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Multi-objective analytical model for optimal sizing of stand-alone photovoltaic water pumping systems

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ABSTRACT

Stand-alone photovoltaic (PV) water pumping systems effectively use solar energy for irrigation purposes in remote areas. However the random variability and unpredictability of solar energy makes difficult the penetration of PV implementations and complicate the system design. An optimal sizing of these systems proves to be essential. This paper recommends a techno-economic optimization model to determine optimally the capacity of the components of PV water pumping system using a water storage tank. The proposed model is developed regarding the reliability and cost indicators, which are the deficiency of power supply probability and life-cycle costs, respectively. The novelty is that the proposed optimization model is analytically defined for two-objectives and it is able to find a compromise solution.

The sizing of a stand-alone PV water pumping system comprises a detailed analysis of crop water requirements and optimal tilt angles. Besides the necessity of long solar radiation and temperature time series, the accurate forecasts of water supply needs have to be determined. The calculation of the optimal tilt angle for yearly, seasonally and monthly frequencies results in higher system efficiency. It is, therefore, suggested to change regularly the tilt angle in order to maximize solar energy output. The proposed optimal sizing model incorporates all these improvements and can accomplish a comprehensive optimization of PV water pumping systems. A case study is conducted considering the irrigation of citrus trees yard located in Antalya, Turkey. The proposed model is also compared with a computational method and it is shown that sizing results are technically and economically more suitable than computational algorithm according to the applications on a 5-yearly basis.

1. Introduction

Solar energy is one of the cleanest among renewable resources and has lower maintenance costs compared to other alternatives, e.g. wind, biomass. Therefore PV applications become the most preferable solution for rural areas [1]. The electricity generation, cooling, heating, water pumping to supply water for drinking and agricultural irrigation are the main implementations of PV systems. However high investment costs of these systems and dependency on weather conditions are the disadvantages. Since the random variability directly affects both capital and operational costs and also contributes to lower capacity factors [2], optimal sizing becomes essential for efficient use of energy resources, secure and economic design of power systems with a view to maximize the feasibility of PV installations.

The optimal sizing and techno-economic evaluation of PV water pumping systems is basically dependent to the required hydraulic energy and its relation to monthly average daily solar radiation. In general, optimal sizing methods which commonly considered single objective are carried out with simulations and heuristic methods. In the present study, multi-objective optimization is handled and a mathematical model is defined according to reliability and cost parameters. Although solving in analytical way is harder than computational methods, a better approximation to the optimal is effectively reached. The technical performance of the system is quantified by the ratio of actual power supplied and total power required for pumping water to meet irrigation requirements. It is obvious that to increase the reliability, i.e. minimize the energy deficit, PV system size must be greater in order to cover water supply requirements, while the costs also increase [3]. Therefore a compromise solution of these two objectives is requisite to guide the system designers and investors.

This article is organized as follows: PV water pumping systems (PVWPSs) and necessities for system design are described in Section 2. This section also includes the explanations of crop water requirements and optimal tilt angle. Section 3 contains a review of optimal sizing methods used for PV systems. Then the proposed

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multi-objective and analytical model for optimal sizing of stand-alone PVWPS takes part in Section 4. The sizing application results are given in Section 5. Finally, Section 6 presents conclusions and future work suggestions.

2. PV water pumping systems

PV based water pumping systems used for agricultural irrigation in remote areas, convert primarily the solar energy into electrical by the PV array. The electrical energy is then transformed to mechanical energy by the motor and the movement of fluid is started. The hydraulic energy (energy possessed by water) is created by the aid of a pump, in order to supply crop irrigation needs with the water obtained from a deep well or a surface water source (Fig. 1). The procurement of drinking water is not considered in this study. The main benefit of PVWPS is that irrigation needs and solar radiation vary similarly in the same seasons. Although the investment costs are high, once optimally designed and protected from dust and shading, PVWPSs are technologically, economically and environmentally favorable regarding the long service life, low maintenance requirements and the disuse of fuel [4]. The technological advantages are applicability, reliability, installation convenience and high performance. The installation of these systems is supported by governmental donations. Their total costs considering the long system life are low while other alternative water pumping systems require high maintenance and use of fuel which affects and increases the life-cycle costs. Additionally PV systems are environmentally friendly since they minimize the emissions of contaminating gases.

A stand-alone PVWPS may consist of a PV array which is a linked collection of solar panels and modules, a motor-pump subsystem, DC/AC inverters, controllers such pump controller, charge regulator and maximum power point tracker (MPPT) integrated with a controller or inverter, a storage unit which can be either a water tank or batteries. These components should be chosen well-matched according to their electrical properties.

