International Journal on Electrical Engineering and Informatics - Volume 8, Number 3, September 2016

A Simplified but Accurate Prevision Method for A Stand-Alone Photovoltaic Pumping System using Linear Interpolation/Extrapolation

Mohammed Yaichi[1], Abdelkrim Mammeri[1], Sid-Ali Chikhi[1], and Mohammed-Karim Fellah[2]

[1]Unité de Recherche en Energies Renouvelables en Milieu Saharien, URERMS, Centre de Développement des Energies Renouvelables, CDER, 01000, Adrar, Algeria
[2]Intelligent Control and Electrical Power Systems Laboratory, Djillali Liabes University of Sidi-Bel-Abbes, Algeria

Abstract: The Saharan medium by its arid nature and the availability of solar immense in our country, 7.8 kWh/m^2/day can return the application of the water pumping via photovoltaic (PV) pumping system. However, due to their relatively high cost, the sizing of these systems implies the use of an accurate tool. In this paper, a new practical formulation is proposed, in order to predict the daily pumped water quantity (Q_d) for a given daily array energy output (E_{pv}) profile and any total manometric head (H). The model based on the linear interpolation/extrapolation, called: translation of the E_{pv}-Q_d characteristics of pumps. This technique has been developed based on experimental study. This makes practical translation procedure much easier; only four □$_{pv}$-Q_d characteristics measured at any E_{pv} and H can be used as the reference E_{pv}-Q_d characteristics. The calculated the Q_d over a wide range of E_{pv} and H well agree with experimental results of PV pumping system. These results indicate that the translation of the E_{pv}-Q_d characteristics based on this method is effective for estimating the performance of the PV pumping system under various climatic conditions.

Keywords: PV pumping, (E_{pv},Q_d) characteristic, Translation, Array energy output, daily pumped, Head.

1. Introduction

During the day, the speed of the brushless DC motor-pump depends on the temperature (T_c) and the quantity of the solar irradiance (G) 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. On the other hand, the flow rate (Q) and the efficiency of the motor-pump for a total head (H) depend on the speed (related to the irradiance) if we considered that the number of stages is fixed (i.e Standard Centrifugal Pump, SCP) [1, 2].

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 Flow-Head characteristics of a centrifugal pump, Figure 1, driven at a rotor speed Ω can be approximated by quadratic form using Pfleider-Peterman model [3, 4]:

$$H = a_0 \cdot \Omega^2 + a_1 \cdot \Omega \cdot Q + a_2 \cdot Q^2 \qquad (1)$$

a_0, a_1 and a_2 are constants depending on the pump dimensions.

For the determination of the pump operating point it is required to know both the pump and pipeline characteristics. The piping system deals with the total head that must be overcome by the pump. The H-Q characteristic of the pipe network is given as a function of the geodetic head and head losses (as function of the flow-rate) [3]. Thus, it should at least equal the head corresponding the flow computed by the pump flow-head equation. It comes:

Received: December 09th, 2014. Accepted: June 10th, 2016
DOI: 10.15676/ijeei.2016.8.3.1

$$H = H_g + k \cdot Q^2 \tag{2}$$

The constant k relates to the head loss caused by fluid friction, H_g: Geodetic head.

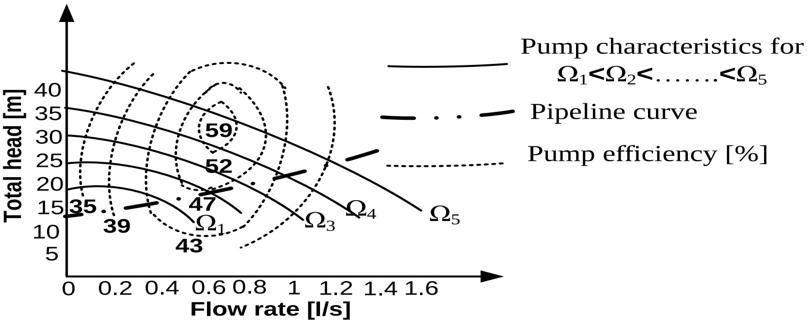


Figure 1. Centrifugal Pump Head-flow-rate characteristics

The pump flow-rate is then obtained by equating pump H-Q characteristics and pipeline H-Q expression, given respectively by equations (1) and (2).
Once the characteristic and power demand curves are defined, the motor-pump efficiency may be calculated as follows [5]:

