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Energy flow modeling and optimal operation analysis of the micro energy grid based on energy hub

Tengfei Ma *, Junyong Wu, Liangliang Hao

School of Electrical Engineering, Beijing Jiaotong University, Haidian District, Beijing 100044, China

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ABSTRACT

The energy security and environmental problems impel people to explore a more efficient, environment friendly and economical energy utilization pattern. In this paper, the coordinated operation and optimal dispatch strategies for multiple energy system are studied at the whole Micro Energy Grid level. To augment the operation flexibility of energy hub, the innovation sub-energy hub structure including power hub, heating hub and cooling hub is put forward. Basing on it, a generic energy hub architecture integrating renewable energy, combined cooling heating and power, and energy storage devices is developed. Moreover, a generic modeling method for the energy flow of micro energy grid is proposed. To minimize the daily operation cost, a day-ahead dynamic optimal operation model is formulated as a mixed integer linear programming optimization problem with considering the demand response. Case studies are undertaken on a community Micro Energy Grid in four different scenarios on a typical summer day and the roles of renewable energy, energy storage devices and demand response are discussed separately. Numerical simulation results indicate that the proposed energy flow modeling and optimal operation method are universal and effective over the entire energy dispatching horizon.

1. Introduction

Energy security and environmental protection issues are attracting significant attentions worldwide with the gradual depletion of fossil fuels and deterioration of environment. At present, the common energy infrastructures such as electricity network and natural gas network are mostly planned and operated independently which will lead to low energy efficiency, high operation cost and low robustness [1]. So optimizing energy structure for integrating more renewable energy, improving energy efficiency and protecting ecological environment are core issues for the development of energy system [2].

With the development of micro grid and smart grid technologies, more renewable energy are integrated which lead the power systems to be more clean, efficient and reliable. However, the energy consumers not only need electricity, but also need cooling, heating and natural gas. In conventional energy systems, these types of energy are supplied independently which lead low energy efficiency and costly operation cost. Recently, combined cooling, heating and power (CCHP) as an advanced efficient nature gas utilization technology is developing rapidly. CCHP system integrates gas turbine, heat collector, boiler and refrigeration device as a whole to implement the energy cascade utilization, reduce carbon emission and meet the cooling, heating and electricity demands simultaneously [3]. The energy efficiency of CCHP system can be up to 60–80% which will greatly improve the energy comprehensive utilization efficiency and bring better economic and environmental benefits [4]. As the coupling node between power system and natural gas system, the CCHP will promote the integration of multiple energy carriers. With the integration of electricity system, natural gas system and other energy system, the power systems are evolving into the integrated energy system. Meanwhile, some new forms of energy system are proposed which are similar to integrated energy system. Such as, the concept of multiple-energy carrier systems proposed in [5] and the concept of Smart Multi-Energy systems introduced in [6]. As the vision for the development of energy system, the Energy Internet proposed in [7] depicts an efficient power grid integrating high penetration of green energy and enables energy sharing in the distributed network just like the information sharing in the Internet today.

Abbreviations: MEG, micro energy grid; PV, photovoltaic; WT, wind turbine; ESD, energy storage device; ES, electricity storage; HS, heating storage; CS, cooling storage; DR, demand respond; TOU, time-of-use price; RTP, real time price; PL, power load; HL, heating load; CL, cooling load; GT, gas turbine; EC, electric chiller; ISC, ice storage conditioner; GB, gas boiler; AC, absorption chiller.

* Corresponding author.
E-mail addresses: 15117386@bjtu.edu.cn (T. Ma), wujy@bjtu.edu.cn (J. Wu), llhao@bjtu.edu.cn (L. Hao).

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However, there are many challenges to overcome to achieve the envisioned Energy Internet. Before the Energy Internet, the integrated energy systems is the development trend of power system. Integrated energy systems generally consist of at least two of the following systems: electricity, natural gas, cooling, heating or traffic systems. Thus, different types of energy will interact and couple. Therefore, integrated analysis of the whole energy system are necessary to coordinate the multiple energy carriers, improve energy efficiency and decrease operation cost [8].

In recent years, the concept of energy hub proposed in Ref. [9] is widely used in the integrated analysis of multiple energy carrier systems. An energy hub is taken as a unit where multiple energy carriers can be converted, conditioned and stored. A typical energy hub consumes electricity and natural gas at input port and provides the electricity, heating and cooling energy services at output port [10]. Extensive researches are carried out on the energy hub, including modeling, optimizing system structures and operation strategies. A framework for integrated modeling and optimization of multiple energy carriers systems is presented and a nonlinear programming model is formulated for the optimization of energy flow basing on the concept of energy hub in [11]. A residential energy hub model for a smart multi-carrier energy home is designed in [12], and the optimal operation mode of the energy hub is analyzed. According to [13], a new framework is developed to coordinate the charging process of plug-in hybrid electric vehicles with the energy hub approach and the 2-point estimation method is used to model the uncertainties of wind energy. Mathematical optimization models of residential energy hub are formulated in [14], which can be incorporated into automated decision making technologies in smart grid. In addition, they can be solved in a real time frame to control all major residential energy loads optimally with considering the customer preferences and comfort level. Another residential energy hub model for a smart home is proposed in [15], including a residential combined heat and power as a co-generation technology and a plug-in hybrid electric vehicle. However, the objects investigated in these references are mainly focused on the energy systems of residential buildings, official buildings or factories. What's more, the proposed modeling methods for energy hubs lack flexibility and versatility which can't intuitively reflect the energy flow relationship.

