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Centrifugal Motor-Pump System Model intended for the Photovoltaic Pumping applications

Abstract. *The Saharan medium by its arid nature and the availability of solar immense can return the application of the water pumping via photovoltaic pumping. To improve their performances for such type of systems, a theoretical study based on experimental tests is necessary. In this paper, the system to be modelled consists of an asynchronous motor coupled to a centrifugal pump immersed of type SPA in order to obtain a pumped flow and efficiency in function of the frequency of the stator voltage for pumping head given. The result has been very satisfactory.*

Streszczenie. *W artykule opisano możliwość nawadniania obszarów Sahary za pośrednictwem pomp zaislanych fotowoltaicznie. Zamodelowano system składający się z silnika asynchronicznego połączonego z pompą. (**System motor-wirująca pompa zasilany fotowoltaicznie**)*

Keywords: Motor-Pump; PV pumping; Modelization; Field-oriented control.
Słowa kluczowe: silnik-pompa, PV pompowanie; modelowanie.

Introduction

*S*ince the ancient ages and till now, solar energy offers good solution to supply desert and isolated regions, it is one of the most typical application in developing countries and has the potential to become a major force for social and economic development; The arid regions represents 80% of Algeria and where the water needs are of utmost importance [3], supported the water pumping as being one of the effective means of an active prevention for the agricultural land irrigation, the access to sate water supply of the populations.

During the day, the speed of the motor asynchronous depends on the temperature and the quantity of the solar radiation that is fallen on the photovoltaic panels to extract the maximum power. This latter, is obtained by the proper adjustment of the inverter frequency (by increase or reduction) instead of the *MPPT* circuit (maximum power point tracker), inducing a total improvement of the efficiency of the system [6]. On the other hand, the flow and the efficiency of the motor-pump for a total head (*HT*) (if we considered that the diameter of wheel is fixed) depend on the speed; this one is related to the stator frequency.

The photovoltaic systems cost is very high and the optimisation problem consists in maximising the daily pumped water quantity via the optimisation of dimensioning of photovoltaic system. The main aim of our work, on the basis of experimental result obtained by using the testing ground developed and studied in details in [2], is the study of the performances of a system pumping by the exact quantification of the flow and the efficiency.

The modelling of any system is essential when we wish to study its performances. For our project, the system to be modelled is an immersed centrifugal motor-pump *SP5A7* (nominal speed 2920rpm for an industrial frequency equalizes with 50*Hz*). The characteristic of the motor-pump of type *SP5A* is given in appendix (Fig. 7) [1].

Solar pumping system

The photovoltaic system is constituted of a self-piloted asynchronous motor operating a centrifugal load. The unit is fed by solar cells through an inverter. Pumping without intermediate power storage enabled us to have a simpler photovoltaic system, more reliable; maintenance-fee is less expensive than a system with battery [8].

The variation of the pump's speed can give us numerous charts (*Q-H*). The use of a centrifugal pump needs a preliminary study of the most important charts that characterize it, where efficiency will be optimum with the total head and the speed envisaged by control the pumped water quantity to a desirable head. In addition, they are related to dimensions, kinds and speed of the pump.

The chart of the water quantity-head (*Q-H*) explains the different variations in the head of pumping, according to water quantity which forms bent charts [7].

According to the various preceding tasks of research, we note that the researchers apply the similarity law to determine the flow during an operation at a different speed (they consider that the motor-pump always functions at the operation point optimal). For example, for a given speed, the pump functions at the operation point optimal. If irradiance decreases, that involves a reduction speed, the system operating point is determined by the intersection point of the (*Q,H*) characteristics of the motor-pump, the *HT* remains fixed and the pump does not function with the optimum. Therefore, at the new speed, the flow is lower than the pumped flow corresponding to the optimal point, i.e. the system efficiency rises whatever is the solar radiation value and the temperature of the environment. As a result, the evaluation and the improvement of the pumping system performances are necessary for a best choice of the motor-pump.

