Modelling, Command and Treatment of a PV Pumping System Installed in Tunisia

Nejib Hamrouni[1], Sami Younsi[2], Moncef Jraidi[3]
Laboratory of Analysis and Treatment of Energetic and Electric Systems (ATEES), Science Faculty of Tunis[1, 3]
Technical College at Dammam–KSA, Technical and Vocational Training Corporation[2]

***Abstract*—This paper studied the modeling, the command and the optimization of a photovoltaic (PV) pumping systems using performed strategies of command laws. The system is formed by a PV generator, a DC-DC converter with a maximal power point tracking (MPPT) command, a DC-AC converter with V/f command law and a submersed motor-pump. The first part of this paper presents the obtained models of the various components of the PV pumping system. Dynamic commands composed of a V/f and MPPT laws are calculated around the converters. The MPPT command insures the power adaptation between PV generator and load whereas the V/f command insures a PWM control of the asynchronous motor and a sinusoidal output signal. Some important results of simulation of the PV pumping system under the environment of MATLAB/SIMULINK are presented. In the second part of this paper some experimental results of a PV pumping system installed in Tunisia are developed. Those results are used to validate the simulating model and to test the performances of the command approach.**

Keywords*—*Stand-alone PV systems; PV pumping; modelling; Louata pumping system

I. Introduction

Agricultural, in some countries, depends largely on rains and is very affected by the non-availability of water in summers. However, optimum irradiance is available in summers as such more water can be pumped to meet increased water requirements. There is a large scope to use PV pumping systems for water supplies in rural, urban and educational institutions. Most of the photovoltaic systems works forever of their optimal functioning points because of the mismatching between the PV generator and the load characteristics, especially with load disturbance and climatic variations [1]. To resolve this problem, many studies, developed in the literature, have used over dimensioning methods. Our approach, in this paper, is based on the performing of the control strategies. The command approach must insure a maximal PV power and a sinusoidal voltage-current for the AC loads. The first objective is reached thanks to a DC-DC converter controlled with a MPPT. The second objective is insured byaV/f command with a PWM interface which generates the control signals to the three phase inverter. Hence, the studyfocuses on modelling and simulation, dynamic control and experimental analysis of a PV pumping system installed in urban region of Tunisia. It is organized as follows: The first section presents the model of the PV pumping system, the dynamic commands and the simulating results under MATLAB/SIMULINK. The second presents some experimental results and characteristics of a PV pumping system installed in Tunisia. Those results are used to validate the simulating model and to test the performances of the command approach.

II. Modelling and Command of the PV Pumping System

The system is composed of a PV generator (230V/2100Wp), an MPPT power adapter, a PWM three phase inverter (3kW-12V/5Hz-127V/60Hz) and a submersed motor-pump (1.5kW, 3x127V) associated according to the configuration illustrated in Fig. 1.

A. Modelling and Control of the PV Generator

The PV cell is simulated by the single-diode model [1] described by the I=f(V) relation as follows:

$$\begin{aligned} Ipv &= Iph - Is.[\exp[(q/nkT).(Vpv + Ipv.Rserie)] - 1] \\ &- (Vpv + Ipv.Rserie)/Rshunt \end{aligned} \tag{1}$$

With:

$$T = T_a + K_t.\Phi$$

$$Iph = (Isc + Tcoef.(T - Toffs)).\ \Phi/1000$$

$$Is = Is0.T3 * \exp(-q.U/k/T)$$

$$A = q/(n.k.T)$$

The model parameters are calculated experimentally for a PV module type AEG PC4050installed in Louata-Tunisia. Those parameters are given in Table 1.

In order to allow the load extracting instantaneously the maximum PV power, an adequate DC-DC converter with a dynamic MPPT command has been used. Several MPPT methods have been proposed in the literature such as; perturbation and observation, incremental conductance, fuzzy algorithms, sliding mode controller [2]. As indicated in Fig. 2, the adaptation method, proposed in this paper is based on numerical algorithm. It calculates the PV maximum power for a given solar radiation and cell temperature and measures instantaneously the load power and after then calculates dynamically the factor of adaptation as the quotient between the two obtained power values. By action on this factor, a better mismatching PV-load around the optimal point can be insured.

