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Sizing of a standalone photovoltaic water pumping system using hybrid multi-criteria decision making methods

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ABSTRACT

Photovoltaic water pumping system (PVPS) is considered one of the most important and promising application of solar energy in remote and rural areas. The random nature of solar energy is one of the main obstacles that encounter the designer to design an effective PVPS. Thus, an optimal and effective sizing approach is essential to ensure satisfactory performance. In this paper, a technique for order performance by similarity to ideal solution (TOPSIS) method integrated with analytic hierarchy process (AHP) method is proposed to optimally size PVPS based on techno-economic aspects. The loss of load probability (LLP) and excess water volume are considered as technical criteria, whereas the life cycle cost (LCC) is represented as an economic criteria to size the system. The hybrid AHP-TOPSIS sorts the PVPS configurations from the best to worst based on predefined weights for each criteria. The optimal configuration is found 5 PV modules and 4 PV strings are connected in series and parallel, respectively with 79 m^3 as a maximum capacity of storage tank. The performance of system is tested based on the proposed optimal configuration over a year using hourly meteorological data. The results show that the proposed system offers high reliability throughout the year with LLP, LCC, and deficit water volume around 0.0004, 10524.9 USD, and 4.4629 m^3, respectively.

1. Introduction

Photovoltaic water pumping system (PVPS) is one of the most popular and promising 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 (Ozturk and Yuksel, 2016; Gan et al., 2015). Furthermore, random vicissitudes and the lack of predictability of solar energy amount cause difficulty in optimal sizing of such a system (Yesilata and Firatoglu, 2008). Therefore, a proper sizing of PVPS is essential to fulfil the demanded water. Thus, considerable research has been dedicated on the sizing of the PV array and other components, such as the storage unit and inverter, to meet the required load at a minimum cost (Mellit et al., 2009; Mohamed et al., 2014).

In general, PV system sizing methods can be classified into intuitive, analytical, numerical, and artificial intelligent methods (Khatib et al., 2013; Chauhan and Saini, 2014). The intuitive method is the simplest one, which is based on the worst month or the average monthly solar radiation (Campana et al., 2013; Ebaid et al., 2013; Al-Smairan, 2012). However, 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. In the analytical method, the designer develop equations for the PV system size in terms of system reliability to size the system (Martiré et al., 2008; Hamidat and Benyoucef, 2009; Campana et al., 2015). The calculation of system's size on the basis of an analytical method is simple and more accurate than intuitive method, but the complexity of deriving the coefficient of these equations is the main drawback of this method.

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 (Kaldellis et al., 2009; Bakelli et al., 2011; Khiareddine et al., 2015). In general, each configuration in this design space is simulated based on hourly meteorological and load data to estimate the reliability of each configuration. Then the configurations that satisfy the predetermined reliability level are nominated (Khiareddine et al., 2015; Belmili et al., 2014; Bouzidi, 2013). 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. In Bakelli et al. (2011) the loss of power supply probability (LPSP) concept is used to specify the reliability of a set of system configurations that meet the desired load demand. After that, an economic evaluation is applied to these

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Nomenclature

A	area of PV array (m^2)
A_i	ith alternative
A^*	ideal solution
A^-	negative ideal solution
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_j	jth criteria
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)
DM	decision matrix
FR	annual inflation rate
g	acceleration due to gravity (m/s^2)
G_h	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)
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
B	Boltzmann's constant ($1.3806503e-23$ J/K)
K_T	motor torque constant (Nm/A)
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 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)
RC	present value of replacement cost (USD)
RC_k	replacement cost of kth component (USD)
R_1	impeller radius at the impeller inlet (mm)
R_2	impeller radius at the impeller outlet (mm)
R_p	shunt resistance (Ω)
R_s	series resistance (Ω)
S_i^*	distance of ith alternative from ideal solution
S_i^-	distance of ith alternative from negative ideal solution
$SOC(t)$	current state of charge of storage tank
T_C	cell temperature (K)
T_m	electromechanical torque of DC 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/s)
V_a	output voltage of PV array (V)
V_t	diode thermal voltage (V)
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/s)
δ	pipeline friction coefficient
ζ_{PV}	efficiency of PV array
ζ_{sub}	subsystem efficiency
AHP	analytic hierarchy process
DC	direct current
GA	genetic algorithm
LCC	life cycle cost
LLP	loss of load probability
LPSP	loss of power supply probability
MCDM	multi-criteria decision making
PMDC	permanent magnet DC motor
PSO	particle swarm optimization
PV	photovoltaic
PVPS	photovoltaic water pumping system
STC	standard test condition
TOPSIS	technique for order performance by similarity to ideal solution

configurations, so as to find the optimal configuration that achieves the minimum cost at the desired reliability. In Bouzidi (2013) a numerical method for sizing a PVPS is presented to minimize system's cost subject to a specific reliability. The method depends on the LPSP concept. It uses hourly solar radiation and ambient temperature data for a year. A constant load profile is used in Bouzidi (2013) with different head levels. Four values of LPSP were used in the simulation; (0, 0.01, 0.05, and 0.1). Olcan (2015) has 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.

However, the drawback of the numerical method is the need for a long time to simulate the performance of the system over a wide range of configurations (Muhsen et al., 2017a). Furthermore, the numerical sizing method selects only one configuration in accordance to the predetermined reliability level by the designer. Therefore, some authors use heuristic techniques to size PVPSs (Ma et al., 2015; Stoppato et al., 2014). Ma et al. (2015) have proposed a method for minimizing the life cycle cost of a standalone PV hydro energy storage system subject to a specific loss of power supply probability using genetic algorithm (GA). In addition, Stoppato et al. (2014) has proposed a particular swarm optimization (PSO) algorithm to size a small PV-pump hydro energy storage based on the same concept that has been proposed in Ma et al. (2015). Moreover, a hybrid sizing method that combines the numerical and heuristic techniques is proposed in Khatib et al. (2012), where a possible design space that contains system configurations that meet the desired system reliability is generated based on a numerical method. GA was then used to select the system that investigates the minimum life cycle cost. Muhsen et al. (2016a) have proposed a differential evolution based multi-objective optimization algorithm to optimally size a PVPS. In Muhsen et al. (2016a) three objective functions, namely loss of load probability (LLP), life cycle cost (LCC) and excess water volume (Q_e) are aggregated by a single function based a predetermined weights. However, the main drawback of sizing method based on heuristic techniques is the nomination of a single or a limit set of configuration that represent the tradeoff between the considered criteria for sizing PVPS. Moreover, the complexity of these sizing methods is increased by increasing the number of objective functions (criteria)