Motor-pump system modelization

The theoretical models of motors exist. Nevertheless, to obtain the parameters of the models applied to concrete motor-pumps, it is necessary to determine their characteristics flow–frequency (*Q–fre*) in relation to the torque and the velocity.

Fig. 1. Sight of the electric (left) and hydraulic (right) part of the test facility under operation.

We need to separate physically the motor from the pump; it is not possible to separate the engine from the pump because they form a single compact block [4]. For these reasons, we have decided to use an empirical model for the complete motor-pump system in which parameters are obtained in a pumping test facility (Fig. 1), built for this purpose, by the team "electronic of the system" in our research unit. It allows us to characterize any pumping system. The test facility is constituted the power circuit (inverter) with the software of a test bench intended to determine the characteristic, total head and efficiency of pumps as a function of water flow, for three-phase solar electro-pumps by variation of the stator's signal frequency.

Experimental test facility

In this pumping test facility, the data can be monitored for different heads and piping by varying only the rate of opening of the control valve.

We use the *V/fre* constant law [2, 9] and we obtain, for each fixed frequency, the pumped flow versus to the pressure, simultaneously we measure the consumed power. All data quite simply measured, the water flow rate was measured by flow metre, the consumed power was measured by watt metre and the pressure was measured by pressure metre. Then, we calculate the hydraulic power. It is given by the relation [9, 11 & 12]:

(1) $$P_{hy} = CH \cdot Q \cdot HT$$

where: P_{hy}: hydraulic power of the pump, expressed in W; $CH = g \cdot \partial = 2.725 kg \cdot \frac{s^2}{m^3}$, g: constant of gravity (equal to $9.81 m \cdot s^2$); ∂: water volumic mass (equal to $10^3 kg \cdot m^{-3}$); Q: water quantity [$m^3 \cdot s^{-1}$];

The HT (total head) is calculated from pressure $HT[m] = Pr[Kg/cm2] \times 10$.

The pumping system efficiency is given by [9, 11 & 12]:

(2) $$\eta = \frac{P_{hy}}{P_e}$$

with P_e : Power electric of the entry, measured in W.

The results, for the frequencies for example $20Hz$ and 38Hz are shown in Table 1.

Table 1. Experimental results. ($Q=0$ Indicate that the valve is completely closed).

$HT[m]$	$Q[m^3/h]$	$P_{hy}[W]$	$P_e[W]$	$\eta_{mo}[\%]$
20Hz*-*24.5Volt				
1,5	2,66	11,07	96	0,11
2	2,40	13,36	96	0,14
4	1,85	20,58	96	0,21
5	1,39	19,30	96	0,20
6	0,61	10,22	88	0,12
7	0	0	80	0
38Hz*-*44.9Volt				
2	5,20	28,90	336	0,09
3	4,99	41,61	344	0,12
5	4,94	68,59	344	0,2
7	4,5	87,61	352	0,25
9	4,2	105,14	360	0,29
10	4,1	113,89	360	0,32
12	3,78	126,18	360	0,35
15	3,34	139,4	360	0,39
17	2,71	127,91	352	0,36
20	1,72	95,46	312	0,3
22	1,05	64,52	272	0,234
25	0	0	216	0

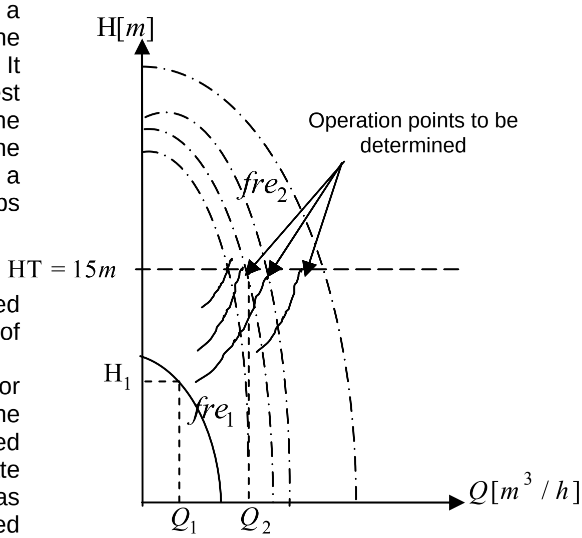

Fig. 2. Relation $HT=f(Q)$ of a pump.