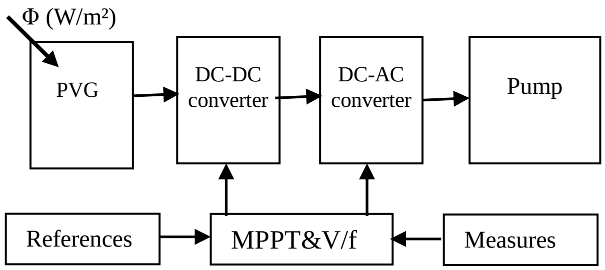


Fig. 1. Global PV Pumping System Association.

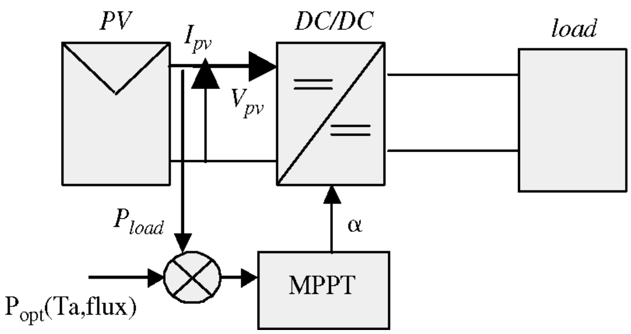


Fig. 2. Diagram of the DC-DC converter monitoring strategy

TABLE I. PARAMETERS OF THE PV CELL-AEG PC4050

Parameters	**Values**
Short circuit current(Isc)	2.804A
Cell reverse saturation current (Is0)	430.34 A/ (°K)^3
Cell temp.at reference cond.(Toffs)	298.15 °K
Cell junction temperature (Tcoef)	1.08e^{-3}AkWm^{-2}(°K)$^{-1}$
Voltage (U)	1.05 eV
Ideal constant of diode (n)	1.29
Series resistance (Rserie)	0.011 Ω
Shunt resistance (Rshunt)	10.92 Ω
Boltzman's constant (k)	1.380662e^{-23} J/°K
Electronic charge (q)	-1.602189e^{-19} C

B. Modelling and Control of the Motor-Pump

The inverter provides a three-phase system voltages variable in amplitude and frequency to operate with variable loads and frequency (from 0.1 up to 1 time the rated frequency) [3]. The current is modulated sinusoidally to obtain a high efficiency. The phase voltage can be expressed as follows [4, 5]:

$$\begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} = \frac{\alpha Vpv}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} c1 \\ c2 \\ c3 \end{bmatrix} \quad (2)$$

With αV_{pv} is the input voltage, c_1, c_2 and c_3 are the PWM control signals. V_{pv} is the PV voltage corresponding to maximum PV power.

To modulate the asynchronous machine (ASM), the phase model has been selected. It is defined by the equations of stator and rotor voltages, the magnetic flux, the electromagnetic torque and the mechanical equation [1,2]. The pump functioning point can be obtained by the intersection point of the pump Hn=f(Q) and the circuit Hs=f(Q) characteristics [3].

$$Hn = \mu N^2 + \lambda NQ + KQ^2 = Hs + XQ^2 \quad (3)$$

The resolution of this equation has allowed obtaining the following centrifugal pump models:

$$\text{If } N = Nmin = \sqrt{\frac{-4(K-X)Hs}{\lambda^2 - 4(K-X)\mu}} \text{ than } Q = Q_{min} = \frac{-\lambda N_{min}}{2(K-X)}$$

$$\text{If } \quad N > Nmin \text{, than } Q = \frac{-\lambda N - \sqrt{(\lambda N)^2 - 4(K-X)(\mu N^2 - Hs)}}{2(K-X)}$$

$$\text{If } \quad N < N_{min} \text{ than } Q_{opt} = \frac{\mu_0 K + \sqrt{(\mu_0 K)^2 + K\lambda_1(\lambda\lambda_0 + \lambda_1\mu)}}{K\lambda_1} N$$

The torque (C_r), the power (P) and the efficiency (η) of the pump, used on the pump modelling, are given by the fallowing expression [4]:

$$C_r = \frac{\varpi}{2\pi g} Q(\mu_0 N - \lambda_1 Q); \; P = C_r\Omega \text{ and } \eta = \frac{\overline{w}QH_n}{2\pi NC_r} \quad (4)$$

The coefficients $\mu_0,\mu,\lambda_1,\lambda$ and K depend on geometric characteristics of the pump. Their values, calculated by referring to the manufacturer pump characteristics, are given in Table 2.

