A MAXIMUM POWER POINT TRACKING FUZZY LOGIC CONTROLLER FOR PHOTOVOLTAIC PUMPING SYSTEM

A. El Jouni, R. El Bachtiri***

* LESSI Laboratory, Department of Physics, Faculty of science, Sidi Mohamed Ben Abdellah University
Dhar El Mehraz, BP: 1796, 30000 Fez-Atlas, Morocco.
Phone: (+212) 62 58 45 08; E-mail: jouni_abde@yahoo.fr
** REEPER Group, High School of Technology, Sidi Mohamed Ben Abdellah University BP: 2427 Fez Morocco
Phone: (+ 212) 61 70 28 50; E-mail: bachtiri@yahoo.fr

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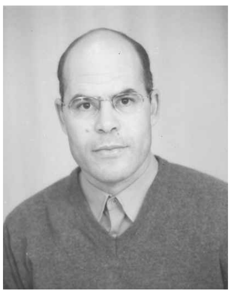
In this paper, the fuzzy controller is used to track the maximum power point (MPP) for a photovoltaic pumping system. For the best use, the photovoltaic (PV) panel must operate at its maximum power point (MPP). The PV panel efficiency, for given conditions, is maximal when its voltage equals a certain value that is optimal voltage which depends on irradiation, temperature and panel state. The pumping system considered in this paper consists of a photovoltaic generator (PVG) with a power electronic converter allowing maximum power point tracking (MPPT), the whole is feeding a DC motor coupling with a centrifugal pump. In the presence of the temperature and irradiation variations, the duty cycle of the converter, which is chosen as the controller law, is adjusted by using fuzzy logic controller (FLC) to track the MPP. The used FLC, incorporates expert knowledge, and doesn't depend on system mathematical model accurate. The effectiveness of the proposed approach is investigated by simulation at different operating conditions in Matlab/Simulink environment.

Keywords: photovoltaic pumping system, DC/DC converter, fuzzy logic controller, maximum power point tracking

Abdeslam El Jouni

Organization(s): Researcher student in laboratory of electronics, signal-systems and Information science (LESSI), Sidi Mohamed Ben Abdellah University (USMBA), Dhar El Mehraz, faculty of science, in Fez, Morocco.
Education: DESA degree (2002-2004) automatic and systems analysis, License degree (1991-1995) physics electronic.
Experience: Since 2000 I'm teacher.
Main range of scientific interests: automatic and electrical engineering, renewable energy in power systems.
Publications: 2 papers in international scientific journals.



Rachid El Bachtiri

Organization(s): Researcher teacher in Sidi Mohammed Ben Abdellah University (USMBA), Higher School of Technology (EST), in Fez, Morocco. Assisting Master (21/10/88), Ability Professor (22/01/97), Higher teaching Professor (22/01/01).
Education: Engineer (1983-1988), Mohammadia School of Engineers (EMI) Rabat, Morocco.
Doctor of Sciences Applied (January 1997), Catholic University of Louvain (1992-1997) at Louvain-LaNeuve (Belgium), Faculty of Science Applied (FSA), Laboratory (LEI).
Experience: Lectures and Directed Work: Power Electronics and Electrical engineering. Person in charge for a team of research "team of research in electrical engineering, power electronics and renewable energies" (REEPER at the higher school of technology in Fez) belonging to the laboratory: "laboratory" (LESSI at the Faculty of Science in Fez).
Main range of scientific interests: electrical engineering, industrial electronics; resonance static conversion, effects of the harmonics, and their attenuation. Renewable energies; optimal use of the photovoltaic electrical power.
Publications: Papers in the power electronics and renewable energy field.