Data treatment and obtained analysis

By using the HT estimated in the first part of the course of our experiment, the well where the pump will be installed has the following characteristics:

Static head: $N_s=8.3m$; the reduction of water: $R=5.2m$ and the diameter: $D=1.5m$.

The HT is static pumping depth + pressure to overcome back pressure valve (m). The head loss due to pipe friction was neglected or constant due to short pipe runs and low flow rates [5].

The HT will then be calculated by using the expression:

(3) $$HT = H_g + \Delta pc$$

H_g: Geodetic head; $H_g= N_s+R=8.3+5.2=13.5m$, Δp_c : loss-of-load; $\Delta p_c = 1.45$, it calculated for average volumetric flow rate.

The HT is then:

(4) $$HT = 14.95 \cong 15m$$

The objective is, therefore, to work out a mathematical model, which simulates any operation point (determination of the flow and the efficiency) for $HT=15m$, according to the frequency of the voltage of entry.

By using the similarity law, we can predict the operation of the centrifugal pump while basing ourselves on its characteristic of origin, i.e., the one which is generally known or on the obtained results in experiments. For that, a set of formulas can be used, namely [9]:

(5) $$\frac{Q_1}{Q_2} = \frac{\Omega_1}{\Omega_2} \text{ and } \frac{HT_1}{HT_2} = \left(\frac{Q_1}{Q_2}\right)^2 = \left(\frac{\Omega_1}{\Omega_2}\right)^2$$

With: Q_1 and HT_1: are, respectively, the flow and the HT correspondents at the speed Ω_1. Q_2 and HT_2: are those correspondents at the speed Ω_2.

Corresponding to the $HT_2=15m$, and knowing the data for $fre_1(Q_1,HT_1)$, The following expressions of the stator frequency fre_1 (or-well the rotor speed) and Q_1 are easily derived.

(6) $$fre_2 = \sqrt{\frac{15}{HT_1}} fre_1 \text{ and } Q_2 = \sqrt{\frac{15}{HT_1}} Q_1$$

This procedure is shown in the Fig. 2. In this manner, we have the trio (Q, P_{hy}, η_{mo}) for a frequency fre and for $HT=15m$. For this head, the system does not contribute to water yield unless frequency exceeds $30Hz$.

After having introduced the characteristics of each operation point of the pump into the 'ORIGINELAB' software, this one enabled us to make the smoothing of these characteristics. This leads to the curves which show the evolution of the flow and the efficiency according to the stator frequency. We are able to obtain the parameters appearing by curve fitting to an experimentally measured curve for a certain frequency.

Fig. 3 shows the clouds of the obtained points in experiments and smoothing (interpolation) by using the model with two exponential. The obtained model giving the flow is an exponential equation. The developed formula is written as follows:

(7)
$$Q = y_0 + A_1\left(1-\exp\left(\frac{-fre}{t_1}\right)\right) + A_2\left(1-\exp\left(\frac{-fre}{t_2}\right)\right)$$

with: y_0=-445.65141; A_1=90.52122; t_1=544.45166; $A2$=443.4417; t_2=5.78246.

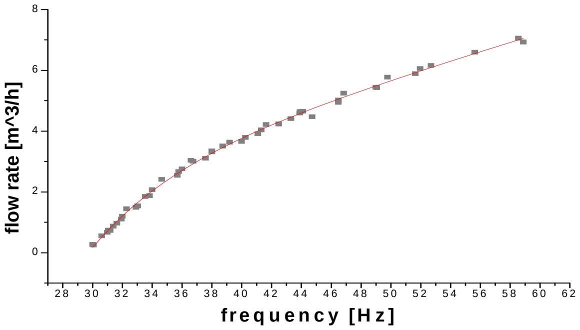

Fig. 3. Characteristic frequency-flow and its smoothing.

We notice that the increase in the stator frequency involves an increase in the outlet side water flow of the pump.