$$\eta_{mp} = \frac{P_{hyd}}{P_{pv}} \times 100\% \tag{3}$$

where

$$P_{hyd} = CH \cdot Q \cdot H \tag{4}$$

P_{hyd} is the power output in terms of pumped water [kW] (i.e. hydraulic output power), $CH = \rho \cdot g$: $\rho = 10^3\ kg \cdot m^{-3}$ water volumic mass the constant, $g=9.81 m \cdot s^{-2}$ the constant of gravity and P_{pv} is the d.c. output power from the PV array is given by:

$$P_{pv} = V_{pv} \cdot I_{pv} \tag{5}$$

where V= d.c. operating voltage (V) ; I = d.c. operating current (A).

After performing the calculation process, the daily pumped water quantity is defined as:

$$Q_d = \int_{t_{sr}}^{t_{ss}} Q\, dt \tag{6}$$

Where the t_{sr} and t_{ss} indicate respectively the solar sunrise and sunset times, which are chosen in the present work for a clear standard day as: t_{sr} = 5h.00' and t_{ss}=20 h.59'.

The hydraulic model is then complete for a given speed (irradiance dependent) and a static head (geological characteristics of borehole site dependent).
Accordingly, the PV panels' energy output ''E_{PV}'' during the same time interval can be expressed as:

$$E_{pv} = \int_{t_{sr}}^{t_{ss}} V_{pv}(G, T_c) \cdot I_{pv}(G, T_c)\, dt \tag{7}$$

The energy output of the array PV depends closely on the climatic conditions (solar irradiance G and temperature T_c).

According to the various preceding tasks that have been carried out in the photovoltaic water pumping system, [6, 7] use the affinity laws and the pump datasheet, a set of curves giving the flow versus the head and parameterized by speed can be then obtained, but in order to use these results during calculations this set of points should be fitted to obtain an algebraic equation, this is done by the use of a two-variables third order polynomial function. However, the procedure to find the flow rate and efficiency is rather difficult. It then requires knowledge of the speed Ω, because the estimation the speed of submersible pump is not easy. It could be noted that despite of the complexity of the model used to describe the pump, it is difficult to have a perfect fit on a broad range of speeds, but the error made is not very large.

The researchers in [8, 9, 10, 11, 12 & 13] developed a model to simulate the performance of photovoltaic water pumping system, this model is given as a function of current output I_{PV} (or P_{PV}) of PV array and head H, where this models was obtained based in the short-term estimates. These estimates were conducted to characterize the performance of the pump over the course of a day. These results were used to determine the efficiency of the solar pumping system at various solar radiation levels and the solar radiation required to start the pump in the morning. In addition, these short-term results were used to ascertain that the pump was operating properly [14].

M. Benghanem and al in [15], the aim of their work is to determine an optimum photovoltaic (PV) array configuration, adequate to supply a DC pump with an optimum energy amount, under the outdoor conditions of Madinah site, without developed a mathematical model.

In this article, a new practical formulation for the linear interpolation was proposed in order to translate the E_{pv}-Q_d characteristic to target conditions of array energy output (E_{pv}) and head (H) using only easier four experimental tests data of motor-pumps, which do not require adjustment of Q-H characteristics datasheet. This method can accurately estimate the performance of various kinds of motor-pump a wide range of E_{pv} and H. In this respect the solar pumping system, installed at three different head, were field tested in order to evaluate their performance under local working conditions. Measurements and data collection were carried out using a data logger system. Also, the purpose of this field test was to characterize the performance of the solar pumping systems under local climatic and working conditions by conducting long-term tests. There tests were conducted to measure the daily output of the pump as a function of total daily array energy output.

2. Solar Pumping Systems

The photovoltaic system is constituted of a self-piloted brushless DC 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.

The system to be investigated is an immersed centrifugal motor-pump PS150 C-SJ5-8 (nominal voltage 12-24Volt). The solar pumping systems was composed of a PV solar generator, d.c./a.c, inverter and motor/pump unit . They were installed at Research Unit in Renewable Energies in the Saharan Medium URER/MS-Adrar, city of Algeria, latitude 29°, longitude 17°W. The PV modules were installed facing South at a tilted angle of 29° with the horizon. The specifications of the tested solar pumping systems and the measuring devices used are shown in Table 1 and 2. The picture of the installation is shown on Figure 2.

