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Optimal planning of combined heat and power systems within microgrids

Aboelsood Zidan [a, c], Hossam A. Gabbar [a, b, *], Ahmed Eldessouky [a]

[a] Faculty of Energy Systems and Nuclear Science, University of Ontario, Institute of Technology, 2000 Simcoe Street North, Oshawa, L1H7K4 ON, Canada
[b] Faculty of Engineering and Applied Science, University of Ontario, Institute of Technology, 2000 Simcoe Street North, Oshawa, L1H7K4 ON, Canada
[c] Department of Electrical Engineering, Faculty of Engineering, Assiut University, 71515 Assiut, Egypt

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ABSTRACT

In this paper, an optimal deployment with respect to capacity sizes and types of DG (distributed generation) for CHP (combined heat and power) systems within microgrids was presented. The objective was to simultaneously minimize the total net present cost and carbon dioxide emission. A multi-objective GA (genetic algorithm) was applied to solve the planning problem including the optimization of DG type and capacity. The constraints include power and heat demands constraints, and DGs capacity limits. The candidate technologies involved in this study include CHP generators (with different characteristics), boilers, thermal storage, renewable generators (wind and photovoltaic), and a main power grid connection. The surplus/deficient electricity can possibly be sold to/bought from the main grid. Costs of CHP generators are based on their types and the capacity range. The approach was applied to a typical CHP system within microgrid system as a case study, and the effectiveness of the proposed method was verified.

1. Introduction

Society's full dependence on energy leads to electricity network congestion. For centuries, energy systems were based on centralized energy generation with a transmission and distribution system. With the rapid increase in fuel prices, capital cost of central generation plants, and electricity/head demand growth; there is a real need to have an alternate generating system with higher efficiency of energy use. Microgrid is a relatively small-scale localized energy network which includes loads, control system and a set of energy resources such as generators and energy storage devices [1,2]. Microgrid can operate in a grid-connected mode where energy resources interact with the main electrical grid, or in an islanding mode where a microgrid feeds its local loads without the use of the main electrical grid. Microgrid is widely recognized as an alternative generating system which can compete with traditional centralized electricity plant [3]. As an alternative to centralized energy systems, microgrids provide energy locally by utilizing DG (distributed generation) with minimum energy transmission from/to remote regions [4].

Diversifying the nature of energy sources improves reliability, power quality, and economics of a system [5]. Therefore, microgrids comprise several types of DGs such as energy generation, energy storage and load management options. Currently, natural gas is the primary fuel for DGs [4]. Renewable energy sources such as wind power and PV (photovoltaic) are receiving a wide acceptance in the power generation industry as they are inexhaustible and nonpolluting. Renewable energy sources are characterized as intermittent power sources due to climate changes in wind speed and solar irradiance. One of the main applications of DGs is CHP which generates heat and electricity simultaneously [4]. CHP and renewable energy sources are key elements in future clean energy systems [6,7]. Flexible CHP production can help along the integration of fluctuating electricity production from renewable energy sources [6,7]. Furthermore, thermal energy storage represents another fundamental element in a microgrid [5]. It reserves the thermal energy surplus to be used during higher demand times, thus effectively shaving the peak of the thermal energy demand. With the gradual depletion of fossil fuels and the keen desire for many countries to meet the environmental constraints established by the Kyoto Protocol in order to reduce

* Corresponding author. Faculty of Energy Systems and Nuclear Science, University of Ontario, Institute of Technology, 2000 Simcoe Street North, Oshawa, L1H7K4 ON, Canada.
E-mail address: Hossam.gabbar@uoit.ca (H.A. Gabbar).

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greenhouse gas emissions, microgrids with CHP and renewable energy resources provide an effective organization form of distributed energy supply units [2].

Microgrids with CHP and renewable energy resources have many benefits such as high reliability, and reduction of: energy loss, emission, wasted heat, capital and running cost of transmission networks, and risk of energy supply failure [1–5,8]. Planning CHP systems is receiving a great deal of attention [1–12] as a reasonable planning is an important premise and guarantee for stable and efficient microgrid operation. A lot of works have been carried out in the pertinent literature, which can be generally divided into three aspects: the assessment indicators and methods, the operation strategy, and the optimal planning of CHP system within microgrid system. With regard to assessment indicators and methods, the performance indices of economy, reliability, emission and energy utilization efficiency are the KPIs (key performance indicators) to analyze the performance of a microgrid system [2]. For example, ref. [1] proposed a hierarchical framework to realize an economic generation schedule of microgrids. However, thermal storage and emissions are not included. Refs. [2,3] focused on evaluating different optimal output sets of DG-mix on the basis of multi-objective optimization compromising between fuel cost and emission. Renewable energy sources and thermal storage are not included in Ref. [3]. Ref. [4] proposed an optimal design of microgrids with CHP units which integrates the results of a life cycle assessment of the microgrids. The objective was to minimize the overall operating cost and emission. However, their work did not consider the integration of renewable energy resources in microgrids. Ref. [5] presented operational results of a real life residential microgrid which includes six apartments, photovoltaic plant, a solar based thermal energy plant, a geothermal heat pump, and a thermal energy storage. Authors in Ref. [6] illustrated why electricity smart grids should be seen as part of overall smart energy systems and emphasized the inclusion of flexible CHP production in the electricity balancing and grid stabilization. For example, CHPs should operate in a way that they produce less energy when the output of renewable energy sources is high and more when the output of renewable energy sources is low. Ref. [7] presented solutions to integrate renewable energy sources into electricity systems using small and medium sized CHPs. Furthermore, the proposed solutions and software tools allow partnerships to offer services which are currently only offered by big power plants to electricity markets.