By analogy, Fig. 4 shows the clouds of the obtained points in experiments for the efficiency as well as the obtained curve by smoothing.

The obtained equation of efficiency is:

(8) $$\eta = a_0 + a_1 fre + a_2 fre^2 + \cdots\cdots + a_5 fre^5$$

with: a_0=-23.92091; a_1=1.9562; a_2=-0.05405; $a_3=4.99471\cdot 10^{-4}$; $a_4=1.\ 67495\cdot 10^{-6}$; $a_5=-3.64613\cdot 10^{-8}$.

According to the Fig. 4, we can say that our systems functions are in an optimal way at a frequency of approximately 38Hz, where the efficiency is maximum.

To validate the obtained results, the comparison between the N values of the measured data and M_i calculated C_i is done by using the regression coefficient R-square (R^2), defines as follows [4, 10]:

(9)
$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(C_i - M_i\right)^2}{\sum_{i=1}^{N} M_i^2 - \frac{\sum_{i=1}^{N} M_i}{N}}$$

In the Table 2, we calculated the value of R^2. for each model (flow/freq and efficiency/freq). The Eqs. (7) and (8) agree very well with the experimental values, and this according to the obtained values R^2.

Table 2. Valeurs of the regression coefficient R^2.

Model	*flow/frequ*	*efficiency/frequ*
R^2	0.9991	0.96724

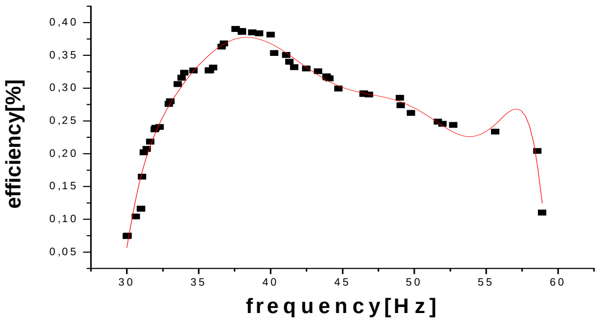

Fig. 4. Characteristic frequency-efficiency and its smoothing.

Validation of the pump model

We used this model for an asynchronous motor supplied with voltage, fed by an asymmetrical nine levels multilevel inverter and controlled by *SVM* technique. This motor is speed controlled by a *PI* regulator in a field oriented control. All this is considered as a converter with $V/f = constant$ improved. It is explained in [5].

Model of induction motor and its control

The electromagnetic torque developed by the machine is expressed according to rotor flow and of the stator current by:

(10) $$T_{em} = \frac{3}{2} p \frac{M}{L_r}\left(\varphi_{dr} I_{qs} - \varphi_{qr} I_{ds}\right)$$

The mechanical load is a centrifugal pump; its resistive torque imposed applies a load torque proportional to the speed-square of the motor [6].

(11) $$T_r = k_{ch}\Omega^2$$

with: k_{ch} Constant which depends on pump nominal data.

In order to maintain the decoupling characteristics of a field-oriented induction motor, given by the following equations. Thus:

(12) $\varphi_{qr} = 0$ and $\varphi_{dr} = \varphi_r$

The speed control of the induction motor actuating the centrifugal pump makes it possible to control its flow and to optimise the extracted electric energy without needing to another (*DC/DC* converter); the *PV* array should always be operated close to its maximum output power by the loop of regulation speed that requires the knowledge of the reference speed. It is then imperative of determine an explicit relation of the reference speed in function of the sunning [6]. The Fig. 5 gives a diagrammatic sight of a drive at variable speed using the principle of the field-oriented control. To ensure the regulation of the speed and the current, we use the regulators of the type *PI*. For the simulation results used in this paper, the numerical values for the pump *SP5A7* are summarized in Table 3. The numerical values of the simulation model are obtained either by measurements or identification from laboratory experiments.

In order to verify the proposed model, digital simulations were carried out for four insulation level.

At the beginning, radiation is worth $R=600W/m^2$, then radiation is brought to $R=1200W/m^2$ in $2s$ then in $R=800W/m^2$ in $6.8s$ and finally, radiation reached $R=240W/m^2$ in $9s$.

