Energy Conversion and Management 118 (2016) 32–43

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Multiobjective differential evolution algorithm-based sizing of a standalone photovoltaic water pumping system

Dhiaa Halboot Muhsen [a,b,*], Abu Bakar Ghazali [a], Tamer Khatib [c]

[a] Department of EC Engineering, University of Tenaga Nasional, Malaysia
[b] Department of Computer and Software Engineering, University of Al-Mustansiriyah, Iraq
[c] Department of Energy Engineering and Environment, An-Najah National University, Nablus, Palestine

ARTICLE INFO

Article history:
Received 3 January 2016
Received in revised form 20 March 2016
Accepted 25 March 2016

Keywords:
Solar water pumping system
Photovoltaic
Multiobjective optimization
Differential evolution
Loss of load probability
Life cycle cost

ABSTRACT

In this paper, a differential evolution based multiobjective optimization algorithm is proposed to optimally size a photovoltaic water pumping system (PVPS). Three weighted individual objectives are aggregated by a single function to optimize the configuration of PVPS. Loss of load probability, life cycle cost and the volume of excess water are considered as three individual objective functions. The proposed pumping system is supposed to provide a daily water volume of 30 m^3 with a static head of 20 m. The complexity of the initializing of the weights for each individual objective function is overcome by testing a wide range sets of weights. The performance of the system is tested based on hourly meteorological data. The performance results of the proposed system show that the loss of load probability and the average hourly water flow rate over a year time are around 0.5% and 3.297 m^3/h, respectively. The life cycle cost, water deficit, and cost of water unit of the system are 9911 USD, 55.015 m^3, and 0.045 USD/m^3, respectively.

1. Introduction

Photovoltaic water pumping system (PVPS) is one of the most important applications of photovoltaic systems (PV) in rural areas. However, the high initial cost and low conversion efficiency of the PV array are the main drawbacks of PVPS [1–3]. Therefore, a proper sizing of PVPS is essential to fulfill the demanded water.

The optimum size of PVPS mainly depends on available solar radiation and load demand nature. Various methodologies were reported in literature for sizing PVPS, such as intuitive, analytical and numerical iterative based methods [4–6]. Among these methods numerical iterative method is the most recommended method for accuracy reasons [7]. In numerical iterative method, a design space containing different configurations of the system (number of PV modules and size of storage tank) is created. After that, each configuration in this design space is simulated based on hourly meteorological and load data to estimate the availability of each configuration. Then the configurations that satisfy the desired availability level are nominated [8–10]. At this point, the cost of each configuration is calculated and then the configuration that achieves the lowest cost is selected as an optimum solution. Examples on the numerical methods can be found in the literature. Olcan in [11] proposed a sizing method for PVPS by minimizing an aggregating function that combines the loss of power supply probability and the life cycle cost of the system. The proposed objective function was solved by a linear iterative programming model. The main drawback of [11] is the unjustified assumption of equal weights for objectives when they are aggregated. Furthermore, [11] used monthly average daily meteorological data, which may not consider the uncertain nature of system performance. Moreover, the relatively long execution time of this method limits its ability to handle large systems.

Based on that, AI techniques have been employed recently in optimally sizing PVPS. Evolutionary algorithms, for example, were employed for sizing PVPS to overcome the drawback of numerical iterative method [12–15]. In addition to that, particle swarm optimization (PSO) and genetic algorithm (GA) are also used for sizing PVPS. In [12] the authors proposed GA for minimizing the life cycle cost of a standalone PV hydro energy storage system subject to a specific loss of power supply probability. Similarly, Stoppato in [13] proposed a PSO algorithm to optimize the size of a small PV-pump hydro energy storage on the basis of the same concept proposed in [12]. The authors of [14] used a hybrid sizing method that combines the numerical and heuristic techniques. Similar

---

* Corresponding author at: Department of EC Engineering, University of Tenaga Nasional, Malaysia.

E-mail addresses: deia_mohussen@yahoo.com (D.H. Muhsen), abakar@uniten.edu.my (A.B. Ghazali), t.khatib@najah.edu (T. Khatib).

http://dx.doi.org/10.1016/j.enconman.2016.03.074
0196-8904/

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
C_n	maximum capacity of storage tank (m^3)
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
k_B	Boltzmann's constant (1.3806503e−23 J/K)
K_T	motor torque constant (N m/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_{excess}	excess water (m^3)
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_c	candidate solution
SOC(t)	current state of charge of storage tank
S_p	parent solution
T_C	cell temperature (K)
T_P	torque of pump (N m)
UC_i	cost per unit of ith component (USD/unit)
V	armature voltage of DC motor (V)
v	average speed of the water (m/s)
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 decision variable 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)
$\widehat{X}_i^G$	mutant vector of ith individual vector in G generation
$y_{j,i}^G$	jth decision variable of ith trial vector
β_1	inclination angle of impeller blade at impeller inlet (°)
β_2	inclination angle of impeller blade at impeller outlet (°)
ρ	water density (kg/m^3)
ω	rotational speed of DC motor (rad/s)
δ	pipeline friction coefficient
ζ_{PV}	efficiency of PV array
ζ_{sub}	subsystem efficiency
ζ_{sys}	overall efficiency of PVPS
DC	direct current
DE	differential evolution
EA	evolutionary algorithm
LCC	life cycle cost
LLP	loss of load probability
MC	maintenance cost
MOO	multiobjective optimization
MPP	maximum power point
PMDC	permanent magnet DC motor
PV	photovoltaic
PVPS	photovoltaic water pumping system

work was conducted in [15]. Similar example on the utilization of evolutionary algorithms for sizing PVPS can be found in [16].

Based on the reviewed literature, most of these optimization practices are based on single objective optimization (minimization of the cost subject to a specific availability). In the meanwhile, multi-objective optimization has not been applied for PVPS. Therefore, in this paper, a differential evolution algorithm based multi-objective optimization is developed to optimally size a PVPS based on technical, economic and excess water criteria. These criteria are normalized, weighted and then aggregated by a single function, which is minimized to obtain the optimal configuration of PVPS. Eventually, the performance of the proposed PVPS is studied based on hourly meteorological and load data.

2. Modeling of PVPS

In general a PVPS comprises four main parts, namely, PV array, DC–DC converter, permanent magnet DC motor coupled with a centrifugal pump, and a tank as a storage device, (see Fig. 1). The storage tank fulfill the load demand when the PV array is unable to power the pump at night or when the volume of pumped water is insufficient to fulfill the water demand.

2.1. Modeling of PV array

A double-diode model of solar cell is considered in this paper. Following that, the output current of a solar cell can be expressed by

$$I_c = I_{Ph} - I_{o1}\left[\exp\left(\frac{V_c + I_c R_s}{V_{t1}}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V_c + I_c R_s}{V_{t2}}\right) - 1\right] - \frac{V_c + I_c R_s}{R_p}, \tag{1}$$

where I_c and V_c are output current (A) and voltage (V) of the solar cell, respectively, I_{Ph} is the photocurrent, I_{o1} and I_{o2} are diode saturation currents of the first and second diodes, respectively (A), R_s is