Introduction

It is well established that energy production and use based on consumption of fossil fuels can have deleterious environmental and human health impacts, including the potential of global warming of the earth through changes in the atmosphere's concentration of carbon dioxide. The worldwide conventional energy sources are rapidly depleting. The increasing of the world energy demand, due to modern industrial society and population growth, is motivating a lot of investments in renewable energy source such as photovoltaic (PV) power, since it is clean, pollution-free and inexhaustible. One of the most popular applications of the photovoltaic energy utilization is the water pumping system driven by electrical motors. A PV array is a non-linear power source. There is a unique point on the curve (Power-Voltage), called the maximum power point (MPP), at which the PV array produces maximum output power and its voltage equals a certain value that is the optimal voltage. As it is well known, the MPP of a PV power generation system depends on array temperature, solar irradiation, and PV cells ageing, so it is necessary to constantly track the MPP [1, 2, 3] of the solar array. A switch-mode power converter, called a maximum power point tracker, can be used to maintain the PV array's operating point at the MPP. The pumping system considered in this paper consists of a photovoltaic generator (PVG) with a power electronic converter allowing maximum power point tracking (MPPT), the whole is feeding a DC motor coupling with a centrifugal pump. Instead of maximizing the PV power, we will maximize the pump power, i.e. his rotation speed.

For years, research has focused on various MPP control algorithms to track the maximum power of the PV array. These techniques include methods using neural networks [4, 5], perturbation and observation (P&O) methods [6, 7], incremental conductance [8], slide control method [1, 9] and computational methods. One of the computational methods which have demonstrated fine performances under different environmental operating conditions is the fuzzy based MPPT technique [3, 10, 11]. In recent years, fuzzy logic control has been widely used for industrial processes owing to their heuristic nature associated with simplicity and effectiveness for booth linear and non-linear systems. However, in a number of cases, such as those, when parameter variations take place, or when disturbances are present, or when there is no simple mathematical model, fuzzy logic based control systems have shown superior performance to those obtained by conventional control algorithms. The main advantages of fuzzy logic controllers over the conventional controllers are: they do not need accurate mathematical model, they can work with imprecise inputs, they can handle nonlinearity and they are more robust than conventional nonlinear controllers. The aim of this paper is to present a fuzzy control of the duty cycle of the boost converter, that is considered as the control law of the system, to track the maximum rotation speed of the pump for different operating conditions. The paper is organized as follows: in section 2 mathematical model of the photovoltaic pumping system is given. In section 3, the structure configuration of the fuzzy logic controller applied of the system is presented. Section 4 presents the simulation results and a conclusion is given at the end of the paper.

Description of the photovoltaic pumping system

A photovoltaic water pumping system is mainly composed by a PV generator, a power electronic converter as a control organ, and an electrical motor usually coupled to a centrifugal pump. The schematic diagram of the proposed system is shown in Fig. 1. It consists of a photovoltaic generator (PVG), a DC/DC boost converter and DC motor with a constant magnetic flux driving a centrifugal pump.

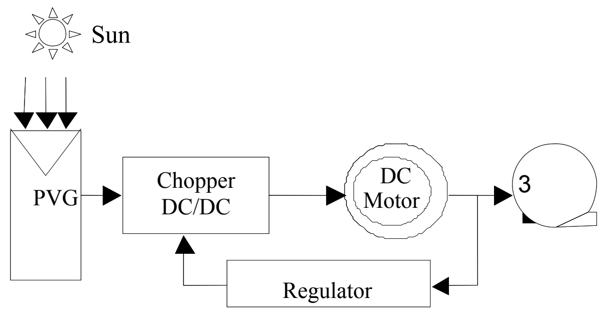


Fig. 1. *General diagram of the photovoltaic pumping system*

Photovoltaic generator model

The solar cell is a non-linear power source, the output current and voltage depend on the irradiation level and temperature. The equivalent circuit of a PV module is shown in Fig. 2. The solar cell modules can only provide maximum power at specific voltage and current levels. So, for the PV array, there is a unique point on its $P - V_p$ curve at which the power is maximum, and for optimum utilization, the equilibrium operating point of the PV array should coincide with this point.