In this field test pumping, the data can be monitored for different heads. All data quite simply measured, they are interfaced to a PC based data logging device Hydra, FLUKE type. It was programmed to collect data for one minute intervals. All data were processed on day basis for seven months measuring period. The daily pumped water quantity was measured by counter for a day.

Table 1. PV-Motor-pump system specifications

<table>
<tr><td colspan="2" rowspan="8">Module</td><td>Module Type</td><td>mc-Si Solar ET-M53675</td><td></td></tr>
<tr><td>P_{max}</td><td>75</td><td>W</td></tr>
<tr><td>I_{pm}</td><td>4.31</td><td>A</td></tr>
<tr><td>V_{pm}</td><td>17.4</td><td>V</td></tr>
<tr><td>I_{sc}</td><td>4.72</td><td>A</td></tr>
<tr><td>V_{oc}</td><td>21.73</td><td>V</td></tr>
<tr><td>Series</td><td>2</td><td></td></tr>
<tr><td>Parallel</td><td>1</td><td></td></tr>
<tr><td rowspan="5">Subsystem brushless DC motor</td><td rowspan="4">Inverter</td><td>Type</td><td>LORENTZ EC-PWM 3phase</td><td></td></tr>
<tr><td>Capacity</td><td>150</td><td>W</td></tr>
<tr><td>Input voltage</td><td>12-24 DC</td><td>V</td></tr>
<tr><td>Output voltage</td><td>4-18 AC</td><td>V</td></tr>
<tr><td>Sub-System</td><td>Motor-pump type</td><td>PS150 C-SJ5-8</td><td></td></tr>
</table>

Table 2. Measuring devices

Parameter	Device
Insolation	kipp zonen CM11 Pyranometer
PV voltage	LV 25-P Hall effect
PV current	LF 306-S/SP10 LEM Hall effect
PV cell temperature	Thermo resistance K
Daily pumped water quantity	Counter

Figure 2. Photograph of the experimental site

3. Linear interpolation/extrapolation method

A. Principe

The procedure of the linear interpolation/extrapolation of the present study is as follows: the experimental daily pumped water-daily array energy output characteristics are corrected to target E_{pv} values by:

$$Q_{d3} = Q_{d1} + p(Q_{d2} - Q_{d1}) \tag{8}$$

Here, Q_{d1} is the daily pumped water of the reference E_{pv}-Q_d characteristic correspond the daily energy E_{pv1} measured at a head H. Q_{d2} is the daily pumped water of the reference E_{pv}-Q_d characteristic correspond the daily energy E_{pv2} measured at a head H. Q_{d3} is the daily pumped water of the E_{pv}-Q_d characteristics correspond the daily energy E_{pv3}, which is the target of the translation at same head H. p is a constant for the interpolation, which has the relation with the energy array output as shown in Eq. (9) (Figure 3). When $0<p<1$, the procedure is interpolation, When $p<0$, the procedure is extrapolation [15].

$$E_{pv3} = E_{pv1} + p\left(E_{pv2} - E_{pv1}\right)\left(\text{i.e } p = \frac{E_{pv3} - E_{pv1}}{E_{pv2} - E_{pv1}}\right) \tag{9}$$

Eq (8) is also applicable from the two references E_{pv}-Q_d characteristics measured field data for H at constant E_{pv} (Figure 4).

When

$$p = \frac{H_3 - H_1}{H_1 - H_2} \tag{10}$$

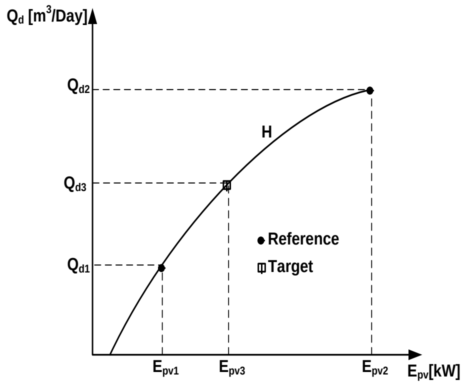


Figure 3. Schematic procedure for the calculation based on Eqs. (8) and (9); translation for E_{pv} at constant H for of deep well solar pumping systems

