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Stochastic programming and market equilibrium analysis of microgrids energy management systems

Ming-Che Hu [a], Su-Ying Lu [b], Yen-Haw Chen [b, *]

[a] Department of Bioenvironmental Systems Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan
[b] Taiwan Institute of Economic Research, Research Division 1, 7F, No. 16-8 Dehuei Street, Jhongshan District, Taipei 104, Taiwan

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ABSTRACT

Microgrids facilitate optimum utilization of distributed renewable energy, provides better local energy supply, and reduces transmission loss and greenhouse gas emission. Because the uncertainty in energy demand affects the energy demand and supply system, the aim of this research is to develop a stochastic optimization and its market equilibrium for microgrids in the electricity market. Therefore, a two-stage stochastic programming model for microgrids and the market competition model are derived in this paper. In the stochastic model, energy demand and supply uncertainties are considered. Furthermore, a case study of the stochastic model is conducted to simulate the uncertainties on the INER microgrids in Taiwanese market. The optimal investment of the generators and batteries installation and operating strategies are determined under energy demand and supply uncertainties for the INER microgrids. The results show optimal investment and operating strategies for the current INER microgrids are also determined by the proposed two-stage stochastic model in the market. In addition, trade-off between the battery capacity and microgrids performance is investigated. Battery usage and power trading between the microgrids and main grid systems are the functions of battery capacity.

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1. Introduction

Microgrids are small-scale electricity subsystems disaggregated from national grids, and microgrids are used for distributed power generation, distribution, storage, and consumption [1–3]. Microgrids are proposed to increase the use of local renewable energy, enhance the utilization of heat generated by combined heat and power (CHP) generator, provide stable electricity supply, reduce power transmission loss, and decrease carbon dioxide emission from centralized fossil fuel power plants [4–6]. Energy management systems have been developed to simulate the performance of microgrids and determine the optimal operating strategies. However, although the management of microgrids is performed under considerable uncertainty, strategies to improve the management of these systems have not been developed thus far [7–9]. This research proposes a stochastic microgrids management model in market equilibrium considering renewable wind and solar power under demand uncertainty [10].

A case study of the proposed energy management system is conducted by using it to simulate the effect of uncertainty on the microgrids systems of the Institute of Nuclear Energy Research (INER) in Taiwan. In this study, the performance of the proposed stochastic energy management system is assessed on the basis of the data obtained for the microgrids at INER. Optimal operating strategies for the INER microgrids are determined and the system performance is measured. The two-stage stochastic programming problem is formulated and solved using the General Algebraic Modeling System (GAMS) [11]. GAMS is a modeling language designed for solving large-scale, complex optimization problems. The uncertain energy management system and stochastic market equilibrium for microgrids are analyzed using GAMS.

The main aim of this research was to develop a stochastic model of energy management system for microgrids in Taiwan. The stochastic model was developed taking into account the uncertainties in the demand and supply of electricity with respect to microgrids. In addition, the model was tested by using it to stimulate the effect of the abovementioned uncertainties on the microgrids at INER. The organization of the paper is as follows: Section 2 provides a review of previous researches related to microgrid systems; the method adopted to develop the stochastic energy management system and market equilibrium for microgrids is presented in

* Corresponding author.
E-mail address: yenhaw@gmail.com (Y.-H. Chen).

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Section 3; Section 4 demonstrates and discusses the results, and Section 5 presents the conclusion.

2. Literature review

Energy management systems for microgrids have been field tested in many countries. Several models for simulating the performance of microgrids have been proposed in previous studies [12–16]. Bando et al. [12,13] presented an economic model for three regional micro power grids of New Energy Industrial Technology Development Organization (NEDO) in Japan. A microgrid model with a CHP generator, gas engines, batteries, and thermal storage tanks was presented. In addition, the economic and environmental incentive of power generation of microgrids in Japan was analyzed. Hawkes and Leach [14] proposed a unit commitment model for microgrids in the UK. In this model, the supply side of the microgrids was considered to consist of wind power generators, solar photovoltaic power generators, CHP generators, boiler generators, electricity storage devices, thermal storage devices, and energy demand. The model determined the optimal investment on installed capacity and best operating strategies for power generating units in the microgrids in the UK. According to Abu-Sharkh et al. [15], local renewable energy sources can be integrated for use in microgrids to obtain reliable and efficient power generation systems. Lasseter and Piagi [16] pointed out that highly reliable microgrids can be realized by integrating distributed generators and demands. These systems offer economic and environmental efficiency and thereby are effective solutions for the generation of electricity.