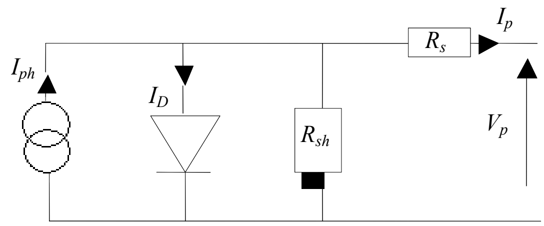


Fig. 2. *PV module equivalent circuit*

The characteristic equation $V_p - I_p$ of a PV module is given by the following equation:

$$I_p = I_{ph} - I_0\left(\exp\left[A\left(V_p + R_s I_p\right)\right] - 1\right) - \frac{V_p + R_s I_p}{R_{sh}} \quad (1)$$

$$\text{with } I_0 = I_{0r} - I_0\left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_{GO}}{K\gamma}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right],$$

$$I_{ph} = \left[I_{SCR} + K_I\left(T - T_r\right)\right]\frac{\lambda}{1000} \text{ and } A = \frac{q}{N\gamma KT},$$

where I_{ph} – photocurrent, I_0 – cell reverse saturation current, I_{0r} – cell saturation current at T_r, I_{SCR} – short circuit current at 298.15 K and 1 kW/m^2, K_I – short circuit current temperature coefficient at I_{SCR}, λ – solar irradiation in W/m^2, E_{GO} – band gap for silicon, γ – ideality factor, T_r – reference temperature, T – cell temperature, K – Boltzmann's constant and q – electron charge.

The PVG is composed of many strings of PV module in series, connected in parallel, in order to provide the desired values of input voltage and current of DC motor system. This PVG exhibits a non-linear $I_g - V_g$ characteristic given, by the following equation.

$$I_g = I_{phg} - I_0\left(\exp\left[A\left(V_g + R_{sg}I_g\right)\right] - 1\right) - \frac{V_g + R_{sg}I_g}{R_{shg}}, \quad (2)$$

where V_g – the PVG output voltage, I_g – the PVG output current, $A_g = A/N_s$ – the PVG constant, $R_{sg} = (N_s/N_p)\, R_s$ – the PVG series resistance, $R_{shg} = (N_s/N_p)$, R_{sh} – the PVG parallel resistance, $I_{phg} = N_pI_{ph}$ – the photocurrent of the PVG, $I_{0g} = N_pI_0$ – the saturation current of the PVG, N_s – the number of PV connected in series and N_p – the number of parallel paths. Both N_s and N_p are designed carefully to have the amount of energy required by the motor pump.
The variation of the output $V_g - P_g$ characteristic of the PVG generator as function of irradiation and temperature is shown in Fig. 3 and Fig. 4 respectively, where $P_g = V_gI_g$ is the PVG power.

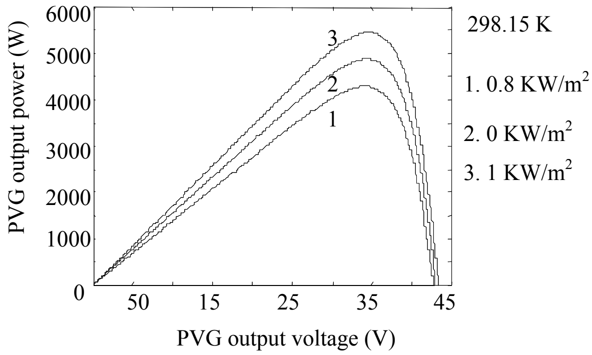


Fig. 3. *Characteristic of the PVG with constant temperature and varying irradiation*

From these figures, at any value of irradiation and temperature, there is only one point at which P_g is maximal. This point is called the MPP. Due to the relatively high cost of the PVGs, it recommended to operate at this MPP at all values of irradiation and temperature to increase the efficiency of the system.