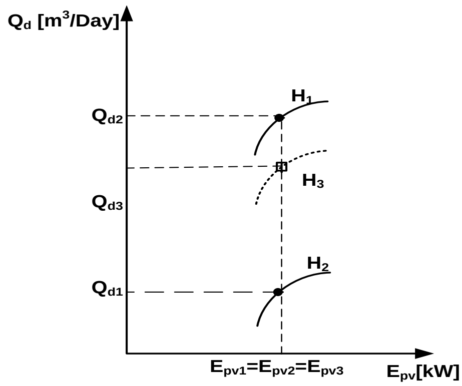


Figure 4. Schematic procedure for the calculation based on Eqs. (8) and (10); translation for H at constant E_{pv}

The primary advantage of the Eqs.(8), (9) and (10), is that there is no restriction for the energy of the E_{pv}-Q_d characteristics. Therefore, any two E_{pv}-Q_d points can be used as the reference E_{pv}-Q_d characteristics at constant array energy output E_{pv} or at constant head H without adjustment.

Another feature of the present formulae is that the E_{pv}-Q_d characteristics (especially the characteristic curve of the pump Q-H provided by the pump's manufacturer for the design shaft speed 50 Hz or 60 Hz) need not be considered, because this procedure uses only two E_{pv}-Q_d operation characteristics. Also, the measurement the speed of submersible pump who is difficult and the polynomial coefficients of the head and power curves needs (i.e the Eq.(1)) not be considered, because the effect of these coefficients in the translation for a array energy output is automatically cancelled by the procedure of Eqs. (9), (10). So, the linear interpolation is conformable with any centrifugal pump immersed.

B. Measurements of the four reference E_{pv}-Q_d characteristics

During the test period of this pump (May-November 2014), solar radiation ranged between 2.32 and 7.58kW h/m^2/day in the plane of the PV modules with array energy output ranged between 0.28 and 1.01kWh/day. Long-term test results shown in Figure 5 indicate the relation of daily water discharge (m^3/day) to the total daily array energy output (kWh /day). For the three pumping head profiles, the results showed that water delivery by the pump ranged from 12.18 to 28.99m^3/day depending on head.

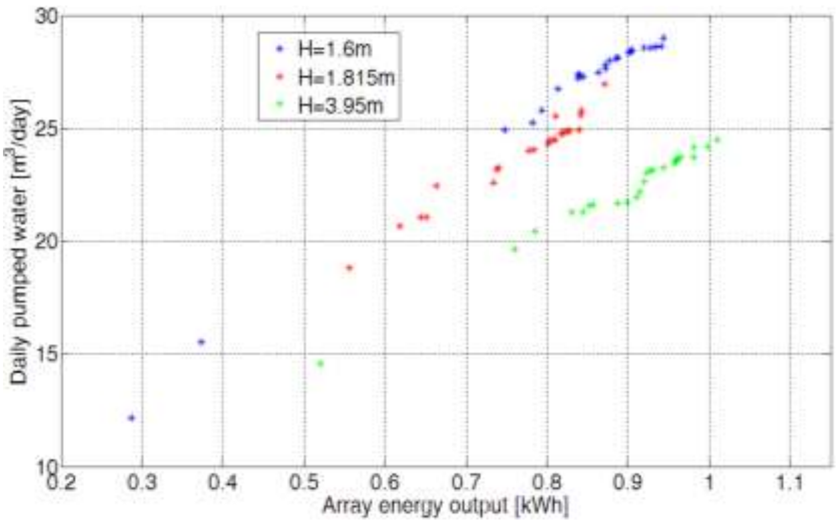


Figure 5. Long-term test results from the Adrar of Algeria as a function of array energy output and heads

The two reference E_{pv}-Q_d characteristics for estimating the performance of PV pumping system at a head H were obtained by using a pumping field test. Table 3 show the result of measurements of the two reference E_{pv}-Q_d characteristics of centrifugal pump PS150 C-SJ5-8. E_{pvmin} and Q_{dmin} was obtained when the day with low radiation, E_{pvmax} and Q_{dmax} was obtained when the day with high radiation.

