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Comparison Between MPPT Controllers for Optimal Operating of Photovoltaic Pumping System

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***Abstract*— This paper presents the optimization of a photovoltaic water pumping system using maximum power point tracking technique (MPPT) in order to optimize its efficiency. Many methods have been developed to determine the maximum power point (MPP), a comparison between perturbation and observation method (P&O), fuzzy logic controller (FLC) and Neuro-fuzzy (NF) technique is presented. The studied Neuro-Fuzzy controller is a hybrid controller, which is the combination of artificial neural network and fuzzy controller. The NF controller has the advantages of robustness, fast response and good performance. The photovoltaic pumping system is composed of a PV generator, DC-DC converter, DC-AC converter, induction motor and centrifugal pump. A vector control of induction motor is applied to improve its dynamic performance. Further, the performance of the NF controller is compared with the two other controllers through simulation studies. Simulation results show that accurate MPPT tracking performance of the proposed system has been achieved and demonstrate the effectiveness and superiority of the proposed approach.**

***Keywords*— Photovoltaic system, MPPT controllers, PV pumping, induction motor**

I. INTRODUCTION

The sun is a clean and renewable energy source, which produces neither green house effect gases nor hazardous wastes through its utilization. The use of photovoltaic as the power source for pumping water is one of the most promising areas in photovoltaic applications. Researches published in photovoltaic water pumping were interested essentially either in water pump modelling and control or in overall system modelling and simulation [1-4]. Recently, more attention has been paid to their design and optimum utilization in order to achieve the most reliable and economical operation.

Tracking the maximum power point of a photovoltaic (PV) array is an essential task in a PV control system because it maximizes the power output of the PV system for a given set of conditions of insulation and temperature, and therefore maximizes the array efficiency. Consequently, various efficient MPPT (Maximum Power Point Tracking) methods and controllers have been developed and proposed in literature [5]. The perturb and observe (P&O) maximum power point tracking algorithm is the most used tracking technique owing to its simple implementation [5-6]. In recent years, the fuzzy logic controllers (FLC) and neural network methods have received attention and increased their use very successfully in the implementation for MPP searching [5-11]. MPPT using FLC provides various advantages of superior performance, robust and simple design. Further more, this technique does not necessitate the particulars of the exact model of system. Neural network has the ability to offer an improved technique of deriving non-linear models, which is complementary to traditional techniques [12] The hybrid neuro-fuzzy (NF) system is an extension of fuzzy and neural network, which is used for obtaining maximum power output from PV generator [8,15].

In this paper, a comparison, between three MPPT algorithms, is tested using a PV pumping system for one day at the university of Bejaia (36◦43,N 5◦04,E 2 m), which is a coastal city of North East of Algeria. A vector control method has been used to improve the dynamic performance of the system based on asynchronous motor and centrifugal pump. The paper is organized as follows. In section 2, we present the system modelling. The MPPT algorithms are presented in Section 3. Section 4 shows the results, using the MATLAB®-SIMULINK® package, and discussions. Finally, Section 6 gives a conclusion.

II. SYSTEM DESCRIPTION

Fig.1 shows the photovoltaic pumping system used in this

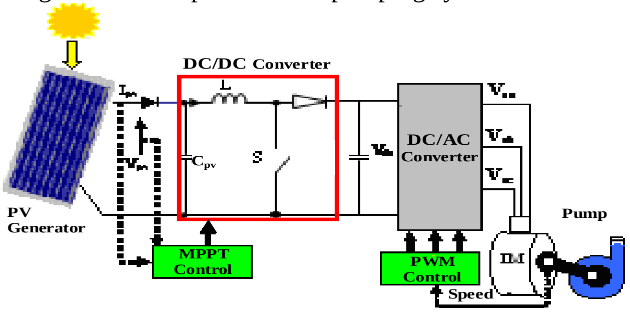

Fig. 1 Structure of a global photovoltaic pumping system.

paper. It includes photovoltaic array generator, DC/DC converter, DC/AC converter, induction motor coupled to a centrifugal pump. The system aims are to ensure a maximum operating of the photovoltaic array.

