

Design and control of pump system based on photovoltaic energy

Hanan Abbes¹, Hafedh Abid²

¹Laboratory of Computer and Embedded Systems (Lab-CES), Sfax, Tunisia

²Laboratory of Sciences and Techniques of Automatic Control and Computer Engineering (Lab-STA), National School of Engineering of Sfax, University of Sfax, Sfax, Tunisia

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ABSTRACT

This paper deals with the use of photovoltaic energy for direct current motor driven water pump. The resort to solar energy is step up day by day. To optimize solar photovoltaic generated power, maximum power point tracking technique is usually required. A DC-DC boost converter operates as an interface unit which aims to enhance the efficiency of photovoltaic array and ensure soft starting of the DC motor with definite control. Proposed system is made up an arrangement of solar panels, boost converter, DC converter, DC motor followed by a water pump. The boost converter acquires constant DC output. Then, the DC converter output supply the DC motor. The centrifugal pump is controlled by fuzzy supervisor so as to get the optimum flow rate for the pump. The behavior of proposed water pumping system is proved by evaluating its diverse performances by means of MATLAB/simulink.

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Corresponding Author:

Hanan Abbes,

Laboratory of Computer and Embedded Systems (Lab-CES), Sfax, Tunisia

Email: hanenabbes2009@yahoo.com

1. INTRODUCTION

Solar energy is a freely available energy source in the world. As a renewable energy, solar power not only reduces dependence on foreign oil and fossil fuels but also causes no greenhouse gases. Tunisia presents a good potential in renewable energy. Thus, the government is trying to warrant a safe and secure energy future. The country potential of solar radiation ranges, on year, from 1800 kWh/m² in the North to 2600kWh/m² in the South. Tunisian government, in 2009, undertook "Plan Solaire Tunisien" or Tunisia Solar Plan to reach 4.7 GW renewable energy capacity by 2030, using for photovoltaic systems, water heating systems and concentrated power units [1]. Photovoltaic (PV) technology is an encouraging solution to harness the solar energy. An array of photovoltaic cells called also PV panels are widely used for electric power generation. In the last decade, grid associated with solar PV system was broadly set up in household applications and industrial purposes with control techniques. Excesspower from SPV may be injected to the grid that can later be utilized by other consumers. International renewable energy agency (IRENA) has estimated a 59% cost reduction for electricity provided by solar PV by 2025. In addition, IRENA specifies that solar PV module prices have dropped roughly 80% since 2009 [2]. As the solar panels cost has been dramatically decreasing, its use is widespread in various sectors. Photovoltaic energy affords electrical energy in several cases, mainly in areas without an electric grid. A usefulness study for the establishment of 400 MW of a pumped-storage power plant is now ongoing in the North of Melah amount place.

Yet, the electrical power coming from PV system is conditional on climate change such as temperature and insolation variations. By this way, a maximum power point tracking (MPPT) technique seems to be essential to get maximum power from the PV arrays. To meet this challenge, several research

relating to the MPPT algorithms study and analysis have been conducted in the literature, such as in [3]. Many commands are examined in general, taking into account a variety of parameters, including easiness, implementation type, cost, time-response, and accuracy. Perturb & observe (P&O) technique, incremental conductance (INC) technique and intelligents techniques are the most frequently used algorithms [4].

In most regions of the world, there is a scarcity of grid electricity in rural and isolated locations. Hence, photovoltaic pumping application based on solar energy seems to be the most promising solution. The technology is comparable to any other traditional water pumping system, with the exception that it is powered by solar energy. PV water pumping has grown in popularity in recent years as a result of the lack of energy and the rise in diesel prices. Pumped water flow rates are determined by incident solar energy and the size of the PV array. A properly designed PV system ensures conspicuous long-term efficiency gains compared to traditional pumping systems. Additionally, instead of using batteries for electricity storage, tanks can be used to store water [5].