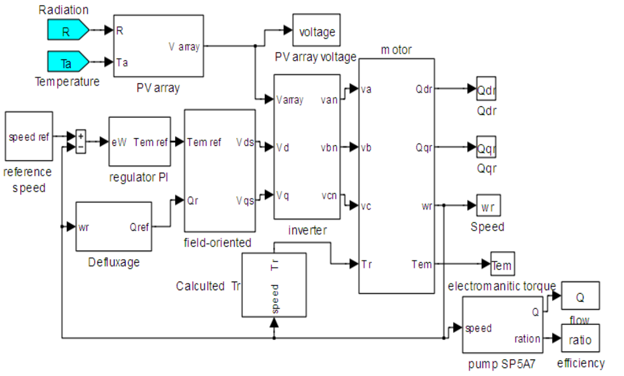

Fig. 5. The block diagram of a field-oriented control of a field-oriented induction motor coupled to a centrifugal pump, fed by solar cells through an inverter.

Simulation Results and interpretations

The response of the system using *MPPT* controller obtained by simulation is shown in Fig. 6. All test results show that the robust tracking speed of induction motor drive with the proposed *MPPT* control strategy is very effective in tracking the selected tracks at all times, it is observed that, in every case, the *PI* controller brings the measured speed to the desired value smoothly and without the overshoot. We observed the flow estimation and also the resistive torque imposed by the quantity of pumped water. The electromagnetic torque compensates for instantaneously this request of the resistive torque.

The field-oriented control using *MPPT* technique is developed and studied in detail in another work.

The figures show that the flow and the couple are decoupled. In addition, flow is constant in permanent mode $\varphi_r = 0.28wb$. The statoric voltage by frequency ratio is always kept constant with a *v/f* value of 1.3 during operation, the motor is thus, managed by the *V/fre* constant law, which shows the effectiveness of the loop of speed regulation. This system is able to adapt the operating point according to variations of the speed (increase or reduction). As a matter of fact, hence the matching efficiency of the daily energy is fairly low because the most the operating motor frequency is different of 38Hz during the day, i.e. the pump always does not function at a point optimal operation.

This motor-pump unit model allows us to obtain the operating point of the system, the efficiency and the exact pumped flow rate during one day and the moments when the system of pumping functions is in an optimal way. This model provides a very useful tool for dimensioning PV pumping systems for ensuring optimal efficiency, which essentially keeps its state optimal during a long duration.