The model scheme of the pump is given in Fig. 3.

According to the disturbances of the load and the climatic conditions, the V/f inverter command is regulated to a variable value to allow the starting of the motor and the generating of a water flow for low solar radiations. The variable V/f law is very adopted for PV pumping systems. For lower irradiances, the inverter frequency is lower than 10Hz. In order to maintain the functioning of the pump, the ratio V/f changes. The couple voltage-frequency, insures the functioning pump, is given in Table 3 [6].

The synoptic of the obtained V/f inverter command is illustrated in Fig. 4.

TABLE II. PARAMETERS OF THE CENTRIFUGAL PUMP

Parameters	**Values**
μ_0	0.8444m²
μ	0.06988m(rd/s)$^{-2}$
λ_1	-2.16e^4 m^{-1}
λ	1309s²/(rdm²)
K	–1.957e^8 s²/m^5
W	1000kg/m^3

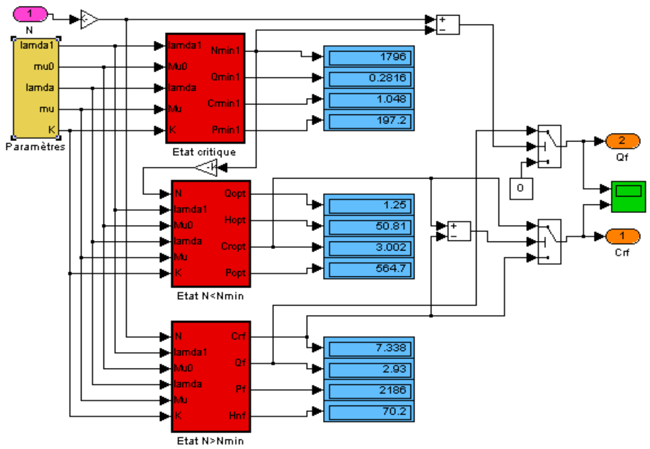


Fig. 3. Model Scheme of the Centrifugal Pump.

TABLE III. CONCEPTION OF THE COMMANDED LAW OF THE THREE PHASE INVERTER

Ø (W/m²)	220	400	500	600	700	740	760
V (V)	175	198	205	213	217	222	224
f (Hz)	36	47.23	49.14	51.1	52	53.2	53.7
V/f (V/Hz)	4.86	4.199	4.179	4.178	4.178	4.172	4.17

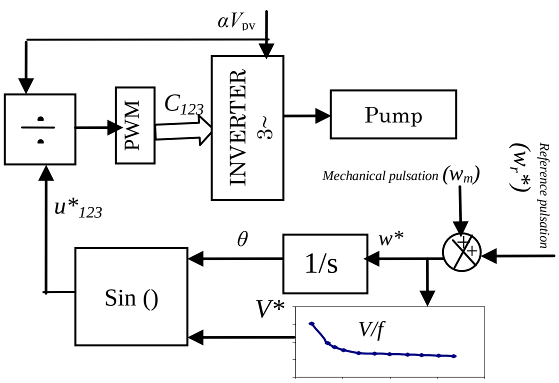
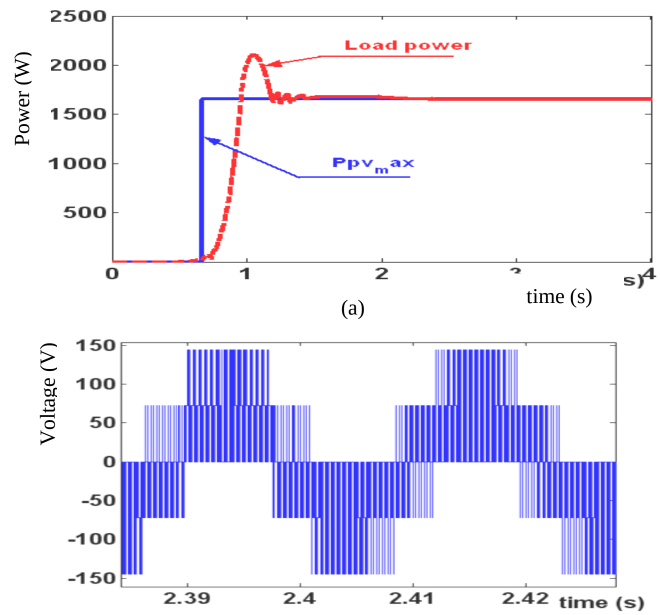


Fig. 4. Synoptic of the Three-Phase Inverter V/f Law.

