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Power demand and supply management in microgrids with uncertainties of renewable energies

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ABSTRACT

An important task of power demand and supply management in microgrids is to maintain a good match between power generation and consumption at the minimum cost. Since the highly fluctuant renewable energies constitute a significant portion of the power resources in microgrids, the microgrid system central controller (MGCC) faces the challenge of effectively utilizing the renewable energies while fulfilling the requirements of customers. To tackle the problem, a novel power demand and supply management scheme is proposed in this paper, which mainly includes three parts as follows. Firstly, a novel uncertainty model is developed to capture the randomness of renewable energy generation which, by introducing a reference distribution according to past observations and empirical knowledge and defining a distribution uncertainty set to confine the uncertainty of renewable energies, allows the renewable energies to fluctuate around the reference distribution. An optimization problem is then formulated to determine the optimal power consumption and generation scheduling for minimizing the fuel cost. Finally, a two-stage optimization approach is proposed to transform and then solve the prime problem. Numerical results indicate that the proposed scheme helps effectively reduce the energy cost. Detailed studies on the impacts of different factors on the proposed scheme provide some interesting insights which shall be useful for policy making for the future MGCC.

Introduction

The smart grid is the innovative future electric power system that will improve the conventional electrical grid network to be more clean, reliable, secure, cooperative, and efficient. The growth and evolution of the smart grid is expected to come with the plug-and-play integration of the basic structures called microgrids. Specifically, microgrids are small-scale low voltage power supply networks designed to supply electrical load for a small community such as a university campus, a commercial area and a trading estate, etc. Microgrids can autonomously coordinate local generations and demands in a dynamic manner. It can operate in either grid-connected mode or islanded mode [1]. There have been world wide deployments of pilot microgrids, e.g., in US, Germany, Greece and Japan [2].

Microgrids are expected to be more robust and cost-effective than the traditional approach of centralized grids. However, a number of technical and regulatory issues have to be resolved before the microgrid can become a commonplace. One problem requiring due attention is the effective management of power supply and demand loads, which amounts to matching the power generation and consumption profiles [3,4]. Specifically, the power generators or microsources employed in microgrids are usually renewable or non-conventional distributed energy resources. While incorporating such renewable resources shall bring great environmental benefits, it imposes new challenges as well: different from that in the traditional power systems with conventional controllable electric generators, generation scheduling in microgrids with fluctuant, climate-dependent renewable energy sources has to cope with the nontrivial uncertainties.

The microgrids may adopt hierarchical or decentralized demand control schemes [5,6]. The decentralized control schemes facilitate distributed control and management of large complex systems. However, such control requires significant experiments before implementation. Also it may introduce new security challenges. Hierarchical control is performed by a master controller which is responsible for matching the generation and load. When the demand resources are controlled upon the occurrence of disturbance, the strategy is often known as direct load control [7,8]. In a direct control program, based on an agreement between the central controller and customers, the controller can remotely control the operations of certain appliances in a household. This

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capability can be especially effective where there are electric devices allowing flexible usage time and/or energy storage, such as electric water heater (EWH) equipped with hot water storage tank and plug-in hybrid electric vehicles (PHEVs), etc. The Kyotango microgrid project in Japan is an example of hierarchically controlled microgrid [2].

This paper tackles the basic problem faced by the microgrid system central controller (MGCC), namely to achieve a good match between power demand and supply subject to uncertainties of renewable energies. On the power demand side, we envision a scenario with real-time communication between the controller and energy consumer premises. Specifically, in each time period, the operator controller receives consumer power demands with different power level requirements, durations and time elasticity levels. The MGCC needs to minimize the electricity generation cost by optimally scheduling the operation of each appliance subject to the requirements set by the users. Here the generation fuel cost is modeled as a convex function of instantaneous total power consumption.

