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A feasibility and load sensitivity analysis of photovoltaic water pumping system with battery and diesel generator

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ABSTRACT

In this paper, a feasibility and load sensitivity analysis is conducted for photovoltaic water pumping systems with storage device (battery) or diesel generator so as to obtain an optimal configuration that achieves a reliable system. The analysis is conducted based on techno-economic aspects, where the loss of load probability and life cycle cost are represented as technical and economic criteria, respectively. Various photovoltaic water pumping systems scenarios with initially full storage tank; battery and hybrid DG-PV energy source are proposed to analyze the feasibility of system. The result shows that the configuration of the PV array and the initial status of the storage tank are important variables to be considered. Moreover, the sensitivity of cost of unit for various PVPS components is studied. It is found that the cost of unit is more sensitive to the initial capital cost of photovoltaic array than other components. In this paper a standalone PV based pumping system with a PV array capacity of 2.4 kWp and a storage tank with a capacity of 80 m^3 was proposed an a optimum system. The system with the aforementioned configuration pumps an average hourly water volume of approximately 3.297 m^3 over one year with a unit of 0.05158 USD/m^3. Moreover, according to results, increasing the maximum capacity of water storage tank is technically and economically better than supporting a photovoltaic water pumping systems with another energy source or extra storage device.

1. Introduction

One of the most important issues worldwide is electrical energy shortage, especially in developing countries, while, it is expected that world's energy demand will increase by 53% by 2035 [1,2]. Therefore, a global renewable energy strategy is an important choice to solve the crisis of energy and environmental pollution, as well as to achieve sustainable social development [3,4]. Solar energy is one of the most renewable, environmentally friendly, and abundant energy sources. Photovoltaic technology is one of direct solar energy application and it directly converts solar energy to electrical energy. Photovoltaic water pumping system (PVPS) is one of the most important applications of PV in remote areas [5–8]. It proved that PV based water pumping systems are technically and economically feasible [8]. Although PVPSs have been designed and created in the past to pump water in rural and remote areas, they are still facing serious obstacles and challenges [6]. Low reliability and high initial cost are the main challenges to PVPSs [7,8]. Thus, a proper sizing of PVPS is essential to fulfill the demanded water. Therefore, considerable research has been dedicated for sizing of the PV array and other components, such as the storage unit and inverter in PVPS to meet the required load at a minimum cost [9,10].

In [11], loss of power supply probability (LPSP) concept is considered to measure the reliability of a set of PVPS configurations that meets the desired load demand. After that, an economic evaluation is applied to these configurations, so as to find the optimal configuration that achieves the minimum cost at the desired reliability. In [12], a numerical method for sizing a PVPS is used to minimize the cost subject to a predefined reliability level based on a LPSP concept. A constant load profile is used in this research with different head levels. Four values of LPSP values are applied in the simulation; (0, 0.01, 0.05, and 0.1). Olcan et al. [13], has proposed a sizing method for PVPS by minimizing an aggregating function that combines LPSP and the life cycle cost (LCC) of the system. The proposed objective function is solved by a linear iterative programming model. Ma et al. [14], has proposed a method for minimizing the LCC of a standalone PVPS with a storage system subject to a specific LPSP using genetic algorithm (GA). In addition, Stoppato et al. [15], has proposed a particular swarm optimization

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Nomenclature

A	area of PV array (m^2)
C_B	maximum capacity of battery (Wh)
C_n	maximum capacity of storage tank (m^3)
$C_{res}(t)$	current resident water in storage tank (m^3)
d	internal diameter of pipeline (m)
D	demand water (m^3/h)
DOD	depth of discharge of battery
FC	hourly fuel consumption by DG (L/h)
F_{DGC}	daily fuel consumption by DG (L/day)
g	acceleration due to gravity (m/s^2)
G_T	hourly solar irradiance (W/m^2)
H	total head (m)
H_d	equivalent head due to friction losses in the fitting components (m)
H_{dd}	drawdown water level
H_D	equivalent head due to friction losses in the pipeline (m)
H_s	static head (m)
I_a	output current of PV array (A)
L	length of pipeline (m)
LLP	loss of load probability
N_p	number of modules are connected in parallel
N_s	number of modules are connected in series
P_{DG}	instantaneous output power of DG (kW)
P_{DGr}	rated output power of DG (kW)
$Q(t)$	water flow rate (m^3/h)
$Q_d(t)$	deficit water (m^3)
$Q_e(t)$	excess water (m^3)
$SOC_B(t)$	current state of charge of battery
$SOC_T(t)$	current state of charge of storage tank
v	average speed of the water (m/s)
V_a	output voltage of PV array (V)
ρ	water density (kg/m^3)
δ	pipeline friction coefficient
ζ_B	efficiency of battery
ζ_{PV}	efficiency of PV array
ζ_{sub}	subsystem efficiency
DC	direct current
DG	diesel generator
GA	genetic algorithm
LCC	life cycle cost
LPSP	loss of power supply probability
PMD	permanent magnet DC motor
PV	photovoltaic
PVPS	photovoltaic water pumping system

(PSO) algorithm to size a small PVPS with a storage unit on the basis of the same concept which has been proposed in [16]. Muhsen et al. [17], has proposed a differential evolution based multi-objective optimization algorithm to optimally size a PVPS. In [17], three objective functions, namely loss of load probability (*LLP*), LCC and excess water volume (Q_e) are aggregated by a single function based a predefined weights. The main drawback of the proposed sizing method is the complexity of the process of initialization the weights. In addition, Muhsen et al. [18], has proposed a differential evolution based multi-objective optimization (DEMO) algorithm to size a standalone PVPS to overcome the aforementioned drawbacks of the method proposed in [17]. In [18], the PVPS is sized based on *LLP* and LCC only. The main drawback of DEMO proposed in [18] is that the increased computation complexity due to the increasing number of criteria that are considered to size PVPS.

On the other hand, many research works are devoted to combine a battery with PVPS. These research focus on the feasibility of using PVPS versus pumping system based on diesel generator (DG). In [19], the performance of PVPS is investigated. The studied system consists of a 6.048 kWp PV-array, a storage battery of a capacity of 1060 Ah, and a centrifugal pump. The switched reluctance motor which is used in the pumping system has an overall efficiency above 85%. According to the results, most of the losses are in pump (31.82%), as the efficiency of pump is limited to about 56%. However, according to the authors, the efficiency of the pumping system can be improved by selecting more efficient pump. In [20], the authors have analyzed the performance of a PVPS in order to determine the overall system efficiency and the water pumping volume. The PV array that is used in the system is configured as 6 parallel strings, where each string contains of two 51 Wp modules connected in series. A 400 Ah lead acid battery, a 1 kW DC charge controller, a 100 W submersible pump and a water reservoir of 0.5 m^3 capacity are utilized in this research. Two operational phases are applied to this system. In the first phase, the PV array charges the batteries without powering the pump. While, in the second phase the PV array is disconnected and the battery bank powers the pump. The results showed that the overall system efficiency is 5% with pumped water of 20 m^3/day (pumping head is 30 m). Bucher et al. [21] has conducted a feasibility study of a PVPS based on a comparison between a PVPS and DG based water pumping system in accordance to experimental results. According to the results of [21], a large PV water pumping system is required as compared to the DG based system which consequently results high initial investment. The unit cost is found to be about 0.6 USD/m^3 which is less than the DG based pumping system (1 USD/m^3). In [22], the feasibility of using PVPS in Egypt is studied. The results of [22] show that PVPS is cheaper than a DG based system in terms of water units pumped. However, the authors concluded that the cost of water pumping unit is more sensitive to the price of PV modules than PV array's lifetime. In [23], the authors investigated the feasibility of replacing the fossil-fuel by renewable energy sources to power a water pumping system in Nigeria. The results show that solar and wind sources are more cost effective than DG based water pumping system.

In spite of using an accurate sizing method, the PVPS still suffers from the most important challenge which is the mismatch between the PV generated energy and load demand. This is because the intermittent nature of solar energy [24]. Therefore, the reliability of such a system is critical and therefore backup energy sources, such as diesel generator (DG) or a storage element, such as a battery are needed [25].

In the present paper a feasibility study and load sensitivity analysis of various PV standalone-diesel generator-battery hybrid pumping systems are presented in tropical climate. The analysis is based on techno-economic aspects to select a pumping system design from various proposed systems in order to minimize the life cycle cost of system with a 100% reliability (*LLP* = 0). An energy balance computation is done for each hour of a year to obtain a perfect design of pumping system for a certain load at a specific site.

2. Sizing of the PVPS

The proposed PVPS is made up of four main parts as shown in Fig. 1. The PV array converts the solar energy to electrical energy, and the DC-DC converter which is integrated with a maximum power point tracking algorithm which plays a buffer role between