III. SIMULATION OF THE PV SYSTEM

A simulating program based on the system model associated with the commands around the converters has been developed under MATLAB/SIMULINK. Under standard climatic conditions (1000W/m² and 25°C), some simulation results, of the system have been presented. Fig. 5 to 7 illustrate, respectively, the dynamic adaptation between the load power and the maximum PV generator power, the variation forms of the stator voltage and current, the rotor current, the electromagnetic and resistant torques, the motor speed and the pump flow.

According to Fig. 5(a), a good adaptation of the load power to the maximum PV power has been obtained. This result demonstrates clearly the performance of the MPPT command calculated around the DC-DC converter. An important starting (2s) stator current (37A), corresponding to the maximum value of the electromagnetic torque (15Nm) has been noted (Fig. 6). After the starting period, those variables take their nominal values 15 A and 5 Nm, respectively. Under 1000W/m² and 25°C, the PV power is equal to 1680 W and the pump flow is equal to 2.5 m^3/h for 2600rd/min motorspeed (Fig. 7b). For several solar radiation and ambient temperature during a normal day, some simulation results have been recorded. Fig. 8 shows the high performances of the MPPT and V/f commands. The adaptation of the photovoltaic power to the MPPT was realized in 2s for various irradiance and temperature. Fig. 9a shows the great depends of the pump flow to the solar irradiance. Fig. 9b shows the V/f law versus the solar radiationcalculated in this paper.



(b)

Fig. 5. (a): Adaptation of the Load Power to the Maximum PV Generator (b): Output Inverter Voltage.

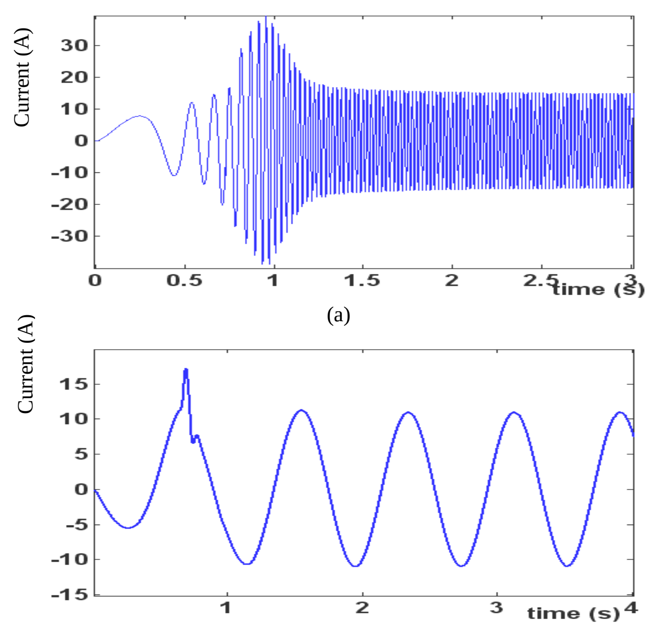


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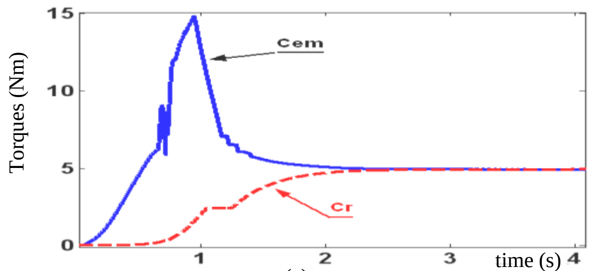
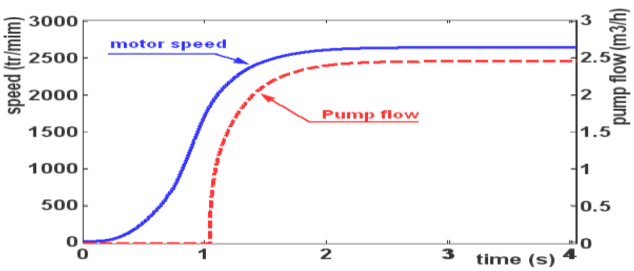
Fig. 6. Variation of the Stator (a) and Rotor (b)Currents.