In the current energy crisis, a solar-powered irrigation system could be a viable option for farmers. In developing countries, agricultural production is extremely influenced by rains and the availability of water in summers. Nonetheless, maximum solar radiation is abundant in summers as such much water can be pumped to meet increased water needs. Researchers are blessed with PV pumping systems for water supplies in rural and industry institutions [6], [7]. An efficient standalone photovoltaic pumping system can be obtained by the set up of highly advanced power electronics converters and motor drives. A variety of motors types are available for this system, and among all these motors induction motor is characterized by low cost and weight, reliability with chiefly less maintenance required [8], [9]. Whereas, DC motors provide highly controllable speed. By varying the armature or field voltage, it's possible to reach wide speed variation and together with this level of controllability, DC motors give the precision required by a broad range of industry applications. In addition, it offers high starting torque [10].

This paper proposes a model of water pump system which is fed by a photovoltaic energy source. It is organized as follows: section 2 touches at the description of the PV pumping system. The first part of this section handles the model of photovoltaic panel and the MPPT algorithm which is based on classic technique. The second part gives the design of the DC motor and the third part presents the centrifugal pump model. In section 3, simulation results are given to show the performances of proposed system and T-S fuzzy supervisor. Finally, the paper is enclosed by a conclusion.

2. PHOTOVOLTAIC PUMPING SYSTEM

The main components of photovoltaic pumping system, as shown by Figure 1, are PV energy source, DC-DC converter, which is under the control of a MPPT item so as to have the maximum amount of energy, assembled with a DC-DC converter. These latest feeds a direct current motor coupled to water pump.

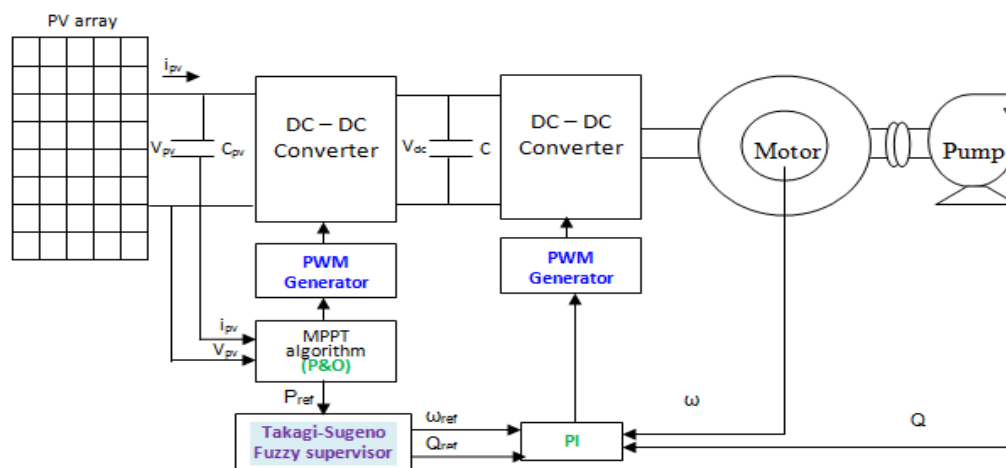


Figure 1. Block diagram of proposed pump system

2.1. Design of PV array and MPPT approach

This section comprises two parts. The first is dedicated to PV array model and converter model, the second concerns the description of the MPPT method. Needless to say, the elementary component of

photovoltaic panel is the photovoltaic cell. A PV array is made of a great number of panels electrically connected in series. In the literature, two basic mathematical models dominate: the model based on one diode and the model based on two diodes describing the operation under temperature and irradiation parameters variations. As the cells should be joined in series-parallel configuration on a panel to get enough high power, the equivalent circuit for the solar module arranged in N_p parallel and N_s series is shown in Figure 2.