Table 3. References E_{pv}-Q_d

H [m]		E_{pvmin}[kWh]	Q_{dmin}[m^3/day]		E_{pvmax}[kWh]	Q_{dmax}[m^3/day]
1.6	Ref_1	0.287	12.18	Ref_2	0.9438	28.99
1.815	Ref_3	0.5557	18.81	Ref_4	0.8706	26.96
3.95	Ref_5	0.52	14.58	Ref_6	1.01	24.47

Then, we pose

$$Q_{d1}= Q_{dmin},\ Q_{d2}= Q_{dmax},\ E_{pv1}= E_{pvmin},\ E_{pv2}= E_{pvmax} \tag{11}$$

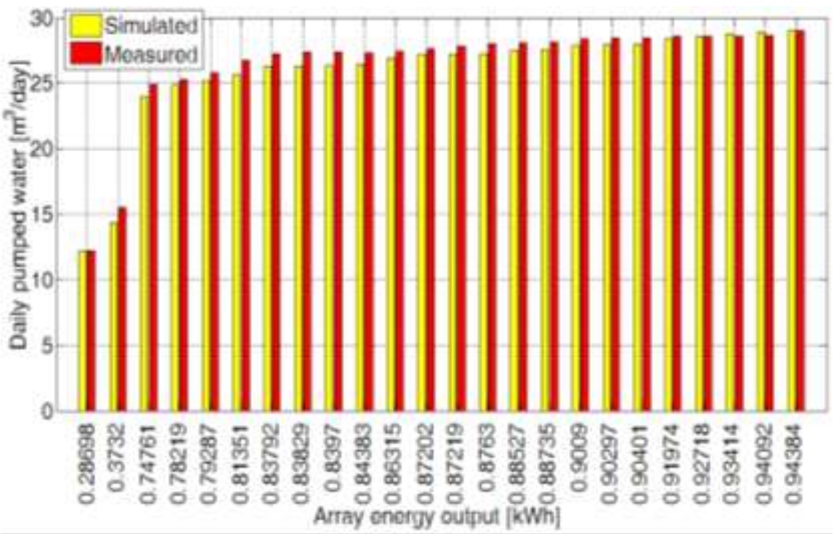
For a day, Q_d and H are defined, it is easy to calculate the pump energy output and efficiency as shown in Eqs. (12) and (13).
Instead the pump output energy may be roughly estimated from

$$E_{hyd} = CH \cdot Q_d \cdot H \tag{12}$$

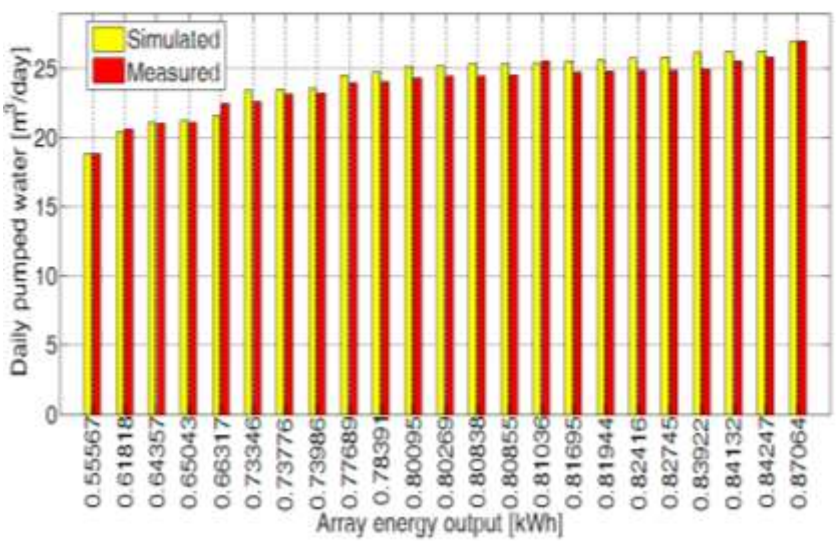
The average efficiencies over day can quite simply be calculated from [15]

$$\overline{\eta_p} = \frac{E_{hyd}}{E_{pv}} \tag{13}$$

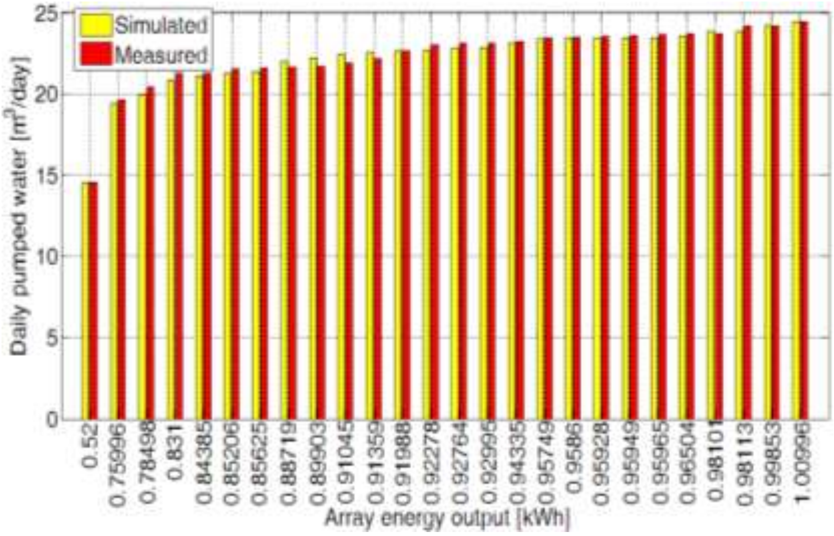
4. Comparison of experimental results and model predictions



