On the Field Performance of PV Water Pumping System in Libya

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Abstract: This paper presents the measured performance of an experimental PV water pumping system of 1200Wp installed in the north-east of Libya. Both the monthly and hourly measured data of the system performance are presented and analysed, and the over-all system efficiency has been calculated as monthly and daily averages. The monthly average output of the system has been estimated and compared with measured data. The economic analysis of the system has been carried out and the specific water discharge cost (SDC) has been determined, the obtained SDC was very competitive with the published SDC of the PV water pumping projects in some countries. The obtained results have demonstrated the technical and economic feasibility of using the PV systems for water pumping especially in the remote areas of high potential of solar insolation.

Keywords: PV array, AC/DC inverter, Water pump, Specific water discharge cost.

1. INTRODUCTION

A drawback that may limit the utilization of PV systems is the need for electric energy storage unit. In case of stand-alone PV water pumping systems, this drawback can be overcome by replacing the electric energy storage unit with a water storage tank, which makes these systems more reliable and more economical compared to the battery-based stand-alone PV systems [3]. Recently, the PV water pumping systems became one of the main alternatives of power sources for providing water for different purposes, especially in the remote areas of high potential of solar insolation. In the framework of Centre for Solar Energy Research and Studies (CSERS) for promoting the use of PV systems for the development of rural areas in Libya, and carrying-out the R/D activities on such systems under the local climatic conditions, a stand-alone PV water pumping system of 1200 Wp has been installed in Mrada city in the north-east of Libya, as a pilot project with UNESCO. The project is aiming at providing water for livestock and evaluating
the performance of the PV system under the local climatic conditions in order to build scientific bases for the wide use of these systems in Libya.

2. WELL DATA

The well is a shallow one used mainly for providing water for livestock. It is 1.2m borehole diameter, 8m total depth, and 6m static level of water. It has a water storage tank of capacity 38m$^3$ located at 10 m from the borehole. The well is located in Mrada city (Long.: 19° 12’ 21”, Lat.: 29° 15’ 22”) which is about 700km east of Tripoli. The monthly average of daily solar irradiation on the horizontal surface and mean ambient temperature for Mrada city are shown in table 1 [1,2]. The demand for water is not well defined; it is generally high in the summer season and decreases considerably in the winter season. It has been estimated that 50m$^3$/day of water as a monthly average in the summer season is adequate to fulfill the demand.

Table 1: Monthly averages of solar radiation and ambient temperature data.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar Irradiation (kWh/m$^2$.day)</th>
<th>Ambient emp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>3.7</td>
<td>19.4</td>
</tr>
<tr>
<td>Feb.</td>
<td>4.6</td>
<td>21.6</td>
</tr>
<tr>
<td>Mar.</td>
<td>5.5</td>
<td>25.5</td>
</tr>
<tr>
<td>Apr.</td>
<td>6.6</td>
<td>30.1</td>
</tr>
<tr>
<td>May</td>
<td>6.8</td>
<td>34.1</td>
</tr>
<tr>
<td>Jun.</td>
<td>7.3</td>
<td>37.5</td>
</tr>
<tr>
<td>Jul.</td>
<td>7.2</td>
<td>36.9</td>
</tr>
<tr>
<td>Aug.</td>
<td>6.7</td>
<td>36.7</td>
</tr>
<tr>
<td>Sep.</td>
<td>5.8</td>
<td>33.7</td>
</tr>
<tr>
<td>Oct.</td>
<td>4.9</td>
<td>30.2</td>
</tr>
<tr>
<td>Nov.</td>
<td>3.9</td>
<td>25.4</td>
</tr>
<tr>
<td>Dec.</td>
<td>3.5</td>
<td>20.6</td>
</tr>
</tbody>
</table>

3. DESCRIPTION OF PV SYSTEM

The PV system consists of a PV array of total power 1200Wp which provides the electric power to an AC submersible water pump of 950W rated power through a special DC/AC inverter of 1500W rated power. The system is equipped with a data acquisition system for auto measuring and logging of both the climatic and electric parameters. The system lay-out is shown in figure 1.