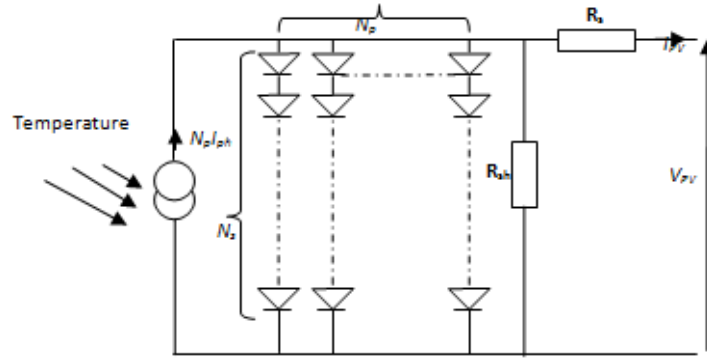


Figure 2. Equivalent circuit of PV array

2.1.1. PV array model

Equations describing the behaviour of PV cell under temperature and irradiation variations are: The final current and voltage expression of PV panel is equal to:

$$I_{PV} = N_p I_{ph} - N_p I_s \left[\ell \left(\frac{\frac{V_{PV} + R_s I_{PV}}{N_s} + \frac{R_s I_{PV}}{N_p}}{n V_T} \right) - 1 \right] - \frac{\frac{N_p V_{PV} + R_s I_{PV}}{N_s} + R_s I_{PV}}{R_{sh}} \quad (1)$$

The photocurrent depends mainly on the solar insolation and cell's operating temperature, the equation of photocurrent is:

$$I_{ph} = (I_{sh} + K_I \Delta T) \frac{G}{G_n} \quad (2)$$

where:

- I_{sh} : The short-circuit current of the cell at a 25°C and 1kW/m²
- K_I : The short-circuit current temperature coefficient of the cell
- G : The solar insolation in kW/m²
- I_s : Saturation current of the cell depends on the cell temperature, described as

$$V_T = \frac{n_s k T}{q} \quad (3)$$

2.1.2. MPPT approach

2.1.2.1. Boost converter

The role of power converter is to allow the adaptation between the PV generator and the load so as to have the maximum power from PV source. The static DC-DC converter type is chosen based on the role that we desire to achieve through the photovoltaic system. There are numerous types of DC-DC converter: Buck, Boost or Buck-Boost. We consider the Boost type (Figure 3).

For $t \in [0, \alpha T]$, the transistor switch is on. So, in this stage, the converter is modeled by (4) and (5):

$$\frac{\partial i_L}{\partial t} = \frac{V}{L} \quad (4)$$

$$\frac{\partial V_2}{\partial t} = - \frac{V_2}{R_L C_s} \quad (5)$$

For $t \in [\alpha T, T]$, the transistor switch is off. So, the equations of the converter in this stage are given as (6) and (7):

$$\frac{\partial i_L}{\partial t} = \frac{V_1 - V_2}{L} \quad (6)$$

$$\frac{\partial V_2}{\partial t} = \frac{i_L}{C_s} - \frac{V_2}{R_L C_s} \quad (7)$$

where, K, L, and C represent respectively the IGBT transistor switch, the inductance and the output capacitor.

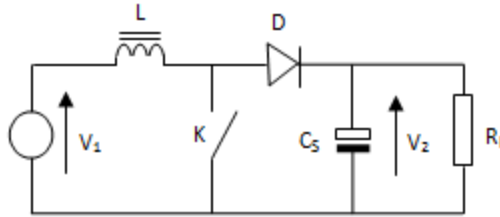


Figure 3. Electrical schema of BOOST converter

2.1.2.2. Perturb and observe MPPT algorithm

Perturb and observe (P&O) as shown in Figure 4 is the easiest among all techniques, it is broadly used and it is inexpensive control technique [11]–[13]. Owing to its simple implementation, we adopt this method to track maximum power point from PV panel.

