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ANALYSIS OF THE ALGORITHM P&O FOR MPPT

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Abstract- In this paper authors study the behavior of the Perturbation and Observation (P&O) maximum power point tracking algorithm (MPPT) used in photovoltaic modules in order to obtain the maximum power from a given set of weather conditions. Three variants of the algorithm are compared under both simulated and real world tests with a DSP 1104 card control. The results obtained show that the variant whose simulated behavior is the best, actually is the worse in real world experiments and vice versa, indicating that it is mandatory to test this kind of algorithms in real facilities.

Keywords: Photovoltaic System, Boost Converter, MPPT, Perturbation and Observation (P&O) Algorithm, Matlab/Simulink.

I. INTRODUCTION

The Spanish energy market has traditionally been determined by a strong dependence on fossil fuels and nuclear energy. This implies a strong dependence on other countries and a great lack of sustainability of the energy system, as well as a high damage to the environment.

Due to the general worsening of the economy in Spain, besides the specific problem of the vertiginous deficit of income of the electrical system, the governments approve a set of successive and unrelated measures since the year 2010 with retroactive effects for photovoltaic systems in operation, which generated a uncertainty situation in the sector.

Since the photovoltaic installations are versatile, and due to an increase in the efficiency of the photovoltaic modules, together with a substantial decrease of the prices of the photovoltaic modules makes the photovoltaic energy a competitive sector, being able to adapt to any location in a world where there are still many countries that do not have access to electricity.

A photovoltaic system requires a current converter (DC/DC) that it works as an impedance adapter and that allows changing the working point of the system for different conditions and control algorithms, they are the responsible for the correct operation. In our case the elements chosen are a Boost converter [8], which obtains an average output voltage higher than supplied voltage, and the Perturbation & Observation algorithm (P&O).

In the literature, they have been proposed and developed a number of MPPT algorithms [2, 3, 7]. Among them, the Perturbation and Observation (P&O) algorithm is the most commonly used in MPPT commercial systems. Some authors also compare it with other control algorithms [5].

Due to different problems, especially economic ones, often the only form of researching is through simulations [4, 6]. This has many advantages, but it is convenient to test the real-world behavior of the simulated models because some of them show a behavior under tose circumstances which is not the same than in the simulations. These algorithms have to go through several phases before their final implementation, among which are the simulation and the testing phases, i.e., after a model is simulated, it should be verified in a real testing phase, analyzing whether the model behavior is as given by the simulations.

In this paper, the behavior of one of the most commonly used MPPT algorithms (P&O) is analyzed. In fact, three different versions will be implied in both simulation and real test phases.

The simulation models are made with Matlab/Simulink, while for real tests we have used the dSPACE DSPDS1104 R&D control board [1].

The structure of the paper is as follows: section II gives a brief background on MPPT systems and P&O algorithm, giving a description of the main components of the facilities that we have used. Section III describes the results of the three variants of the P&O algorithm under simulation conditions, while section IV discusses the real-world experiments. Finally, section V summarizes our conclusions.

II. BACKGROUND

Due to the current situation of renewable energies in Spain, in which the economic primes granted to the generation of renewable energy have been reduced considerably, maximizing the efficiency of photovoltaic installations is a basic priority to amortize the investment. Through the use of the control algorithms for maximum power point tracking, it is possible to obtain the maximum advantage of the solar resource. The optimal operation of a photovoltaic system depends on two types of variables, the firsts are imposed and they are mainly the meteorological conditions (Irradiance and Temperature). The second ones are those that can be modified to look for the optimal operation of the system for the given meteorological conditions.

Fundamentally, a MPPT system shown in Figure 1 is composed of a DC-DC converter connected between the photovoltaic module and the load, controlled by a system executing an MPP tracking algorithm. This control system generates a Pulse Width Modulation (PWM) signal with a suitable duty cycle ratio (δ), which is used by the DC-DC converter.

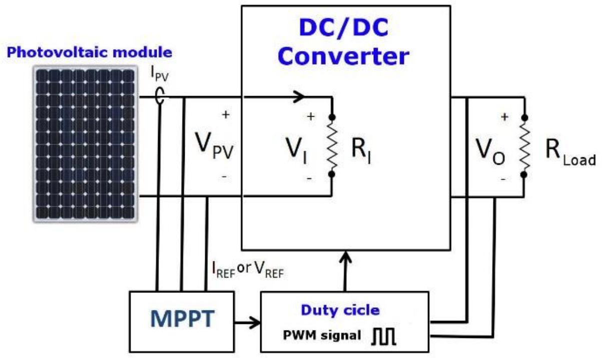

Figure 1. Basic scheme of a MPPT system

The converter has an input impedance (R_I), which basically depends on the load impedance (R_{Load}) and the duty cycle (δ). Therefore, the MPPT algorithm will look for the optimum duty cycle (δ) relationship, so that the working point of the interaction of the *I*-*V* characteristic of the photovoltaic module with the load line (R_I) coincides with the maximum power point (MPP).