A. Photovoltaic generator model

Various mathematical models of photovoltaic generators were developed to represent their very strongly nonlinear behavior which results from the semiconductors junctions which are at the base of their realization. In our work, we chose the following model [9]. The PV array equivalent circuit current I_{pv} can be expressed as a function of the PV array voltage V_{pv}

$$I_{pv} = I_{sc}.\{1 - C_1[\exp(C_2 V_{pv}^m) - 1]\} \tag{1}$$

Where, C_1= 0.01175 is determined experimentally and the coefficients C_2, C_3 and m are defined as:

$$C_2 = \frac{C_4}{V_{oc}^m} \tag{2}$$

$$C_3 = \ln\left[\frac{I_{sc}(1+C_1) - I_{mpp}}{C_1 I_{sc}}\right] \tag{3}$$

$$C_4 = \ln\left[\frac{1+C_1}{C_1}\right] \tag{4}$$

$$m = \left[\frac{C_3}{C_4}\right] \Big/ \ln\left[\frac{V_{mpp}}{V_{oc}}\right] \tag{5}$$

With V_{mpp} voltage at maximum power point; V_{oc} open circuit voltage; I_{mpp} current at maximum power point; I_{sc} short circuit current. The parameters determination is achieved with the standard test conditions (STC).

Eq. 1 is only applicable at one particular irradiance level G and cell temperature T, at (STC) (G_{ref}=1000 W/m^2, T_{ref}=25 °C). When irradiance and temperature vary, the parameters change according to the following equations, where α_{sc} is the current temperature coefficient and β_{oc} the voltage temperature coefficient, R_s is the cell resistance and (ΔT=T-T_{ref})

$$\Delta I_{pv} = \alpha_{sc}\left(\frac{G}{G_{stc}}\right)\Delta T_c + \left(\frac{G}{G_{stc}} - 1\right) I_{sc,stc} \tag{6}$$

$$\Delta V_{pv} = -\beta_{oc}\Delta T_c - R_s \Delta I_{pv} \tag{7}$$

The new values of the photovoltaic tension and the current are given by:

$$V_{pv,new} = V_{pv} + \Delta V_{pv} \tag{8}$$

$$I_{pv,new} = I_{pv} + \Delta I_{pv} \tag{9}$$

The data of PV panel for SIEMENS SM 110-24 which was used for the simulations are [P_{pv}=110W, I_{mpp}=3.15A, V_{mpp}= 35V, I_{sc}=3.45A, V_{oc}=43.5V, α_{sc}=1.4mA/°C,β_{oc}=-152mV/°C].

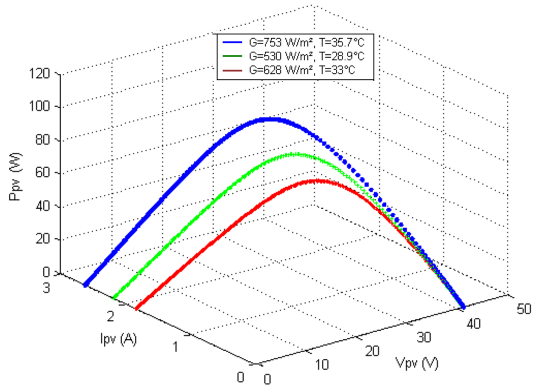

Fig. 2 Experimental PV panel I_{pv}-V_{pv}-P_{pv} 3-D characteristic curves.

From these characteristics the non-linear nature of the PV array is apparent. Therefore, an MPPT algorithm must be incorporated to force the system to always operate at the maximum power point (MPP). We introduce a fuzzy logic controller to determine the operating point.

B. Induction machine model

The mathematical model of the induction machine is given by the following equations [13,14]. Where R_s, L_s, R_r and L_r are the stator and rotor phase resistances and inductances respectively, M is the magnetising inductance and ω_s and ω_r are the stator and rotor pulsations respectively. Besides, V_{sd}, i_{sd} , V_{sq} and i_{sq} are the d-q stator voltages and currents respectively. i_{rd} and i_{rq} are the rotor currents, along the d and q axis,

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s & -\omega_s.L_s & 0 & -\omega_s.M \\ \omega_s.L_s & R_s & \omega_s.M & 0 \\ 0 & -\omega_r.M & R_r & -\omega_r.L_r \\ \omega_r.M & 0 & \omega_r.L_r & R_r \end{bmatrix} . \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} . \begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \\ \frac{di_{rd}}{dt} \\ \frac{di_{rq}}{dt} \end{bmatrix} \tag{10}$$

The electromagnetic torque (T_e) developed by the induction machine is expressed as follows:

$$T_e = p.M.(i_{rd}.i_{sq} - i_{rq}.i_{sd}) \tag{11}$$

Where: p the pair pole number of the machine

C. Centrifugal pump model

The useful power of the centrifugal pump is expressed by:

$$P_u = \eta P_l = \rho . g . H . Q \qquad (12)$$

Where ρ is the density (Kg/m²), g is the acceleration of gravity (m/s²), H is the height of rise (m), Q is the water flow (m^3/s) and η is the pump efficiency.

