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

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Abstract: The Saharan medium by its arid nature and the availability of solar immense in our country, 7.8 kWh/m²/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 \( E_{pv}-Q_d \) 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 \( \Omega \) can be approximated by quadratic form using Pfeider-Peterman model [3, 4]:

\[
H = a_0 \cdot \Omega^2 + a_1 \cdot \Omega \cdot Q + a_2 \cdot Q^2
\]

\( a_0, a_1 \) 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:
\[ H = H_g + k \cdot Q^2 \]  

(2)

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

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]:

\[ \eta_{mp} = \frac{P_{hyd}}{P_{pv}} \times 100\% \]  

(3)

where

\[ P_{hyd} = CH \cdot Q \cdot H \]  

(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:

\[ P_{pv} = V_{pv} \cdot I_{pv} \]  

(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:

\[ Q_d = \int_{t_{sr}}^{t_{ss}} Q \, dt \]  

(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 \( t_{ss} = 20h.59' \).

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:

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

(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 \( \Omega \), 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>
<thead>
<tr>
<th>Module Type</th>
<th>mc-Si Solar ET-M53675</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{max}} )</td>
<td>75 W</td>
</tr>
<tr>
<td>( I_{\text{pm}} )</td>
<td>4.31 A</td>
</tr>
<tr>
<td>( V_{\text{pm}} )</td>
<td>17.4 V</td>
</tr>
<tr>
<td>( I_{\text{sc}} )</td>
<td>4.72 A</td>
</tr>
<tr>
<td>( V_{\text{oc}} )</td>
<td>21.73 V</td>
</tr>
<tr>
<td>Series</td>
<td>2</td>
</tr>
<tr>
<td>Parallel</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Measuring devices

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

3. Linear interpolation/extrapolation method

A. Principle

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 \( E_{\text{pv}} \) values by:

\[
Q_{d3} = Q_{d1} + p(Q_{d2} - Q_{d1})
\]  

(8)
Here, $Q_{d1}$ is the daily pumped water of the reference $E_{pv1}$-$Q_d$ characteristic correspond the daily energy $E_{pv1}$ measured at a head $H$. $Q_{d2}$ is the daily pumped water of the reference $E_{pv2}$-$Q_d$ characteristic correspond the daily energy $E_{pv2}$ measured at a head $H$. $Q_{d3}$ is the daily pumped water of the $E_{pv3}$-$Q_d$ 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].

\[
E_{pv3} = E_{pv1} + p(E_{pv2} - E_{pv1}) \quad \text{i.e. } p = \frac{E_{pv3} - E_{pv1}}{E_{pv2} - E_{pv1}}
\] (9)

Eq (8) is also applicable from the two references $E_{pv1}$-$Q_d$ characteristics measured field data for $H$ at constant $E_{pv}$ (Figure 4).

When

\[
p = \frac{H_3 - H_1}{H_1 - H_2}
\] (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 \( E_{pv\cdot Q_d} \) characteristics. Therefore, any two \( E_{pv\cdot Q_d} \) points can be used as the reference \( E_{pv\cdot Q_d} \) characteristics at constant array energy output \( E_{pv} \) or at constant head \( H \) without adjustment.

Another feature of the present formulae is that the \( E_{pv\cdot Q_d} \) 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 \( E_{pv\cdot Q_d} \) 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 \( E_{pv\cdot Q_d} \) characteristics

During the test period of this pump (May-November 2014), solar radiation ranged between 2.32 and 7.58 kW h/m\(^2\)/day in the plane of the PV modules with array energy output ranged between 0.28 and 1.01 kWh/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 28.99 m\(^3\)/day depending on head.

![Figure 5. Long-term test results from the Adrar of Algeria as a function of array energy output and heads](image)

The two reference \( E_{pv\cdot Q_d} \) 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 \( E_{pv\cdot Q_d} \) characteristics of centrifugal pump PS150 C-SJ5-8. \( E_{pv\ min} \) and \( Q_{d\ min} \) was obtained when the day with low radiation, \( E_{pv\ max} \) and \( Q_{d\ max} \) was obtained when the day with high radiation.

<table>
<thead>
<tr>
<th>( H ) [m]</th>
<th>( E_{pv\ min} ) [kWh]</th>
<th>( Q_{d\ min} ) [m(^3)/day]</th>
<th>( E_{pv\ max} ) [kWh]</th>
<th>( Q_{d\ max} ) [m(^3)/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>Ref(_1)</td>
<td>0.287</td>
<td>12.18</td>
<td>Ref(_2)</td>
</tr>
<tr>
<td>1.815</td>
<td>Ref(_1)</td>
<td>0.5557</td>
<td>18.81</td>
<td>Ref(_1)</td>
</tr>
<tr>
<td>3.95</td>
<td>Ref(_1)</td>
<td>0.52</td>
<td>14.58</td>
<td>Ref(_6)</td>
</tr>
</tbody>
</table>

Table 3. References \( E_{pv\cdot Q_d} \)
Then, we pose
\[ Q_{d1} = Q_{d_{\text{min}}}, \quad Q_{d2} = Q_{d_{\text{max}}}, \quad E_{pv1} = E_{pv_{\text{min}}}, \quad E_{pv2} = E_{pv_{\text{max}}} \]  \hspace{1cm} (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
\[ E_{\text{hyd}} = C_H \cdot Q_d \cdot H \]  \hspace{1cm} (12)

The average efficiencies over day can quite simply be calculated from [15]
\[ \eta_p = \frac{E_{\text{hyd}}}{E_{pv}} \]  \hspace{1cm} (13)

4. Comparison of experimental results and model predictions

![Graph (a)](image1)

![Graph (b)](image2)
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 \( C \) is done by using the error, defines as follows:

\[
\delta = \left( \frac{\sum_{i=1}^{N} (C_i - M_i)}{N} \right)^2
\]

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 \( \delta \) for each head. If the accuracy of the calculation of \( Q_d \) was good, accuracies of efficiency was also good.

<table>
<thead>
<tr>
<th>H[m]</th>
<th>1.6</th>
<th>1.85</th>
<th>3.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta ) [%]</td>
<td>2.5081</td>
<td>2.8307</td>
<td>1.2086</td>
</tr>
</tbody>
</table>

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$_5$, & Ref$_6$ that are indicated in Table 3) measured by above field test. The calculated the $Q_d$ at $H=1.815$m 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 $H=1.815$m
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


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.

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