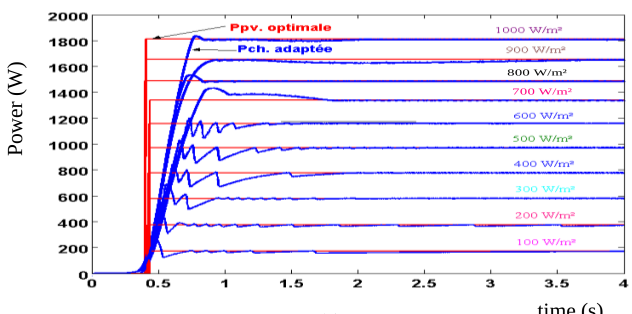


(a)



(b)

Fig. 7. (a): The Electromagnetic and Resistant Torques, (b):The Motor Speed and Pump Flow.



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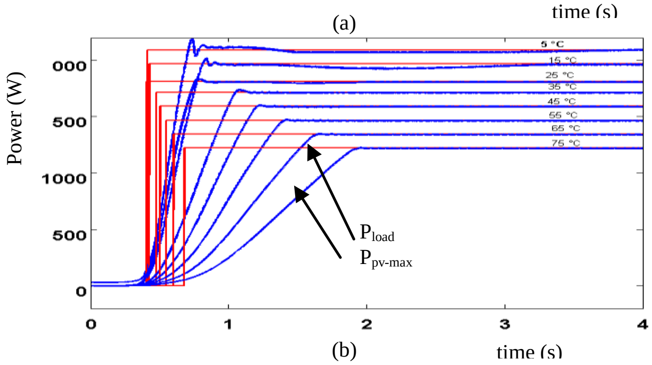

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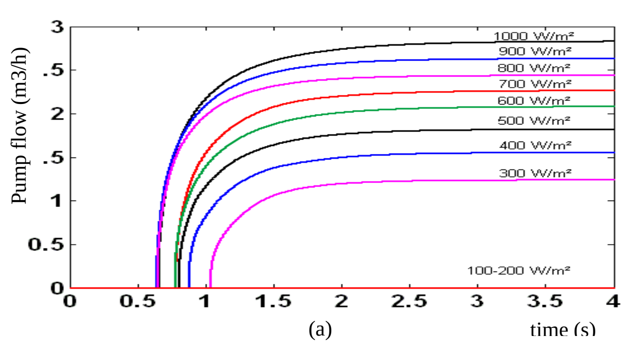
Fig. 8. Power Adaptation: (a): Several Irradiance and 25°C, (b) Several Ambient Temperature and 1000W/m².



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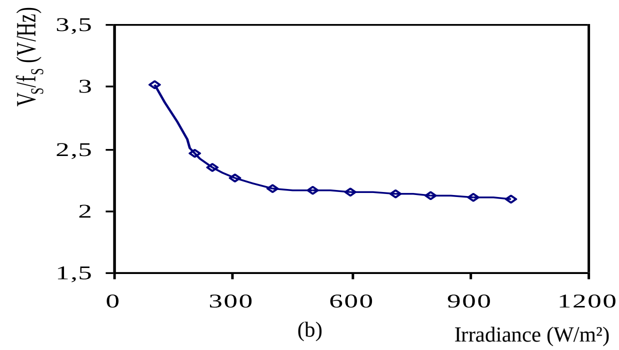


(b)

Fig. 9. (a): Pump Flow Rate Variation, (b): V/f Ratio Versus the Solar Radiation.