It is considered that the machine is coupled to a centrifugal pump having a load torque T_l which can be expressed as:

$$T_l = k\,\omega \qquad (13)$$

$$k = T_{e,\max} / \omega_{\max} \qquad (14)$$

Where $T_{e,max}$ is the maximum rated torque and ω_{max} is the maximum rated speed.

D. Vector control strategy

The vector control is based on the field-oriented control method. In our application, we choose the orientation of rotor flux such as: $\Phi_{rd} = \Phi_r = \Phi_r$ and $\Phi_{rq} = 0$ = 0. This means that the flux Φ_r is aligned permanently along the d-axis. Finally, as the chosen frame implies Φ_{rq} = 0, the expression of the electromagnetic torque becomes:

$$T_e = p . \frac{M}{L_r} . \Phi_r . i_{sq} \qquad (16)$$

The rotor flux as a function of the current i_{sd} and the rotor time constant $T_r = L_r/R_r$ is given by the following expression:

$$\Phi_r = \frac{M . i_{sd}}{1 + T_r . s} \qquad (17)$$

Where: s represents the derivative operator.

The knowledge of ω_s , by using the internal angular relation $\omega_s = \omega_r + p.\Omega$ and the mechanical speed of the machine Ω is measured continuously; the speed of the rotor field is estimated by the following expression:

$$\omega_r = \frac{M . i_{sq}}{T_r . \Phi_r} \qquad (18)$$

Then, ω_s can be written in the following way:

$$\omega_s = \frac{M . i_{sq}}{T_r . \Phi_r} + p . \Omega \qquad (19)$$

III. MPPT Control Algorithms

The output power induced in the photovoltaic modules depends on solar irradiance and temperature of the solar cells. The PV array has a unique (MPP) that can supply maximum power to the load. The locus of this point has a non-linear variation with solar irradiance and the cell temperature.

The P&O method measures the derivative of power (dP_{pv}) and the derivative of voltage (dV_{pv}) to determine the movement of the operating point. If the sign of (dP_{pv}/dV_p) is positive, the perturbation of the operating voltage should be in the same direction of the increment. However, it is negative, the system operating point obtained moves away from the MPPT and the operating voltage should be in the opposite direction of the increment.

The fuzzy logic controller measures the PV array characteristics and then perturbs the operating voltage by an optimal increment ($\Delta V_{pv,ref}$) and the resulting PV power change. The power variation (ΔP_{pv}) is either in the positive direction or in the negative one. The value of (ΔP_{pv}) can also be small or large. From these inferences, the reference photovoltaic voltage variation ($\Delta V_{pv,ref}$) is increased or decreased in a small or respectively large way in the direction which makes it possible to increase the power P_{pv}. The fuzzy logic controller structure is shown in Fig. 3.

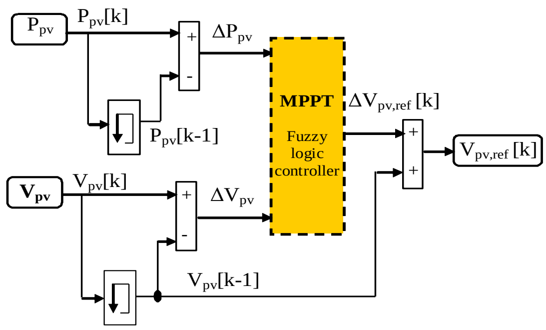

Fig.3 Structure of MPPT fuzzy controller.

The function of fuzzy controller is mainly based on fuzzy rules that are generated through fuzzy set theory. The fuzzy controller performs three processes: fuzzification, fuzzy rule algorithm, and defuzzification. Fuzzification is the process of changing the crisp value into fuzzy value. The membership functions of inputs variables ΔP_{pv} and ΔV_{pv} are triangular and have seven fuzzy subsets. The fuzzified output is subjected to the decision making process, which contains set of rules. By using the fuzzy rules, the corresponding output is determined. Finally, the defuzzification process is performed and the output of the fuzzy controller $\Delta V_{pv,ref}$ is obtained. The structure of designed FLC is shown in Figure 3. The control rules are indicated in reference [9].

Neural network architecture is specified in finding the appropriate solution for the non-linear and complex systems or the random variable ones. Among its types, there is the back propagation network which is more widespread, important and useful. The function and results of artificial neural network are determined by its architecture that has different kinds [12].