The MPPT block contains the tracking algorithm of the maximum power point, which is responsible for generating the reference value I_{REF} (or V_{REF}) from the measurement of the current, I_{PV} (or voltage V_{PV}) at that instant in the photovoltaic module. The controller block that generates the duty cycle (δ) receives the I_{REF} (or V_{REF}) reference value of the MPPT block corresponding to the appropriate current (or voltage) value at which the photovoltaic module should work. With this reference and taking into account the load, the duty cycle (δ) of the converter is modified.

The Perturbation & Observation algorithm (P&O), is the most used in photovoltaic systems, mainly due to its easy implementation. Assuming that the photovoltaic module is working at any point which is not the MPP, the MPPT system disturbs (varies) the working voltage of the photovoltaic module at a small value ΔV.

Then, it is noted (is measured) that the change has occurred in the power ΔP. If $\Delta P>0$, the point of operation has approached to the MPP, where upon the next disturbance will be occured in the same direction as the previous one (same algebraic sign). If on the contrary $\Delta P<0$, the system has moved away from the MPP, then the next disturbance will be done in the opposite direction (opposite algebraic sign).

This perturbation is achieved by the only variable to which the control system has access, which is the duty cycle (δ). An increase of the duty cycle implies a decrease of the input resistance R_I of the DC-DC converter and, therefore, a decrease of the working voltage of the photovoltaic module and vice versa. Once the maximum power point is reached, the P&O algorithm will cause the PV module to operate around it.

In this work, we analyze the behavior of one of the algorithms most used in the operation of photovoltaic installations. The original algorithm is base don the flowchart of Figure 2.

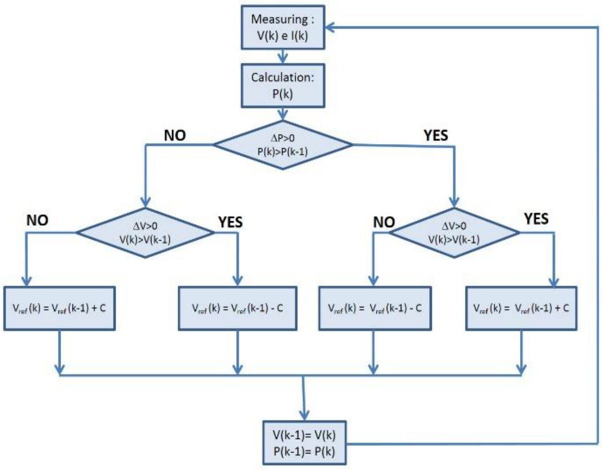

Figure 2. Perturbation & observation algorithm flowchart

The different implementations of the algorithm have been developed in Simulink and they are based on the characteristic *P*-*V* curves shown in Figure 3.

If the optimum behavior of the photovoltaic module is when it operates at the maximum power point for the existing climatic conditions, the duty cicle should be increased or decreased or the voltage at terminals of the photovoltaic module, so that the module is running at that point, as explained in Table 1 in the case of the P&O algorithm. The difference between optimized models is the smoothness with which increments or decrements are made when searching for the maximum power point.

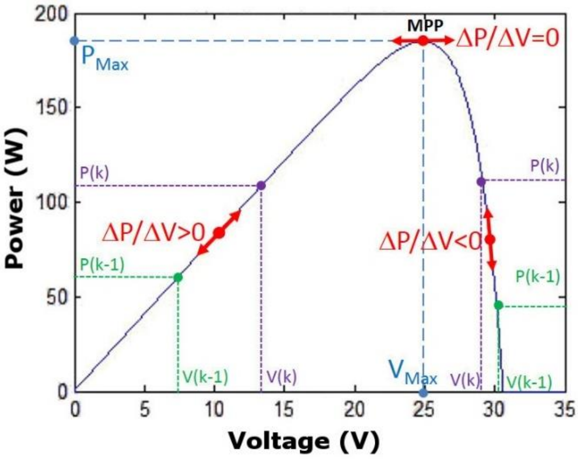

Figure 3. Behavior of P&O on a *P-V* characteristic curve

Table 1. Summary of P&O algorithm behavior

Measurements	Duty cycle	Voltage
$\Delta V>0$, $\Delta V>0$	Decrease	Increase
$\Delta V>0$, $\Delta V<0$	Increase	Decrease
$\Delta V<0$, $\Delta V<0$	Decrease	Increase
$\Delta V<0$, $\Delta V>0$	Increase	Decrease

III. SIMULATION TESTS

In this paper three variants of the P&O algorithm are analyzed. The behavior of each one will be shown when a sudden change in temperature or irradiance happens.

