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A novel framework for optimal design of hybrid renewable energy-based autonomous energy systems: A case study for Namin, Iran

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ABSTRACT

An optimization model is developed to determine the most advantageous size of autonomous hybrid photovoltaic/wind turbine/fuel cell, wind turbine/fuel cell and photovoltaic/fuel cell systems for electrification of a remote area involving five homes (1 block) located in Namin, Ardabil, Iran. The model is developed based on three decision variables related to the system renewable energy components: number of storage tanks, total swept area by the rotating turbine blades and total area occupied by the set of photovoltaic panels. The former is an integer decision variable, while the latter two are continuous decision variables. All the components are modeled and an objective function is defined based on minimizing the life cycle cost and satisfying the maximum allowable loss of power supply probability. To determine optimal values of the variables that satisfy the load in the most cost-effective way, the use of simulated annealing and a combination of simulated annealing with harmony search and chaotic search is proposed. The simulation results indicate that the grid-independent hybrid photovoltaic/wind turbine/fuel cell system is the most cost-effective for supplying the block's electrical energy demands and that the simulated annealing-based harmony search algorithm yields more promising results than the other algorithms.

1. Introduction

A reliable, environmentally benign, and affordable energy supply is a goal for many countries. Reduced accessibility to natural resources and increasing energy consumption are increasing the cost of electricity, while greenhouse gas emissions are threatening natural and anthropogenic ecosystems. Consequently, renewable energy systems have been considered as future alternatives [1]. Among renewable energy systems, WTs (wind turbines) and PV (photovoltaic) systems are often considered the most promising technologies to meet electrical loads in remote areas [2]. However, the intermittent characteristics of these natural resources can be problematic. To enhance energy system reliability, a hybrid renewable energy system (photovoltaic/wind) can be used in which the characteristics of wind and solar energies are combined complementarily.

Gas-to-power and power-to-gas conversion systems provide an option for energy storage, which can assist in achieving sustainability and high efficiency. Such systems can operate with hydrogen as the gas. Hydrogen is regarded by many as an environmentally friendly fuel that can be effectively produced from water and stored. Hydrogen can be produced using electricity from renewable energy sources (solar and wind) when it is available in excess. The use of such energy sources can substantially reduce emissions of greenhouse gases.

An autonomous hybrid PV (photovoltaic)/WT (wind turbine)/FC (fuel cell) system for electricity generation is considered here. The system includes an electrolyzer to produce hydrogen from excess electrical energy generated by the renewable energy sources. WT and PV energy are used as the primary energy sources for the hybrid system and the fuel cell acts as a backup power supply for periods when the demand is high.

Optimization studies of various hybrid renewable energy systems have been reported, including PV/battery [3–5], wind/battery [6–8], PV/wind [9], PV/wind/battery [10–15], PV/diesel/battery [16], PV/diesel [17], PV/wind/diesel/battery [18–20], PV/wind/fuel cell [21], PV/fuel cell [22], PV/fuel cell/battery [23], PV/micro gas

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turbine [24], PV or wind based pumped storage [25–27], and several other hybrid renewable energy systems [28–30]. Some of these are particularly informative and discussed below.

Belfkira et al. [18] determined the optimal size of an off-grid hybrid wind/photovoltaic/diesel system with a methodology that uses a deterministic algorithm to determine the optimal number and type of the units by guaranteeing the availability of energy and minimizing the total system cost. Diaf et al. [31] optimize the size of a hybrid system based on levelized cost of energy and the LPSP (loss of power supply probability). Caballero et al. [32] present a method for optimal design and techno-economic analysis of a small grid-connected hybrid PV-wind energy system without energy storage considering the LCC (life cycle cost). Prasad and Natarajan [33] optimize a hybrid system size based on life cycle cost, deficiency of power supply probability, levelized energy cost, unutilized energy probability, relative excess power generated, and life cycle unit cost of power generation with a battery bank. Kaabeche et al. [34] present an optimal sizing model based on an iterative technique that optimizes the capacities of the components of a hybrid wind/photovoltaic power generation system incorporating a battery bank. Belmili et al. [35] present a detailed sizing method for stand-alone wind/photovoltaic hybrid systems. Khatib et al. [36] optimize a building integrated hybrid photovoltaic/diesel generator system for zero load rejection in Malaysia. Papaefthymiou and Papathanassiou [37] investigate the optimum sizing for a pumped storage hybrid power station operating in an island system using a genetic algorithm. Koutroulis et al. [38] present a methodology for the optimal sizing of stand-alone wind/photovoltaic systems, in order to determine, among a list of commercially available devices, the optimal number and type. The methodology ensures that the total system cost over a 20-year period is minimized and invokes a constraint that the energy load must be completely covered, resulting in zero load rejection. The cost (objective) function minimization is implemented using a genetic algorithm, and it was found that hybrid wind/photovoltaic systems have lower system costs compared to cases where either exclusive wind turbine or PV sources are used. Shrestha and Goel [39] present a methodology for optimization of a stand-alone photovoltaic system based on simulation, while an energy balance approach has been used for design of hybrid wind/photovoltaic systems [40]. Borowy and Salameh [41] introduce the loss of load probability concept for optimization of an off-grid hybrid wind/photovoltaic energy system.