Neuro-fuzzy refers to combinations of artificial neural networks and fuzzy logic. It is widely termed as Neuro-Fuzzy (NF) system in the literature [15]. A multi-layered neural network drives the fuzzy inference mechanism is shows in fig.4. Neural network is used to tune membership functions of fuzzy systems that are employed as decision-making systems. Although fuzzy logic can encode expert knowledge directly using rules with linguistic labels, it design and tune the membership functions which quantitatively define these linquistic labels. Neural network learning techniques can automate this process and substantially reduce development time and cost while improving performance.

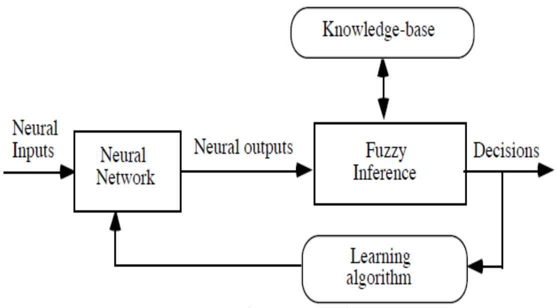

Fig.4 Structure of the neuro fuzzy system.

The Neuro-fuzzy (NF) MPPT controller developped, consists of two inputs ΔP_{pv} and ΔV_{pv} and one output $\Delta V_{pv,ref}$. It present respectively the PV power variation, the PV voltage variation and the reference photovoltaic voltage variation in order to optimize the duty ratio for PV maximum power at any irradiation level.

IV. Numerical Simulation of the Global System

The PV pumping system is composed of (08) photovoltaic panel of 110W connected in series. Various simulations evaluate the performances of the system. The various parts of the system (photovoltaic panel, DC/DC converter, DC/AC converter, induction motor and centrifugal pump) are modeled by blocks which are then linked in a coherent way.

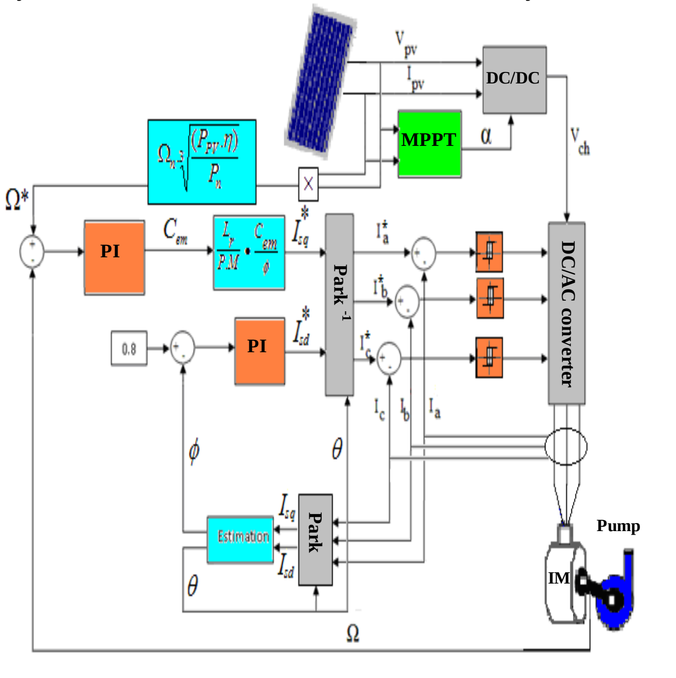

Fig.5 The global schemes of the vector control photovoltaic pumping system.

The bloc diagram of fig.5 is used to verify the performance of the vector control of the induction motor with optimization. The reference speed is variable with the variation of the irradiance and is function of maximum power obtained from the MPPT algorithm that allows the system to operate at optimal conditions. Simulation results using the vector control strategy are given. The flux and V_{dc} reference values are applied. These ones are: $\Phi_{rd-ref} = 0.8Wb$; $V_{dc} = 465V$.

The MPPT is controlled by using neuro-fuzzy controller (NF). In order to test the robustness of the proposed algorithm, a comparison is made with the (FLC and P&O) methods under similar test conditions. Figs.(6-13) present waveform of photovoltaic voltage, current and power for the three MPPT controllers (P&O, FLC and NF) for different irradiance and temperature. The NF gives us a fast response compared to two other methods which requires much time to track the MPP.