(a)



(b)



(c)

Figure 6. Measured (field) and simulated daily pumped water as a function of PV array energy output of the well at different heads. (a) H=1.6m , (b) H=1.815m, (c) H=3.95m

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 error, defines as follows:

$$\delta = \sqrt{\left(\frac{\sum_{i=1}^{N}\left(C_i - M_i\right)}{\sum_{i=1}^{N} M_i}\right)^2} \tag{14}$$

Modeling of the E_{pv}-Q_d characteristics was investigated by using the above experimental field test. Translation of the E_{pv}-Q_d characteristics was investigated by comparing the E_{pv}-Q_d characteristics measured with the E_{pv}-Q_d characteristics calculated by linear interpolation method using the reference two E_{pv}-Q_d characteristics measured by above test facility. The E_{pv}-Q_d characteristic calculated by using input parameter (E_{pv}, H) showed very good agreement with the experimental data (Figure 6).

In the Table 4, we calculated the value of δ for each head. If the accuracy of the calculation of Q_d was good, accuracies of efficiency was also good.

Table 4. Values of the error δ

H[m]	1.6	1.85	3.95
δ [%]	2.5081	2.8307	1.2086

By utilizing present procedure, the E_{pv}-Q_d characteristics at wide range of E_{pv} and H can be calculated from the four reference E_{pv}-Q_d characteristics measured field data. Figure 7 shows the example of the linear interpolation of the four reference E_{pv}-Q_d characteristics into the target E_{pv}-Q_d characteristic. One to four are the reference E_{pv}-Q_d characteristics. Seven is the target E_{pv}-Q_d characteristic. First, the E_{pv}-Q_d characteristic 5 under target energy array output E_{pv} at head H_1 is calculated from the E_{pv}-Q_d characteristics 1 and 2 by using the equations (8) and (9). Similarly, the E_{pv}-Q_d characteristic 6 under target energy array output E_{pv} at head H_2 is calculated from the E_{pv}-Q_d characteristics 3 and 4. Then the E_{pv}-Q_d characteristics 7 under target energy array output E_{pv} and head H is calculated from the E_{pv}-Q_d characteristics 5 and 6 by using the equations (8) and (10).

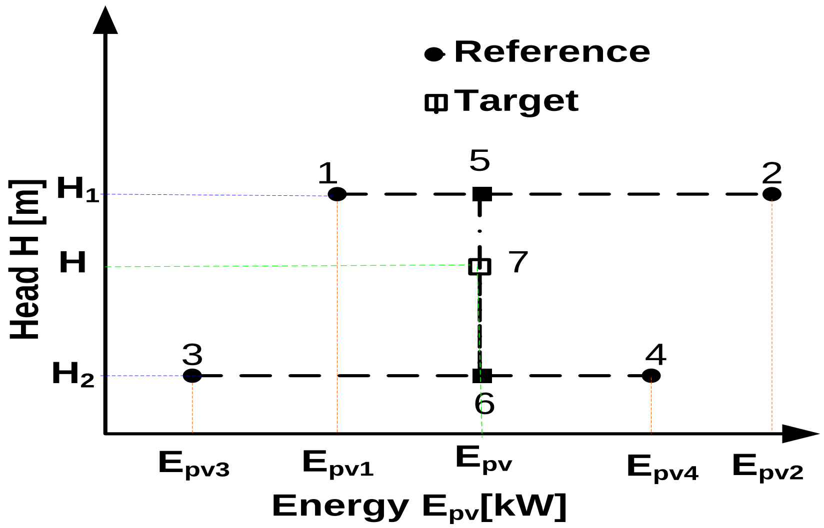


Figure 7. Example of the linear interpolation of the four reference E_{pv}-Q_d characteristics into the target E_{pv}-Q_d characteristic. One to four are the reference E_{pv}-Q_d characteristics. Seven is the target E_{pv}-Q_d characteristic