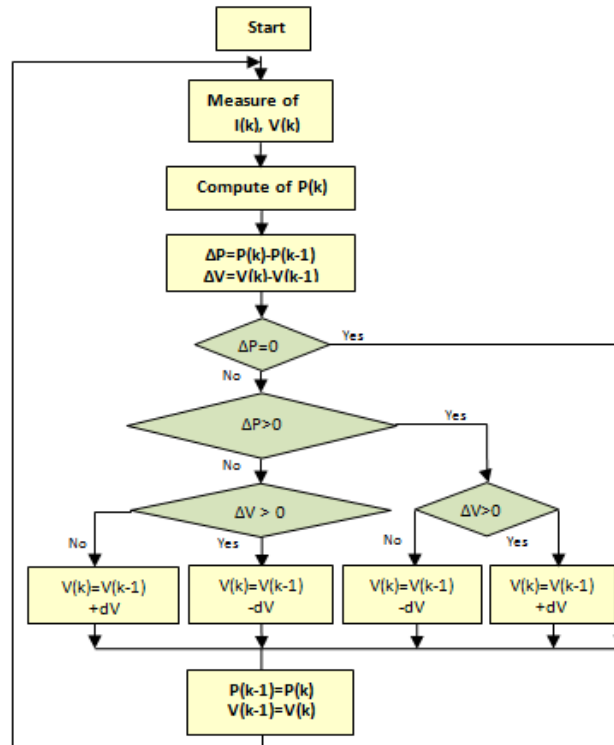


Figure 4. Flowchart of P&O algorithm

The principle of this algorithm is to do a perturbation on the voltage of the PV panel while varying the duty cycle α . Indeed, subsequent to this perturbation, we compute the power given by the PV panel at instant k , then we compare it to the previous one at instant $(k-1)$. If the power increases, we go toward the point at maximum power (PMP) and the variation of the duty cycle is uphold in the same direction. In the opposite side, if the power decreases, we move away from the PMP. So, the sense of the variation of the duty cycle should be reserved.

2.2. Modeling of direct current motor

DC motors have many applications and used for multi-purpose applications [14]–[16]. Modeling a dynamic process is often necessary before the determination of a control law. In order to obtain an accurate model, different methods can be used. As a result, design a numerical model is done through the determination of the discrete or continuous transfer function whose structure is often determined by empirical methods. To ensure the determination of a classic control technique, a such model is usually sufficient [17], [18]. The operating equations of the separately excited direct current motor are as (8):

Electrical equation:

$$V = RI + L \frac{\partial I}{\partial t} + E \quad (8)$$

where:

V : Voltage supply of the armature

R : Total resistance of the armature (with compensation winding)

I : armature current

L : Total leakage inductance of the armature

E : Back emf developed

Mecanical equation:

$$C_m - C_r = J \frac{\partial \Omega}{\partial t} \quad (9)$$

where:

W : Cm: motor torque

Cr : Resistant torque

J : Overall moment of inertia (motor + driven machine)

F : Viscous coefficient of friction

Ω : Angular speed of rotation of the motor shaft

Electromechanical equations

$$E = K_m \Omega \quad (10)$$

$$C_m = K_m I \quad (11)$$

$$\text{Output power is equal to } P_u = C \Omega \quad (12)$$

Direct current motor is considered as a second order system of the hyper damped type ($\tau_e \ll \tau_m$) whose transfer function is close to a first order system.

$$H(p) = \frac{K}{1 + \tau_e p} \quad (13)$$

The numerical regulator is PI type, which recurring as (14)

$$u_r(n) = u_r(n-1) + K_p [e(n) - e(n-1)] + K_p \frac{T_e}{T_i} e(n-1) \quad (14)$$

