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Sizing of stand-alone photovoltaic/wind/diesel system with battery and fuel cell storage devices by harmony search algorithm

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ABSTRACT

This paper focuses on modeling, sizing and cost analysis of a photovoltaic (PV)/wind generator (WG)/diesel hybrid system considering two storage devices: battery and fuel cell (FC). In comparison with the traditional PV/WG/diesel/battery systems in which battery banks are used as the storage system, PV/WG/diesel/FC systems combine fuel cell, electrolyzer and hydrogen storage tanks as the energy storage system. For cost analysis, a mathematical model is introduced for each system's component and then, in order to satisfy the load demand in the most cost-effective way, one discrete version of harmony search (HS) algorithm is developed to optimally size the systems components. As an efficient search method, HS has simple concept, is easy to implement, can escape local optima by use of probabilistic mechanisms, and only needs one initial solution to start its search. Two robust optimization techniques are used for comparison and validation purposes, the simulated annealing (SA) algorithm and HOMER software. In addition the economic aspects of PV/WG/diesel/FC system are compared with those of the traditional PV/WG/diesel/battery system and break down of the total annual cost of the systems is given in detail.

1. Introduction

Because solar and wind energies are abundant, renewable and clean without causing greenhouse gases, they can significantly contribute in decreasing the electricity generation cost in stand-alone systems which produce power independently of the utility grid. Owing to seasonal and periodical variations, hybrid renewable energy systems have more reliability than single-renewable energy systems because they provide more continuous electrical output. Hybrid systems based on photovoltaic (PV) panels and wind generators (WGs) have a long lifetime and normally low maintenance cost [1]. Thanks to the fluctuating nature of solar and wind energies, energy storage is necessary in PV/WG hybrid systems. Conventionally, deep-cycle lead acid batteries are used for energy storage. However, environmental concerns related to using these batteries limit the application of PV/WG/battery-based hybrid systems. As a result, other alternatives are sought for energy storage [1].

As an alternative, fuel cells (FCs) in combination with an electrolyzer (for hydrogen production) and hydrogen storage tanks are being considered for energy storage. Using PV/WG/diesel/FC energy source leads to a non-polluting reliable energy source and reduces the total maintenance cost. In such system, electrolyzer produces hydrogen by the excess electrical energy of the PV and wind sources. The hydrogen can then be used to supply a FC which is considered as a secondary power source when the demand is high. Fig. 1 shows the configurations of PV/WG/diesel/battery and PV/WG/diesel/FC systems.

In recent years, investigation of stand-alone hybrid systems based on renewable sources and hydrogen power has attracted significant attention [2–21]. In the literature, Belfkira et al. [3] have proposed a method for size optimization of a WG/PV/diesel system. This approach makes use of a method to find out the optimum number of the units by the aim of minimizing the total cost and ensuring the energy availability. Dufo-López et al. [5] have proposed a heuristic approach to a multi-objective problem related to a PV/WG/diesel system. This approach tries to minimize two indices: levelized cost of energy (LCOE) and life cycle emissions (LCE) of equivalent CO_2. Dufo-Lopez and Bernal-Agustin [7] have developed a triple multi-objective problem by simultaneously minimizing three issues: total cost, pollutant emissions (CO_2), and unmet load. They have used multi-objective evolutionary algorithm (MOEA) and genetic algorithm (GA) to discover the best components and the control strategies. For zero load rejection in Malaysia, Khatib et al. [9] have designed a building system. Ma et al. [22] have presented a detailed feasibility study and techno-economic evaluation of a stand-alone hybrid solar-wind system with battery energy storage for a remote island. Ngan and Tan [11]