By using the above procedure from the four reference E_{pv}-Q_d characteristics (Ref_1, Ref_2, Ref_4 & Ref_6 that are indicated in Table 3) measured by above field test. The calculated the Q_d at H=1.815m was created as shown in Figure 8. The E_{pv}-Q_d characteristic calculated by using input parameter (E_{pv}, H) showed very good agreement with the experimental data (Figure 8). The error between the measured and calculated Q_d was about 2.0658%, which demonstrates the accuracy of the present procedure of the linear interpolation.

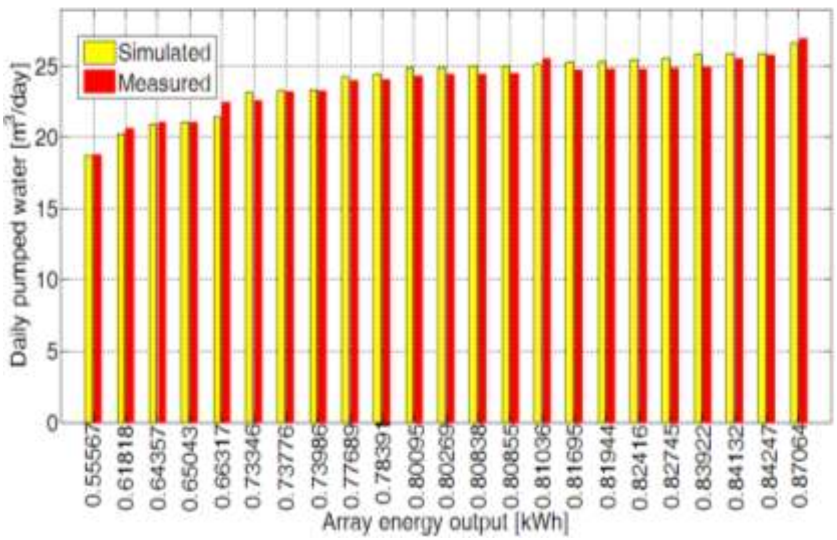


Figure 8. Measured (field) and simulated daily pumped water as a function of PV array energy output created from the four reference E_{pv}-Q_d characteristics (Ref_1, Ref_2, Ref_5 and Ref_6) at H=1.815m

5. Conclusions

To predict the total volume of water pumped per day before the installation of a pumping station, it is interesting to have a good simulation. A new practical formulation for the linear interpolation has been investigated, in order to translate the E_{pv}-Q_d characteristics and predict the daily pumped water and efficiency of the photovoltaic pumping applications for the array energy output and head. The accuracy of the translation has been investigated based on the field test located in Adrar city from Algeria.

Only four E_{pv}-Q_d characteristics can be used as the reference E_{pv}-Q_d characteristics. This makes the practical translation procedure and performance prediction much easier than the other parametric models. The results well agree with measured daily pumped water and head of PV pumping system. The present method is expected to be very useful for the performance of the PV pumping system.

One other advantageous feature is that the above model is mainly transposable to other kinds of motors-pumps with only a few different references values considerations. Encouraging motor-pump manufacturers to develop rating pump not by various (Q_d,H) for radiation but by new rating pump used only four E_{pv}-Q_d characteristics.

6. References

[1]. M. Yaichi, M-K. Fellah, "Centrifugal Motor-Pump System Model intended for the Photovoltaic Pumping applications", *Przegląd Elektrotechniczny* 89(2013), 100-105.

[2]. Daniele Fiaschi, Roberto Graniglia, Giampaolo Manfrida, "Improving the effectiveness of solar pumping systems by using modular centrifugal pumps with variable rotational speed", *Solar Energy* 79 (2005) 234–244.

[3]. A. Betka, A. Attali, "Optimization of a photovoltaic pumping system based on the optimal control theory". *Solar Energy* 84 (2010), 1273–1283.

[4]. B. Ben Ghanem, "Performance of submersible PV water pumping systems in Tunisia", Energy for Sustainable Development (2012), http://dx.doi.org/10.1016/j.esd.2012.10.003.

[5]. Brian D. Vick, Byron A. Neal, "Analysis of off-grid hybrid wind turbine/solar PV water pumping systems", *Solar Energy* 86 (2012), 1197-1207.