2.3. Centrifugal pump model

The centrifugal pumps are broadly applied for water pumping systems since they afford high flow-rates and low or medium depths (10 to 100m). The centrifugal pump is popular with its head-flow rate

characteristic curve $H(Q)$ which depends on the motor speed value as depicted by Figure 5 [14]. The flow rate is proportional to the rotational speed motor value while the head manometric (HMT) is proportional to the square speed. The flow head characteristic of a centrifugal pump can be estimated by a quadratic function based on the Pfleider-Peterman model [15], where rotor speed ω is assumed as a parameter:

$$H_{MT} = a_1 \omega_r^2 - a_2 \omega_r Q - a_3 Q^2 \quad (15)$$

The following equation of $H(Q)$ characteristic of the pipe can be couched by:

$$H = H_g + K_p Q^2 \quad (16)$$

If $\omega = \omega_{\max}$, the power is $P_{\max}$ and the flow rate is $Q_{\max}$

If $\omega = \omega_{\min}$, the power is $P_{\min}$ and the flow rate is $Q_{\min}$

The HMT (Q) curve as exposed by the Figure 5, has a parabolic look. The intersection of the HMT (Q) curve with the ordinate axis is the point zero flow. It is called the bubbling point or the closed valve point. The operating point of the pump is appointed by the intersection of water pipe characteristic with the pump dependent on the rotation speed of the motor. Nonetheless, the pump is described by a particular characteristic for each speed value, thus, as the speed varies, the operating point varies. Thereby, it is arduous, sometimes infeasible to anticipate the operating point coordinates. To deal with this arduousness, Takagi sugeno fuzzy type supervisor is a bright alternative as shown in figure. The concept aims at use the coordinates of the two extreme operating points. The first extreme operating point represents the highest rotational speed of the motor whilst the second point represents the lowest rotational speed. Given the reference power, the optimum speed and as a consequence the reference flow rate of the centrifugal pump can be deduced.

The torque of the pump is expressed as (17):

$$C = k\Omega^2 \quad (17)$$

From (13) and (18), the equation output power becomes

$$P_u = k\Omega^3$$

$$\text{Then, } \Omega = \sqrt[3]{\frac{P}{k}}$$

And

$$\Omega_{ref} = \sqrt[3]{\frac{P_{ref}}{k}}$$

So, the flow rate of the pump depends on the ω , ω depends on the power which varies according to the irradiation and the temperature variations.

For (G_{opt}, T_{opt}) , we get $P_{\max}$ and $\Omega_{\max}$

For (G_{min}, T_{min}) , we get $P_{\min}$ and $\Omega_{\min}$

Then, for (G_i, T_i) values corresponds P_i and Ω_i

From the extreme cases, we note that for:

(1000, 5°): P_1 , (1000, 75°): P_2 , (200, 5°): P_3 , (200, 75°): P_4

We deduce $P = h_1 P_1 + h_2 P_2 + h_3 P_3 + h_4 P_4$

The member ship functions of the rotational speed of the motor are given by the Figures 6 and 7. They can be expressed by (17) and (18).

$$M_{32} = \frac{\omega - \omega_{min}}{\omega_{min_{max}}} \quad (18)$$

$$M_{31} = 1 - M_{32} = \frac{\omega_{max} - \omega}{\omega_{min_{max}}} \quad (19)$$

where, $\omega_{\min}$ and $\omega_{\max}$ represent respectively the minimum and maximum mechanical rotation speeds of the motor. The reference flow can be estimated by (20):

$$Q_{ref} = Q_{opt} = M1Q_{refmax} + M2Q_{refmin} \quad (20)$$

where, Q_{refmax} and Q_{refmin} represent the optimum maximum and minimum pump flow rates respectively.

