Design, modeling and simulation of perturb and observe maximum power point tracking for a photovoltaic water pumping system

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ABSTRACT

Maximum power point tracking (MPPT) is considered one of the important factors in minimizing the installation costs and improving the efficiency of any photovoltaic water pumping system. The MPPT controller is specifically used to extract the maximum available power from the photovoltaic (PV) array. The maximum power can be achieved by using a specific algorithm. This work aims to raise awareness among farmers about the energy benefits available in the region of Meknes in Morocco, the economic gain and the environmental impact applied to the solar pumping system so that it can be generalized. To obtain the maximum power at each moment, a direct current (DC) water pump (SQF 0-6-2) powered by the solar panels (REC_330NP) through a buck converter was adapted. In addition, this study illustrates the theory of operation of the perturb and observe (P&O) algorithm and simulates the evaluation of this algorithm under different operating conditions (temperature and solar irradiation), and showed the advantages of this system that can operate at the optimal power regardless of disturbances.

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1. INTRODUCTION

Energy has become the great central debate of our modern civilizations [1]. About 90% of this energy is fossil, and poses a potential danger to this universe through global warming [2]. The use of renewable energies considerably reduces the undesirable emissions of these gases [2].

The price of fossil energy is constantly increasing [3], [4]. The fight against greenhouse gas emissions makes urgent control of energy consumption, and the diversification of energy resources and its development [5], [6]. The agricultural sector in Morocco consumes about 13% of energy, mainly concentrated in irrigation equipment. Therefore; solar pumping will allow the farmer to have access to free energy [7], [8]. It is a clean and renewable energy, which is carried out without noise or carbon dioxide polluting the climate, and which fits perfectly with the current ecological policy of the government (Green Morocco Plan) [9].

Morocco's strategic geographical location offers favorable conditions for investment and use of renewable energies, especially solar energy. The introduction of these energies could easily be considered on many applications such as: photovoltaic water pumping system, off-grid rural electrification or direct injection of the produced energy into the electrical grid. The solar water pumping system is a promising solution of photovoltaic systems that can be used to provide water to rural and remote areas. The advances in photovoltaic panel technology have reduced the cost of solar panels and increased the feasibility of solar water pumping systems [10].

In addition, agriculture is expected to play a role as a locomotive for the economic growth of countries in the future. In this way, the Green Morocco Plan has aimed to create a framework conducive to the development of the sector through: strengthening the capacities of the various actors involved; focusing on raising awareness among farmers on the economic and environmental interest of solar pumping in order to make it more widespread; the establishing financing mechanisms facilitating the acquisition of photovoltaic (PV) water pumping systems; standardizing solar installations for irrigation; and establishing a framework for monitoring the impacts of the project in terms of mitigation of greenhouse gas emissions.

In the case of a direct connection between a photovoltaic generator and an electrical water pump, the point of operation of this installation depends on the impedance of the latter. This choice is mainly related to simplicity, reliability and low cost of the installation. However, this configuration does not offer any type of limitation or adjustment of the pump voltage. Indeed, the power extracted from the photovoltaic generator is often very far from the maximum power that this solar power can deliver [11]. So to address this issue, we need an adaptation stage with an algorithm. This algorithm constantly seeks the maximum power available on the photovoltaic generator to ensure that the energy transfer can be carried out under optimal operating conditions. Nowadays, there are different types of algorithms performing the search for maximum power point (MPP): hill climbing [12], perturb and observe (P&O) [13], Inc Cond [14], fuzzy control [15] and proportional-integral-derivative (PID) [16]. Despite the advantages of solar water pumping systems, the use of photovoltaic generator in pumping systems is not well known in Morocco. The problem is directly related to the operators who are not aware of the advantages of these systems and their contributions from an economic, ecological as well as other benefits.

In the present work, certain measurements were taken on the efficiency of using solar water pumping systems in agriculture. Indeed, the country has enough solar energy resources to reduce water pumping using butane and diesel. Indeed, photovoltaic converters are characterized by a very low conversion efficiency [17]. Thus, another efficiency drop is mainly related to the intersection of the two curves: photovoltaic generator and load characteristics. To solve this problem, a buck converter must be inserted before the pump. This buck converter is equipped with one of the above mentioned algorithms. Due to the evolution of the metrological parameters of the region that will be shown later, P&O algorithm studies show the ease by which this can be implemented and the need for a simple calculator. In addition, this algorithm allows to decrease the cost to improve the profitability of agricultural facilities.