Other simulation results are carried out under variation of environmental conditions, during a day of 10 may 2012 at the university of Bejaia (36◦43,N 5◦04,E 2 m) which is a coastal city of North East of Algeria. The corresponding photovoltaic current and the maximum power tracked from the PV array are represented in Figs.(15,16). The NF controller determines quickly the optimal operating voltage for tracking the MPP even when the operating environmental conditions change in the day.

Fig. 17 shows the variation of the speed which is due to the variation of photovoltaic power. Fig. 18 shows the waveform of the water flow, its variable and depends on speed variation due to the change in environmental conditions. By comparing the pumping water flow produced by the classical MPPT control, FLC and the new approach (NF), it is observed that the new approach offers an improvement of 01H and 20mn of water pumping. Fig.19 shows that an increase of the daily pumped water is reached by the proposed approach.

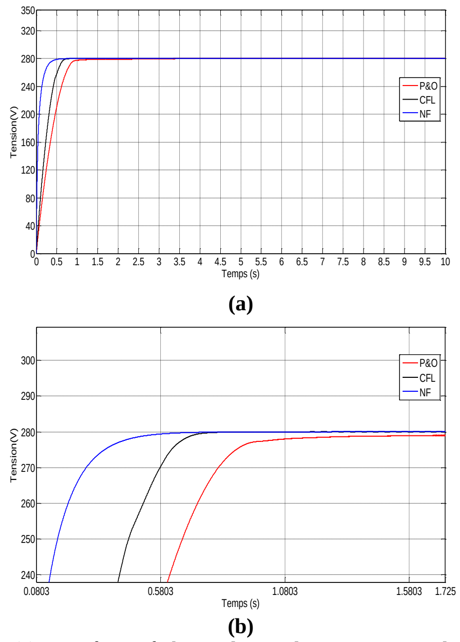

Fig.6 (a) Waveform of photovoltaic voltage at STC conditions, (b). zoom of transitional state.

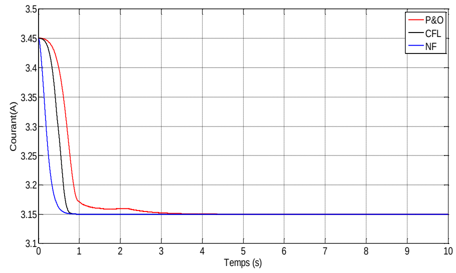

Fig.7 Waveform of photovoltaic current at STC conditions.

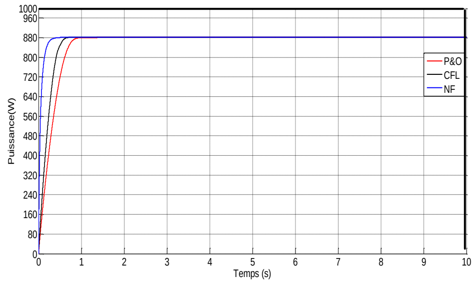

Fig.8 Waveform of photovoltaic power at STC conditions.

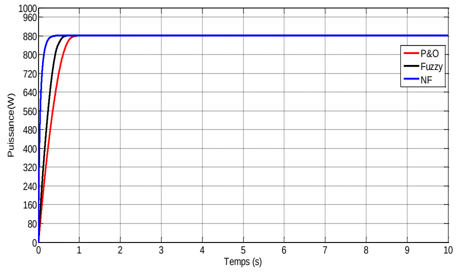

Fig.9 Waveform of photovoltaic power at (1000W/m², 45°C)

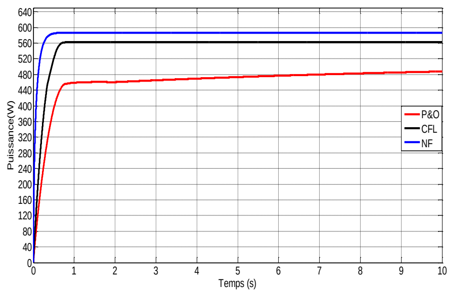

Fig.10 Waveform of photovoltaic power at (800W/m², 25°C)

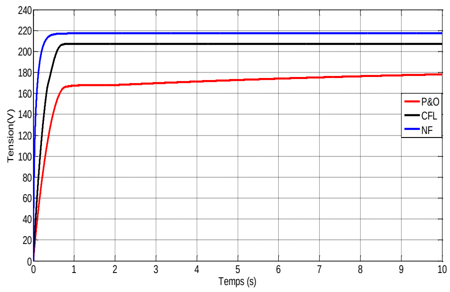

Fig.11 Waveform of photovoltaic voltage at (800W/m², 25°C)