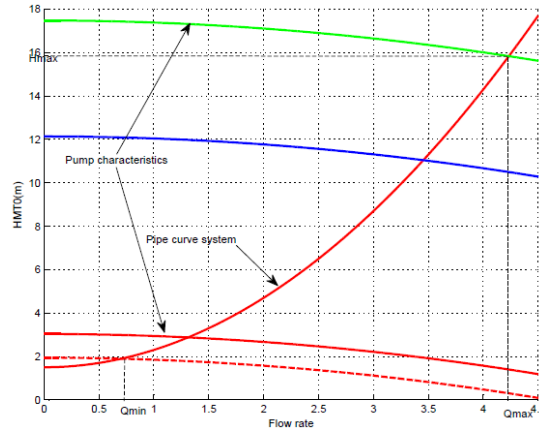


Figure 5. Pump characteristic

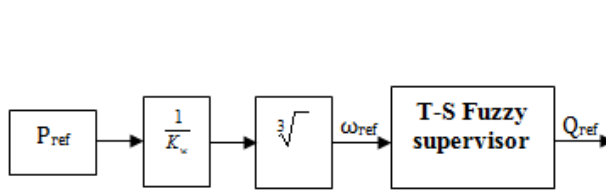


Figure 6. T-S fuzzy supervisor principle

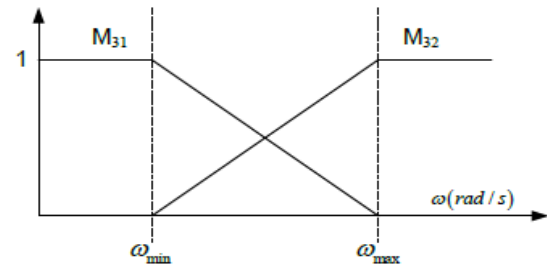


Figure 7. Member ship function for rotational speed

3. SIMULATION RESULTS

The PV generator used consists of 10 photovoltaic panels. They are connected in two parallel strings; each one includes five panels connected in serial. The parameters of a panel are given in Table 1.

Table. 1. Parameters of one panel	
Parameters at 25°C and 1000 W/m ² for one panel	Nominal value
Maximum power P	81.5 W
Short circuit current Isc	4.8 A
Open circuit voltage Vco	21.38 V
Optimal voltage	18.4 V
Optimal current	4.4 A

The panel's fuzzy model consists of the following four local models:

$$G = 1000 \text{ w/m}^2, T = 5^\circ\text{C}, V_{MPP} = 20\text{V}, I_{MPP} = 4.45\text{A}, P_{MPP} = 87.25\text{W}$$

$$G = 1000 \text{ w/m}^2, T = 75^\circ\text{C}, V_{MPP} = 15.8\text{V}, I_{MPP} = 4.4\text{A}, P_{MPP} = 69.77\text{W}$$

$$G = 200 \text{ w/m}^2, T = 5^\circ\text{C}, V_{MPP} = 12\text{V}, I_{MPP} = 0.611\text{A}, P_{MPP} = 7\text{W}$$

$$G = 200 \text{ w/m}^2, T = 75^\circ\text{C}, V_{MPP} = 13.24\text{V}, I_{MPP} = 0.52\text{A}, P_{MPP} = 6.914\text{W}$$

The variation of irradiation and temperature are given by the Figures 8 and 9.

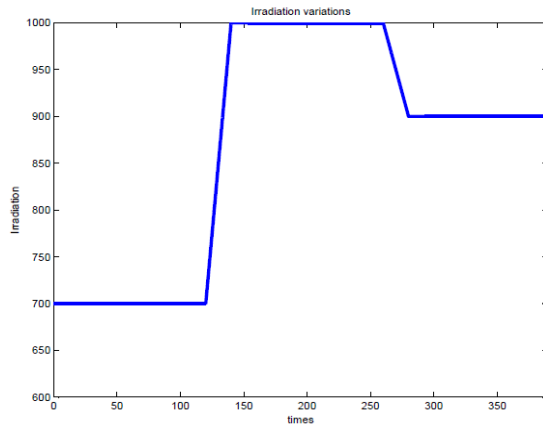


Figure 8. Irradiation variations

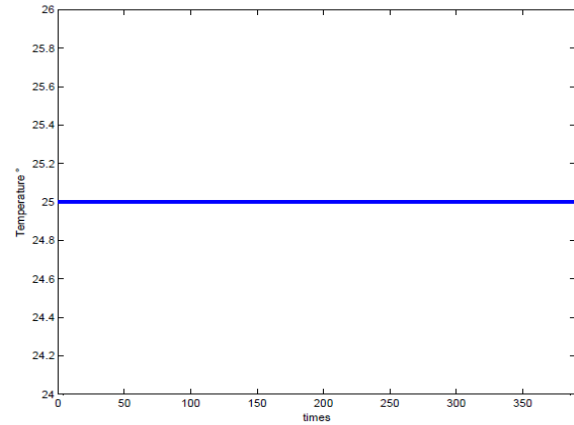


Figure 9. Temperature variations

All losses are not computed and we suppose that the motor pump efficiency is equal to unity $\eta = 1$. The evolution of the power generated by the photovoltaic panels is given by the following figures. They show the power required by the motor pump, the pump flow rate, the flow error, the flux, the current, the torque, and the rotation speed of the DC motor, as shown in Figures 10, 11, 12, 13 and 14, respectively.