2. RESEARCH METHOD

2.1. Principle of solar water pumping systems

The system is designed around a direct current (DC) water pump connected to PV generator by an maximum power point tracking (MPPT) controller as shown in Figure 1. The latter is used for two purposes in the solar pumping system: The first is to regulate the required voltage of the pump and to operate it by the maximum power produced. The second objective is to protect the pump from low voltages when the system is turned off if the voltage is too low or too high compared to the nominal voltage [18]. This aims at increasing the life of the pump and thus reduces the need for maintenance.

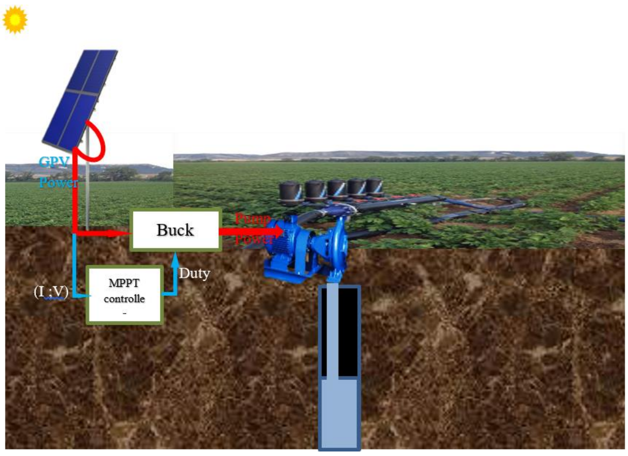


Figure 1. Concept of PV water pumping system

2.2. The advantages of P&O MPPT technique on a PV water pumping system

The principle of P&O MPPT controller [19] is to disturb the voltage of photovoltaic generator V_{pv} of a small amplitude around its initial value, and to analyze the behavior of the resulting power P_{PV} variation. If a positive V_{PV} voltage increment results in an increase in P_{PV} power, this means that the operating point is to the left of the MPP. If, on the contrary, the power decreases, this implies that the system has exceeded the MPP. A similar reasoning can be made when the voltage decreases as shown in the Figure 2. It is then easy to locate the operating point in relation to the MPP and to make the power generated is maximum (PPM) converge towards the maximum power through an appropriate command order.

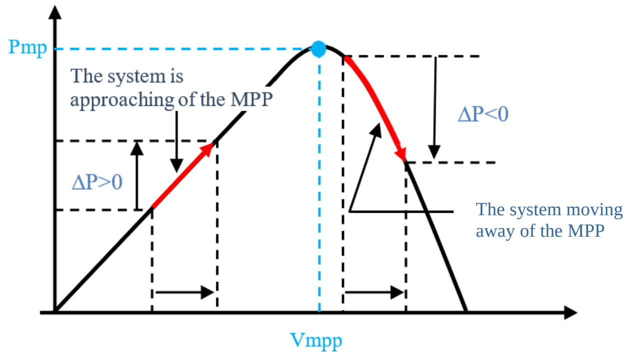


Figure 2. P&O MPPT Search and recovery of the maximum power point

2.3. Meteorological conditions in the region

The average amount of sunshine is more than 8 hours per day. Moroccan regions present all the favorable conditions for solar water pumping system. Winter insolation for these regions varies between 934 and 1,520 hours. Based on digital data captured by CR1000 Meteorological Station at the Meknes Faculty of Science in Figure 3, where Figure 3(a) represents the variation of irradiance and Figure 3(b) represents the variation of temperature of the city of Meknes since the year 2014. The interval of these digital data can be simulated to estimate the quantity of energy in the region as elaborated in the next section.

It can be seen from Figure 3 that the temperature varies from 0-45 °C, but the average temperature is still around 20 °C. The maximum solar irradiance varies from 600 W/m^2 to almost 1,500 W/m^2. But the average value is still around 900 W/m^2. To be more practical, it is preferable to make the simulation related to the real parameters of the region in order to estimate the real performance of such a solar pumping system in the region.

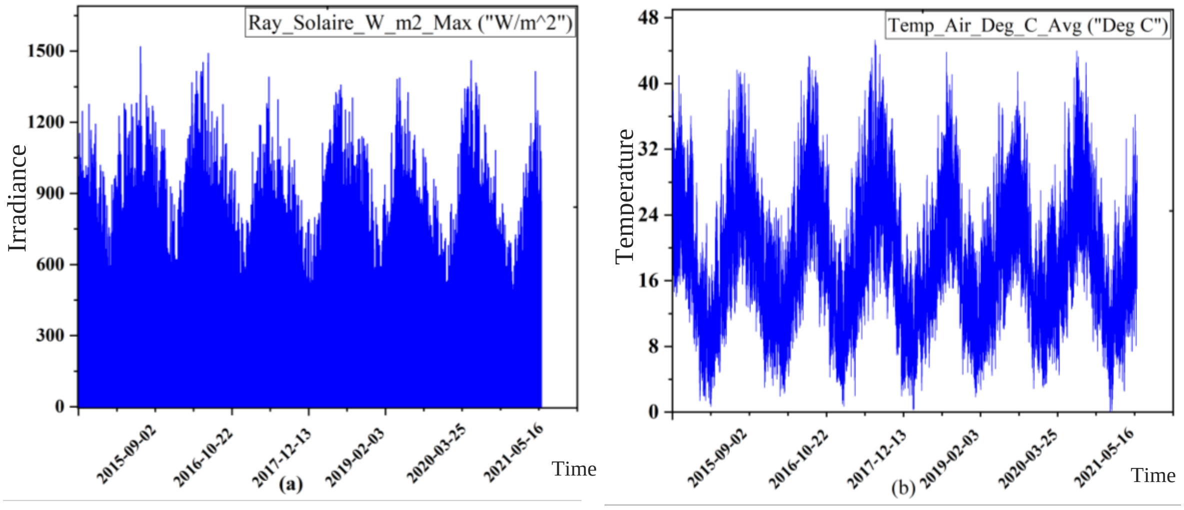


Figure 3. Digital data captured by CR1000 Meteorological Station at the Meknes Faculty of Science in, where (a) the variation of irradiance and (b) temperature of the city of Meknes since the year 2014

Figure 4 shows the evolution of irradiance over the course of a day on randomly selected days. It can be seen that the evolution of irradiance over time does not change brutally during the day. Furthermore, most PV-based applications (such as solar water pumping) do not run all the time, so a very simple controller with P&O algorithms is sufficient.

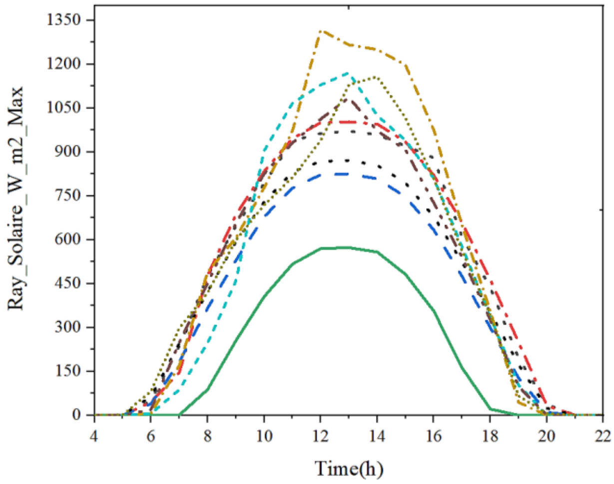


Figure 4. The variation of irradiance on random days

2.4. Modeling of the PV power station

The equivalent diagram of a real solar cell is represented in Figure 5, by a current generator (I_{ph}), a diode and two types of parasites resistance (R_s) and (R_{sh}). Where the current generator (I_{ph}) delivers a current I_{ph} corresponding to the photogenic current, it is a perfect source; the diode (D) models the P-N junction materializing the fact that the current only flows in one direction; the series resistance, R_s modeling the resistive losses within the solar cell, it is a resistance that the electric current encounters on its course (intrinsic resistance of the layers and resistance of the contacts); the shunt resistance R_{sh} corresponds to a leakage resistance between the two zones N and P of the junction. It takes into account the inevitable leaks of the current which occur between the opposite positive and negative terminals of a photocell (micro short circuit in silicon in particular).

