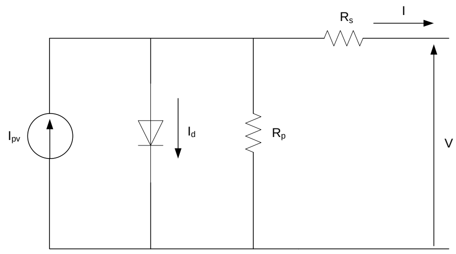

Fig.1 Equivalent circuit of a PV cell.

We adopted the one-diode model instead of the two diode model because the steady state performance of the first one is accurate enough and also the simulation cost is low (faster convergence).
In Fig.1 the controlled current source is dependent of the temperature and irradiation as follows:

$$I_{pv} = \left(I_{pv,n} + K_I \Delta_T\right)\frac{G}{G_n} \tag{1}$$

Where $I_{pv,n}$ is the nominal generated current (given at nominal conditions: $T=25°C$ and $G=1000\ W/m^2$), K_I is the short-circuit current/temperature coefficient, $\Delta_T = T-T_n$ (T and T_n are the current and nominal temperature), G and G_n are the current and nominal irradiation.

The current in the diode is given by:

$$I_d = I_0\left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] \tag{2}$$

I_0 is the saturation current and is given as follows:

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta_T}{a V_t}\right) - 1} \tag{3}$$

Where $I_{sc,n}$ is the nominal short-circuit current, $V_{oc,n}$ is the nominal open circuit voltage (both parameters are given in the pv panel datasheet). K_V is the open-circuit voltage/temperature coefficient, a is a diode constant, V_t is the thermal voltage of the array: $V_t=N_s kT/q$, with N_s cells connected in series, k is the *Boltzmann* constant and q is the electron charge. R_s is the series resistance which depends on the material used to construct the cell and its effect is stronger in the voltage source operating region. R_p is the parallel resistance (R_{sh} in some references, for *shunt resistance*), its effect is stronger in the current source operating region.

Usually the values of R_s and R_p are not given in the datasheet of the pv panel, their values has to be identified online by iterative algorithms like the one developed in [9] or deduced from the technical data provided in the datasheet.

For a PV array with *Npp* parallel cells and *Nss* series cells the equivalent circuit is given in Fig.2.

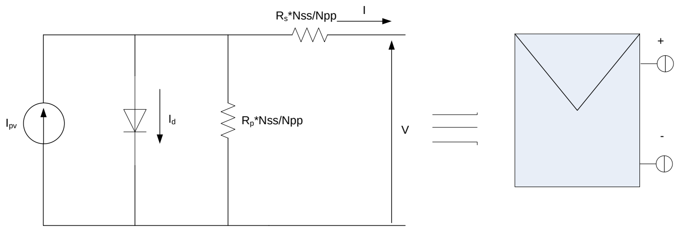

Fig.2 Equivalent circuit of a PV panel.

The output current becomes then:

$$I = I_{pv}N_{pp} - I_0 N_{pp}\left[\exp\left(\frac{V + R_s \cdot \left(\frac{N_{ss}}{N_{pp}}\right)\cdot I}{V_t \cdot a \cdot N_{ss}}\right) - 1\right] - \frac{V + R_s\left(\frac{N_{ss}}{N_{pp}}\right)I}{R_p\left(\frac{N_{ss}}{N_{pp}}\right)} \quad (4)$$

Table.1 gives the parameters for the PV panel used in the following sections.

Table 1. PV panel parameters

Parameter	Value
Iscn	3.56A
Ipvn	3.8713A
Vocn	42.1V
Ns	72
A	1.3977
Ki	0.065 %/°C
Kv	0.080 V/°C
Npp	10
Nss	10

3. Control of Arrays with Faulted Panels

A PV array is the combination of multiple PV panels connected in series and parallel, hence any fault in one PV panel will affect the performance of the overall PV array. This is why some research work considers the case where a small number of PV panels have their proper controller. In this work we consider that the PV array is composed of large number of PV panels due to the expensive cost of the proposed solution.

3.1. Controller configuration

A DC/DC boost converter is used to obtain a high voltage at the output, the MPPT method P&O is used. Fig.3 illustrates the controller configuration. The parameters of the converter are given in Table.1.

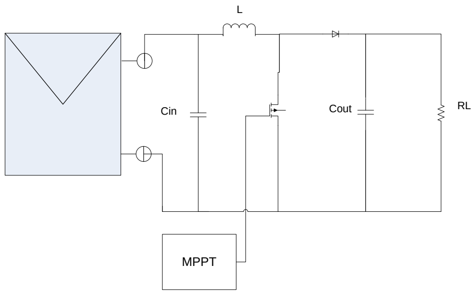

Fig.3 Controller Configuration.

Table 2. Boost converter parameters

Component	Value
Cin	478.6uF
L	444uH
Cout	154.69uF
RL	24.3ohm

3.2. Control of PV arrays with shaded panels

As stated in [2]: mismatch, shading, soiling, cell degradation, different type of PV panels and cell heating have the same signature in the *I-V* characteristic. In this study, we consider the shading effect to represent all the other faults. The variation of weather conditions is another parameter that affects the performance of the PV array.

The partial shading effect is the most frequent because many of the PV arrays are placed in the presence of buildings and even when this is not the case, the soiling caused by the dust is more important in saharian regions and has the same effect on the PV arrays as the partial shading (hot spot).

The system depicted in Fig.3 is modified to integrate the effect of shading, the resulted model is given is Fig.4. The PV array is subject to partial shading, 3x10 of the panels are 70% shaded and 2x10 are 50% shaded the irradiation is 300W/m² and 500W/m² respectively, the rest of the panels are not shaded.

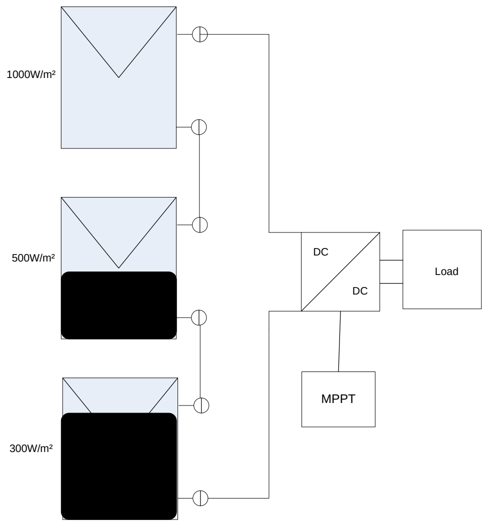

Fig.4 PV Array with partial shading

In Fig. 5 the power-voltage curve shows the effect of the partial shading on the pv array where multiple local maximum power points are present.

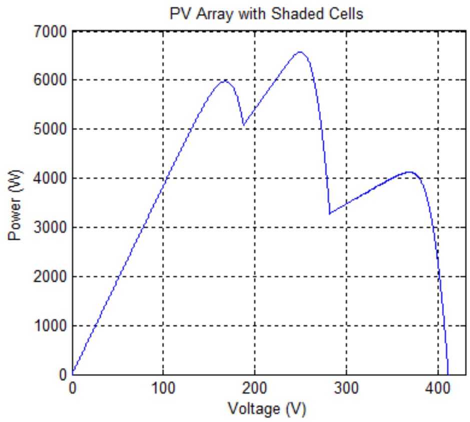

Fig.5: Power-Voltage (P-V) curve of the PV Array with partial shading.

The classical P&O Maximum Power Point Tracking (MPPT) [5] method is used to find the optimal operating point of the PV system. This method is based on the variation of the reference current and checking its effect on the output power. Fig.6 gives the output power curve of the PV array subject to partial shading, where the algorithm has landed on a local Maximum Power Point (MPP). This algorithm is then unable to achieve maximum performance by tracking the global MPP.

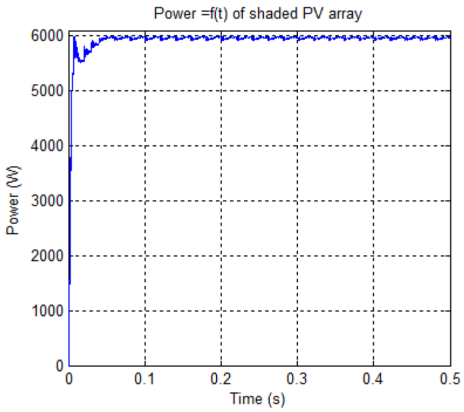

Fig.6 Power curve of the shaded PV array with P&O MPPT algorithm.

4. Fault-Tolerant control of PV panels

The PSO method is well known for the optimization of complex problems with multivariable objective function. This method is also effective in the case of the presence of multiple local maximum power points where the control strategy is tolerant to the different faults that can affect the PV array.

The PSO algorithm is based on the cooperation of multiple agents that exchange information obtained in their respective search process [6].

The movement of agents is governed with the following equations:

$$v_i^{k+1} = w \cdot v_i^k + c_1 \cdot r_1 \cdot pbest_i + c_2 \cdot r_2 \cdot gbest \tag{5}$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{6}$$

Where: w is a learning factor; c_1 and c_2 are positive constants; r_1 and r_2 are the normalized random numbers and are in the range [0 1]; $pbest_i$ is the best position that the i^{th} agent has found so far by evaluating the objective function; *gbest* is the best position of all agents.

In our case we take the agents to represent the reference current i_{ref} that is used to control the boost dc/dc converter as follows:

$$s^k = \left[iref_1^k \quad iref_2^k \quad .... \quad iref_n^k \right] \tag{7}$$

Where n represents the size of the swarm (the number of agents). The objective function used in this work is the measure of power delivered by the PV array.

$$f\left(s^k\right) = P_{PV}^k \tag{8}$$

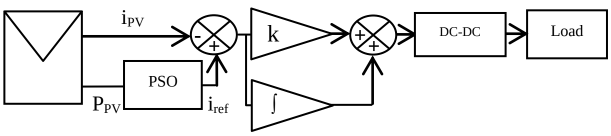

Fig.7 PSO-PI Based control architecture.

The control strategy used in this work is illustrated in Fig.8 the PSO algorithm gives the reference value of the current that is tracked using the PI controller to accelerate the response and eliminate the error between the actual value and the reference given by the PSO optimization algorithm.

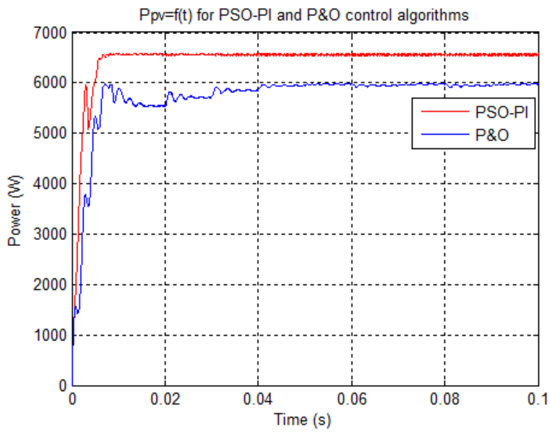

Fig.8 Power curve of the shaded PV array with the PSO-PI algorithm.

The performance of the PSO-PI based method is far better than the classical P&O algorithm; the global MPP is reached with better performance. The proposed FTC control law allows us to get an extra 700W of power from the PV array which represents a considerable amount of gained energy.

The evolution of the particles of the swarm is presented in Fig.9, and the last position is presented in Fig.10; most of the agents converge at the optimal value, the rest investigate other choices in the case of the presence of disturbances.

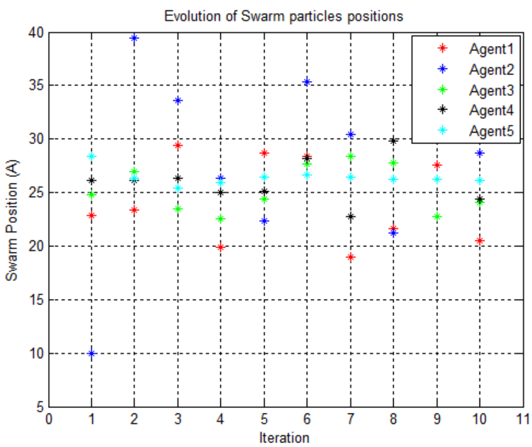

Fig.9 Evolution of particle swarm’s position for each iteration.

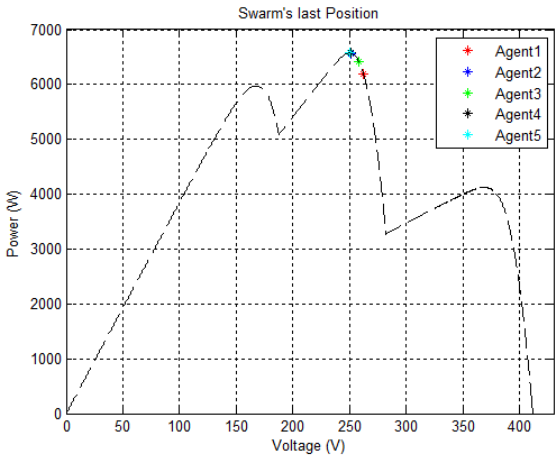

Fig.12 Swarm's last position in the *P-V* curve.

5. Conclusion

PV panels are subject to different operation conditions, in most of the cases they are installed at isolated areas and are affected with the changing weather conditions. In order to get the maximum amount of energy from such installations, the design of a fault-tolerant control strategy has a major impact on the global performance of the system. In this study we proposed an algorithm based on a metaheuristic method that uses a swarm of particles to find the optimal operating point of the PV array. Simulation results show the effectiveness of the MPPT control strategy in the case of the presence of the partial shading effect and the performance is far better than the classical P&O method.

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