3.1. PV array

The PV generator consists of two strings connected in parallel; each string is formed from eight PV modules connected in series. The PV module is of multi-crystalline silicon solar cells (encapsulated in tempered glass, EVA and tedlar/polyester backing) of 75Wp under STC and 12V nominal voltage. The 16 PV modules (1200Wp) are mounted on four modular and adjustable tilt angle supporting structures fabricated from aluminium. The tilt angle was optimized and set at 15 degree to the south [4].

![Figure 1: Lay-out of PV water pumping system](image_url)
of 1500W. The inverter can accept a DC voltage of level ranges from 105 to 120 VDC, and generates a three-phase AC voltage of level varies from 8 to 80 VAC and frequency varies from 6 to 60 Hz. The output voltage of the inverter varies in its level and frequency as a response to the variation in the output power of PV array (i.e. the variation in solar irradiation intensity). This facility leads to maximizing the pumping flow rate in low solar irradiation periods. In addition, the inverter has the facilities of dry running protection and overload protection.

3.3. Motor and water pump

The water pump is a stainless steel submersible pump which is run by an integrated three-phase 80 VAC brushless electric motor of 950W rated power, 60Hz rated frequency, and 3480 cycle/s rated running speed. Both the pump and the inverter are made of the same company (Grundfos company), which guarantees the best matching between them and highest overall performance.

3.4. Data acquisition system

In order to follow up the field performance of the PV water pumping system, a data acquisition system has been used for auto measuring and logging with interval of 10 minutes for the following parameters:
- Solar irradiation at tilt angle of PV array
- Ambient temperature
- Wind speed
- PV array output dc voltage
- PV array output dc current
- PV modules temperature
- Water pumping flow rate

4. PERFORMANCE OF PV SYSTEM

4.1. Estimated performance of system

Based on the well data and technical specifications of the components of PV system, the monthly average of daily pumped water has been estimated using the equation 1 [5], and the estimated results are shown in figure 2.

\[
Q = \frac{P_n G \eta_{inv} \eta_{mp} F[1-\beta(T_c-T_a)]}{2.725 H_t}
\]  

(1)

The PV module temp. can be calculated using equation 2 [6]

\[
T_c = T_a + 2.7 G_t
\]  

(2)

Where:
- Q: the monthly average of daily pumped water (m³/day).
- \( P_n \): total power of PV array (W).
- \( G_t \): monthly average of daily solar irradiation on the tilted surface of PV array (kWh/m².day).
- \( \eta_{inv} \): inverter efficiency.
- \( \eta_{mp} \): motor/pump efficiency.
- F: factor considers the mismatch between PV modules, loss in cables and wires, and threshold solar irradiation to start the pump.
- \( \beta \): temperature coefficient (0.005/°C).
- \( T_a \): monthly average of daily mean ambient temperature (°C).
- \( T_c \): monthly average of daily mean PV module temp. (°C).
- \( H_t \): total effective height of pumping (m).

4.2. Measured performance of system

The PV system is adjusted to operate automatically without stop whenever the solar insolation is available. To avoid the waste of water due to over-pumping, a water pipe has been installed to return the surplus of pumped water from the storage tank back to the well (see figure 1). The system is up to date working automatically for six years without stop. During this period, the beneficiaries were very satisfied with the system performance and reliability, where, in contrast to the case for the diesel generator, it has no need for a daily follow-up, fuel supply and frequent maintenance.

Figure 2 shows the measured data compared with the estimated data of the monthly average of daily pumped water. The estimated system output is higher
because the estimation model is a rough one
and it doesn’t consider some specifics of the
system components. For more reliable
results, a sophisticated simulation computer
programs should be used.

\[ E_h = 2.275QH_t \]  \hspace{1cm} (3)

Where:

- \( Q \): the monthly average of daily pumped
  water (\( \text{m}^3/\text{day} \)).
- \( H_t \): total effective height of pumping (m).

**Figure 2**: The measured and estimated data of pumped water

Figure 3 demonstrates the instantaneous
system performance on a sunny day in
December. According to the performance
record of this day, the pump starts working
at one hour after the sunrise, and at this
time, the PV array output power is 145W
(corresponding to 160W/m\(^2\) of solar
irradiation) which is equivalent to 15% of
pump motor rated power. It has been found
that threshold power of pump causes a loss
of 5-9% of the available solar energy
throughout the year; the loss is higher in the
months of lower level of solar irradiation.

