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Applying Pump Affinity Laws to an Isolated Solar-Powered Pumping Station †

F. Javier Martínez-Solano *, Josep Francesc Pons-Ausina, Pedro L. Iglesias-Rey and Gonzalo López-Patiño

Department of Hydraulic Engineering and Environment, Universitat Politècnica de València, 46022 Valencia, Spain; joponau@upv.es (J.F.P.-A.); piglesia@upv.es (P.L.I.-R.); glpatin@upv.es (G.L.-P.)
* Correspondence: jmsolano@upv.es
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Abstract: Water pumping is highlighted as the major energy consumer in the water cycle. Solar energy has emerged as a promising alternative to traditional electric networks, particularly in areas lacking an electrical infrastructure. Solar-powered pumping stations are categorized as connected and isolated, with the latter adapting the pump operation based on available solar energy. This article proposes a scheme to adjust the pump operation according to natural factors, like irradiance and temperature, aiming to optimize energy use and minimize investment costs in solar panels. An application of this method in Valencia, Spain, demonstrates significant savings.

Keywords: solar-powered pumping station; pump affinity laws; irrigation; green energy

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1. Introduction

As the world population grows, so does the concern for the availability of water and energy resources. Water pumping makes up most of the energy consumption in the water cycle. The transport and distribution of water account for up to 40% of these energy expenses. Ref. [1] conducted a field study in ten irrigation districts. The average energy consumption in the districts resulted in 0.39 kWh/m^3. These figures suggest that using solar energy as an alternative to traditional electric networks might be interesting. Furthermore, in agricultural applications where the electrical network is not always available, solar-powered pumping stations can become not only the only solution but also a worthwhile one [2].

Solar-powered pumping stations can be divided into groups: electrically isolated and connected pumping stations. The main difference is how they deal with the available solar energy. While connected pumping stations use solar energy to supplement the traditional electric network, isolated pumping stations must adequately operate using the available solar energy. In this article, an operation scheme will be presented to adapt the operation of isolated pumping stations to energy availability.

Since energy depends on several natural factors, such as irradiance, air temperature, clouds, etc., the pump power needs to be adapted to these factors. Pump affinity laws allow for relating pump performance variables (head, flow, efficiency, and power) to rotational speed. Hence, pumped flow can be optimized using these laws to make the most of the solar energy. The method described in this article seeks to minimize investment costs in solar panels by modifying the pump rotational speed, taking advantage of the available storage capacity in the system. The method will be applied to an irrigation community in Valencia (the Mediterranean shore of Spain). The results show that important savings can be obtained with this type of solar pumping station.

2. Materials and Methods

2.1. Design Parameters

The procedure for designing photovoltaic solar pumping systems begins with analyzing the energy balance of the installation. Determining the annual water needs is essential to estimate the pumping operating point. Subsequently, selecting the appropriate pump allows for us to determine the peak power for sizing the photovoltaic installation. The photovoltaic installation is designed to power a pumping station for water conveyance to a regulation reservoir, where surpluses are stored during months with lower water demand. Finally, using variable speed drives enables the application of similarity laws by changing the pump speed, as it is an isolated photovoltaic pumping installation that operates at variable frequency (variable flow and head) based on available photovoltaic power.

2.2. Calculation Methodology

To calculate the annual volume of water generated by the photovoltaic system, it is necessary to calculate the amount of energy the system can produce at the pump terminals and the hydraulic behavior of the pump, considering that it will operate at variable flow rates. A dynamic hourly simulation is performed using horizontal radiation and ambient temperature data from an annual meteorological dataset at the installation site. The hourly calculation procedure for obtaining energy (power) at the pump terminals is described as follows:

- Calculation of incident radiation (diffuse, direct, and reflected) on the generator plane, considering type of structure, inclination and azimuth of the structure, latitude and longitude of the location, and directional properties of diffuse radiation.
- Calculation of effective radiation considers the incident radiation on the generator while accounting for the effect of dirt on the photovoltaic module's angle of incidence and the power losses due to shadows on the photovoltaic generator; it considers the losses due to the spectral response of the photovoltaic cell type.

Once the effective radiation on the photovoltaic generator is obtained, the generated power at the pump terminals is calculated at each simulation step, considering the following loss factors: threshold power losses at the frequency converter input (minimum power at which the frequency converter can operate), which is related to the minimum frequency at which the pump can operate; seasonal losses are only considered in amorphous silicon photovoltaic modules and affect module performance; cell temperature losses—the electrical characteristics of photovoltaic modules are modified depending on the temperature of the photovoltaic cells; low irradiance losses—photovoltaic module efficiency is modified based on the irradiance received (efficiency vs. incident irradiance curve); DC wiring losses—joule losses in DC wiring (from the photovoltaic generator to the frequency converter input); converter saturation losses and converter efficiency losses—converter efficiency based on load level; AC wiring losses—joule losses in AC wiring; sinusoidal filter and autotransformer losses—if a filter and/or autotransformer are installed at the frequency converter output, the losses of both elements are considered based on the load level.

