Simulation Modelling Practice and Theory 52 (2015) 40–51

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

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

Optimal design of hybrid renewable energy systems using simulation optimization

Kuo-Hao Chang [a,*], Grace Lin [b]

[a] Department of Industrial Engineering and Engineering Management, National Tsing Hua University, Hsinchu, Taiwan
[b] Advanced Research Institute, Institute for Information Industry, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 5 December 2014
Accepted 6 December 2014
Available online 31 January 2015

Keywords:
Hybrid renewable energy system
Energy management
Monte Carlo simulation
Simulation optimization

ABSTRACT

A hybrid renewable energy system (HRES) provides a viable solution for electrification of remote areas when grid extension is impossible or uneconomical. Such a system has several power stations and each of which includes photovoltaics (PV) and wind power generators, along with a diesel power generator as backup when renewable energy supply is insufficient. While the HRES is attractive due to the minimal environmental and health impact compared to fossil fuels, the design of HRES, specifically the determination of the size of PV, wind, and diesel power generators and the size of energy storage system in each power station, is very challenging. This is mainly due to a large number of factors involved in the problem, the profound uncertainty arising from the renewable resources and the demand load, and the complex interaction among factors. In this paper, we investigate the use of Monte Carlo simulation, along with simulation optimization techniques, for obtaining the optimal design of HRES in uncertain environments. The proposed model considers not only the equipment installation, including PV, wind and diesel power generators and the energy storage systems in each power station, but also the power generation, allocation and transmission within the HRES so as to achieve minimum expected total cost, while satisfying the power demand. An extensive computational study shows that the proposed model of realistic size can be solved efficiently, enabling quality decisions to be generated in practice.

1. Introduction

Renewable energy, such as photovoltaics (PV) and wind power, is viewed as green and clean because they are non-depletable, non-polluting and have minimal environmental and health impacts compared to fossil fuels. As the price of fossil fuel continues to increase, renewable energy has become more popular over the decades. However, renewable energy is highly volatile and unpredictable due to the unknown and variable sunshine hours and wind speeds from day to day [12]. This raises some concern about the use of renewable energy as it may lead to unstable power supplies and inability to satisfy power demand in some areas. Consequently, according to *Renewables 2013 Global Status Report*, renewable energy only accounts for 19% of the total world energy demand in 2013. To this end, many power system designers started to look for other alternatives. A hybrid renewable energy system (HRES), which combines several power stations and each of which includes photovoltaics (PV) and wind power generators, along with a diesel power generator as backup when renewable energy supply is insufficient, is one viable and attractive solution that brings into play the advantages, while at the same

* Corresponding author.

http://dx.doi.org/10.1016/j.simpat.2014.12.002

time eliminating the disadvantages of renewable energy. Specifically, the HRES first capitalizes on the renewable energy and, if the renewable energy supply is not sufficient, the diesel power generator is used to cover the shortage, thereby ensuring the stability of the power supply.

In the literature, extensive studies have been conducted on the feasibility and performance of HRES in various forms, e.g., Nehrir et al. [22], Celik [4], Kolhe et al. [17], Papadopoulos and Karagiannidis [24], Rentizelas et al. [25] and Xydis [29]. In particular, Nehrir et al. [22] developed a computer-based approach for evaluating the general performance of stand-alone PV/wind generating systems. Celik [4] proposed a technique to analyze the performance of the autonomous small-scale PV and wind hybrid energy systems. Kolhe et al. [17] presented an analysis of the performance of a hybrid PV/wind energy system with hydrogen energy storage for long-term utilization. Papadopoulos and Karagiannidis [24] presented a study on determining the achievable penetration of renewable energy sources into an insular system for the purpose of electricity generation. Rentizelas et al. [25] investigated the effect of various scenarios for emission allowance price and provided direction as to which technologies are most probable to dominate the market in the future. Xydis [29] studied the wind potential of Kythira Island and provided a techno-economic analysis aimed at identifying the optimal solution for the proposed Wind Farms (WF) to be installed so that this isolated island could be interconnected to the mainland.