[6]. T. Martiré, C. Glaize, C. Joubert, B. Rouvière, "A simplified but accurate prevision method for along the sun PV pumping systems", *Solar Energy* 82 (2008), 1009-1020.

[7]. A. Mokeddem, A. Midoun, D. Kadri, S. Hiadsi, I. A. Raja, "Performance of a directly-coupled PV water pumping system", *Energy Conversion and Management* 52 (2011), 3089–3095.

[8]. Y. Bakelli. Hadj Arab, B. Azoui,"Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept", *Solar Energy* 85 (2011), 288–294.

[9]. A. A. Ghoneim, "Design optimization of photovoltaic powered water pumping systems", *Energy Conversion and Management* 47 (2006), 1449–1463.

[10]. S. Ould-Amrouche, D. Rekioua, A. Hamidat, "Modelling photovoltaic water pumping systems and evaluation of their CO_2 emissions mitigation potential", *Solar Applied* Energy 87 (2010), 3451–3459.

[11]. P . Elia Campana. Li. Yan, "Dynamic modelling of a PV pumping system with special consideration on water demand", Applied Energy (2013), http://dx.doi.org/10.1016/j.apenergy.2012.12.073.

[12]. T. Ma, H. Yang, Lin. Lu, J. Peng, "Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong", *Renewable Energy* 69 (2014), 7-15.

[13]. T. Ma, H. Yang, Lin. Lu, J. Peng, "Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization", *Applied Energy* (2014), http://dx.doi.org/10.1016/j.apenergy.2014.06.005.

[14]. A. A. Hamza, A. Z. Taha, "Performance of submersible PV solar pumping systems under conditions in the Sudan", *Renewable Energy*, Vol. 6, No. 5-6, pp. 491-495, 1995.

[15]. M. Benghanem, K.O. Daffallah, A.A. Joraid, S.N. Alamri, A. Jabe, "Performances of solar water pumping system using helical pump for a deep well: A case study for Madinah, Saudi Arabia", *Energy Conversion and Management* 65 (2013) 50–56.
[16]. T. Yuki, H. Yoshihiro, K. Kurokawa, "Modeling of the I-V curves of the PV modules using linear interpolation/extrapolation", *Solar Energy Materials & solar cells* 93 (2009) 1070–1073.

Mohammed Yaichi was born on 1980 in Adrar, Algeria. He received the Engineer degree in Electrical Engineering from University of Bechar, Algeria, in 2003, and the magister degree from Djillali Liabes University, Sidi-Bel-Abbes, Algeria in 2006, and the Ph.D. degree from Djillali Liabes University, Sidi-Bel-Abbes, Algeria in 2016. Since 2009, he is with the Photovoltaic Pumping Team, Research Unit in Renewable Energies in the Saharan Medium (URER/MS) Adrar, Algeria. His research interests include a study on performance improvement of a stand-alone photovoltaic pumping system, variable-speed AC motor drives, and different multilevel inverter circuit topologies thus its technique of control PWM.

Abdelkrim Mammeri was born on 1979 in Bechar, Algeria. He received the Engineer degree in Hydraulic from University of Sciences and Technology (USTO), Oran, Algeria, in 2006, and now studying for master degree. Since 06/11/2006, he is with the Photovoltaic Pumping Team, Research Unit in Renewable Energies in the Saharan Medium (URER/MS) Adrar, Algeria. His research interests include a study on performance improvement of a stand-alone photovoltaic pumping system.

Sid-Ali Chikhi was born on 1965 in Algeria; He received the engineer degree in electronic engineering from National Polytechnic Institute of Algeria, in 1989. He is Member of the Electronic system Team, Research Unit in Renewable Energies in The Saharan Medium (URER/MS) Adrar, Algeria. His current research interest includes Power Electronics and different inverter circuit topologies thus its technique of control PWM.

Mohammed-Karim Fellah was born in Oran, Algeria, in 1963. He received the Eng. degree in Electrical Engineering from University of Sciences and Technology, Oran, Algeria, in 1986, and the Ph.D. degree from National Polytechnic Institute of Lorraine (Nancy, France) in 1991. Since 1992, he is Professor at the University of Sidi Bel-Abbes (Algeria) and Member of the Intelligent Control and Electrical Power. His current research interest includes Power Electronics, HVDC links, and Drives.