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Nomenclature

A	Denotes the PV area (m^2)
A_D	Coefficients of the consumption curve of the diesel generator (L/kWh)
B_D	Coefficients of the consumption curve of the diesel generator (L/kWh)
bw	Bandwidth of generation
bw_{max}	Maximum bandwidth
bw_{min}	Minimum bandwidth
C_T	Total annual cost ($)
C_{Cpt}	Annual capital cost ($)
C_{Mtn}	Annual maintenance cost ($)
C_f	Hourly cost of the fuel consumption ($)
$C_{FC/Elect}$	Present worth of FC/electrolyzer system ($)
$Cons_D$	Fuel consumption of the diesel generator (L/h)
C_{Fuel}	Total annual cost of fuel consumption ($)
C_{Diesel}	Unit cost of the diesel generator ($)
C_{PV}	Unit cost of PV panel ($)
C_{Wind}	Unit cost of wind generator ($)
C_{Tank}	Unit cost of hydrogen storage tank
C_{Batt}	Present worth of battery ($)
$C_{Conv/Inv}$	Present worth of converter/inverter components ($)
C_{Mtn}^{FC}	Annual maintenance cost of fuel cell ($/year)
C_{Mtn}^{Elect}	Annual maintenance cost of electrolyzer
C_{Mtn}^{PV}	Annual maintenance cost of PV ($/year)
C_{Mtn}^{Wind}	Annual maintenance cost wind generator ($/year)
C_{Mtn}^{Diesel}	Hourly maintenance cost of the diesel generator ($/h)
DOD	Maximum depth of discharge
$E_{Batt(t)}$	Charge quantities of battery bank at time t (kWh)
$E_{Batt}(t-1)$	Charge quantities of battery bank at time $t-1$ (kWh)
E_{Load}	Load demand (kWh)
$E_{Stor}(t)$	Energy stored in the hydrogen tanks at hours t (kWh)
$E_{Stor}(t-1)$	Energy stored in the hydrogen tanks at hours $t-1$ (kWh)
E_{Stor}^{min}	Minimum storage capacity of the hydrogen tanks (kWh)
E_{Stor}^{max}	Maximum storage capacity of the hydrogen tanks (kWh)
E_{Batt}^{max}	Maximum charge quantity of battery bank (kWh)
E_{Batt}^{min}	Minimum charge quantity of the battery bank (kWh)
HMCR	Harmony memory considering rate
I	Solar radiation (kW/m^2)
i	Interest rate
iter	Iteration index
$iter_{max}$	Maximum number of iterations
n	Life span of the system (years)
N_{Tank}	Number of storage tanks
N_{Wind}	Number of wind generators
N_{Batt}	Number of batteries
N_{PV}	Number of PV panel
$N_{Conv/Inv}$	Number of converter/inverter systems
N_{Wind}^{max}	Maximum available number of wind generators
N_{PV}^{max}	Maximum available number of PV panels
N_{Batt}^{max}	Maximum available number of batteries
N_{Tank}^{max}	Maximum available number of hydrogen tanks
$P_{r\text{-}WG}$	Rated power of the wind generator (kW)
P_{fuel}	Fuel price ($/L)
P_{Batt}	Battery price ($)
$P_{FC/Elect}$	FC/electrolyzer price ($)
$P_{Conv/Inv}$	Converter/inverter price ($)
P_D	Output power of the diesel generator (kW)
p_{WG}	Produced power of each wind generator (kW)
p_{PV}	Output power of each PV system (kW)
PAR	Pitch adjusting rate
PAR_{max}	Maximum pitch adjusting rate
PAR_{min}	Minimum pitch adjusting rate
P_N^D	Rated power of the diesel generator (kW)
$P_{FC/Elect}^{ins}$	Denotes FC/electrolyzer installation fee ($)
SOC	State of the charge
S_{Batt}	Nominal capacity of battery bank (kWh)
v	Wind speed (m/s)
v_r	Rated speed of the wind generator (m/s)
$v_{cut\text{-}in}$	Cut-in speed of the wind generator (m/s)
$v_{cut\text{-}out}$	Cut-out speed of the wind generator (m/s)
x(iter)	Current solution
x_{new}	New solution
σ	Hourly self-discharge rate
η_{BC}	Charge efficiency of the battery bank
η_{BF}	Discharging efficiency of battery bank
η_{Elect}	Efficiency of the electrolyzer
η_{FC}	Efficiency of the fuel cell
η_{PV}	Efficiency of PV panel
η_{Inv}	Inverter efficiency

have evaluated the potential of using PV/WG/diesel system in southern city of Malaysia, Johor Bahru. HOMER software has been used to find the system feasibility and conduct the economical analysis. Raj and Ghosh [13] have conducted an economic comparison between DG-based system and H_2-based systems appropriate for 5 kW applications. Hiendro et al. [15] have shown techno-economic analysis of WG and PV panel in a remote area. They found that battery and wind generator are the most important components of the PV/WG hybrid system to meet demand loads at night hours. Karakoulidis et al. [17] have tried to model a renewable system that satisfies electricity demand by combining PV array, a diesel generator and batteries. The only available design tool capable of carrying out the design of this type of hybrid system is HOMER [23]. This tool uses an enumerative method to obtain the optimal design by evaluating all the possible solutions. However, when the number of possible design points is very high, the enumerative method requires excessively high calculation time [21]. Size optimization of a hybrid energy system is a continuous type optimization problem. Therefore, this property also increases the possible design points of decision variables, drastically [21]. Thus, we propose utilizing heuristic techniques, such as the evolutionary algorithms, to solve these kinds of optimization problems. The evolutionary algorithms have been applied successfully to solve many problems of design in engineering [21,24]. Another design tool, HOGA, is developed by Bernal-Agustín and Dufo-López [25] which uses an evolutionary algorithm for the design of hybrid systems. HOGA is capable of applying an enumerative algorithm and useful for validating the results reached by means of the evolutionary algorithm [21]. We are motivated by the usefulness of the evolutionary algorithms in solving such time-consuming optimization systems. Ekren and Ekren [21] have used the simulated annealing (SA) algorithm for optimizing size of a PV/WG integrated hybrid energy system with battery storage. The optimum result obtained by SA algorithm is compared with other method. Consequently, it is come up with that the SA algorithm gives better result than the response surface methodology (RSM).