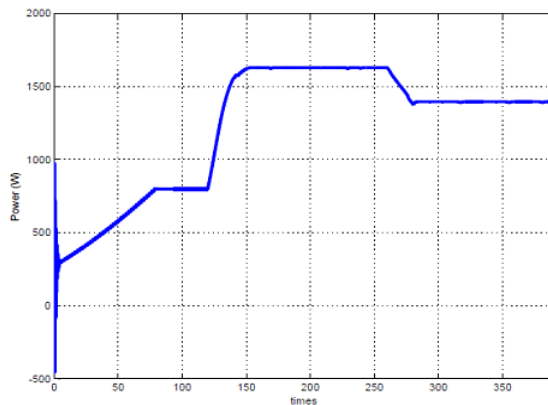


Figure 10. Power by PV array



Figure 11. Voltage across the armature

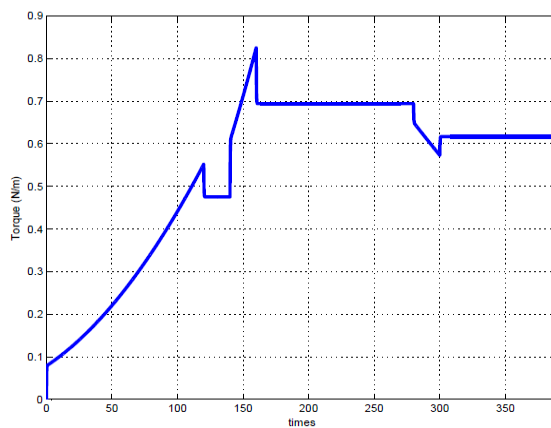


Figure 12. Torque of DC motor

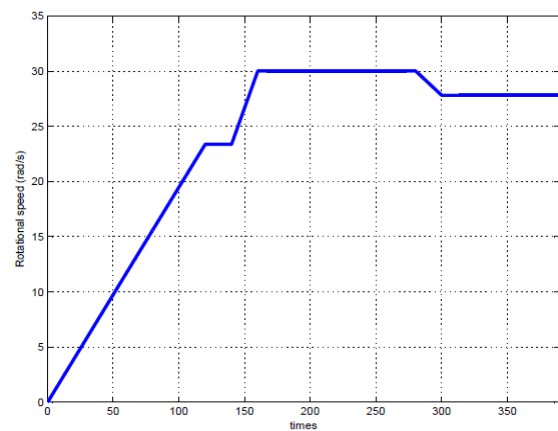


Figure 13. Speed of DC motor

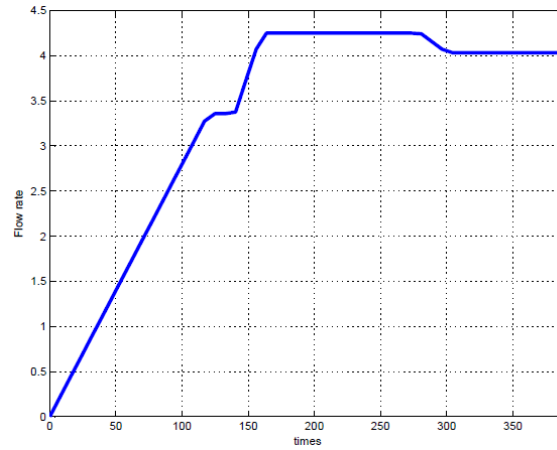


Figure 14. Flow rate of wtaer pump

It is expected that the power delivered by the panels vary. If the irradiation increases, the power increases and inversely. Figure 13 clearly show the flow rate results of the pump which match theoretical values as previously developed. Results got as estimated. Then, Figure 12 shows that the speed varies smoothly as a function of the power supplied to the motor.

- The nominal rating of the motor is

Armature: 220V / 6.8A

Inductor: 220V / 0.4A

Speed: 1500 rpm

Fonctional power: 1.6 KW

Table. 2. DC motor parameters

Parameters	Value
resistance of the armature (R)	6.8 Ω
Leakage inductance of the armature(L)	135 mH
Electrical time constant (τ_e)	19.85 ms
Constant f.c.e.m for excitation nominal (K_m)	1.7 V.s.rd ⁻¹
Coefficient of viscous friction(f)	2.10 ⁻³ Kg.m ⁻² .s ⁻¹
Global Inertia(J)	77.10 ⁻³ Kg.m ⁻²
Mechanical time constant (τ_m)	38.4 s
Electromechanical time constant (τ_{em})	180 ms
Static gain (K)	0.588

Centrifugal pump parameters are:

$$\omega_n=157 \text{ rad/s}, a_1=4.9234 \cdot 10^{-4} \text{ m/ (rad / s)}^2; a_2=-1.5286 \cdot 10^{-5} \text{ m/ (rad / s)}^2 \text{ (m}^2\text{/s)}; a_3=-0.091 \text{ m/ (m}^3 \text{/ s)}^2; \\ g=9.81 \text{ m}^2 \text{ / s}, \rho = 1000 \text{ kg / m}^3$$

4. CONCLUSION

In this work, an efficient operation of a pump system powered by photovoltaic source is described. Fuzzy and conventional techniques are exploited to control DC motor pump. Irradiation and temperature variables are the inputs for the system control which act out current, voltage and power values of the photovoltaic source. Maximum power point tracking algorithm aims to extract the maximum amount of energy from the PV panels. As well, a fuzzy system control provides the optimum flow rate of the pump driven by a DC motor. Simulation results exhibit the effectiveness of the proposed approaches.

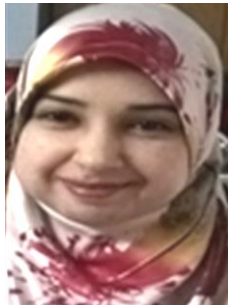
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Title of manuscript is short and clear, implies research results (First Author)

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BIOGRAPHIES OF AUTHORS



Hanen Abbes    holder of an electrical engineering diploma from national school of engineering of Sfax, Tunisia in 2012. She gets a Ph. D thesis degree in computer engineering in December 2017. His current research interests are fuzzy systems, photovoltaic systems and embedded Systems. She has then been investigating the design and implementation issues on FPGA reconfigurable chip. She is the author and co-author of many research and contribution papers published in national and international conferences.



Hafedh Abid    had a diploma in electrical engineering from the ENIS: National School of Engineering of Sfax, Tunisia, in 1989, then Electrical and Electronic diploma in 1995 from the High School of Technical Sciences of Tunis and the Aggregation in Electric Genius in 1996. From 1996 to 2006, he was a 'Technologue' Teacher of the Electric Department in High Institute of Technologies of Sousse. He is working now as a lecturer at National School of Engineering of Sfax, University of Sfax, Tunisia. His research interests are fuzzy systems and photovoltaic systems. He is the author and also a co-author of numerous national and international publications.