Multi-objective optimization of the hybrid wind/solar/fuel cell distributed generation system using Hammersley Sequence Sampling

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ABSTRACT

As the development of China’s economy, environmental problems in China become more and more serious. Solar energy and wind energy are considered as ones of the best choices to solve the environmental problems in China and the hybrid wind/solar distributed generation (DG) system has received increasing attention recently. However, the instability and intermittency of the wind and solar energy throw a huge challenge on designing of the hybrid system. In order to ensure the continuous and stable power supply, optimal unit sizing of the hybrid wind/solar DG system should be taken into consideration in the design of the hybrid system. This paper establishes a multi-objective optimization framework based on cost, electricity efficiency and energy supply reliability models of the hybrid DG system, which is composed of wind, solar and fuel cell generation systems. Detailed models of each unit for the hybrid wind/solar/fuel cell system were established. Advanced $\varepsilon$-constraints method based on Hammersley Sequence Sampling was employed in the multi-objective optimization of the hybrid DG system. The approximate Pareto surface of the multi-objective optimization problems with a range of possible design solutions and a logical procedure for searching the global optimum solution for decision makers were presented. In this way, this work provided an efficient method for decision makers in the design of the hybrid wind/solar/fuel cell system.

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Introduction

The fast-growing economy of China gives a huge challenge for China’s energy industry in the early 21st century. The Statistical Review of World Energy published by British Petroleum (BP) Company in 2015 shows that the total energy consumption of China in 2014 was 2972.1 Mtoe, of which 66% came from the coal [1]. This inevitably leads to the increase of the emissions. To achieve the goals of energy-saving and emission-reduction, the reform of Chinese energy consumption structure becomes imperative. The proportion of the renewable
energy should be increased greatly [2]. Solar energy and wind energy, as two of the most efficient renewable energy, have been developed rapidly in recent years. However, both the solar energy and the wind energy have inherent disadvantages: instability and intermittency. The integration of the above two sources could overcome the problem partially [3,4] and is considered as one of the best alternatives to the fossil fuel generated energy [5]. In order to ensure the continuous and stable power supply for a long period of time, a power storage system is generally considered to be added into the hybrid system as well.

In recent years, the hybrid systems combined with the solar energy, the wind energy and the power storage systems have been built and in operation [6,7]. The hybrid wind/solar distributed generating (DG) system has the advantages of clean and renewable, however, the cost, the electricity efficiency and the reliability of energy supply are still the important issues that need to be considered [8–10]. The unit sizing of the hybrid wind/solar DG system has a huge impact on the performance of the whole system. Therefore, it should be taken into consideration during the design phase of the whole hybrid system. And the integration of the wind and solar energy in the hybrid system becomes complex and requires consideration with regard to grid stabilisation [11]. For the design of a Zero Energy Building, the problems caused by the mismatch between the demand and the production and the challenge of coordinating fluctuating and intermittent renewable energy production should be addressed well when considering integrating the DG system into the electricity grids [12].

Many researches have been published on the optimization of the unit sizing for the hybrid wind/solar DG system. A fuel cell vehicle powered by photovoltaic and wind energy system was modeled by Huang et al. and the influence of temperature on hydrogen flow and efficiency of the electrolyzer was studied in their paper using MATLAB Simulink software [13]. Coupled operation of electrolyzer with wind turbine and four different electrolyzer models are presented and evaluated for the renewable energy system by Mena et al. [14]. Chen et al. have investigated the optimal contract and installed capacities of the wind and PV generation system for a time of use rate for industrial users [15]. Fazelpour et al. performed an economic analysis of a standalone solar and wind energy system which produces energy for a household in Tehran Iran [16]. Wang and Singh use the particle swarm optimization (PSO) algorithm to balance the cost, the reliability and the pollutant emissions of a grid-connected hybrid DG system, which is composed of wind turbine generators, photovoltaic panels and storage batteries, and a set of non-dominate solutions is given in their paper [17]. Chedid et al. try to help decision makers in designing and sizing of hybrid power systems with solar and wind power energy by using the Analytic Hierarchy Process, and a trade-off surface in 3D space is presented in their works [18]. PSO, Hopfield neural network (HNN) and HNN-PSO algorithm have been proposed to optimize unit size for a hybrid wind/photovoltaic DG system respectively and the comparative studies and analysis of the three algorithms were carried out in Ref. [19]. Vikas et al. presented the optimization of hydrogen based hybrid renewable energy system using BIG BANG CRUNCH algorithm, HOMER and GAMBIT software [20]. An improving particle swarm optimization was employed in the optimal capacity allocation of standalone wind/solar/battery hybrid power system by Wang et al. [21]. However, most of the researches focused on the optimization algorithm, using some simplified models of each unit for the hybrid system. The complicated processes of each energy conversion in each unit were not involved.

In this paper, a fuel cell system comprising fuel cell stacks and an electrolyzer was added into the hybrid wind/solar DG system for a long period of time power storage. Detailed models of each unit in the hybrid wind/solar/fuel cell DG system were built. A multi-objective optimization framework based on cost, electricity efficiency and the reliability of energy supply models of the hybrid wind/solar/fuel cell DG system was established. Because of the high calculation efficiency and the great uniformity properties, Hammersley Sequence Sampling was employed in the multi-objective optimization [22,23]. On the base of the traditional ε-constraint multi-objective optimization method, the multi-objective problem is converted into a certain amount of single-objective problems by using Hammersley Sequence Sampling. The Pareto optimal solution set could be formed by the solution set of those single-objective optimization problems. The approximate Pareto surface of the multi-objective optimization problem is given in the end aimed to search the global optimum solution. In this way, this paper provides an efficient evaluation method for design makers.

Hybrid models

The hybrid wind/solar/fuel cell DG system is combined with wind energy system, the photovoltaic power generation system and the fuel cell system comprising the fuel cell stacks and an electrolyzer, which is used for a long period of time power storage. Fig. 1 shows the energy management strategy for this hybrid DG system from Wang [24]. During the operation, the excess electricity power generated by wind and PV is used to generate hydrogen by the electrolyzer. Then, the hydrogen is stored in hydrogen reservoir tanks. When the electricity power generated by wind and PV is not enough for the power demand, the fuel cell stacks begins to produce electricity fueled from the hydrogen reservoir tanks. Thus, the existence of the electrolyzer and the fuel cell system, according to the power demand, play a role of the energy storage and the energy generation respectively.

Electrolyzer model

To simplify the model, the following hypotheses are made:

1. The water vapor in the cathode and the anode of the electrolytic cells is fully saturated;
2. The water in the electrolytic cells is incompressible;
3. The gas phase, liquid phase can be separated;
4. The pressures and the temperature of the electrolytic cells in gas flow channels are constants;
5. The water vapor enthalpy is constant within the working temperature;

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