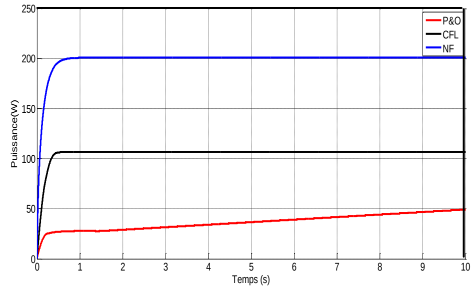

Fig.12 Waveform of photovoltaic power at (400W/m², 25°C)

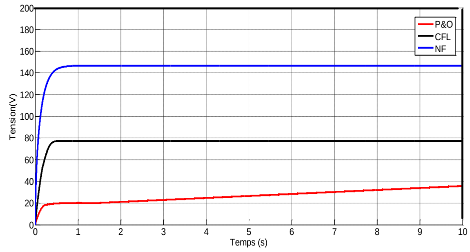

Fig.13 Waveform of photovoltaic voltage at (400W/m², 25°C)

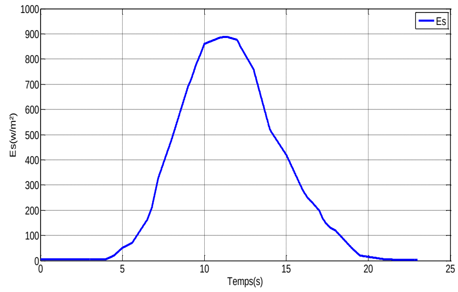

Fig.14 Solar radiance.

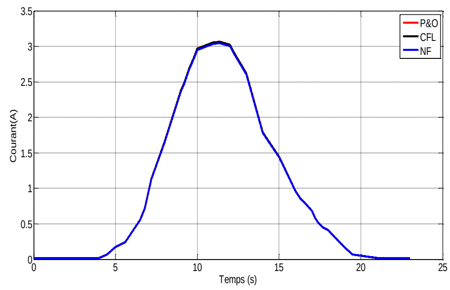

Fig.15 Photovoltaic current

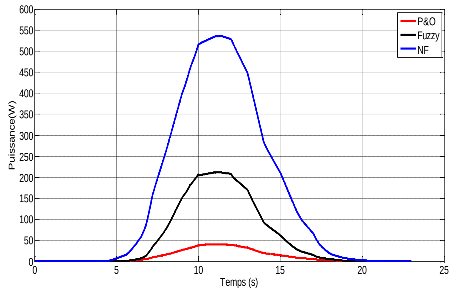

Fig.16 Photovoltaic power.

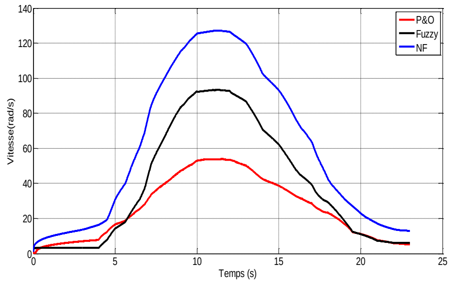

Fig.17 The speed of the induction machine

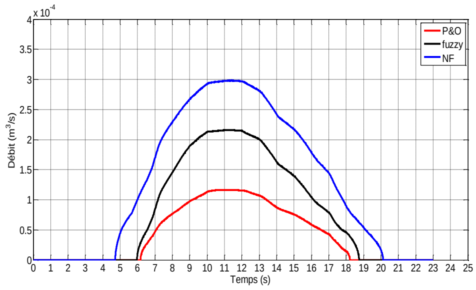

Fig.18 Water flow

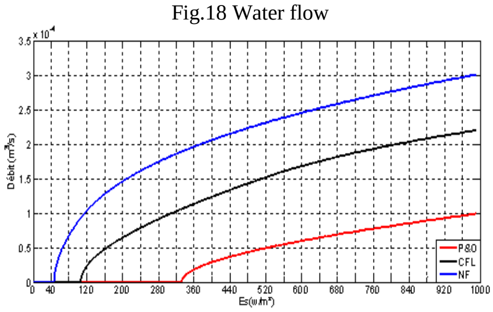

Fig.19 Water flow versus solar radiance

V. CONCLUSIONS

This paper has presented the optimal operation of the photovoltaic pumping system. The optimization criterion fixes the maximization of the extracted power by the chosen of the appropriate MPPT method. A comparative study was carried out on three MPPT controllers. The simulation results show that an increase of both the daily pumped water and in times of pumping are reached by the neuro-fuzzy controller.

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