Further, mathematical optimization models for simulating the performances of microgrids and formulating optimal operating strategies have been developed in previous studies [17–22]. A cost-minimizing optimization model of distributed energy resources (DER) system was developed by Mitra et al. [17]. A linear programming model for microgrids was proposed by Zoka et al. [18]. Using this model, an economic analysis was performed, and optimal operating conditions for microgrids were determined. In addition, a mixed linear programming model was developed for optimally scheduling microgrids for energy generation by Morais et al. [19]. This model was used to solve the optimal scheduling problem of microgrids with fuel cell generators, batteries, and renewable energy sources such as wind and solar power. In this study, the methodology for solving the scheduling problem was demonstrated and an application was presented. A microsource model was developed by Lopes et al. [20]. The model determined feasible and stable operating strategies for island microgrids. A real-option model for distributed microgrids power systems in California was developed by Siddiqui and Marnay [21]. In this model, uncertainties in both electric power price and electricity production cost using gas turbines were considered. The results obtained using this model illustrated the optimal investment on capacity and energy management strategies. An analysis of uncertainty in the prices of electricity generated by decentralized microgrids power systems was performed by Handschin et al. [22]. They developed a model of a decision support system and presented optimal management strategies for dispersed microgrids.

Several other simulation models for microgrids have been developed [23–27]. Microgrids simulation model for an energy manager (EM) was developed by Firestone and Marnay [28]. The model simulated optimal control and best energy management strategies for microgrids. The technical and financial feasibilities of microgrids were analyzed. A distributed intelligent energy management system (DIEMS) for single-phase high-frequency alternating current (HFAC) microgrids was proposed by Chakraborty et al. [29]. The DIEMS is an optimized system with fuzzy neural network simulation component that is capable of predicting daily power consumption, optimizing power control, integrating renewable energy sources, and minimizing total cost of microgrids. In addition, a multi-agent system (MAS) for the simulation of strategies for the distribution of power from power producing units in microgrids to power consumers was presented by Dimeas and Hatziargyriou [30]. For given electricity demand, selling price, and purchase price, this agent-based model simulates the conditions for accepting the demand, rejecting the demand, negotiation, and other interactions between the power suppliers and consumers.

Uncertainty analysis for energy management systems has been carried out in previous researches. Kanudia and Loulou [31] developed the stochastic MARKAL model for the uncertainty analysis of energy markets. Using this model, an effective solution was presented to overcome the uncertainties due to climatic changes. Morgan and Henrion [32] developed a stochastic simulation model for dealing with uncertainties in quantitative policy analysis. The value of information and the expected cost of uncertainty were investigated for the stochastic model. Kim et al. [33], Kim and Moon [34], and Kim and Moon [35] analyzed the uncertainty of the hydrogen economy in energy market. A two-stage multiobjective programming model was formulated for the demand uncertainty in Korean energy market. A two-stage stochastic MARKAL model for the analysis of multipollutant policies was proposed by Hu and Hobbs [36]. In this stochastic programming model, uncertainties in energy technology and environmental policy in the U.S. power sector were considered. On the basis of decision tree analysis, information values including the expected value of perfect information (EVPI), expected cost of ignoring uncertainty (ECIU), and value of policy coordination (VPC) were evaluated. Strachan [37] discussed stochastic mitigation and adaptation strategies to achieve the carbon dioxide emission reduction target. In addition, Usher and Strachan [38] developed a two-stage stochastic MARKAL model to simulate the uncertainties in the U.K. energy market. The results provided optimal stochastic solution by pursuing first-stage hedging decisions and second-stage operating strategies.

Compared with previous related studies, the aim of this research is to formulate a stochastic microgrids energy management model and stochastic Cournot competition model. The proposed model considers demand and supply uncertainties. Next, this model was tested by using it for the INER microgrids in Taiwan. Using this model, the optimal investment on capacity and energy management strategies are determined in Taiwanese market.

3. Methodology

This section begins with formulating a two-stage stochastic programming model for microgrid energy management systems; then a Cournot competition model is derived to analyze microgrid systems in the electricity market. In the two-stage stochastic programming model, the decision for investment on microgrids devices is determined in the first stage and energy management strategies are determined in the second stage. In this model, t and s denote time period and uncertain scenario sets, respectively. n^{GT}, n^{FC}, n^{PV}, n^{WD}, and n^{BT}, are the first-stage decision variables representing the numbers of gas turbine generators, fuel cell generators, photovoltaic power generators, wind power generators, and batteries installed in the microgrids systems. The objective function of the microgrids system is the total installation cost of microgrids devices, $(FC^{GT} \times n^{GT}) + (FC^{FC} \times n^{FC}) + (FC^{BT} \times n^{BT}) + (FC^{PV} \times n^{PV}) + (FC^{WD} \times n^{WD})$, as shown in the first part of Eq. (1). In the second stage, $x^{GT}_{t,s}$ and $x^{FC}_{t,s}$ are decision variables representing the power generated using gas turbine and fuel cell generators, respectively. Further, variables representing fuel consumption for

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