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Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept

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Abstract

This paper recommends an optimal sizing model, to optimize the capacity sizes of different components of photovoltaic water pumping system (PWPS) using water tank storage. The recommended model takes into account the submodels of the pumping system and uses two optimization criteria, the loss of power supply probability (LPSP) concept for the reliability and the life cycle cost (LCC) for the economic evaluation.

With this presented model, the sizing optimization of photovoltaic pumping system can be achieved technically and economically according to the system reliability requirements. The methodology adopted proposes various procedures based on the water consumption profiles, total head, tank capacity and photovoltaic array peak power. A case study is conducted to analyze one photovoltaic pumping project, which is designed to supply drinking water in remote and scattered small villages situated in Ghardaia, Algeria (32°29′N, 3°40′E, 450 m).

Keywords: PV water pumping system sizing; Loss of power supply probability (LPSP); Life cycle cost (LCC); Remote areas; Motor-pump model

1. Introduction

Water is the primary source of life for mankind and one of the most basic necessities for rural development. The rural demand for water for crop irrigation and domestic water supplies is increasing. At the same time, rainfall is decreasing in many arid countries, so surface water is becoming scarce. Groundwater seems to be the only alternative to this dilemma, but the groundwater table is also decreasing, which makes traditional hand pumping and bucketing difficult.

As these trends continue, mechanized water pumping will become the only reliable alternative for lifting water from the ground. Diesel, gasoline, and kerosene pumps (including windmills) have traditionally been used to pump water. However, reliable solar (photovoltaic (PV)) and wind turbine pumps are now emerging on the market and are rapidly becoming more attractive than the traditional power sources. These technologies, powered by renewable energy sources (solar and wind), are especially useful in remote locations where a steady fuel supply is problematic and skilled maintenance personnel are scarce.

In the most Algerian rural region, there exists substantial solar potential to use photovoltaic sources of energy for supplying water pumping system. Thus, the photovoltaic water pumping systems (PWPS) are very appropriate to use because of the availability of solar radiation and water in the no deep underground sheet particularly the

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one that the groundwater represents the major source for water supply.

In the last decades, efforts are being made in Algeria as well as throughout the world to supply water to meet drinking and irrigation needs in remote regions. Thus, for rural applications, various established models (Badescu, 2003; Hadj Arab et al., 2004; Hamidat et al., 2003; Hamidat et al., 2007; Hamidat and Benyoucef, 2008), sizing techniques (Hadj Arab et al., 2004; Hamidat and Benyoucef, 2009; Martiré et al., 2008; Odeh et al., 2006) and optimization methods (Ghoneim, 2006; Glasnovic and Margeta, 2007; Kaldellis et al., 2009; Meah et al., 2008; Odeh et al., 2006; Qoaider and Steinbrecht, 2010) of photovoltaic water pumping system (PWPS) have been reported in the literature.

In this paper, the photovoltaic water pumping system optimization sizing model, is developed based on the loss of power supply probability (LPSP) and the life cycle cost (LCC) concepts. The LPSP technique, which is considered to be the criteria for sizing, is the probability that an insufficient power supply results when the PWPS is unable to satisfy the load demand. Using the LPSP objective function, the configurations of a PWPS which can meet the system reliability requirements can be obtained. There are two sizing parameters in the simulation, i.e. the capacity of PV system and the capacity of the water storage tank. The optimum configuration can be identified from the set of the above obtained configurations by reaching the lowest life cycle cost (LCC).

2. Photovoltaic pumping system description

Water pumping for irrigation and water supply for rural communities represents an important area of stand-alone PV systems; these systems usually consist of a photovoltaic generator, source of water, a water storage tank, and a DC pump (see Fig. 1).

The role of batteries is here played by the water storage tank and the electric power load demand L in now replaced by water demand. If expressed in Wh/day, this represents the energy needed to pump the required volume of water demanded by the user into the storage tank. These considerations show that PV pumping systems can be sized in a similar way than PV systems with other applications (Markvart and Castaner, 2003).

3. PV generator model

The hourly output power of the PV generator with an area A_{PV} (m^2) at a solar radiation on tilted plane module G_t (W/m^2), is given by (Markvart and Castaner, 2003):

$$P_{PV} = \eta_{PV} A_{PV} G_t \tag{1}$$

where η_{PV} represents the PV generator efficiency and is given by (Habib et al., 1999; Kolhe et al., 2003):

$$\eta_{PV} = \eta_r \eta_{pc} + [1 - \beta(T_c - T_{cref})] \tag{2}$$

where η_r is the reference module efficiency, η_{pc} is the power conditioning efficiency which is equal to 1 if a perfect maximum power tracker (MPPT) is used. β is the generator efficiency temperature coefficient, it is assumed to be a constant and for silicon cells the range of β is 0.004–0.006 per (°C), T_{cref} is the reference cell temperature (°C) and T_c is the cell temperature (°C) and can be calculated as follows (Markvart and Castaner, 2003):

$$T_c = T_a + \left[\frac{(NOCT - 20)}{800}\right] G_t \tag{3}$$

where T_a is the ambient temperature (°C) and $NOCT$ is the nominal cell operating temperature (°C). η_{pc}, β, $NOCT$ and $A_{PV,}$ are parameters that depend upon the type of module used. The data are obtained from the PV module manufacturers.

4. Pumping subsystems model

The mathematical models of the inverter and the motor pump set are described in a great number of research papers. Thus, we can quote (Daud and Mahmoud, 2005; Hadj Arab et al., 2006; Kou et al., 1998; Mezghanni et al., 2007; Pande et al., 2003). These models describe the characteristic of each component of the pumping subsystem as the inverter, the motor or the pump. But these models do not give a direct relationship between the operating electrical power of the pumping subsystem and the water flow rate of the pump. In this paper, we use a mathematical model which directly links the output water flow rate Q versus the input operating electric power P_a and total head h. This model is based on the analysis of the experimental results of two types of pumping subsystems (Hamidat et al., 2007; Hamidat and Benyoucef, 2008).

The equation of the used pumping model is given as follows:

$$P_a(Q, h) = a(h)Q^3 + b(h)Q^2 + c(h)Q + d(h) \tag{4}$$

where $a(h)$, $b(h)$, $c(h)$ and $d(h)$ depend on total head and can be described by the following equations:

$$a(h) = a_0 + a_1 h + a_2 h^2 + a_3 h^3 \tag{5}$$

$$b(h) = b_0 + b_1 h + b_2 h^2 + b_3 h^3 \tag{6}$$

$$c(h) = c_0 + c_1 h + c_2 h^2 + c_3 h^3 \tag{7}$$

$$d(h) = d_0 + d_1 h + d_2 h^2 + d_3 h^3 \tag{8}$$

where a_i, b_i, c_i and d_i are the parameters of the model and depend only on the pumping subsystem type.

The calculation of the instantaneous water flow rate Q according to the power P_a is obtained from the Eq. (4) using the Newton–Raphson method with a constraint of $d - \mathrm{Pa}(Q) > 0$. At the kth iteration, the instantaneous Q is given by:

$$Q_k = Q_{k-1} - \frac{F(Q_{k-1})}{F'(Q_{k-1})} \tag{9}$$