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Hierarchical aggregation method for a scalable implementation of demand side management

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ABSTRACT

Demand side management (DSM) aims to efficiently manage power flow by engaging energy customers, through offering incentives via price signals to alter their consumption patterns or directly controlling their loads. However, the integration of renewable energy generators and batteries in residential premises requires new approaches for DSM as they offer more flexibility. Moreover, as there are often a large number of residential energy customers within a distribution network, it is quite challenging to accommodate all of them in the DSM. In this paper, we propose an Aggregated Method (AM) that allows the treatment of distribution grid as a composition of several microgrids, which helps to aggregate underlying energy customers' power and energy constraints and operating preferences. In addition, we provide methods for distributing the aggregated energy demand decisions among the participating energy customers. In contrast to the alternative centralized method, our approach requires less computational time to obtain decisions and hence scales well with increasing network size. Moreover, our results indicate that when using our method, energy customers receive more benefits through satisfying their energy requirements and operating conditions. Our overall analyses showed that the proposed framework can be easily adopted by the electricity market operators to create scalable DSM programs.

1. Introduction

The changes in the electricity distribution grid have resulted in rethinking of the electricity market (Aliprantis et al., 2010; Brown and Salter, 2011). Previously, electricity providers were more focused on the supply assuming that energy customers were unwilling or unable to change their power consumption patterns (Spees and Lave, 2007). Moreover, for demand side management (DSM) programs that aim to match the demand to the supply, industrial loads were the major contributors while residential and commercial energy customers contributed less (Eid et al., 2015). However, today, distribution level energy customers are increasingly participating in demand response programs by changing their consumption within desired limits according to the price. In addition, as energy customers can also integrate their own renewable energy sources on site (Mutale, 2006) and even storage capabilities (web, 2015), they could participate directly in the energy market to maximize benefits through an active orchestration of demand, usage patterns, generation, and storage of energy. With such changing customer expectations and behavior, it is also becoming necessary for the operators to maintain the quality and balance in the electricity grid through appropriate DSM mechanisms (Vandael et al., 2013). However, accommodating a large number of residential energy customers in DSM is challenging due to the large scale of the network.

The computational complexity of designing DSM is tackled in literature through decision-making tools such as optimization (Anderson et al., 2011; Galus et al., 2010; Tushar et al., 2014) and game theory (Rasoul et al., 2015; Reka and Ramesh, 2016; Stephens et al., 2015; Tushar et al., 2015). However, integrating a large number of energy customers into these tools is problematic because as the number of decision variables increase, the time to compute the optimal decisions increases due to limited resources such as memory (Galus et al., 2010; Tushar et al., 2014). Therefore, in this paper, we investigate and provide an effective solution to the scalability of the DSM when incorporating a large number of distribution grid energy customers.

We propose a hierarchical structure that scales well with increasing number of energy customers in the DSM. We begin by decomposing the distribution electricity grid as a set of microgrids interconnected by a transmission network (Asmus, 2010; Hatziargyriou et al., 2005). The microgrid is an island of the electricity network that interconnects electricity generators (both of traditional and distributed renewable), electrical loads from residential and commercial energy customers, and storage elements. As

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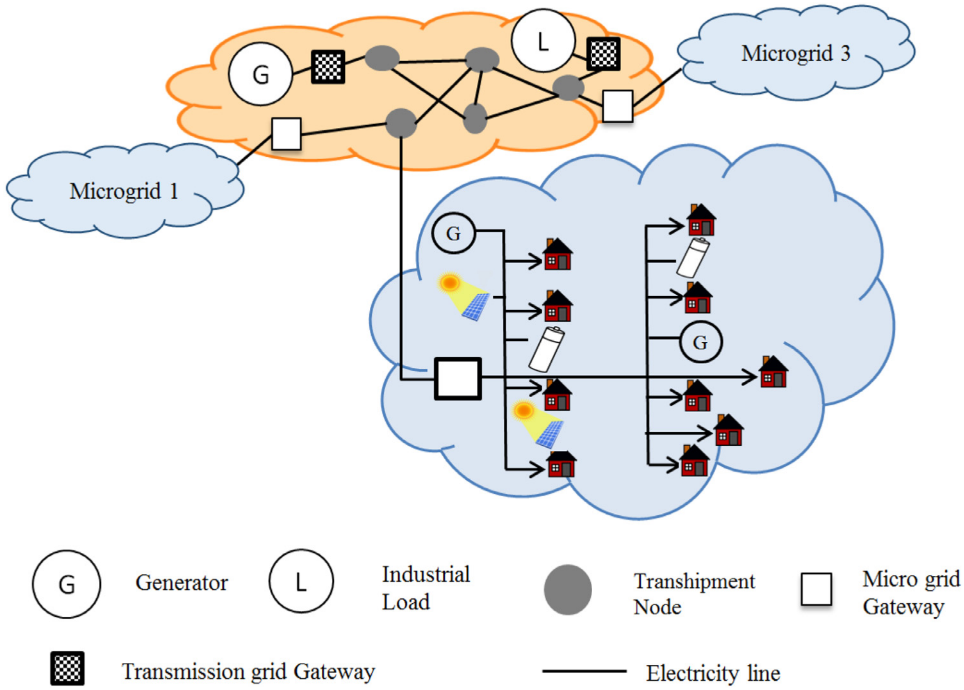