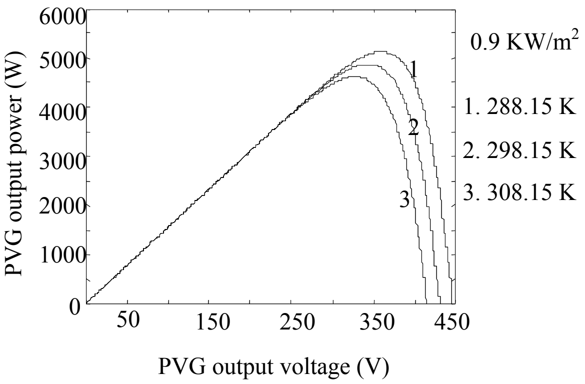


Fig. 4. *Characteristic of the PVG with constant irradiation and varying temperature*

Power electronic converter

In order to improve the performance of a photovoltaic pumping system, a controlled DC–DC converter known as a maximum power point tracker is used to match continuously the output characteristics of a PVG to the input characteristics of a DC motor. The power electronic converter is a boost chopper (Fig. 5) inserted between the PVG generator and the motor with a variable duty cycle α. The output voltage of the PVG is fed to the boost converter. It has to be adjusted to the optimum value by adjusting the duty ratio to the required value. The main function of the converter is to adjust the PVG output voltage to a value in which the PVG transfers maximum energy to the motor. The duty ratio of the boost converter is adjusted with the help of a fuzzy logic controller (FLC).

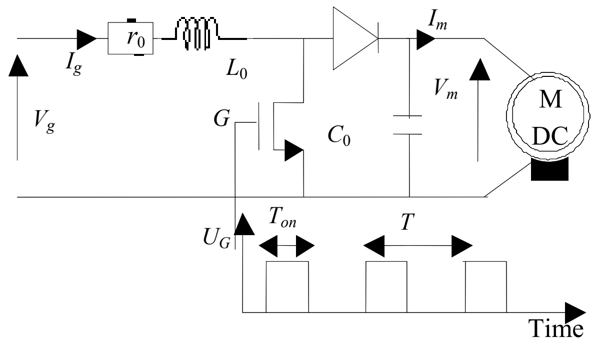


Fig. 5. *Boost chopper*

If the chopping frequency is sufficiently higher than the system characteristic frequencies, we can replace the converter with an equivalent continuous model. By considering the mean values of the electric quantities over a chopping period, the state equations of the converter are:

$$I_m = (1-\alpha)I_g - C_0\frac{dV_m}{dt}, \quad (3)$$

$$V_g = (1-\alpha)V_m + L_0\frac{dI_g}{dt} + r_0I_g + \alpha R_{DS}I_g, \quad (4)$$

where L_0 – the inductor of the converter, C_0 – the output capacitor of the converter, r_0 – the inductor equivalent resistance, and R_{DS} – the *MOSFET* resistance *ON*.
The inductor value, L_0, required such the converter operates in the continuous conduction mode is calculated such that the peak inductor current at maximum input power does not exceed the power switch current rating. So L_0 is calculated as: $L_0 \ge V_g\frac{\alpha_m}{f_s|\Delta I|}$. The output capacitor value calculated to give the desired peak-to-peak output voltage ripple is: $C_0 \ge \frac{I_m}{\Delta V_c}\frac{\alpha_m}{f_s}$, where f_s – the switching frequency, ΔI – the maximum input current ripple, ΔV_C – the maximum output voltage ripple and α_m – the duty cycle at maximum converter input power.

Electrical motor modeling

We consider a DC motor with a constant magnetic flux and we neglect the magnetic reaction and the commutation phenomena. The choice of a DC motor for a PV powered system is economical because PV arrays supply DC power. Also, photovoltaic modules produce direct current, so using DC motors eliminates the need for AC/DC power converters. The mathematical relation that describes the dynamic model of a DC motor with constant magnetic flux can be expressed as follows:

$$V_m = RI_m + L\frac{dI_m}{dt} + E_c \tag{5}$$

with $E_c = K_e\Omega$.
The motor torque is:

$$C_m = K_m I_m . \tag{6}$$

The parameters of the DC motor are: K_e – the back emf constant, K_m – the torque constant, L – the armature inductance, R – the armature resistance and Ω – the rotation speed.

Centrifugal pump model

For PV water pumping systems, two types of pumps are widely used: the volumetric pump and the centrifugal pump. It is found in the case of the centrifugal pumps, the operation takes place for longer periods even for low irradiation levels, and the load characteristic is in closer proximity to the PVG maximum power locus [12]. The centrifugal pump opposes to the motor a resistant torque C_r that is given by the following equation [13]:

$$C_m - C_r = K_r\Omega^2 , \tag{7}$$

where K_r – the proportionality coefficient.
The mechanical equation of the system is given by:

$$C_m - C_r = J\frac{d\Omega}{dt} , \tag{8}$$

where J – the group inertia.

Fuzzy logic controller structure and design

The fuzzy logic permits to define control laws of any process starting from a linguistic description of the control strategy to be adopted. Fuzzy logic uses instead of numerical variables linguistic a variables whose values (fuzzy subsets) are labels or sentences in a natural or artificial language.

Fuzzy logic controller structure

In a typical basic configuration of a fuzzy logic controller (FLC) one can find:
– Fuzzification or linguistic coding of input variables, which transforms a given set of numerical inputs (measured or calculated) into a fuzzy linguistic variables set composed of fuzzy subset called also membership functions.
– Inference fuzzy rules which contains a set of fuzzy rules in linguistic form as well as the database which is a collection of expert control objectives. This control rules base can be set up using IF-THEN rules, based on expert experience and/or engineering knowledge, and learning rule-based system which has learning capabilities.
– Defuzzification of the inference engine, which evaluates the rules based on a set of control actions for a given fuzzy inputs set. This operation converts the inferred fuzzy control action into a numerical value at the output by forming the “union” of the outputs resulting from each rule. The deffuzification produces a non-fuzzy output control action that best represents the recommended control actions of the different rules.

Fuzzy logic control design

The typical power-voltage characteristic of photovoltaic generator is shown in Fig. 3 and Fig. 4. The MPP is reached when the PVG output voltage V_g for given conditions equals its optimal value V_{op}. One has also $P_u = K_r\Omega^3$ the centrifugal pump power that must be maximum. Then at the MPP the rotation speed is maximum. The boost converter with an adjusted duty cycle permits the maximization of the rotation speed by an online adaptation of the PVG output voltage to steer in finite time at its optimal value. The duty cycle α of the converter, which is chosen as controller law is adjusted by using fuzzy logic controller (FLC), is proposed to keep the rotation speed at its maximum according to the solar irradiation (λ) and the temperature (T) variations. Fig. 6 shows the block diagram of this fuzzy controller.

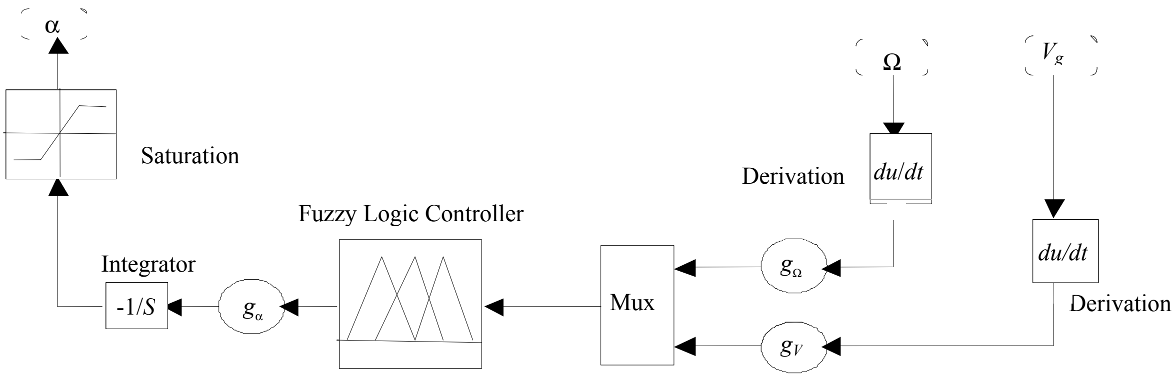


Fig. 6. *Synoptic scheme of the proposed fuzzy controller*

The two input control variables of this fuzzy controller are the rotation speed variation $d\Omega$ and the PVG output voltage variation dV_g; $d\Omega$ and dV_g are normalized using the two input scaling factors g_Ω and g_v. The output of the controller is the duty cycle variation $d\alpha$ that is normalized by scaling factor g_α.

In the fuzzification process the numerical variable is converted into a linguistic variable or subset. The following five fuzzy levels are chosen for the controlling inputs and output of the fuzzy controller ($d\Omega$, dV_g and $d\alpha$) in fuzzification {NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big)}. Membership functions for both controller inputs and output variables are defined on the common normalized range of [-1, 1]. In this paper, asymmetric triangular membership functions are considered and their representation is shown in Fig. 7.

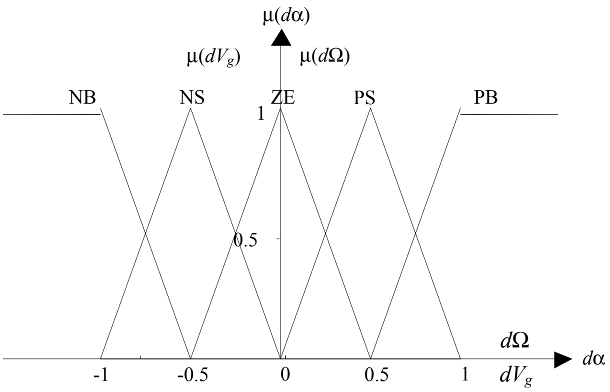


Fig. 7. *Membership functions of dV_g, $d\Omega$ and $d\alpha$*

The generated rules should be done properly and arranged in a fuzzy matrix table. Twenty five rules have been deduced from a qualitative analysis of the influence of the rotation speed variation $d\Omega$ and the PVG output voltage variation dV_g which are given in Table 1. This rule table can reflect experiences of the human experts basis of Fig. 8. The fuzzy rules are designed to incorporate the following considerations keeping in view overall tracking performance.

1 – If a negative variation of the rotation speed is accompanied with a negative variation of PVG output voltage and vice versa, then we would decrease the duty cycle.

2 – If the variation of the rotation speed is sufficiently close to zero which means that its maximum is reached, then we would not make any variation in the duty cycle.

3 – If a positive variation of the rotation speed is going with a negative variation of PVG output voltage and vice versa, then we would increase the duty cycle.

During the inference process, the product-sum inference mechanism is used to calculate the fuzzy output of the controller. This is achieved by forming the union of the fuzzy output resulting from each rule, which is the corresponding output membership function weighted by the rule strength. The gravity center deffuzification method is used to convert the fuzzy output of the fuzzy controller into a numerical value. In this case, the change of the controller output is computed by the following equation:

$$d\alpha = \frac{\sum \mu_i y_i S_i}{\sum \mu_i S_i}$$

with ($1 \le i \le 25$),

where μ_i – represents the ith rule degree of the fulfillment at the kth sampling period, y_i – the gravity center abscissa of the output fuzzy membership function corresponding to the ith rule and S_i – its surface.

The final control signal sent to the system is: $\alpha(K) = \alpha(K\text{-}1) + g_\alpha\, d\alpha\,(K\text{-}1)$.

Table 1

Rule base of fuzzy logic controller

Change of PVG output voltage (dV_g)	**Change of the rotation speed ($d\Omega$)**				
	NB	**NS**	**EZ**	**PS**	**PB**
NB	NB	NB	EZ	PB	PB
NS	NB	NS	EZ	PS	PS
EZ	PS	PS	EZ	PS	PS
PS	PB	PS	EZ	NS	NB
PB	PB	PB	EZ	NB	NB

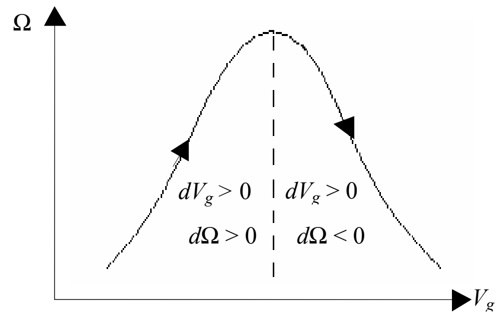


Fig. 8. *Fuzzy rules deduction from versus V_g function*

Simulation results

For the simulation we consider the parameters of the system:

– The photovoltaic panel SM55:
$R_s = 0.1124\ \Omega$, $R_{sh} = 6500\ \Omega$, $\gamma = 1.7404$, $I_{SCR} = 3.45$ A, $I_{0r} = 4.842\ \mu$A, $K_I = 4\cdot10^{-4}$ A/K, $N = 36$, $N_s = 20$, $N_p = 5$ and $T_r = 298.15$ K.

– *DC* motor: ABB DMI 180B: $V_{mn} = 400$ V, $I_{mn} = 12.2$ A, $\Omega_n = 104.7$ rad/s, $R = 9.84$ W, $L = 0.12$ H, $J = 0.06$ Kg m^2.

– Chopper parameters: $L_0 = 3.5$ mH, $C_0 = 4.7$ mF, $r_0 = 60$ mΩ, $R_{DS} = 85$ mΩ .

– Centrifugal pump parameter: K_r = 28·10^{-4} W (s/rad)^3, Ωn = 104.7 rad/s.

– Fuzzy logic controller parameters: $g_\Omega = 10^{-4}$, $g_v = 7\cdot10^{-4}$, $g_\alpha = 1.2$.

Fig. 9, 10, Fig. 11, 12 and Fig. 13, 14 show respectively the good concordance between the rotation speed Ω, the PVG power P_g and the duty cycle control α with the theoretical results when the irradiation and the temperature increase (decrease) (Table 2).

It is noted that when the irradiation and temperature vary, the duty cycle control is judiciously adjusted to its optimal value. Consequently the rotation speed converge to their optimal values which is corresponding to maximum power.