On the power supply side, MGCC has to focus on effectively managing power generation in order to match the user load and maintain system reliability. A novel uncertainty model is proposed to capture the fluctuant nature of renewable energies. Compared with previous robust optimization based approaches which confine the renewable energy within a lower bound and an upper bound, the proposed model provides more statistical details in describing the underlying uncertainty. (The previous robust approaches will be discussed in Section 'Related work'.) Specifically, an empirical distribution is extracted as a useful reference, which allows the actual distribution of renewable energies to vary around it. To the best of our knowledge, this is the first time that the distribution uncertainty model is adopted to depict the indeterminacy property of renewable energy generation. The load balance constraint is aptly approximated using the chance constraint representation, which allows convenient tuning of the conservation level of the solution using a single parameter. A tractable robust optimization approach is developed for transforming the chance constraints into linear constraints and then solve the problem. It is shown that the proposed power demand and supply management scheme greatly reduces the energy cost for the microgrid system. Furthermore, some of the desirable properties of the proposed scheme are investigated, which sheds light on policy making for the future MGCC.

The remainder of this paper is organized as follows. Section 'Related work' provides a brief survey of the related work. In Section 'Formulation of the microgrid demand and supply management problem', we show the mathematical depiction of the power demand and supply management problem and the uncertainty model of the renewable energies. Section 'Optimization algorithms' presents the robust approach for handling the load balance constraint. Simulation results and discussions are presented in Section 'Simulation results and discussions'. Finally the paper is concluded in Section 'Conclusion'.

Related work

The problem being tackled in this paper can be viewed as containing two different parts. On the power supply side, we need to build a hierarchical demand control scheme so as to achieve the economic consumption scheduling and fulfill the requirements set by energy users; on the power demand side, there is a need to properly model the randomness of renewable energy generation, which may account for a significant portion of power supply in microgrids. Note that load balance constraints act as the connection between power consumption and generation.

Demand control techniques can be categorized into either price based load control techniques, referred to as demand response methods, or direct load control, referred to as demand side management. Under price based load control scheme, users are encouraged to make energy consumption decisions individually according to the price information. Demand side management strategies, however, are usually applied directly by a central controller and require consumer subscription to an economic incentive program. Some representative work has studied demand control techniques in residential microgrids. A recent paper [9] developed a real-time pricing scheme which aims at reducing the peak to average load ratio (PAR) through demand response management in smart grid systems. A two-stage optimization problem was proposed and solved. Fathi et al. developed a stochastic model for scheduling in a local area network with the objective of cost minimization and PAR minimization [10]. The work [11] presented a linear programming formulation for minimizing the energy cost through direct load control. In [12] a robust optimization approach was presented to adjust the hourly load level of a given consumer in response to hourly electricity prices. The uncertainties of renewable energies, however, were not considered in these studies. As such, the control schemes may not be readily optimal and applicable to the microgrid scenario where renewable energies constitute a significant portion of power resources.

There also exist some studies considering renewable energy uncertainties when scheduling the energy generation. Such work can be categorized into two groups: the stochastic based approaches and the robust optimization based approaches. For instance, Wang et al. defined stochastic upper and lower supply curves to capture a broad range of fluctuations in the power system, where energy generated by each power source was modeled as stochastic arrivals in the queuing model [13]. In [14], scenario-based stochastic operation management methods were developed to tackle the fluctuant demands and renewable energies using the probability distribution function (PDF) of each uncertain variable. Hidden Markov models have also been adopted to characterize renewable energy generation [15–17]. Stimulated by observations that in practical scenarios, obtaining an accurate distribution function could be computationally costly and renewable energy may not follow Markov process or any simple distributions, robust optimization has recently received growing attention as a modeling framework for optimization under uncertainty. Instead of assuming explicit probability distribution, robust optimization confines the renewable generation in a pre-defined uncertainty set containing the worst-case scenario. For example, Zhang et al. considered a distributed economic dispatch problem for microgrid with high penetration of renewable energies [18]. The intrinsically stochastic properties of renewable energy sources are captured by a polyhedral uncertainty set with deterministic lower and upper bounds. Similar methods for modeling renewable energies can also be found in other recent work [19,20]. Different from the existing work, our approach jointly considers power demand and supply management. Rather than assuming there is available knowledge of the specific distribution of renewable energy generation, the proposed approach describes the underlying uncertainty in a more detailed yet flexible manner. It allows more information of renewable energy generation to be effectively incorporated into the uncertainty model when such information is available.

Formulation of the microgrid demand and supply management problem

In this section, a mathematical representation of the energy consumption and generation scheduling problem in an islanded microgrid with renewable energies is provided. An MGCC is