Fig. 1. Architecture of the proposed framework.

these microgrids have an inbuilt energy generation and storage capacity to meet the energy demands inside the grid, they can be operated as isolated units at least partially over a certain operational time window. In addition, it is possible to manage the excess and shortfall in energy through the interconnection of microgrids and the transmission network. We represent these microgrids using an aggregation framework that sums up both physical and cost characteristics of the microgrid's lower level entities to include in the DSM problem. This methodology allows DSM to be seen as a hierarchical system as illustrated in Fig. 1 - the transmission network as the upper level and the microgrids in the bottom level and thus this method is neither a fully centralized nor a distributed problem-solving approach.

We then use those aggregated values of microgrid energy customers as opposed to individual energy customer integration for obtaining the optimal decisions through an optimization algorithm. This algorithm also incorporates the transmission network elements such as generators and industrial loads. In addition, we provide methods for distributing the optimal aggregated energy generation and demand decisions to individual energy customers in microgrids. We demonstrate the scalability of this approach by applying it to a standard network and then by increasing the size of the network and the number of time intervals in the scheduling horizon. In particular, our main unique contributions in this work are as follows:

- Formulation of an aggregation model for a microgrid in terms of its energy generation, storage capacity, and consumption patterns to fulfill DSM objectives.
- Development of specific algorithms to first optimize energy plans in DSM and then to distribute the optimal aggregated energy plans to individual microgrid energy customers.
- Evaluation of the proposed approach and a comparison of the performance with the benchmark model of the centralized approach.

Our analyses show that the proposed approach significantly decreases the computational time with increasing scale while successfully achieving the goals of individual microgrid energy customers in DSM.

The remainder of the paper is organized as follows. Section 2 presents related work and Section 3 describes the model of the transmission network, microgrids, and gateways. The formulation of aggregated models for microgrids, participation of these aggregated models in DSM, and distribution of optimal decisions obtained by aggregated entities to individual energy customers are presented in Section 4. Section 5 describes a use case of applying the proposed aggregated model into power markets and the comparison model. The key results of our model followed by comparative analyses are presented in Section 6. Section 7 concludes the paper.

2. Related work

Approaches on incorporating residential energy customers in DSM has been explored in previous studies (Anderson et al., 2011; Galus et al., 2010; Li et al., 2011; Rasoul et al., 2015; Reka and Ramesh, 2016; Shi et al., 2014; Stephens et al., 2015; Tushar et al., 2015; 2014). The first approach is the centralized method (CM) in which energy scheduling is carried out by a centralized controller. This allows optimal energy schedules being achieved by using techniques like global optimization (Anderson et al., 2011; Galus et al., 2010; Tushar et al., 2014). A major problem of this method is the increasing computational complexity with the size of the network (Tushar et al., 2014). As a solution, approximation methods and algorithms such as gradient method (Zhang et al., 2014), evolutionary algorithm (Li et al., 2016; Vidal et al., 2014), and genetic algorithm (Awais et al., 2015) are proposed to solve the optimization problem. However, authors in Galus et al. (2010) showed that when the scale of the network increases, the controller could potentially face problems of running out of memory space even with approximation methods as the optimization space grows exponentially with the number of users.

The second method is the distributed approach, where the above global optimization problem is distributed across the number of participants in DSM program and each participant is then