The sizing of PV array and storage unit is crucial in order to effectively convert the received solar energy and satisfy electrical demands. The system design contains the optimization of PV array area and the capacity of water storage tank (or batteries), the determination of the optimal tilt angle, and the selection of all components and necessary subsystems. The optimal system design should consider the cost analysis, as well as the reliability of supply to obtain an effective system [5].

Assuming a deep well water source and a PVWPS with submersible pump subsystem, the following information needs to be gathered to begin the system design: solar radiation and temperature time series data, crop water requirements, total dynamic head (TDH) for submersible pump, quantity and quality of the water source which are assumed sufficient, and also installation and optimal tilt suggestions for the PV array. The location to install the PV array has to be chosen carefully in order to avoid shading, to be close to the pump and to protect from bad weather conditions and dust.

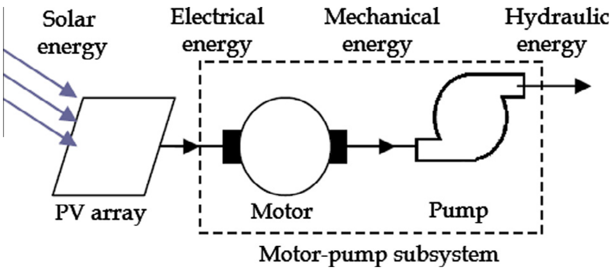

Fig. 1. Energy conversions in a PV water pumping system.

2.1. Crop water requirements

Crop water requirements (CWR) can be supplied by precipitation, groundwaters or irrigation. In order to meet the losses occurred from evaporation, transpiration, infiltration and runoffs, the net irrigation water requirements (NIWR) should be calculated. The water needs of the crops are expressed by the evapotranspiration (ET), which is the total of evaporation and transpiration in ideal growing conditions. The calculation procedures developed by the Food and Agriculture Organization of the United Nations (FAO) are frequently applied for this purpose (see [6]). In order to compute ET_{crop}, the reference ET_0 is mostly calculated with FAO Penman–Monteith method which is easier to apply with Cropwat and Climwat softwares. Then NIWR are calculated with the difference between ET_{crop} and the sum of effective rainfall, groundwater and stored soil water.

2.2. Optimal tilt angle

The performance of PV systems is influenced by the tilt angle and orientation of the array. Therefore it is necessary to install according to an optimal tilt angle maximizing the solar radiation captured by PV panels. The tilt angle depends on the latitude and the day of the year. In most of the cases, tilt is considered equal to the latitude or latitude ± 15° ("–" for summer, " + " for winter) [7–8]. In order to find the optimal tilt, many researchers carried out optimization studies. The optimization process is mostly realized with a search algorithm which computes energy losses for angles between 0° and 90° by increasing steps of 1°. The optimal tilt angle can be either calculated for monthly, seasonally or yearly changes and then energy losses are compared [9]. There exist also single or dual-axis solar tracking systems where PV panels always change their tilt according to sun's position. Although the energy output is greater than fixed systems, the economical aspect restricts their implementation.

When the tilt angle is changed, an update is obligated in the solar radiation data used in the system design. In general, the total solar radiation data for a specific location are only measured for horizontal surfaces. Therefore the radiation for inclined surfaces should be estimated with correlation procedures. Various studies developed mathematical expressions in order to calculate global radiation on tilted surface from the available global radiation data on a horizontal surface [10].

The extraterrestrial radiation is reaching the PV panel surface after some losses of diffusion and reflection. Hence the monthly average daily global radiation on a tilted surface ($\overline{H}_T$) with slope β, is expressed by the sum of direct beam ($\overline{H}_{bT}$), diffuse ($\overline{H}_{dT}$) and reflected ($\overline{H}_{rT}$) components of the radiation on a tilted surface (1) [11].

$$\overline{H}_T = \overline{H}_{bT} + \overline{H}_{dT} + \overline{H}_{rT} \tag{1}$$

Each of these components are expressed by Eqs. (2)–(4) respectively, where $\overline{H}_b$ is the direct beam and $\overline{H}_d$ is the diffuse radiation on a horizontal surface. $\overline{H}$ is the monthly average daily global radiation on a horizontal surface which is also the total of $\overline{H}_b$ and $\overline{H}_d$.

$$\overline{H}_{bT} = \overline{H}_b \overline{R}_b \tag{2}$$

$$\overline{H}_{dT} = \overline{H}_d \overline{R}_d \tag{3}$$

$$\overline{H}_{rT} = \overline{H}\overline{R}_r = (\overline{H}_b + \overline{H}_d)\overline{R}_r \tag{4}$$