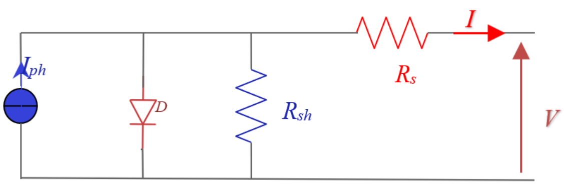


Figure 5. Electrical model of a cell PV [20]

It follows that part of the current I_{ph} will be derived from Rsh and cannot be delivered to the load; thus, to increase the PV efficiency, Rsh must be as high as possible in the cell. The load will be connected at the terminals of PV cells. The impedance of this load will impose the operating point on the photocell as a function of its current-voltage characteristic (I, V) that depends on the considered irradiance and other parameters. The output current of the PV module can be written as shown in the relation (1) [21].

$$I = I_{ph} - I_s \left[exp^{\frac{V+I.R_S}{nV_{th}}} - 1 \right] - \frac{V+I.R_S}{R_{sh}} \quad (1)$$

where:
Is (A) = corresponding to the saturation current;
V_{th} (V) = the thermodynamic potential;

K (J.K^{-1}) = the Boltzmann constant;
T (K) = the effective temperature of the cell;
e (C) = the charge of the electron;
n = a factor of non-ideality of the junction;
I (A) = the current supplied by the cell;
V (V) = the voltage across the cell, I_{ph} (A), the short-circuit current of the cell, depending on the sun irradiance and the temperature.

In a PV generator, there are usually several photovoltaic cells put together with different modes (series/parallel) to build a power supply [22], [23]. This combination depends on the voltage and the currents required to meet certain load specification requirements. The resulting characteristic (I, V) or (P, V) of a series grouping obtained for n identical cells by summing the elementary characteristics of constant current is as follows: V_n = n.V1, and for a grouping of p parallel cells is I_n = p.I1 [24].

3. RESULTS AND DISCUSSION

3.1. Simulation results of PV under different atmospheric conditions

PV generator is composed of a mono-crystalline solar panel, model REC_330NP. The electrical characteristics of this module are presented in the Table 1. According to the manufacturer tests under standard conditions (E=1000 W/m², AM=1.5, T_c=25 °C) indicate we find:

Table 1. The REC_330NP characteristics

R_{sh}	R_s	V_{mpp}	I_{mpp}	P_{mpp}	I_{sc}	V_{oc}
1 kΩ	73mΩ	34.6 V	9.55 A	330 W	10.33A	41 V

To study this PV generator, we need its electrical model of (1), which takes into account the relationship between the different variables that influence photovoltaic generator production. We can also use simulation software. Figure 6 shows the electrical behavior of the REC_330NP module by simulation, where Figure 6(a) shows the power-voltage characteristic and Figure 6(b) shows the current-voltage characteristic.