In Ref. [8], an algorithm to find the optimal types, sizes, and placement of DGs in a microgrid was proposed. The objective considered is to minimize the capital and operational cost and they did not include emissions. Furthermore, renewable energy sources and thermal storage are not included. Ref [9] aimed to reduce the fuel consumption rate of DGs in a microgrid. However, emissions and maintenance costs are not included. An optimization algorithm for optimal dispatching of DGs and storage systems in an islanded microgrid was proposed in Ref. [10]. The objective was to minimize the overall operating cost and emission. However, their work did not consider the thermal energy demand. Authors in Ref. [11] presented a comprehensive analysis of seven different technologies to integrate fluctuating renewable energy sources into the electricity supply. The seven technologies are electric boilers, heat pumps, electrolysers with local CHP, electrolysers with micro CHP, hydrogen fuel cell vehicles, battery electric vehicles and flexible electricity demand. These different technologies were analyzed and compared in terms of their ability to integrate renewable energy sources and their fuel efficiency in different scenarios. Ref [12] proposed a deterministic model to analyze the economic feasibility of using compressed air energy storage plant in the Danish electricity system in comparison with other flexible technologies including heat pumps and hydrogen storages.

For the operation strategy of CHP within microgrid system, there are two basic strategies: FTL (following thermal load) and FEL (following electrical load) [2]. When microgrid works at FTL mode, cogeneration units put the priority on heat production. If the microgrid could not meet the electrical demand, the deficient electricity can possibly be purchased from the main grid. When microgrid works at FEL mode, cogeneration units put the priority on electricity production. If the microgrid could not meet the heat demand, the deficient heat can possibly be supplied by a boiler. However, the strategy of following hybrid thermal-electric load which can switch between the two basic modes according to load represents the higher economic and environmental performance [13,14].

Investment in natural gas-power technologies increases continuously. Power generation using natural gas has received significant attention due to the following reasons [15]: 1) short construction times and low initial investment costs which makes it attractive in a deregulated market; and 2) burning natural gas emits less harmful emissions compared with other fossil fuels such as coal and oil. DGs based on gas engines and micro turbines represent a reliable option generally for countries that have an access to natural gas [16]. Gas technologies such as NGFCs (natural gas fuel cells), H_2FCs (hydrogen gas fuel cells) and NGTs (natural gas turbines) can be used to balance the required power/heat demand in microgrids. Furthermore, power-to-gas (P2G) storage can be implemented to converts the surplus power from renewable energy to hydrogen fuel to be used where and when it is needed [17] through one or more of the following ways: 1) Clean fuel source; 2) To be fed to the natural gas grid as fuel for low carbon heating or/and fuel for generating controllable electricity; and 3) Industrial customers.

Modern energy systems are faced with a high degree of complexity and uncertainty due rising factors such as penetration of renewable energy resources, new loads (e.g. EVs (electric vehicles)), rise of energy storage devices, variable demand, and demand response programs. For example, some consumers are producing electricity/heat themselves. However, if they use PV and/or wind based generators and are temporality not provided with energy, they may still need to be fully supplied by the main grid. Thus, the net load profile will be less predictable [18]. Scenarios help in capturing the conceptual system as visualized by a user by means of operational examples. Scenarios simulate events a user would experience in performing tasks that constitute the operation of a system. Optimization under uncertainty can be solved using scenario-based modeling with three phases [19]: 1) gathering and processing of relevant background data and judgmental knowledge; 2) creating a coherent set of scenarios; and 3) building and solving a stochastic optimization model. Furthermore, several techniques have been applied for modeling uncertainties such as Monte Carlo [20], scenario reduction technique [21], fuzzy modeling [22], and information gap decision theory [23].

Several challenges may appear in dealing with the future energy system [18,24]. Examples of these challenges are [18,24]: 1) the demand at customer side will be surrounded with more uncertainty; 2) emerging new technologies and their timing and penetration levels; 3) the degree in which residential loads are controllable; 4) use of smart grid information and communication technologies to intelligently integrate actions of users; and 5) uncertainties regarding economic development, international policies and trade, and climate policies.

Microgrid performance is mainly dependent on its DGs type and capacity. The goal of the work presented in this paper is therefore to