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Sizing of a standalone photovoltaic water pumping system using a multi-objective evolutionary algorithm

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ABSTRACT

In this paper, a differential evolution based multi-objective optimization algorithm is proposed to optimally size a photovoltaic water pumping system (PVPS). Non-dominated sorting and crowding distance concepts are used to increase the elitism and diversity of the proposed algorithm. The proposed objective function is composed of technical and economic objectives. Loss of load probability is used as a technical objective, whereas life cycle cost is considered as an economic objective. The proposed PVPS is designed to provide a daily water demand of 30 m^3 with a 20 m static head and a drawdown level. The optimal configuration of the system is selected from an optimal Pareto set of configurations to achieve balance between reliability, cost, and excess water of the system. The performance of the system is tested using hourly metorological data for one year time. Results show that the loss of load probability of the proposed system is around 0.5%. The life cycle cost, water deficit, and cost of water unit of the system are 9910 USD, 55 m^3, and 0.045 USD/m^3, respectively.

1. Introduction

One of the most popular and promising applications of standalone photovoltaic (PV) systems is PV water pumping system (PVPS) [1]. Previous research has been dedicated to study the performance of PVPSs. These research works prove that PVPSs are more feasible than systems which are based on diesel generator and grid connection. Moreover, the average daily water flow rate of PVPSs is in the range of 5.3 m^3/kWp–26 m^3/kWp, and their overall efficiency is in the range of 1.3%–5% [2–6]. However, the high initial cost of the PV array is one of the main drawbacks of PVPSs [7,8]. Random vicissitudes and the lack of predictability of solar energy amount cause difficulty in optimally sizing such systems [9]. Therefore, an optimal sizing approach is important to ensure the satisfactory performance of PVPSs [10]. Researchers have focused on the optimal size of the PV array, as well as other components, such as the storage unit and inverter so as to meet the required load at a minimum cost [11,12]. In general, PV system sizing methods can be classified into intuitive, analytical, and numerical methods [13]. The intuitive method is the simplest one, which is based on the worst month or the average monthly solar radiation [14–16]. This method may lead to an over or under sizing of the PVPS, which consequently either increases the cost or decreases the reliability of the system. As a result, the intuitive method is only convenient to be used for estimating initial and rough approximation size of PV system [17]. In the analytical method, equations for the PV system size in terms of system reliability can be developed and utilized [18–20]. The calculation of system's size on the basis of an analytical method is simple and accurate, but the complexity of deriving the coefficient of these equations is the main drawback of this method. López et al. [21] proposed an analytical design method for sizing a direct PV pumping system to substitute the deficit water to irrigate an olive orchards. One of the most drawbacks of method presented in Ref. [21] is the efficiency of motor-pump set as it is

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Nomenclature

A	Area of PV array (m^2)
a	diode ideality factors
b_1	height of impeller blade at impeller inlet (mm)
b_2	height of impeller blade at impeller outlet (mm)
CA_i	capacity of ith component of PVPS
cd_i^m	crowding distance of solution i along mth objective function
CR	crossover rate parameter
d	internal diameter of pipeline (m)
D	demand water (m^3/h)
D_P	dimension of individual vector
F	mutation scaling factor
FR	annual inflation rate
g	acceleration due to gravity (m/s^2)
G	generation number
G_T	hourly solar radiation (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	armature current of DC motor (A)
I_a	output current of PV array (A)
I_c	output current of solar cell (A)
IC	initial capital cost (USD)
ICI	installation and civil works costs (USD)
I_o	diode saturation current (A)
I_{Ph}	Photocurrent (A)
IR	annual interest rate
KB	Boltzmann's constant (1.3806503e-23 J/K)
K_T	motor torque constant (Nm/A)
K_P	Pump constant
L	length of pipeline (m)
LP	lifetime of PVPS (year)
MC	present value of maintenance cost (USD)
MC_r	maintenance cost of rth component (USD)
MC_{0r}	maintenance cost of rth component in the first year (USD)
N_r	number of component replacements over the lifetime of system
N_P	number of individual vectors in population set
N_p	Number of modules are connected in parallel
N_s	Number of modules are connected in series
q	electron charge (1.60217646e-19 C)
Q	water flow rate (m^3/h)
Q_d	deficit water (m^3)
Q_e	excess water (m^3)
R_1	impeller radius at impeller inlet (mm)
R_2	impeller radius at impeller outlet (mm)
RC	present value of replacement cost (USD)
RC_k	replacement cost of kth component (USD)
R_p	shunt resistance (Ω)
R_s	series resistance (Ω)
S_o	offspring solution
$SOC(t)$	current state of charge of storage tank
S_p	parent solution
T_C	cell temperature (K)
T_m	electromechanical torque of motor (Nm)
T_P	torque of pump (Nm)
UC_i	cost per unit of ith component (USD/unit)
V	armature voltage of DC motor (V)
v	average speed of the water (m/sec)
V_a	output voltage of PV array (V)
V_c	output voltage of solar cell (V)
V_t	diode thermal voltage (V)
$X_{j,i}$	jth parameter of ith individual vector
$X_{j,L,i}$	lower limit of jth parameter of ith individual vector
$X_{j,H,i}$	upper limit of jth parameter of ith individual vector
X_i^G	ith individual vector in G generation (target vector)
$\hat{X}_i^G$	mutant vector of ith individual vector in G generation
$y_{j,i}^G$	jth parameter of ith trial vector
β_1	inclination angle of impeller blade at impeller inlet (degree)
β_2	inclination angle of impeller blade at impeller outlet (degree)
ρ	water density (Kg/m^3)
ω	rotational speed of DC motor (rad/sec)
δ	pipeline friction coefficient
ζ_{PV}	efficiency of PV array
ζ_{sub}	subsystem efficiency
ζ_{sys}	overall efficiency of PVPS
DEMO	differential evolution for multi-objective optimization
DC	direct current
DE	differential evolution
EA	evolutionary algorithm
LCC	life cycle cost
LLP	loss of load probability
LPSP	loss of power supply probability
MC	maintenance cost
MOO	multi-objective optimization
MPP	maximum power point
NSGA	Non-dominated sorting genetic algorithm
MC	maintenance cost
PMDC	permanent magnet DC motor
PV	photovoltaic
PVPS	photovoltaic water pumping system
SOO	single objective optimization

considered a constant value (about 60%).

On the other hand, the numerical method is the most popular PVPS sizing method, which is generally based on hourly meteorological data to describe system performance over a wide range of system configurations [22–24]. In general, the optimal configuration is selected from a set of possible configurations on the basis of a techno-economic objective function [25,26]. Olcan in [27] proposed a sizing method to size a PVPS by minimizing an aggregating function that combines the deficiency of power supply probability and the life cycle cost of the system. The proposed objective function is usually solved by a linear iterative programming model. The main drawback of method presented in Ref. [27] is the unjustified assumption of equal weights for objectives when they are aggregated. Furthermore, the authors of [27] have used monthly averages of daily meteorological data, which does consider the uncertain nature of system performance.

In general, the drawback of the numerical method is the long computational time needed to simulate the performance of the