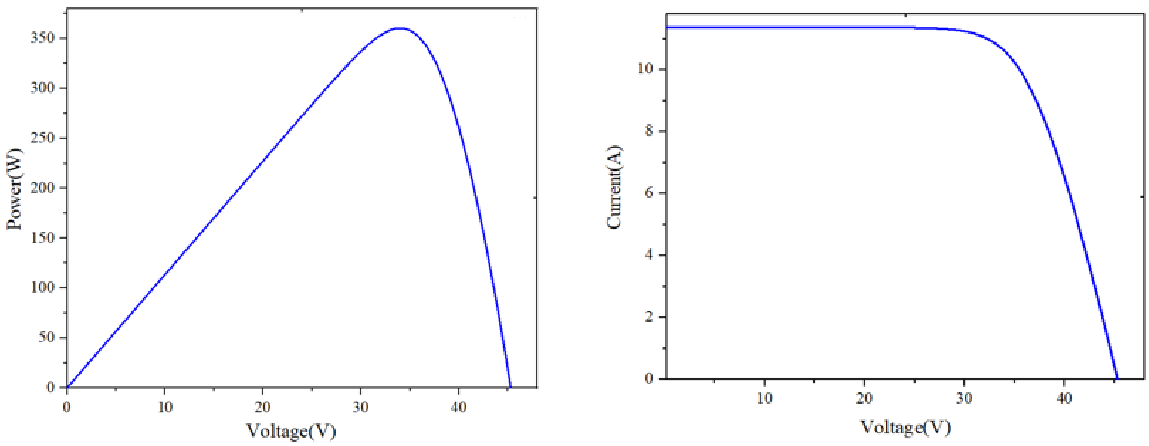


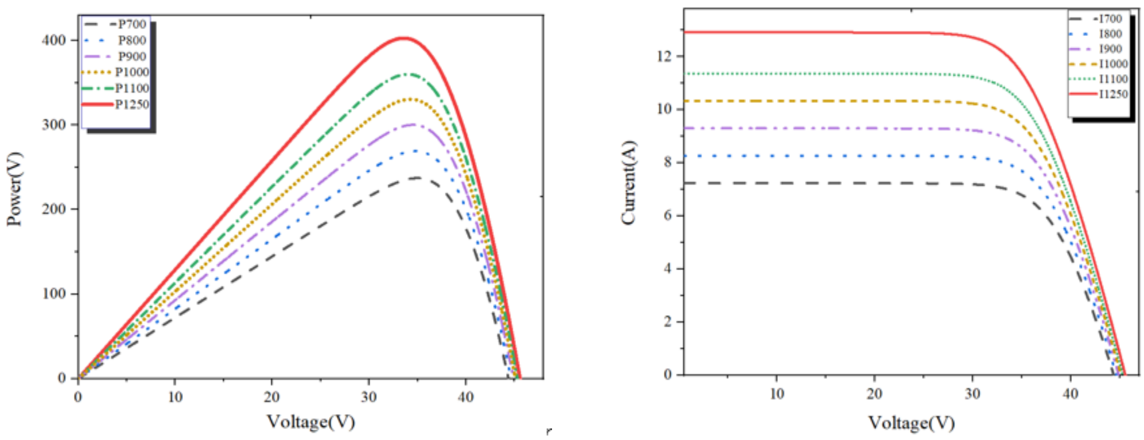
Figure 6. Characteristics of the REC_330NP module (a) the power-voltage characteristic and (b) the current-voltage characteristic

From the results of simulations, we notice that the maximum current (I_{sc}=10.33 A) occurs when the module terminals are short-circuited. It is called short-circuit current, the Isc strongly depends on the level of illumination; no-load voltage (V_{oc}=41 V) for zero current. This voltage is also called open-circuit voltage. The maximum power point MPP (V_{mpp}=34.6 V, I_{mpp}=9.55 A, the maximum electrical power delivered (P_c=330 Watt peak). From the current-voltage characteristic, we can deduce the characteristic of the electrical power generated by the cell as a function of the voltage across its terminals. There is a photo current value corresponding to a voltage across the cell for which this generated electrical power is optimum [25], [26].

This value varies depending on several meteorological parameters such as temperature, irradiance, and position of the panel relative to the sun.

3.1.1. Irradiance influences

The network of characteristics (I, V) according to a variable irradiance (for a junction temperature of 25 °C) is shown in the following Figure 7 where Figure 7(a) represents the power-voltage characteristic and Figure 7(b) the current-voltage characteristic. Under higher solar irradiance, the current Icc directly increased along with (the relationship is proportional) the voltage remaining relatively constant. It is clear that when the irradiance increased from 400 W.m-^{2} to 1,200 W.m-^{2}; the power increased from 140 W_p to 380 W_p.



(a) (b)

Figure 7. The REC_330NP characteristics under several radiation modes (a) the power-voltage characteristic and (b) the current-voltage characteristic