IV. Experimental Results

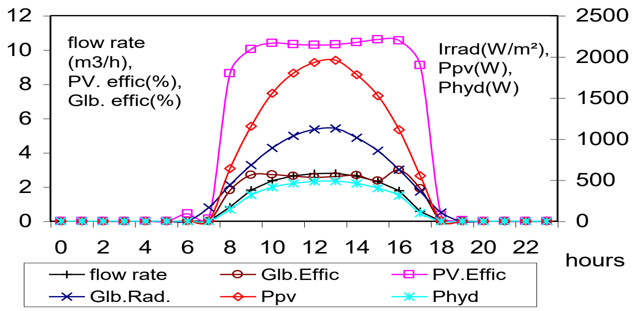
Several photovoltaic pumping systems have been installed in developed countries in order to contribute to the improvement of the water supply in rural regions [7-12]. Fourteen photovoltaic pumping systems have been installed in Tunisia [1-3]. The objective of those systems is to demonstrate the reliability of the technology. Such system consists of the PV generator (2.1 or 2.8 kWp), a three phase inverter (3 kVA) connected directly to the PV generator with an MPPT command law, a submersed motor-pump (1.5 kW) and a water storage tank ($8m^3$). These systems have been equipped by data acquisition systems collecting meteorological, electrical and hydraulic data. The collected information has been analysed and treated in order to evaluate the system's performances and to validate the model and the command approach of the PV pumping system developed in Paragraphs 2 and 3.The PV pumping system installed in Louata-Tunisia is given in Fig. 10. Its parameters are given in Table 4.

Fig. 11 illustrates respectively the hourly (Fig. 11a), the daily (Fig. 11b) and the monthly (Fig. 11c) variations of the PV pumping system parameters. They are principally the pump flow rate, the solar radiation, the solar and hydraulic powers, the PV generator and the global system efficiencies. The solar radiation fluctuates according to the season of the year around the mean value is equal to 6kW/m². The pump flow, the hydraulic power, the PV power and the global efficiency fluctuate, respectively, around mean values of 10 m^3/day, 2 kWh/day, 11% and 3%.

Fig. 10. The Photo of the PV Pumping System Installed in Louata-Tunisia.

TABLE IV. PARAMETERS OF THE PV PUMPING SYSTEM OF LOUATA

Parameters	Values
Photovoltaic power	2.1kWp
Total high (H)	65m
Water demand	$2m^3$/day
Global efficiency	3%
Pump flow (Q)	$2.5m^3$/h
Hydraulic power	320W
Inclination angle	35°
Latitude of Louata region	60m



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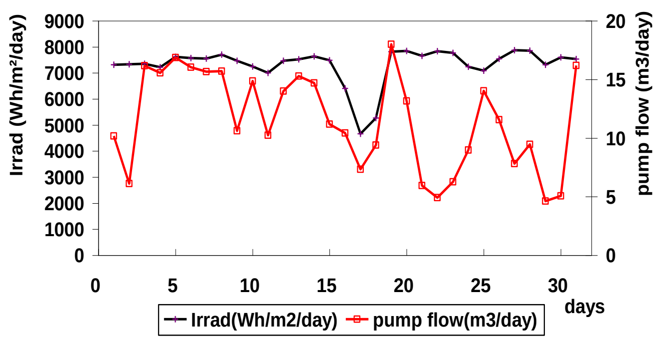

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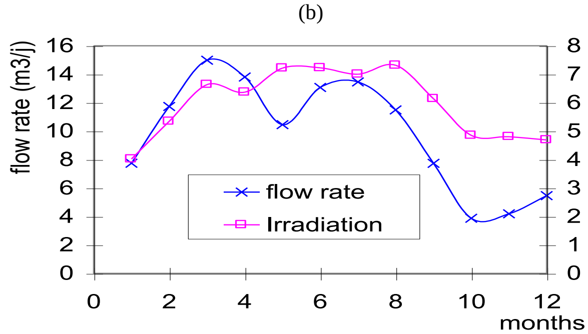


(c)

Fig. 11. Experimental Results of the PV Pumping Systems: Hourly Variations (a), Daily Variations (b) and Monthly Variations (c) of the Pump Flow and the Irradiance

Fig. 12 to 17 illustrates the typical variation curves of the PV system characteristics of Louata. According to these curves, all the parameters of the PV pumping system vary with the meteorological conditions, in particular with the solar radiation.