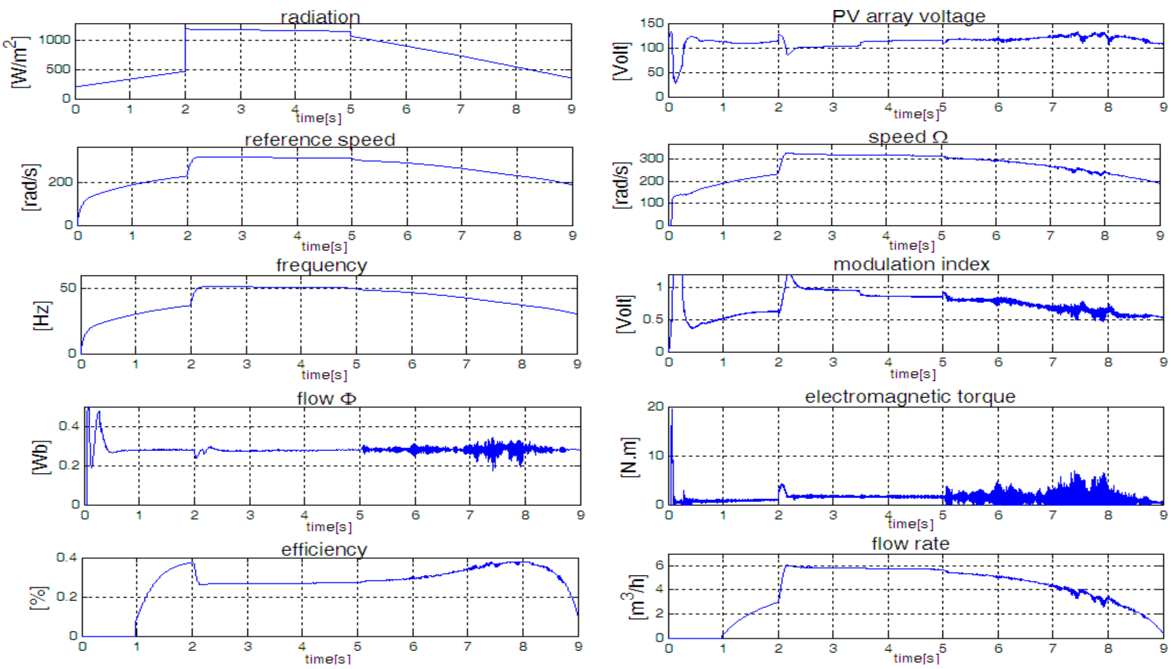

Fig. 6. Behavior of the pump by considering radiation variations

Conclusion

In this work, we have proposed and developed an empirical model for immersed centrifugal *SP5A7* pump for photovoltaic (*PV*) applications coupled to *AC* motors. The models is based on experimental results, which have been characterized completely in the pumping test facility in order to obtain the parameters of the models, built by the team "electronic of the system". These models will allow us to obtain the operating point with the flow rate of the pumped water for any radiation value. The modelled motor-pump characteristics are frequency–flow and frequency–efficiency. Then, we validated these models by using the field oriented control to see the behavior of the pump during the variation of illumination. Simulation shows that the results of the continuation of the reference speed (i.e. illumination) coincide with those acquired in the experimental part.

To predict the photovoltaic pumping system performance, it is necessary to use a simulation program, because it takes into account the different parameters of the system and its geographic location. From the data of estimate, and for one typical day for from distinct climatic regions, we can easily obtained the determination of the best couple generator configuration-pump for a given installation site and a daily load profile according to the energy needs. Consequently, we dimensioned the pump in order the selected pump must show its competitiveness with respect to other pump for the same rendered service and to impose and/or maximize the increase of both the daily pumped quantity and pumped efficiency which is appropriate for our installation (speed is regulated according to radiation so as to guarantee an optimal efficiency all the day).

From the point of view of a later development of the system, the following axe will be approached: The generalization of the described model for the case of variable heads for any value.

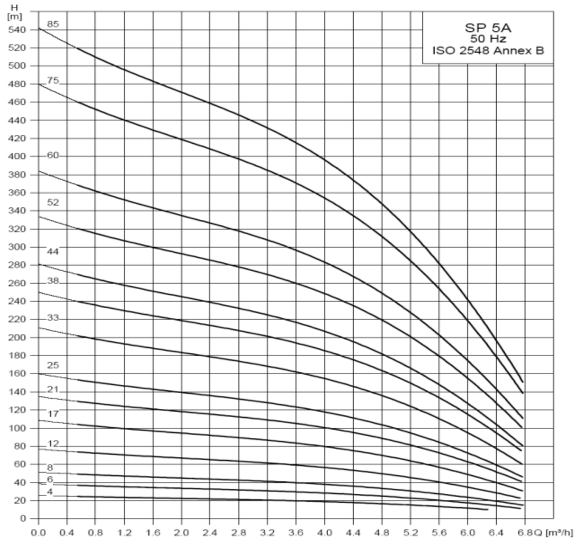

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Fig. 7. *(Q,H)* Characteristic of pumps *SP5A* for an industrial frequency (equal 50Hz).

Table 3. PV pumping system specifications**.**

Subsystem	Specification	
Pump and motor	Type	GRUNFOS
	Speed	2920 rmp
	Power	550 W
	Voltage	65 V
PV array	Type	Isofotón
	Peak power	75 W
	Optimal voltage	17.3 V
	Optimal current	4.34 A
	Open circuit	21.6 V
	Short current	4.67 A
	Number of module	8 Np × 2 Ns

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