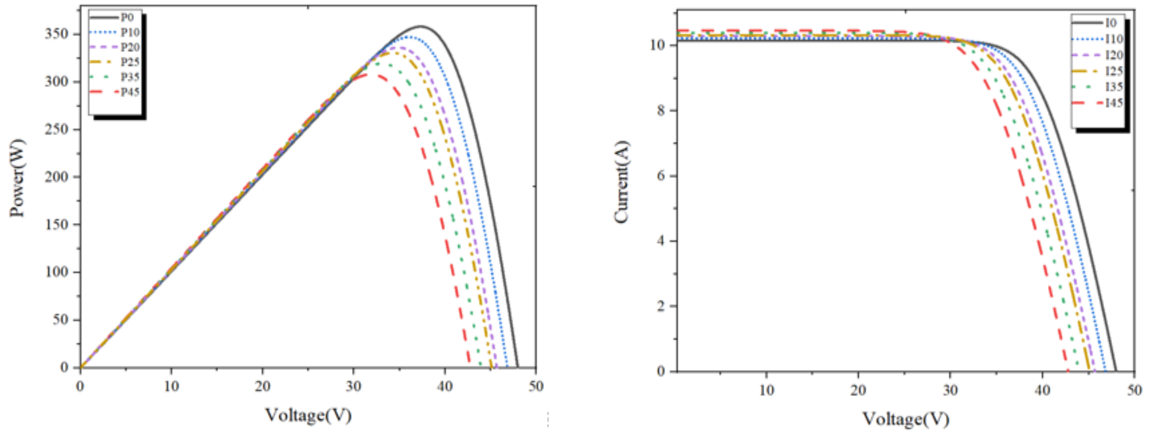
3.1.2. Temperature influence

Figure 8 displays the characteristics of a PV panel under constant lighting and variable temperature, where Figure 8(a) represents the power-voltage characteristics and Figure 8(b) represents the current-voltage characteristics. The temperature also has a significant influence on the characteristics of this panel. When the temperature increases, the voltage decreases and therefore the power too. The curves in the previous figure show this drift in the characteristics of this crystalline silicon panel as a function of temperature. We note that we moved from an optimal power of 305 W_p at 45 °C to a power of 360 W_p for a temperature of 0 °C. Thus, we will have to take into account the temperature of use of the solar cell in order to apply for a reduction coefficient of the optimal power at 25 °C.

3.2. Simulation results of a PV water pumping system

The following section presents the result of the simulation of the photovoltaic water pumping system, which is composed of a DC electric pump SQF 0-6-2, its technical characteristics are: nominal current in = 8.4 A, average voltage 30 to 300 VDC. This is connected to a photovoltaic generator through a step-down chopper with a P&O algorithm, as shown in Figure 9. This array consists of five photovoltaic panels (REC_330NP), which will generate a total peak power of 1650 Wp under standard conditions, where the temperature of the PV array is maintained at a fixed value of 25 °C. It should be noted that the irradiance changes almost every three seconds.

Figures 10, 11 and 12 show the irradiance, duty cycle, and power delivered by the MPPT controller to the pump over time, respectively. It can be seen in Figure 10 as the time increases, the irradiance increases in steps. This evolution presents a real situation of the system in which it will operate. According to Figure 11, the evolution of the duty cycle depends on the evolution of the irradiance. This change is reflected in the amount of energy available on the PV generator. Concerning the power, Figure 12 shows the extraction ratio between the PV generators traversing the converter. This figure shows the efficiency of the P&O MPPT controller. It also displays the amplitude and frequency of the pump power oscillations which depend on the step size of the duty cycle variation. It is worth noting that a small step size of duty cycle variation indicates very good performance when the irradiance varies very slowly, yet a relatively poor dynamic response when sudden changes in irradiance happen. In this case, a step size of 0.001 in duty cycle gives a pump power variation fluctuating around 2 watts.



(a) (b)

Figure 8. The REC_330NP caracteristics under variable temperature (a) the power-voltage characteristics and (b) the current-voltage characteristics

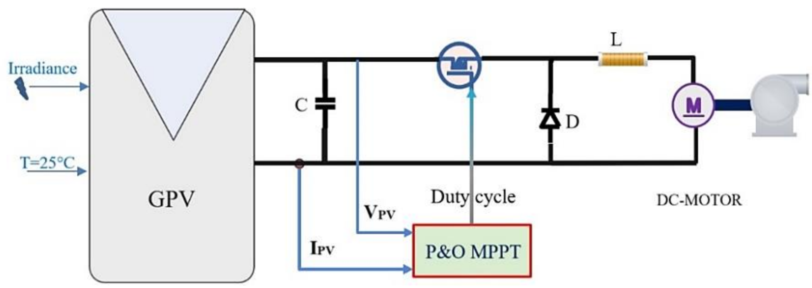


Figure 9. Simulation block diagram of the photovoltaic water pumping system

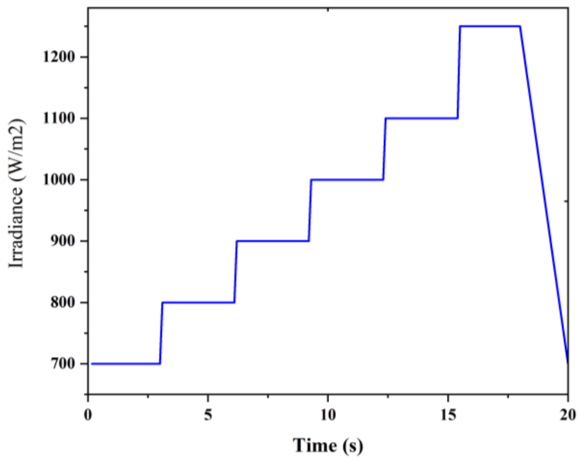


Figure 10. Profile of irradiance variation

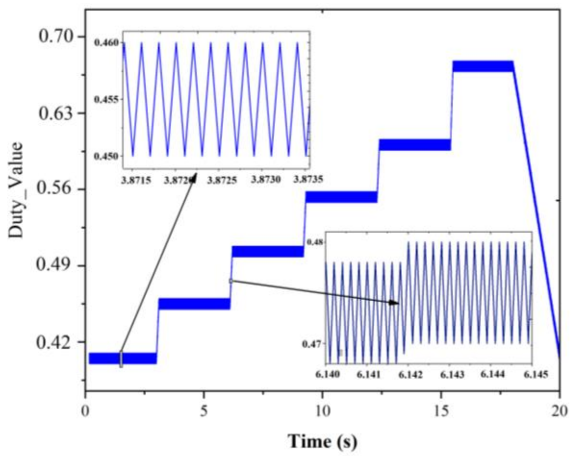


Figure 11. Variation of duty cycle

Table 2 summarizes the different power output points of this system under different metrological conditions. Based on the metrological data of the region, the average irradiance value is about 900 W/m2, presents an efficiency of 95% energy extraction. It can be concluded that this P&O MPPT presents a very acceptable dynamic response for this solar pumping system. It also reaches and converges to the maximum power point despite the irradiance variations. From the beginning of this simulation, we can note that the system is stagnant, and works at MPP on the one hand. On the other hand, the operating point does not deviate from the MPP under unstable weather conditions.

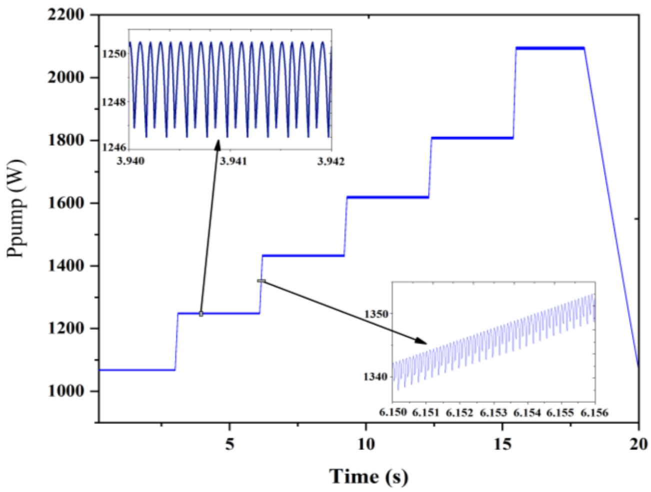


Figure 12. The power delivered by the P&O MPPT controller to the pump

Table 2. Recorded results of a solar water pumping systems

Irradiance (W/m2)	700	800	900	1000	1100	1250
Temperature °C	25	25	25	25	25	25
Power max (W)	230	265	300	330	356	429
Power GPVmax (W)	1150	1325	1500	1650	1780	2145
Duty	0.40	0.45	0.50	0.55	0.60	0.67
Pump Power (W)	1073	1250	1434	1620	1735	2100
efficiency	0.93	0.94	0.95	0.98	097	0.97

4. CONCLUSION

Energy charges are the main expense for farmers. Once the pumping system is installed, the use of solar energy presents a technological solution to reduce energy costs. The maximum power is the main index to assess the performance of the pumping system of the photovoltaic generator. There is an optimal voltage value for this power, which is the maximum power point on the one hand. On the other hand, the maximum power point varies with meteorological conditions, which leads to a change in this point and energy loss. In this work, the P&O MPPT controller presents a better solution for the operation of photovoltaic water pumping system.

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