The variable-voltage variable-frequency
facility of system inverter provides more
efficient operation of pump motor and best
use of available power coming from the PV
array. This feature contributes to reducing the
threshold power of the pump and
maximizing the use of available solar
energy. As a result of this feature, the pump
flow rate increases logarithmically with the
increase of solar irradiation intensity as
shown in figure 3-D. The pump flow rate
reaches 75% of its rated value at 50% of
pump rated power.

Based on the measured data, and by
finding the hydraulic energy, \( E_h \) (kWh),
 corresponding to the measured quantity of
pumped water using equation 3 [6], the
yearly average of overall system efficiency
has been calculated, and the value of 2.2%
has been found.

**Figure 3**: Performance record of a sunny day
in December

The system efficiency depends on many
factors interrelated to each other such as;
solar irradiation intensity, pump threshold
power, and PV module temperature, and
therefore no general certain trend has been
found for the change of efficiency throughout the year. In spite of that, it has been noticed that for a semi-equal ambient temperature period, the over-all system efficiency was higher in the day of lower solar irradiation as shown in figure 4 which demonstrates the daily change in the over-all system efficiency with the change of solar irradiation in December. The logarithmic increase of pump flow rate versus the increase of solar irradiation intensity is a major issue behind this behaviour.

Figure 4: Daily over-all system efficiency and solar irradiation in December

As it is shown in figure 3-D, the pumping flow rate reaches about 85% of its rated value at 700 W/m² of solar irradiation intensity. The pumping flow rate increases by 25% when the solar irradiation increases from 500 W/m² to 700 W/m², while it increases by only less than 10% when the solar irradiation increases from 700 W/m² to 900 W/m². As a result, the over-all system efficiency is about 2.6% and 1.7% at 500 W/m² and 900 W/m² of solar irradiation respectively.

Figure 5: Pumping flow rate and over-all system efficiency

Figure 5 demonstrates the change in pumping flow rate and over-all system efficiency as a function of solar irradiation intensity of a sunny day in December, the over-all system efficiency reaches its maximum value at relatively low level of solar irradiation (about 200 W/m²) then it declines linearly with the increase of solar radiation.

5. ECONOMIC ANALYSIS

The comparison of economic feasibility among the different methods of water pumping can be determined according to the cost of unit volume (cost/m³) of the pumped water along the expected life time of the pumping system. The cost of unit volume depends on many factors such as the daily pumping quantity, the pumping head, and the demand profile of water. For more fair comparison, the criterion of cost of unit volume of pumped water to the unit of pumping height (cost/m³.m) is mostly used; this criterion is called the specific water discharge cost (SDC).

The specific water discharge cost of the PV water pumping system has been determined using the equations 4-8 [7, 12] under the following assumptions:

- Expected life time of the system = 20 years
- Expected life time of the PV modules (N) = 20 years
- Expected life time of the inverter (n) = 10 years
- Expected life time of the water pump/motor (n) = 10 years
- Yearly interest rate (i) = 1 %
- Increase in components cost = 0
- Yearly maintenance cost = 1 % of the initial system cost (C_T).

\[
K_a = \frac{1 - (1 + i)^{-N}}{i} 
\]

\[
K_T = \frac{1}{(1 + i)^n} 
\]

\[
C_{TT} = C_T + 0.1C_TK_a + C_rK_T 
\]
6. CONCLUSION

Based on the practical experience, the use of PV systems for water pumping in remote areas is preferred than the use of diesel generator due to some advantages of the PV systems among of which are; high reliability, fully automatic operation, no need for fuel supply, and the little need for maintenance.

The variable-voltage variable-frequency (VVVF) facility of the inverter has a significant contribution in raising the overall efficiency of PV water pumping systems, and this facility well compensates the negative effect of high temperature which reduces the PV array efficiency.

In case of using VVVF inverters, the rated power of pump motor should be comparable to the rated power of PV array in order to minimize the loss of available solar irradiation and raise the over-all system efficiency.

The technical and economical assessment of PV systems requires a long term monitoring of the operation of these systems. Using good designed data acquisition system is of immense value to the engineers to evaluate the PV system using reliable and detailed measured data.

7. REFERENCES


