Solar Energy 173 (2018) 964–975

Contents lists available at ScienceDirect

Solar Energy

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

Simulated annealing-chaotic search algorithm based optimization of reverse osmosis hybrid desalination system driven by wind and solar energies

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ARTICLE INFO

Keywords:
Hybrid renewable energy system
Solar/wind/desalination
Optimization
Hybrid search algorithm
Simulated annealing
Chaotic search

ABSTRACT

Small reverse osmosis (RO) based desalination plants driven by wind and solar energies are attractive options to meet the requirements of autonomous areas. The complexity of these systems requires proper optimization of the solar and wind energy generation with storage needs. The main contribution of this study is a design optimization method of a hybrid reverse osmosis desalination plant powered by solar and wind energy. There are many investigations based on hybrid energy systems but the investigation of a useful model and effective methods are rarely found. Here, the possibility of three autonomous hybrid arrangements, namely, solar-wind-battery-RO desalination, solar-battery-RO desalination, and wind-battery-RO desalination, are investigated. Integer and continuous variables in the optimization model of the hybrid schemes for an autonomous region of Iran are considered. The main optimization function of minimizing the life cycle cost is used to evaluate different types of renewable energy systems for powering reverse osmosis desalination. Also, the probability of power interruption is used to measure the reliability of the hybrid schemes. For this aim, a new hybrid search algorithm is developed for simulating annealing and chaotic system. The results are compared with those from original chaotic search and simulated annealing algorithms. The simulation results show that the relative error in the hybrid scheme between the best performances of the hybrid search algorithm and the simulated annealing algorithm is 47.75%, and 4.08% for the hybrid search algorithm and chaotic search algorithm. In overall terms, the results demonstrate that the hybrid search algorithm provided the best performance between the original simulated annealing and the chaotic search algorithm. Additionally, the hybrid renewable energy system decreases system cost and increases system reliability for increasing fresh water availability and meeting the electricity load demands.

1. Introduction

Energy and fresh water resources are among the most important assets of any country. It is a well-known fact that the high rate of industrial growth and development of any nation is a function of the amount of energy and water available (Maleki, 2017; Shaaban and Petinrin, 2014). Electricity produced from renewable energy can be used to power desalination systems and serve the energy needs of populations residing in remote areas. Various combinations of solar photovoltaic (PV), wind turbines (WT), and storage capacities are available to address the intermittency issues associated with these renewable energy conversion technologies and produce a system designed for sustainable operation. Optimal sizing a reverse osmosis (RO) hybrid desalination scheme driven by wind and solar energies can lead to increased cost-effectiveness, reliability, and environmental management. For this aim, a battery bank affords energy storage and is particularly useful for meeting loads during high demand times.

In the literature, several RO desalination (ROD) systems powered by renewable energy have been studied and implemented. These include ROD units powered by wind energy (De la Nuez et al., 2004; Koklas and Papathanassiou, 2006) and solar energy systems (Ahmad et al., 2015; Jones et al., 2016; Joyce et al., 2001; Masson et al., 2005; Qiblawey et al., 2011; Shalaby, 2017; Yadav and Sudhakar, 2015), More specifically, hybrid energy systems including, wind/battery (Tzen and Morris, 2003), solar/diesel (Helal et al., 2008), PV with or without battery storage (Clarke et al., 2013; Edalati et al., 2016b; Kyriakarakos et al., 2017), solar/wind/battery (Bourouni et al., 2011; Nagaraj et al., 2016; Peng et al., 2018), solar/wind (Al Malki et al., 1998; Caldera

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https://doi.org/10.1016/j.solener.2018.07.094
Received 16 April 2018; Received in revised form 21 July 2018; Accepted 30 July 2018

Nomenclature

A_{PV}	total area occupied by the set of photovoltaic panels (m^2)
A_{WT}	area of wind turbine blades (m^2)
$A_{PV\text{-}Max}$	maximum total area occupied by the PV arrays (m^2)
$A_{WT\text{-}Max}$	maximum total area swept by the WT blades (m^2)
BAT	battery
CS	chaotic search
CC	capital cost ($)
C_{BAT}	cost of batteries ($)
$C_{Mnt\text{-}BAT}$	annual maintenance cost for each battery ($/year)
CRF	capital recovery factor
C_{ROD}	daily cost of RO system per unit (m^3) capacity of the desalinated water of RO system ($/$m^3$/day)
Ca_{WD}	reverse osmosis desalination system volumetric daily capacity (m^3/day)
$C_{Mnt\text{-}ROD}$	annual maintenance cost of ROD ($/year)
C_{WTa}	water tank cost ($/$m^3$)
C_{MR}	membrane replacement cost ($/$m^3$)
C_{CH}	cost of chemicals ($/$m^3$)
DOD	maximum depth of discharge
D_{WC}	desalination water production capacity per day (m^3/day)
D_{WD}	total daily volumetric fresh water demand (m^3/day)
ED_l	energy demand (kWh)
E_G	energy produced by the PV collectors and wind turbines (kWh)
H_{WD}	hourly volumetric water demand (m^3/h)
HSA	hybrid search algorithm
i	iteration index
i_{max}	maximum number of iterations
j	interest rate (%)
LPSP	loss of power supply probability
$LPSP^m$	maximum allowable *LPSP*
LPS	loss of power supply
LCC	life cycle cost ($)
MC	operation and maintenance ($)
n	life span of the system (years)
N_{BAT}	number of batteries
N_{Me}	number of membrane replacements per year
$N_{BAT\text{-}Max}$	maximum number of batteries
PV	photovoltaic
PW_{BAT}	present worth of the batteries ($)
P_{DEM}	desalination electric power (kW)
P_D	desalination installed power (kW)
P_{MD}	ROD unit minimum load (kW)
P_{DI}	ROD unit nominal load (kW)
P_{DES}	instantaneous power utilization of ROD unit (kW)
RO	reverse osmosis
ROD	reverse osmosis desalination
r	uniform random number in the range [0, 1]
SA	simulated annealing
SOC	state of charge
S_{DC}	desalination energy consumption (kWh/m^3)
S_{BAT}	nominal capacity of battery bank (kWh)
s	step size
TLCC	total life cycle cost ($)
TC_{CH}	cost of chemicals of ROD unit ($)
TC_{MR}	membrane replacement cost of ROD unit ($)
T	temperature
T_0	starting temperature
V_{WTa}	fresh water tank volumetric capacity (m^2)
WTa	water tank
WT	wind turbine
WF	a vector having elements randomly distributed in the range [-*wf*, *wf*]
$x(i)$	current solution
x_{new}	new solution
η_{bc}	battery bank charging efficiency (%)
η_{bf}	discharging efficiency of battery bank (%)
η_{INV}	inverter efficiency (%)
σ	hourly self-discharge rate

et al., 2016; Cherif and Belhadj, 2011; MOkheimer et al., 2013), solar/wind/diesel (Setiawan et al., 2009), solar/hydrogen/battery (Clarke et al., 2015), renewable energy/battery (Voivontas et al., 2001), renewable energy/fuel cell (Maleki et al., 2016b).

In the literature, several approaches based on traditional and new artificial intelligence methods have been studied and implemented for optimization of the hybrid renewable energy systems (Table 1). These include the Genetic algorithm (Esfahani and Yoo, 2016; Koutroulis and Kolokotsa, 2010) which is applicable to problems having multiple solutions, the Particle Swarm optimization (Maleki et al., 2017a; Maleki and Rosen, 2017; Maleki et al., 2017c) which has simple calculations in comparison to other techniques, the Simulated Annealing (SA) (Ekren

Table 1
Sizing method.

Algorithm Name	Reference	Description
Genetic Algorithm	Esfahani and Yoo (2016), Koutroulis and Kolokotsa (2010), Merei et al. (2013)	Mimics process of natural evolution, like inheritance, mutation, selection, and crossover
Particle Swarm Optimization	Maleki et al. (2017a), Maleki and Rosen (2017), Maleki et al. (2017c) and Yahiaoui et al. (2016)	Mimics bird and fish movement behavior
Simulated Annealing	Ekren and Ekren (2010)	Mimics an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process)
Ant algorithms	Fetanat and Khorasaninejad (2015)	Inspired by the pheromone-based strategy of ants foraging in nature; foraging behavior of ants is based on finding the shortest path between source and their nests
Bee algorithms	Maleki (2017) and Roy et al. (2016)	Based on the intelligent foraging behavior of honey bee
Harmony Search	Chauhan and Saini (2016), Maleki et al. (2016a)	Based on improvisation process of jazz musicians
Biogeography-based optimization	Kumar et al. (2013)	Biogeography is the science of studying the behavior of species in nature against time and space and species immigration and emigration between habitats, which is a probable solution of the problem
Gravitational Search algorithm	Niknam et al. (2012)	Based on Newton's law of gravitation and the second law of motion
Imperialist Competition algorithm	Ranjbar and Kouhi (2015)	Based on a socio-politically inspired optimization strategy
Tabu Search	Katsigiannis et al. (2012)	Tabu search is a metaheuristic search method employing local search methods used for mathematical optimization