Some research has been focused on determining the optimal size of a hybrid PV/wind energy system. In particular, Ai et al. [1] presented a method to calculate the optimal size of a hybrid PV/wind energy system in which performance was compared on an hourly basis. The optimization approaches used to design the hybrid PV/wind energy system in the most cost effective way include linear programming, e.g., Wene and Rydén [28], Kellogg et al. [16], Chedid and Saliba [8], Ferrer-Martí et al. [14], probabilistic analysis, e.g., Karaki et al. [15], Bagul et al. [3], iterative technique, e.g, Kellogg et al. [16], dynamic programming, e.g., Musgrove [20], and multi-objective method, e.g., Yokoyama et al. [30]. In particular, Chedid and Rahman [7] used a linear programming approach to design a hybrid PV/wind power system for autonomous or grid-linked applications. Elhadidy and Shaahid [13] and Shaahid and Elhadidy [26] detailed a variety of aspects of PV, wind, and battery-based hybrid systems including optimal sizing and operation. Karaki et al. [15] presented a probabilistic assessment for an autonomous PV–wind energy conversion system (SWECS) composed of several wind turbines (wind farm), several PV modules (PV park), and a battery storage feeding a load.

Furthermore, Makkonen and Lahdelma [19] formulated the decision problem of a power company as a large mixed integer programming (MIP) model and developed a customized Branch-and-Bound algorithm for solving the sub-problems efficiently. Ferrer-Martí et al. [14] proposed a mathematical programming model to optimize the design of hybrid wind–PV systems. Gomez et al. [11] proposed a new model for characterizing the energetic behavior of grid connected PV inverters. Chang [5] proposed a decision support system that integrates a proposed model and an efficient solution method to support the planning and coordination of HRES. Maheri [18] developed a robust method for obtaining the optimal design of wind–PV–diesel hybrid systems. Cicirello and Langley [9] developed efficient algorithms for propagating parametric uncertainty using the hybrid Finite Element/Statistical Energy Analysis (FE/SEA) approach to the analysis of complex vibro-acoustic systems. Alsayed et al. [2] used a suitable procedure based on a Multi Criteria Decision Analysis (MCDA) optimization approach to achieve the optimal design of grid connected PV–WT PGSs.

In this research, we investigate the use of Monte Carlo simulation, along with simulation optimization techniques, for obtaining the optimal design of HRES in uncertain environment. As shown in Fig. 1, we consider a region consisting of several demand areas and several power stations and all the power stations jointly supply power for all demand areas. Each power station includes PV, wind and diesel power generators as well as the energy storage systems, and there is an electricity grid that connects all power stations and demand areas. The model is to seek the optimal size of PV, wind, and diesel power generators and the optimal size of the energy storage systems so as to achieve minimum expected total cost, while satisfying the power demand of each area. We propose a simulation optimization model to characterize the problem. Compared to the model in Chang [5] where only the size of PV and wind power generators is considered, the proposed model is more elaborate. This is not only because it further takes into consideration the diesel power generator, but also it integrates the decisions on the size of PV, wind and diesel power generators as well as on the size of the energy storage system in each power station. Other special characteristics of the proposed model distinct from the literature are described as follows: first, the renewable energy supply and the power demand are treated as continuous random variables chosen based on data collected in the real world. This contrasts with the models in the literature where uncertainties are represented by a few scenarios associated with a given probability that reflects how likely is the scenario to happen. In practice, however, a limited number of scenarios may not be sufficient to fully represent the outcome of the uncertainty. Second, the number of decision variables and the number of uncertain parameters pertaining to the problem are large due to more practical considerations. When further taking into account the complex interactions between decision variables and uncertain parameters, the traditional approaches are not applicable and the only feasible way is to resort to simulation. Third, the maintenance and operation cost as well as the carbon emission cost are taken into consideration in the objective function used for determining the optimal design of HRES. Details about the proposed model and the solution method will be presented in later sections.

The remainder of this article is organized as follows. In Section 2, we present the proposed model that characterizes the decisions on the equipment installation of the HRES in uncertain environments. In Section 3, we present the metamodel-based solution method that allows us to obtain the optimal design of HRES efficiently. In Section 4, we conduct an extensive computation study to understand of performance of the proposed solution method when solving problems of realistic size. We also compare the performance of the proposed solution method with that of other two existing algorithms. We conclude with future research in Section 5.