In order to carry out the simulations, we have chosen the following values:

- Varying temperature from 20 ºC to 40 ºC and constant irradiance of 1,000 W/m^2.
- Constant temperature of 25 ºC and varying irradiance from 900 W/m^2 to 700 W/m^2, and finally to 1,000 W/m^2.

A. Variants of Implementation

The first variant of the algorithm has been developed in Simulink as shown in Figure 4, being the theoretical P&O algorithm.

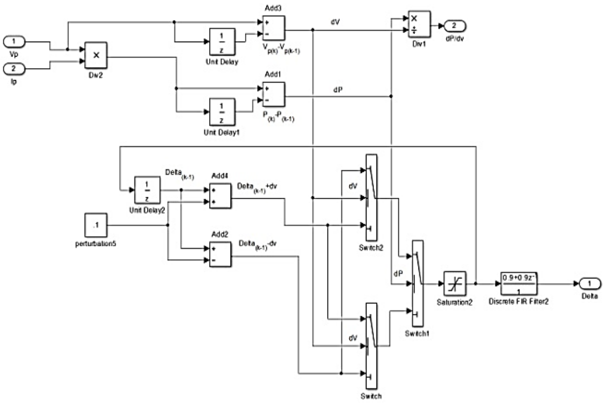

Figure 4. Simulink scheme of variant 1

The second variant of the algorithm has also been developed in Simulink as shown in Figure 5, being the Relay P&O algorithm.

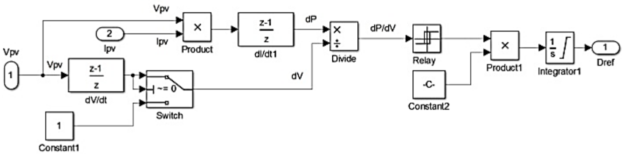

Figure 5. Simulink scheme of variant 2

Figure 6 shows the scheme of the third variant of the P&O algorithm developed also in Simulink, being the Tanh P&O algorithm.

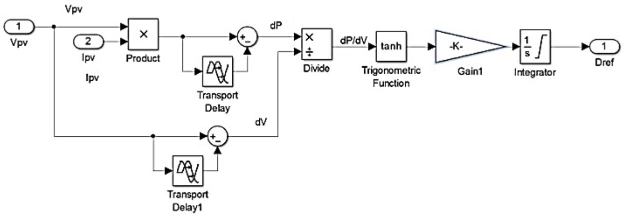

Figure 6. Simulink scheme of variant 3

B. Conditions for Validation through Simulation

The behavior of each variant will be shown when there is a sudden change in temperature or irradiance. To carry out the simulations the following conditions have been chosen:

- Constant temperature of 25 ºC and variable irradiance from 900 W/m^2 to 700 W/m^2, and finally to 1,000 W/m^2. The value of the first irradiance, 900 W/m^2, is maintained for one second more, three in total, to allow the system to stabilize, while the remaining irradiances are maintained only during two seconds, as shown in Figure 7.

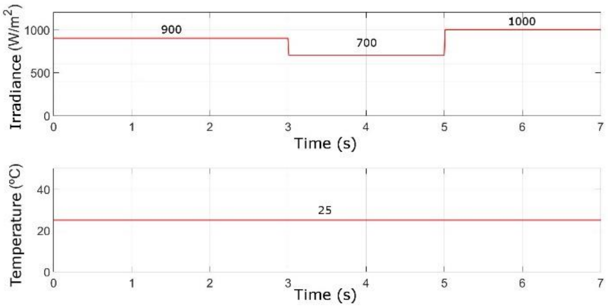

Figure 7. Simulation conditions with varying Irradiance

- Variable temperature from 20 ºC to 40 ºC and constant irradiance of 1,000 W/m^2. The value of the first temperature, 20 ºC, is maintained for a second more, three in total, to allow the system to stabilize, while the final temperature value, 40 ºC, is maintained only for two seconds, as shown in Figure 8.

For the Theoretical P&O algorithm of Figure 2, in the case of sudden changes of irradiance, the results of the simulation are shown in Figure 9. The power of the photovoltaic module (in red) changes very quickly when the irradiation changes suddenly and is kept constant throughout the time until there is no change of irradiance.

The behavior of the algorithm under the different irradiance values is as follows:

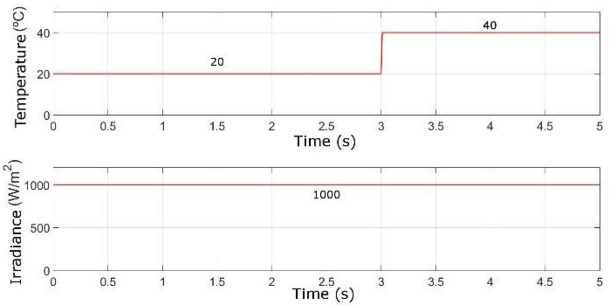

Figure 8. Simulation conditions with varying Temperature

- In the first segment, from the start to the second three, the algorithm operates at an irradiance of 900 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained under these conditions is 102.2163 W according to the characteristic curve *P-I* of the module, being the value obtained 96.2 W. There is a loss of power with respect to the ideal power to obtain of 5.88%. The power obtained at the output of the converter in load (in blue) is 83.3 W, i.e., there is a power loss in the converter of 13.40%.
- In the second segment, from the second three to five, the model operates at an irradiance of 700 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained under these conditions is of 91.4356 W according to the characteristic curve *P-I* of the module, being the value obtained of 90.48 W. There is a loss of power with respect to the ideal power to obtain of 1.045%. The power obtained at the output of the converter in the load (in blue), is 79.55 W, having losses in the converter of 12.08%.
- In the last segment, from second five to seven, the algorithm operates at an irradiance of 1,000 W/m^2 and at temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained under these conditions is 117.831 W according to the characteristic curve *P-I* of the module, being the value obtained 106.6 W. There is a loss of power with respect to the ideal power to obtain of 9.53%. The power obtained at the output of the converter in the load (in blue), is 91.25 W, having losses in converter of 14.40%.

Analyzing the results, it is observed that, the higher the irradiance, the greater the percentage of ideal power loss to obtain. In the case of power in the load, the more irradiance there is, the greater the losses in the converter.

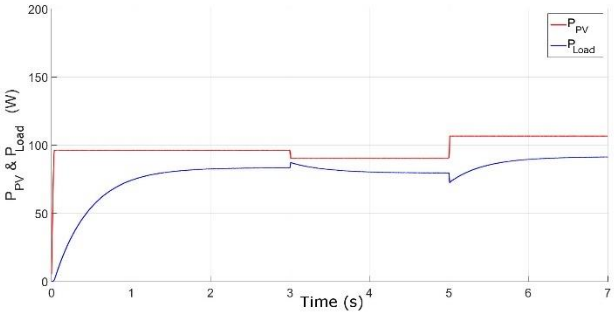

Figure 9. Power under varying Irradiance and constant Temperature

For the theoretical P&O algorithm, in the case of sudden changes of temperature, the results of the simulation are shown in Figure 10. The behavior of the algorithm under different temperature values is as follows:

- In the first segment, from the start to the second three, the algorithm operates at a temperature of 20 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained is 135.2077 W according to the characteristic curve *P-I* of the module, being the value obtained of 120.06 W. There is a loss of power with respect to the ideal power to obtain of the 11.20%. The power obtained at the output of the converter in the load (in blue) is 102.94 W, so the loss in the converter is 14.26%.
- In the second segment, from the second three to five, the algorithm operates at a temperature of 40 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained in this segment is 95.4237 W according to the characteristic curve *P-I* of the module, being the value obtained 86.645 W. There is a loss of power with respect to the ideal power to obtain of 9.25%. The power obtained at the output of the converter in the load (in blue), is 74.16 W, i.e., there is a loss in the converter of 14.41%.

Analyzing the results, it is observed that at the lower temperature, the higher the percentage of ideal power loss to obtain. In the case of the power at the load, the more temperature there is, the greater the losses at the converter, although they are very similar in both cases.

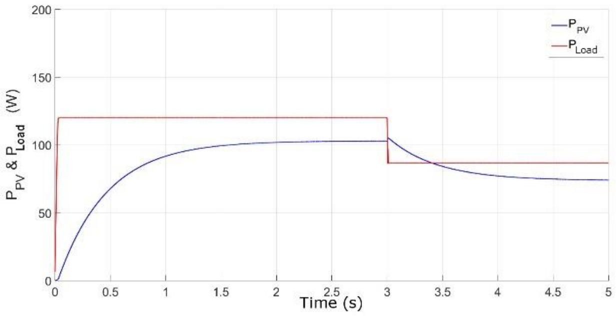

Figure 10. Power under varying Temperature and constant Irradiance

For the Relay P&O algorithm, in the case of sudden changes in irradiance, the results of the simulation are shown in Figure 11. The power of the photovoltaic module (in red) takes longer to stabilize than in the theoretical algorithm. The power behavior of the converter (in blue) is very similar to the previous variant, but in this case a higher power value is achieved, having less loss in the converter. The behavior of the algortihm under the different irradiances is as follows:

- In the first segment, from the start to the second three, the model operates at an irradiance of 900 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this segment is 102.2163 W according to the characteristic curve *P-I* of the module, being the value obtained 101.95 W. So, there is a power loss with respect to the ideal power to obtain of 0.26%.

The power obtained at the output of the converter in the load (in blue), is 93.91 W, so the loss in the converter is 7.88%.

- In the second segment, from the second three to five, the algorithm operates at an irradiance of 700 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this segment is 91.4356 W according to the characteristic curve *P-I* of the module, being the value obtained of 91.39 W. There is a loss of power with respect to the ideal power to obtain of 0.05%. The power obtained at the output of the converter in the load (in blue), is 84.16 W, so the loss in the converter is 7.91%.
- In the last segment, from second five to seven, the algorithm operates at an irradiance of 1,000 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this section is 117.831 W, according to the characteristic curve *P-I* of the module, being the value obtained 117.8 W. There is a loss of power with respect to the ideal power to obtain of 0.026%. The power obtained at the output of the converter in the load (in blue), is 108.75 W, so there is a loss in the converter of 7.68%.

Analyzing the results, it is observed that at the higher and lower irradiance the losses are almost nulls, being minimally higher for 900 W/m^2, being the values almost zero. The algorithm takes a little time to stabilize, but when it does, it gets the ideal power. In the case of the power in the load, the lower irradiance implies that the losses in the converter are larger, being very similar in the three analyzed segments.

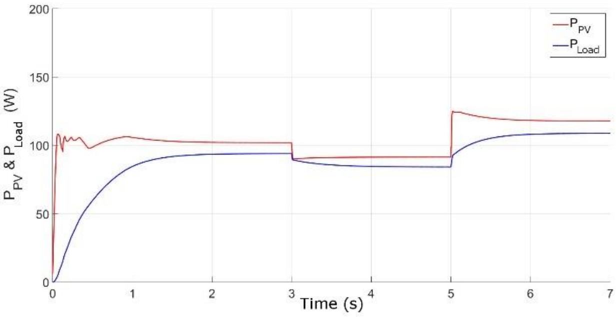

Figure 11. Power under varying Irradiance and constant Temperature

In a similar way than with the previous algorithm, we have tested the response of the algorithm to sudden changes in temperature and the results of the simulations are shown in Figure 12. The behavior of the algorithm under different temperature conditions is the following:

- In the first segment, from the start to the second three, the algorithm operates at a temperature of 20 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained in this segment is 135.2077 W according to the characteristic curve *P-I* of the module, being the value obtained 135 W. There is a loss of power with respect to the ideal power to obtain of 0.15%. The power obtained at the output of the converter in the load (in blue) is 124.94 W, so the loss in the converter is 7.45%.
- In the second segment, from the second three to five, the algorithm operates at a temperature of 40 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained in this section is 95.4237 W according to the characteristic curve *P-I* of the module, being the value obtained 95.355 W. There is a loss of power with respect to the ideal power to obtain of 0.071%. The power obtained at the output of the converter in the load (in blue) is 87.795 W, i.e., the loss in the converter is 7.93%.

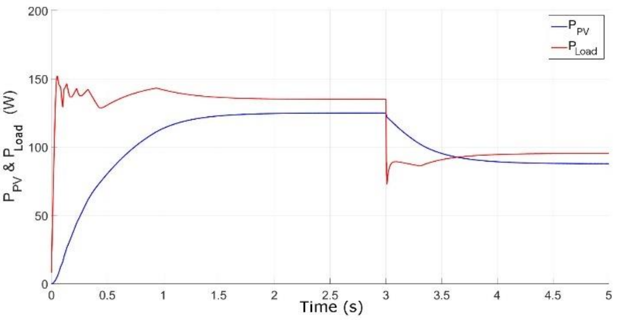

Figure 12. Power under varying Temperature and constant Irradiance

Finally, for the Tanh P&O algorithm, the results of the simulation are shown in Figure 13. It is the variant that has the biggest noise at the beginning, but when it stabilizes the behavior is similar to the previous variant. The power behavior of the converter (in blue) is very similar to the previous variant having a similar loss in the converter. The behavior of the algorithm for different irradiances is as follows:

- In the first segment, from the start to the second three, the model operates at an irradiance of 900 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this section is of 102.2163 W according to the characteristic curve *P-I* of the module, being the value obtained of 101.95 W. There is a loss of power with respect to the ideal power to obtain of 0.26%. The power obtained at the output of the converter, in the load (in blue), is 93.91 W, so the loss in the converter is 7.88%.
- In the second segment, from the second three to five, the model operates at an irradiance of 700 W/m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this section is of 91.4356 W according to the characteristic curve *P-I* of the module, being the value obtained of 91.39 W. There is a loss of power with respect to the ideal power to obtain of the 0.05%. The power obtained at the output of the converter, in the load (in blue), is 84.16 W, having a loss in the converter of the 7.91%.
- In the last segment, from the second five to seven, the model operates at an irradiance of 1,000 W/ m^2 and a temperature of 25 ºC. The power of the photovoltaic module (in red) that should have been obtained in this segment is of 117.831 W according to the characteristic curve *P-I* of the module, being the value obtained of 117.8 W. There is a loss of power with respect to the ideal power to obtain of the 0.026%. The power obtained at the output of the converter, in the load (in blue), is 108.75 W, showing a loss in the converter of the 7.68%.

Analyzing the results, it is observed that with the higher and lower irradiance the losses are almost nulls, being minimally higher for 900 W/m^2. The algorithm takes a little time to stabilize, but when it does, it gets the ideal power. In the case of the power in the load, the lower irradiance implies a larger the loss in the converter, being very similar in the three cases.

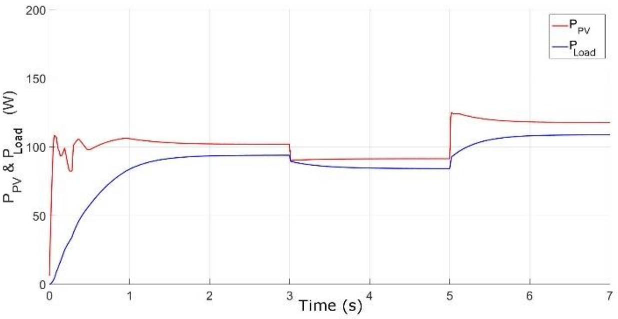

Figure 13. Power under varying Irradiance and constant Temperature

The simulation results of the algorithm under different temperatures are shown in Figure 14, being the behavior of the algorithm as follows:

- In the first segment, from the start to the second three, the model operates at a temperature of 20 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained in this section is 135.2077 W according to the characteristic curve *P-I* of the module, being the value obtained of 135 W. There is a loss of power with respect to the ideal power to obtain of the 0.15%. The power obtained at the output of the converter in the load (in blue), is 124.935 W, having a loss in the converter of the 7.45%.
- In the second segment, from the second three to five, the algorithm operates at a temperature of 40 ºC and irradiance of 1,000 W/m^2. The power of the photovoltaic module (in red) that should have been obtained in this section is of 95.4237 W according to the characteristic curve *P-I* of the module, being the value obtained of 95.365 W. There is a loss of power with respect to the ideal power to obtain of 0.061%. The power obtained at the output of the converter in the load (in blue), is 87.79 W, showing a loss in the converter of the 7.94%.

Analyzing the results, it is observed that at the lower temperature, it is greater the value of the percentage of the loss with respect to the ideal power to obtain. The algorithm takes a little time to stabilize, but when it does it gets the ideal power. In the case of the power on the load, when the temperature is higher, greater is the loss in converter, although they are very similar in both cases.

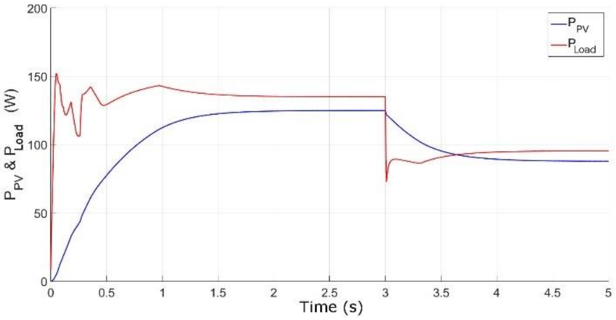

Figure 14. Power under varying Temperature and constant Irradiance

IV. EXPERIMENTAL RESULTS

The experimental validation is performed using these algorithms in the real photovoltaic system, which is placed at the Electrical Engineering Department, (University of the Basque Country), on the roof of the Faculty of Engineering of Vitoria-Gasteiz. As these are ntot laboratory tests, we cannot control the two fundamental parameters that serve for this validation, i.e., Irradiance and Temperature.

As these values depend on the climatic conditions existing at each moment, the experiments that have been carried out in very similar environmental situations. With these approximate values of irradiance and temperature and with a simulated model of the Mitsubishi Electric PV-TD185MF5 photovoltaic module, it is analized which is the maximum power point at which the module should work with these ambient conditions. Thus, it will be known which of models has a more appropriate behavior.

For the real-time experimental tests of the photovoltaic system, we have used a personal computer to save the results, a dSPACE 1104 controller card and a variable load with a maximum value of 450 Ω.

The validation of the P&O algorithms will be carried out with climatic conditions of an approximate irradiance of 900 W/ m^2 and an approximate temperature of 57 ºC. These are the approximate values at which the three measurements are done. For these values a characteristic curve *P-I* is obtained as shown in the Figure 15, which will provide us with the value of the maximum power point in which the photovoltaic module is working. In this case the value is 77.3964 W.

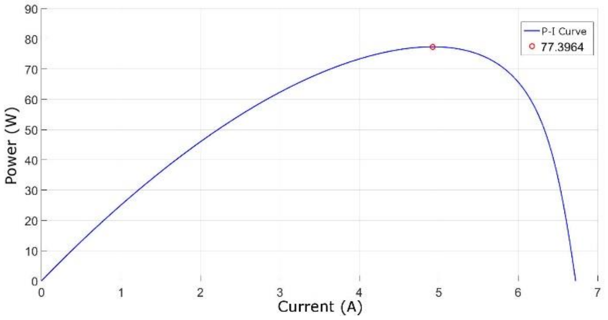

Figure 15. *P-I* curve and maximum power point for working conditions

For the experimental validation of the Theoretical P&O algorithm, the load resistor has been varied at the output of the DC/DC converter in the way shown in Figure 16, i.e., the initial charge value is 302 Ω, is increased to 415 Ω and finally it is reduced to 279 Ω.

In Figure 17, it can be seen that the behavior of the experiment in the real world of this algorithm, which is neither as good nor stable as when it was tested under simulation conditions.

The variation of the load for the experimental validation of the Relay P&O algorithm is shown in Figure 18 and for this second variant, the imposed change in the variable load value starts from an initial value of 362 Ω, it is decremented to 292 Ω, it is increased to 346 Ω, is decreased to 279 Ω and finally increases to 349 Ω.

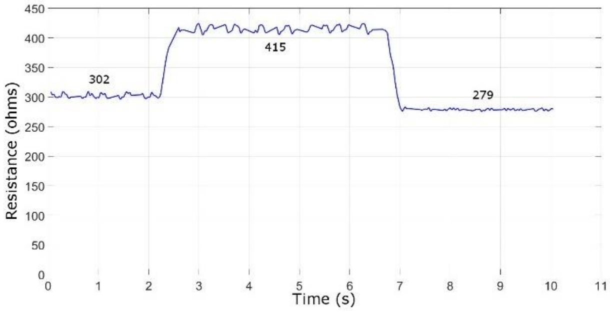

Figure 16. R_{Load} changing values

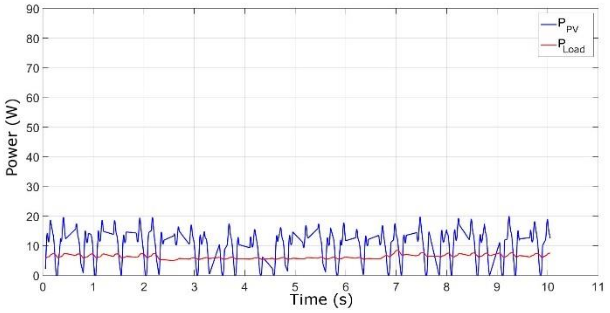

Figure 17. Simulation results for variations of the load resistance

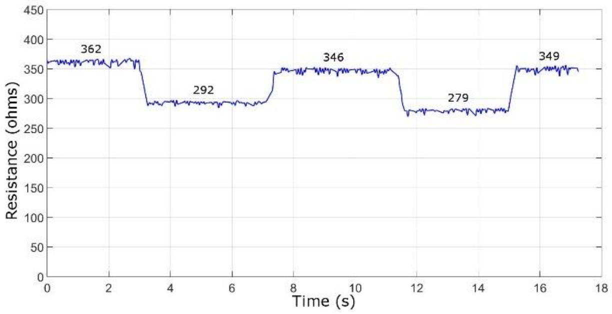

Figure 18. R_{Load} Values

In Figure 19, it is shown that the power of the photovoltaic module is maintained at an approximated value to the desired one, about 74 W for the upper values of the load resistance, but the power decreases for the two lower values. In these two values the converter will be working in discontinuous mode.

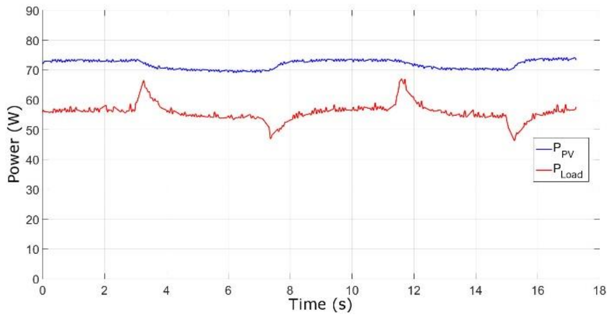

Figure 19. Simulation results for variations of the load resistance

The real experiment performed with the last variant of the algorithm, Tanh P&O, was starting from the load value of 344 Ω, it is decreased to 247 Ω, it is increased to 342 Ω, it is decreased to 275 Ω and then increased to 346 Ω, as shown in Figure 20.

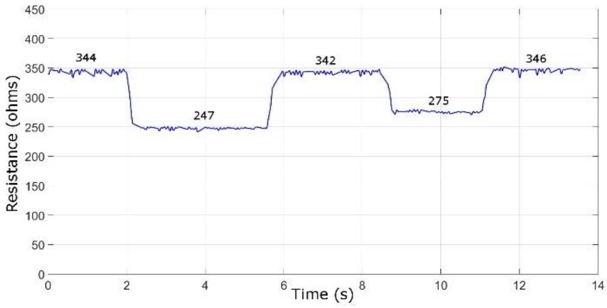

Figure 20. R_{Load} values

In the case of this last variant, we obtained the best performance of all of them with respect to the stability and power obtained. The resulting power varies between 75 W and 77 W, as shown in Figure 21. The changes in load only affect slightly MPP tracking: the photovoltaic module continues operating at the maximum power point after changes in the value of the load, adapting the values of V_{PV} and I_{PV} so that the value of the P_{PV} is the same. The model works well for high load values.

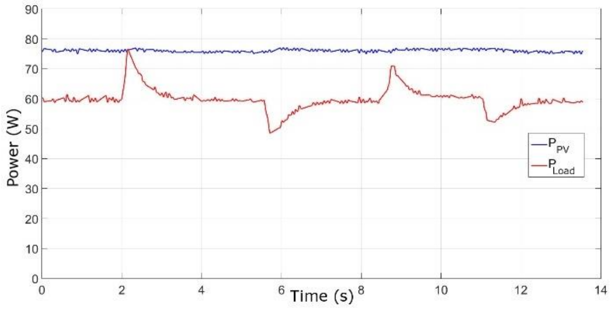

Figure 21. Simulation results for variations of the load resistance

V. CONCLUSIONS

Currently a lot of research work has focused on how to extract more energy from photovoltaic systems. In a photovoltaic generation system, it is necessary to extract the maximum power of the photovoltaic arrays. The way to obtain maximum power is through Maximum Power Point Tracking (MPPT) strategies, which maximize the output power of a photovoltaic system for a set of atmospheric conditions.

The validation of the standard P&O algorithm and their optimized variations is performed on simulated and experimental conditions. During the simulated validation phase, the optimized algorithms behave in an optimal and similar way, and better than the Teorethical algorithm of Figure 2, i.e., they can not make the photovoltaic module to operate at the optimum power.

When the experimental validation is carried out, the Theoretical algorithm does not work properly, even their behavior is much worse than when doing the validation through simulation. The algorithm whose experimental behavior is the best is the Tanh P&O algorithm. For load resistors with values larger than 247 Ω it has an acceptable behavior, not being so good in the case of the Relay P&O algorithm, that has worse behavior for resistances of value inferior to 279 Ω.

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