As demand response (DR) can guide the customers to consume electricity rationally and play a vital role in peak load shifting, more attentions are paid to it nowadays. However, the researches on DR implemented in multiple energy system are rare and the DR models or strategies are far from full investigation. Considering the possible uncertainties in the decisions of customers, the DR module is embedded into the energy hub as a unit and then a model of multi energy DR based on stochastic model is established in [16]. In [17], the integrated scheduling of renewable generations and demand response programs for a micro grid is investigated. Different types of electricity customers can participate in demand response programs to respond to the energy or reserve scheduling. According to [18], a stochastic energy procurement problem is proposed for large electricity consumers with considering the effects of demand response programs. Results show that the demand response programs can shift the loads from high price period to low price period which will decrease the expected operation cost. In order to identify and quantify the potential of distributed generations to participate in real-time DR programs, a comprehensive framework is established and the novel concept of electricity shifting potential is introduced in [19]. However, these studies are mainly concentrated on the modeling and potential analysis of DR. The coordinated operation and optimal scheduling of multi energy carriers with DR are not considered enough.

In contrast to the existing researches introduced above, this paper try to expand the well known concept of micro grid which is mainly concentrated on improving the distributed renewable resources penetration of the distribution networks [20]. The expanded concept of micro grid is entitled Micro Energy Grid (MEG). The main difference between Micro Energy Grid and micro grid is that the former is an integrated energy system including cold, heat, power, gas and other forms of energy. Besides, the coordinated operation and optimal scheduling strategies of multi energy carriers will be investigated at the whole MEG level. The innovative contributions of this paper are mainly embodied in the following three aspects. (1) A novel sub energy hub structure is developed including power hub, heating hub and cooling hub which can realize the collection and allocation of energy. According to the sub energy hub structure, a generic architecture of energy hub integrating CCHP is designed and a generic modeling method of energy flow is proposed. (2) A generic optimal dispatch model for the MEG is formulated with considering the operation cost and environmental cost. This model is a mixed integer linear programming problem essentially which aims to maximize the local consumption of renewable energy and minimize the total operation cost. (3) A real time pricing model is developed and the roles of renewable energy, electricity/cold/heat energy storage devices and demand response are discussed separately.

The remainder of the paper is organized as follows: Section 2 introduces the MEG and designs a basic architecture for the MEG basing on energy hub. Section 3 designs the structure of energy hub and formulates its energy flow as well as the optimal dispatch model. Case studies and numerical simulation results are discussed in Section 4. Finally, the conclusions are summarized in Section 5.

2. The micro energy grid based on energy hub

Micro Energy Grid (MEG) is an expansion of micro grid, which is a new evolution trend for the traditional distribution network. MEG mainly has the following three advantages. (1) From the energy supply aspect, the MEG can promote the local consumption of renewable resources and coordinate natural gas, electricity, cooling, heat and other energy carriers. Moreover, it can implement multi energy complement, alternative utilization of energy and improve the security and reliability of the energy supply system with considering the effects of energy price and environment. (2) From the energy service perspective, the MEG can decrease the energy cost, reduce carbon emission and realize peak load shifting through optimal dispatch. (3) From the energy grid angle, the coordinated operation of electricity network, gas grid and thermal network will accelerate the development of the multi energy technology and improve the energy efficiency which will promote the sustainable development of energy system eventually.

The physical objects of MEG can be buildings, residential communities, industrial parks, towns, cities and so on. As illustrated in Fig. 1, this paper designs an architecture of a community MEG whose critical component is energy hub. To be specific, the energy hub is composed of input energy carriers (gas and electricity), energy converters (transformer, gas turbine, gas boiler, electrical chiller and absorption chiller), energy storage devices and output energy carriers (power, cooling and heating). Through the energy hub, the natural gas from natural gas network and the electricity supplied by utility grid are converted to power, cold and heat to satisfy multi energy demands.

Dispatch center is responsible for the energy management of the MEG. The information including the device status, energy consumption historical data, weather reports, appliance parameters, electricity price and gas tariff will be collected by advanced meters and sent to the dispatch center. After analyzing and processing these data, the dispatch center will forecast the energy demands, the outputs of renewable resource and send optimal dispatch sig-