Energy 85 (2015) 433–448

Contents lists available at ScienceDirect

Energy

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

Optimal design of distributed energy resource systems coupled with energy distribution networks

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ARTICLE INFO

Article history:
Received 22 December 2014
Received in revised form
14 March 2015
Accepted 21 March 2015
Available online 18 April 2015

Keywords:
Distributed energy resource
Optimal design
Synthesis and operation strategies
Energy distribution networks
Mixed integer linear programming

ABSTRACT

This study focuses on the optimal design of DER (distributed energy resource) systems coupled with heating, cooling, and power distribution networks. A superstructure-based MILP (mixed integer linear programming) model is constructed. The model can achieve simultaneous optimization of synthesis (i.e., type, capacity, number, and location of equipment as well as structure of the energy distribution networks) and operation strategies of the entire system. The model is built in consideration of discreteness of equipment capacities, equipment partial load operation and output bounds as well as the influence of ambient temperature on gas turbine performance. The objective function is the annual total cost for investing, maintaining, and operating the system. To provide an illustrative example, the model is applied to an urban area in Guangzhou, China. Comparative studies are performed to quantify the impact of distributed generation and the introduction of energy distribution networks and/or storages. Results show that the adoption of the DER system provides significant economic benefits. The introduction of energy distribution networks and/or storages has significant and similar effects on optimal system configuration and can improve the system's economic efficiency because of the elimination of some of the strong coupling relation between demands and generators.

1. Introduction

A DER (distributed energy resource) system is an electricity-generation system located in or near end users. This system can simultaneously provide electricity, cooling, and heating to meet the demands of local users [1]. The DER system allows for the achievement of high thermodynamic efficiency and primary energy saving through the efficient utilization of exhaust heat; it also results in low transmission and distribution losses through on-site generation [2,3]. This type of system has elicited an increased amount of interest over the past few years because it is a good option for future energy systems with respect to sustainable development and low-carbon society construction [4].

Compared with conventional central energy supply, a DER system employs a wider range of technologies, including prime movers (e.g., internal combustion engines, gas turbines, stirling engines, fuel cells), waste heat recovery equipment (e.g., waste heat boilers, absorption chillers), PVs (photovoltaics), small-scale wind turbines, and other equipment that use renewable energy resources [5]. In addition, several energy storage technologies (e.g., hot/cold water storage, ice storage) are commercially available [6–9]. Wu and Wang [10] reviewed the status of the utilization and development of various DER technologies and presented their technical performance characteristics. Raj et al. [11] provided a comprehensive review of current cogeneration technologies based on renewable energy resources and discussed their design, modeling and simulation, economic and environmental issues, and related energy policies. Deng et al. [12] examined thermally activated cooling technologies for DER systems and discussed their products and prototypes, existing problems, and applications in DER systems.

The rational design and management of DER systems is vital to maximize the economic and energy saving benefits of these systems [13]. However, this is not an easy task [14]. The design of such a system requires the determination of its structure rationally by selecting appropriate equipment from numerous alternatives as

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http://dx.doi.org/10.1016/j.energy.2015.03.101
0360-5442/

well as determining the capacities and numbers of each type of selected equipment to match the energy requirements of specific customers [13–15]. Meanwhile, management of DER systems requires determining their operating strategies, such as operation status (on/off) and load allocation of the selected equipment corresponding to the relative spatial and temporal variations in energy demands [13].

To address such a complex and difficult task, a systematic analysis and evaluation procedure should be developed. Mathematical programming techniques have been widely utilized for decision making in the optimal design and operation of DER systems [16]. LP (linear programming) techniques have become the primary methods because of the complexity of problems that involve thousands of variables [17]. MILP (mixed integer linear programming) [16,18–20] and MINLP (mixed integer nonlinear programming) techniques [21,22] have been presented and adopted to address the requirement of considering the realistic operation of equipment (e.g., start-up/shutdown, load regulation range, and performance deterioration under partial load) at the design stage. Superstructures embedded with many potential configurations of DER systems have recently been introduced to optimal models [23–25]. Yokoyama and Ito [13] developed an MILP model based on superstructure modeling method and achieved the simultaneous optimization of system structure, discreteness of equipment numbers and capacities, and operation strategies; such simultaneous optimization represents frontier DER system optimization. In Ref. [8], energy storage was successfully introduced to the model proposed in Ref. [13].

Both energy and environmental advantages can increase if DER system boundaries are extended from building level to district scale, permitting heating cooling and power distribution between buildings [26–28]. This increase is possible because mixing various energy demand profiles may compensate for fluctuations and achieve a smooth operation of DER systems, improving their utilization rate and overall efficiency [14].

Recent studies considered energy distribution in their models. Söderman and Pettersson [29] studied the design of CHP (combined heating and power) systems in consideration of the district heating pipelines and developed an MILP model for decision makers. Different types of DER equipment, including heat storages, were considered in the model; however, their operational optimization was disregarded. The Chinese [30] developed a cost minimization MILP model that combines an optimal network flow and capacity planning problem with an energy system optimization problem to design district heating and cooling systems in a distributed generation context. Specific legislation constraints, such as special tariffs or tax abatements as in the case of Italy, limited the application of this model. Buoro et al. [31] investigated the optimization of CCHP (combined cooling heating and power) systems integrated with district heating and cooling networks and presented an MILP model to obtain the optimal synthesis (i.e., type, number, and location of equipment and size and position of heating and cooling pipelines) and operation strategies of the entire system. Mehleri et al. [14,32] proposed an MILP model for optimal DER system design and operation; the model involves a Greek neighborhood, including PVs and storages, combined with the design of a heating network. In this model, electricity transfer is possible between dwellings through a microgrid that is based on the existing power transmission network. Bracco et al. [33] developed an MILP optimization model to optimally design and operate a CHP system located in an urban area where buildings are connected by a heating distribution network; the aim of the study was to minimize an objective function that takes into account both annual costs and CO_2 emissions. Omu et al. [15] created an MILP model for the design of a CHP system to meet the electricity and heating demands of a cluster of commercial and residential buildings. The proposed optimization algorithm permits the selection of equipment type, size, and location and determination of their operation strategies as well as heating and power distribution network structures.

Each of the aforementioned models has its own characteristics as well as advantages and disadvantages. Several of the models focus on CHP systems, whereas others focus on CCHP systems without considering renewable energy technologies and storages. As for district energy networks, some refer to the heating network, whereas others refer to both heating and cooling networks or both heating and power networks; however, none refers to all three types of networks. In addition, the equipment is often modeled through a very simplified approach. For example, several models regard equipment capacities as continuous variables, whereas others neglect the decrease in equipment efficiency under partial load, especially for prime movers. Most models also neglect the influence of environment temperature on the performance of gas turbines. Lastly, most models are grounded on the economic and energy policy context of a specific county and should not be applied directly to other countries.

The novelty of the work presented here is that we developed an advanced and complex MILP model for the optimal design and operation of DER systems integrated with energy distribution networks. The advancements and complexities mainly show in three aspects. First, in addition to traditional energy technologies (e.g., gas engines, gas turbines etc.), various renewable energy technologies (e.g., PVs and wind turbines) and heat and cold storages are also considered in the model. Second, the model is built in consideration of discreteness of equipment capacities, equipment partial load operation and output bounds as well as the influence of ambient temperature on gas turbine performance. Finally, as for energy distribution networks, the model refers to three types of networks, e.g., district heating, cooling, and power networks. Basing on local climate data, consumers' energy demands, electricity and gas tariffs, and technical and economic information on candidate DER equipment, the model minimizes the total annual cost of supplying energy to consumers through the proposed energy system by determining the optimal type, capacity, number, and location of the equipment as well as the optimal route of district heating, cooling, and power networks. The model thus identifies the optimal operation strategies of the entire system.

To provide an illustrative example, the optimization model is applied to an urban area in Guangzhou City, South China. The optimal equipment combination, network routes, and operation strategies are determined. The results of the economic evaluation under different scenarios are presented. A sensitivity analysis is conducted by varying the capital cost and energy subsidies of PVs and wind turbines.

The paper is organized as follows. Section 2 presents a description of the mathematical problem. The mathematical formulation of the proposed optimization model is described in detail in Section 3. In Section 4, the model is applied to a case study in South China. The results of this case study and the discussions are presented in Section 5. Lastly, the conclusions are provided in Section 6.

2. Problem definition

A superstructure-based MILP model was developed and applied to optimally design and operate a DER system integrated with district heating, cooling and power networks located in an urban