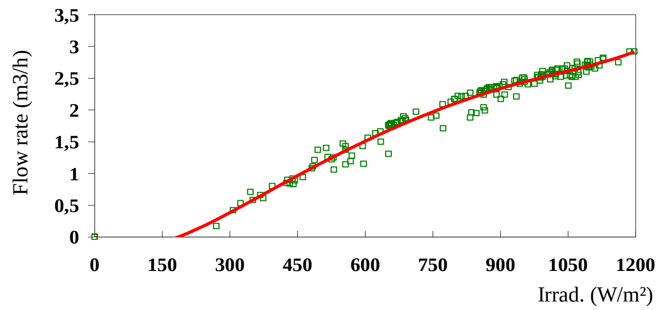


Fig. 12. Variation of the Pump Flow versus the Solar Radiation.

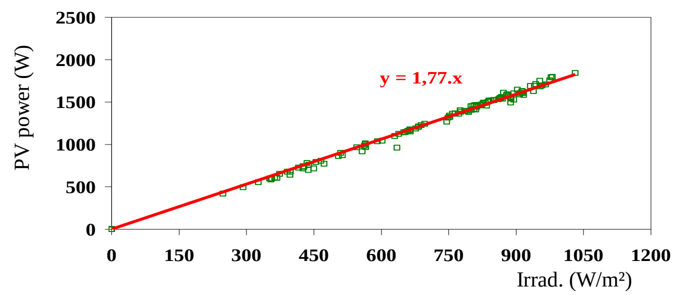


Fig. 13. Variation of the PV Power versus the Irradiance.

The pump starts to generate a flow rate for about 320 W/m² (Fig. 14 and 16). It reaches the maximum about $3m^3$/h at midday for 1000W/m² (Fig. 12). This maximum of the pump flow corresponds to the maximum efficiency (3%) of the global PV pumping system (Fig. 17). For a variation of the solar radiation from 350 to 1000 W/m², the PV power varies from 500 to 1700 W (Fig. 13), the inverter frequency varies from 27 to 45 Hz (Fig. 15) and the pump flow varies from 0 to $2.6m^3$/h.

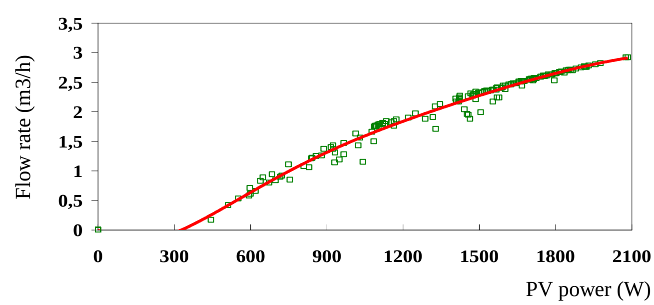


Fig. 14. Variation of the Pump Flow versus the PV Power.

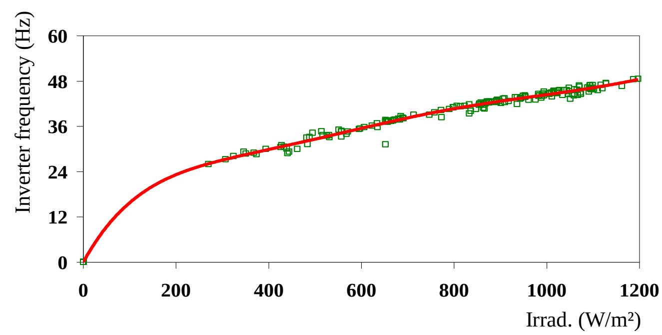


Fig. 15. The Inverter Frequency versus the Solar Radiation.

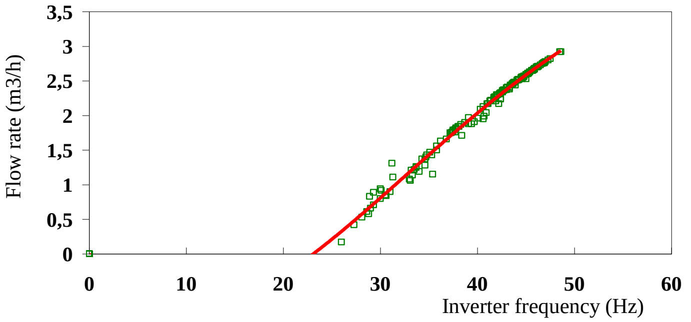


Fig. 16. The Pump Flow versus the Inverter Frequency.