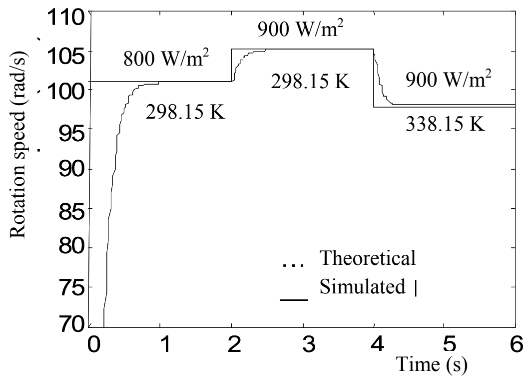


Fig. 9. *Rotation speed with increasing irradiation and temperature*

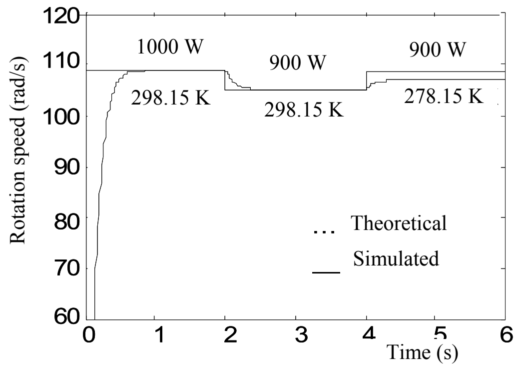


Fig. 10. *Rotation speed with decreasing irradiation and temperature*

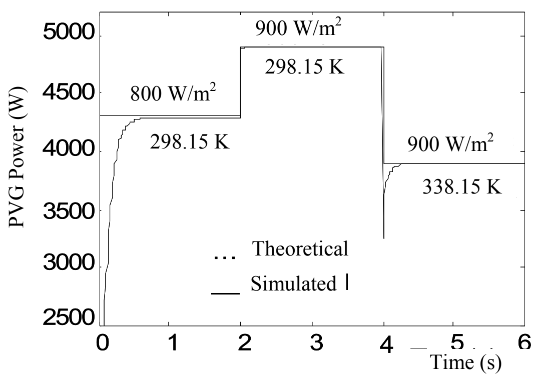


Fig. 11. *PVG power with increasing irradiation and temperature*

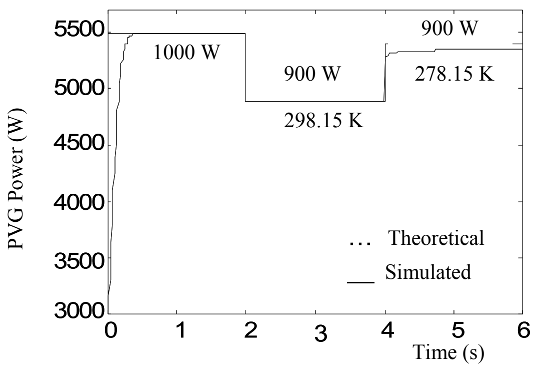


Fig. 12. *PVG power with decreasing irradiation and temperature*

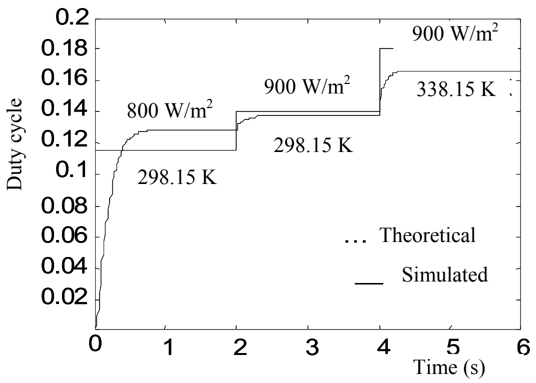


Fig. 13. *Duty cycle with increasing irradiation and temperature*

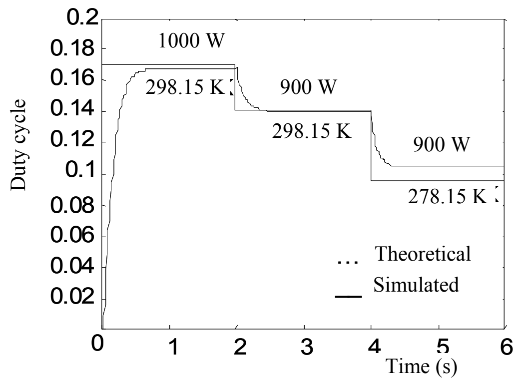


Fig. 14. *Duty cycle with decreasing irradiation and temperature*

Table 2

Theoretical results for given irradiation and temperature

Irradiation λ and temperature *T*	PVG Power Pg (W)	Rotation speed Ω (rad/s)	Duty cycle α
λ = 800 W/m^2 *T* = 298.15 K	4313	101.1	0.1039
λ = 900 W/m^2 *T* = 278.15 K	5409	108.3	0.0964
λ = 900 W/m^2 *T* = 298.15 K	4897	105.1	0.1405
λ = 900 W/m^2 *T* = 338.15 K	3384	97.94	0.1830
λ = 1000 W/m^2 *T* = 298.15 K	5484	108.8	0.1720

Conclusion

In this paper, a fuzzy logic controller is derived and applied to a photovoltaic pumping system in order to track the optimal operating point. The system is consisting of a photovoltaic generator with a power electronic converter that assure maximum power point tracking (MPPT). The converter feed a DC motor coupling with a centrifugal pump. The PV generator is forced to operate at its maximum power point by using fuzzy logic controller that adjusts the duty cycle of the converter to control the motor rotation speed to reach its maximum value. The drive system performance has been simulated at different solar irradiations and temperatures. The simulation shows that the use of the proposed controller gives good results for the maximum power tracking.

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