Once the power at the pump terminals is obtained for each simulation step, the pumped flow is calculated considering the system resistance curve and the selected pump:

- Calculation of the system manometric head: the system resistance curve is calculated based on the pump discharge pipe data as a function of the instantaneous flow rate. Thus, the total manometric head is adjusted according to a 2nd-degree polynomial regression of the form

$$H^{(m)} = A + B \cdot Q - C \cdot Q^2 \quad (1)$$

  where $H^{(m)}$ is the manometric head in meters (m) and Q is the flow rate in m^3/h.
- Calculation of the system characteristic curve (P vs. Q), based on the pump's technical data at 50 Hz (H-Q curve, hydraulic P2, motor P2, voltage, number of poles, rpm, efficiency, power factor, etc.), and the system resistance curve, using similarity laws and successive iterations, a system characteristic curve representing the pumped flow

(pump operating point considering the system resistance curve) as a function of the power at the pump terminals (motor P1) can be obtained. The pumped flow highly depends on the solar power. Therefore, the pumped flow was represented against the power. A regression to a 2nd-order polygon presented a good adjustment and was taken as an estimate to ease the calculations:

$$Q = a + b \cdot P^2 \quad (2)$$

where the power at the pump terminals (P) is in kW and the flow rate (Q) is in m^3/h.

Using this equation, and with the power at the pump terminals (P) calculated previously, the pumped flow by the system is obtained for the operating frequency range compatible with the pumping system resistance.

3. Results and Discussion

To show the potential benefits of this work, the methodology described above was applied to an irrigation community of 2200 ha from which 370 ha would be projected to be irrigated using solar-powered pumping. In this community, there are two other pumping stations, so there is an alternative in case the irradiance is not enough for solar pumping. The water needs for this area, according to the report 56 of the FAO [3], were calculated as 23,000 m^3/day in July and 2,590,000 m^3/year. An initial design for a fully isolated pumping station resulted in three pump units, with 830 m^3/h of flow pumped with a head of 110 m and power of 350 kW per unit, totaling an installed power of 1050 kW. A detailed energy analysis gives an average energy consumption of 0.395 kWh/m^3. The irrigation network has a reservoir with a capacity of 250,000 m^3. This reservoir will allow for the accumulation of water when the solar power is insufficient.

For an isolated installation, the calculated solar field was 3500 m^2. This installation was sufficient to satisfy the demands in the most demanding time, that is, in July. Furthermore, the reservoir had a storage capacity of more than ten days, ensuring water even in the event of cloudy days. Figure 1 shows the fitting between the solar energy and the flow rate pumped.

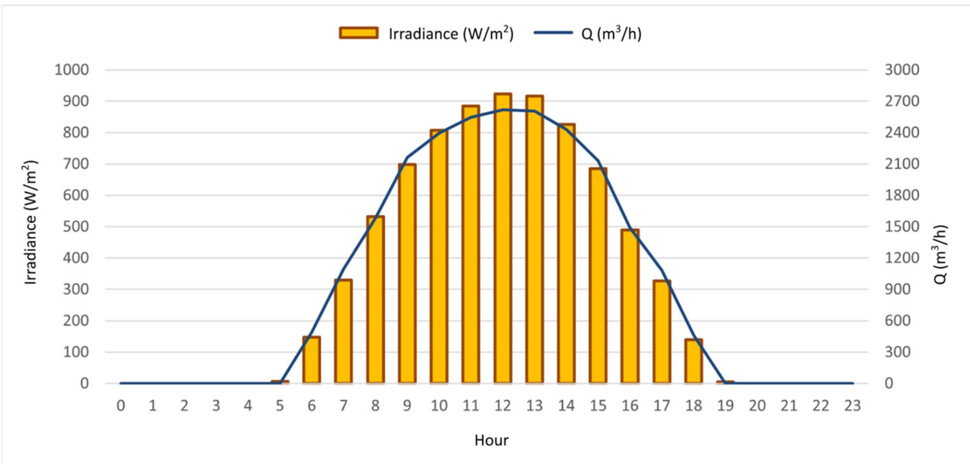

Figure 1. Solar irradiance and flow rate pumped by the three-pump station.

Application of the affinity laws to the operation of solar-powered pumping stations together with a suitable number of pumps will allow for the maximum outcome from the installation in the critical times. However, the outcome of this approach is not entirely based on solar energy, since there are moments when this energy will not be used for pumping. This implies the need for optimizing the installation.

A very simple economic analysis shows the savings in energy. For this analysis, a price of 260 €/unit of solar panel and 0.16 €/kWh as energy cost was assumed. Without considering selling the excess of energy, the balance is as follows:

- Capital cost (solar panels): (163 × 10) × 260 = 423,800.00 €;
- Operational costs (energy): 0.40 kWh/m^3 × 2.59 × 10^6 m^3 × 0.16 = 163,706.92 €.

With these figures, the investments would be paid back in 31 months (approximately two and a half years.

4. Conclusions

This study tested the possibility of using solar panels as an alternative to the use of electricity coming from the electric network in a pumping station in an irrigation community. The operation of the pumping station was optimized to take advantage of the storage capacity of the network. This was possible by using the pump affinity laws to adapt the rotational speed to the power availability. This operation was compared to a standard operation fully connected to the electric network. Using normal prices for solar panels and consumed electricity, this study showed that the payback period for the solar installation was approximately 3 years. This period might even be reduced with a hybrid setup that allows for selling the energy surplus in times when irrigation is small or null.

The results confirm that solar-powered pumping might be an environmentally friendly and economically profitable investment for isolated irrigation communities. This conclusion applies when there is some kind of storage capacity, either as volume (reservoir) or power (batteries), so the water demand could be disengaged from power availability.

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