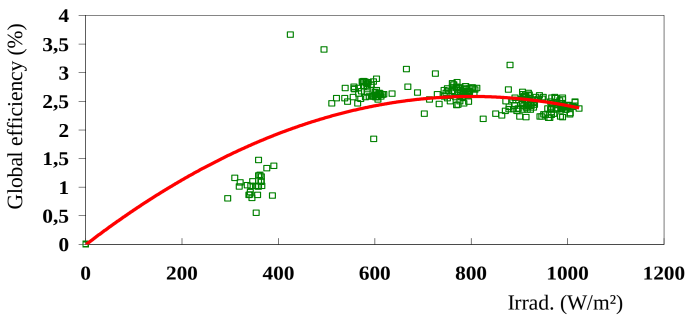
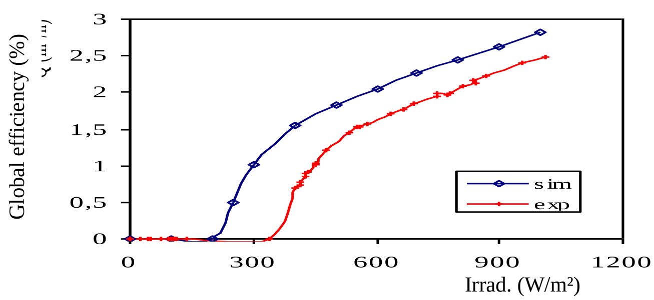
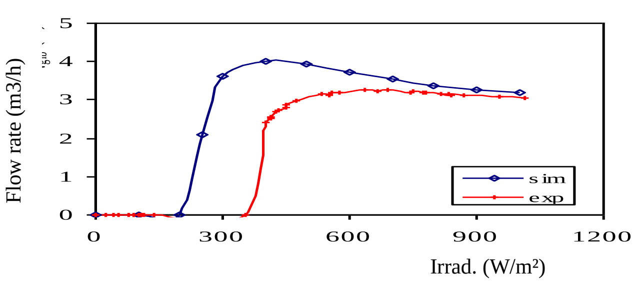


Fig. 17. Variation of the Global PV System Efficiency versus the Solar Radiation.



(a)



(b)

Fig. 18. Experimental and Simulating PV Pumping System.

Fig. 18a and 18b represent, respectively, the simulating and the experimental global efficiency and the flow rate versus the solar radiation. The comparison between experimental and simulation curves reflect clearly the optimization of the simulation results that is obtained thanks to the dynamic aspect of modeling and the high performances of the control approach.

These experimental results represented an important support which are used to validate the developed models and to test the performances of the command approach of the PV pumping system.

V. Conclusion

In this paper, we have presented some of the important results obtained by treatment and evaluating of the experimental data collected from the pumping system installed in Louata-Tunisia. Those results have been exploited to validate the system component models. We have demonstrated that the best method to perform the functioning of the PV pumping system is to introduce dynamical control laws of the converters in particular for a system functioning without batteries.

In fact, the main problems of standalone PV systems are the mismatching of the PV-load association (extraction of the maximal PV output power), the compensation of climatic variations and load disturbances and finally the storage (Battery replacement). Our approach has permitted to resolve these problems thanks to the new strategies of command. The MPPT command insures an adaptation between the load power and the maximum PV power, whereas the inverter PWM-V/f control insures an optimum load functioning in lower radiations.

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AUTHOR PROFILE

NejibHamrouni received his engineering degree from the National Engineering School of Sfax, in 2000 and the PHD from the National Engineering School of Tunis, in 2009, both in electrical engineering. He is an Assistant professor at National Engineering School of Gabés from 2010 to 2015. Since September 2015 he is an assistant professor at ISSAT of Mateur He has participated in several research and cooperation projects, and is the author of more than 20 international communications and publications.

Sami Younsi obtained his engineering degree from the National Engineering School of Sfax and his PHD in electrical engineering in 2013 from the Science Faculty of Tunis. He is an Assistant professor at the Institute of Technologies of Tunis.

Moncef Jraidi obtained his engineer diploma in electric engineering, his master degree in 1998 and his doctorate thesis in 2005 from ENIT. Actually, his is an assistant professor at the National Engineering School of Carthage. He has participated to several international cooperation projects in the field of renewable energies. He was the author and co-author of two books and several communications and publications.