In the present article, an optimization model is developed for a hybrid renewable energy (PV/WT/FC) system. The model is developed based on three decision variables related to the system components, namely, number of storage tanks (an integer variable), total swept area by the rotating turbines' blades (a continuous variable) and total area occupied by the set of PV panels (a continuous variable). Since optimal sizing in hybrid renewable energy systems is a non-linear and non-convex optimization problem and contains integer and continuous decision variables, a powerful optimization technique is needed for effectively solving such problems.

Although studies of various aspects of PV-wind-based hybrid systems are reported in the literature, informative models and efficient optimization tools for optimal sizing and techno-economic analysis are seldom found. Also it is observed in the literature that the numbers of components, namely, the number of wind turbines and PV panels, are usually used as the decision variables of the optimization model. This drawback limits the optimization flexibility since the optimization problem is solved for a given type of wind turbine and PV collector, and if the type of wind turbine or PV collector varies the optimization problem needs to be solved again. To overcome this drawback, in this study two decision variables related to the areas of wind turbines and PV collectors are treated as decision variables in the optimization model.

As a branch of AI (artificial intelligence), heuristic algorithms (inspired by natural processes or phenomena) are robust optimization tools which have received considerable attention, especially for solving complex optimization problems. Heuristic algorithms have in fact been applied to various aspects of hybrid energy systems [2,42–46]. SA (Simulated annealing) has been recognized as one of the most promising algorithms [12,47], primarily because it normally outperforms the other approaches in terms of accuracy. Not only does SA exhibit high efficiency, it also is easy to implement, is simple in concept and has a fast convergence rate.

In this article, we consider the continuous variables (total swept area by the rotating turbine blades and total area occupied by the set of PV panels) in the optimization model for a hybrid PV/WT/FC system and propose an efficient version of heuristic algorithms for optimally designing a stand-alone hybrid system for electrification of a small load area in Namin, Ardabil, Iran. For achieving this objective, this study proposes a simulated annealing algorithm for determining the optimum sizing of the PV/WT/FC system. The SA algorithm is then expanded by using the merits of two other heuristic algorithms, namely, CS (chaotic search) and HS (harmony search). Consequently, three algorithms are developed here: CSA (chaotic simulated annealing), SAHS (simulated annealing-based harmony search) and CSAHS (chaotic simulated annealing-based harmony search).

2. Optimization framework

A block diagram of the proposed hybrid renewable energy system is shown in Fig. 1, integrating several electrical power sources: PV (photovoltaic), WT (wind turbine), and FC (fuel cell). An energy storage system is included, comprised of hydrogen storage tanks and an electrolyzer. Wind turbines are connected to an inverter and an inverter before connecting with electrical consumers, since many electrical devices are supplied with AC power. The balance of energy at any time during the year is a factor that should be considered before the optimization. For this purpose, mathematical modeling of each component of the hybrid system is performed and the energy generated by each source of the system is determined. In the next sections, the modeling of each component of the hybrid system and the optimization framework are described in detail.

2.1. Modeling

2.1.1. PV array power

The output power of each photovoltaic panel, with respect to the solar radiation power, can be calculated as follows:

$$p_{PV}(t) = \eta_{PV} \cdot I(t) \cdot A_{PV} \tag{1}$$

where P_{PV} denotes the power generated by each PV panel at time t, η_{PV} the efficiency of the PV panels, I the solar insolation (in kW/m^2) and A_{PV} the total surface area occupied by the set of PV panels (in m^2). It is assumed that the photovoltaic panels have a MPPT (maximum power point tracking) system.

2.1.2. WT (Wind turbine) power

The power of the wind turbine (P_{WT}) can be written in terms of the wind speed as [32,48]: