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Hierarchical control framework for integrated coordination between distributed energy resources and demand response☆

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ABSTRACT

Demand response represents a significant but largely untapped resource that can greatly enhance the flexibility and reliability of power systems. This paper proposes a hierarchical control framework to facilitate the integrated coordination between distributed energy resources and demand response. The proposed framework consists of coordination and device layers. In the coordination layer, prior to each scheduling period, each coordinator receives the aggregated utility or cost functions as well as the power operating ranges from aggregators or device controllers. Then, various resources or their aggregations are optimally coordinated in a distributed manner to achieve the system-level objectives. The obtained regulation signals are sent back to aggregators or device controllers for real-time control. In the device layer, at the scheduling stage, the controller at each device reports to coordinators (directly or through aggregators) the required information for optimal coordination, and receives the regulation signals from its commander once the coordination is completed. During the real-time operation, individual resources are controlled to follow the optimal power dispatch signals. For practical applications, a method is presented to determine the utility functions of controllable loads by accounting for the real-time load dynamics and the preferences of individual customers. The effectiveness of the proposed framework is validated by detailed simulation studies.

1. Introduction

With growing emphasis on system efficiency and reliability, a great effort has been made in developing distributed generator (DG) and distributed energy storage, which are collectively referred as distributed energy resources (DERs). These resources are small and highly flexible compared with conventional generators, and are playing an increasingly important role in the future smart grid [1,2]. On the other hand, demand-side control has presented a novel and viable way to supplement conventional supply-side control [3–5]. In fact, demand response (DR) represents a significant but largely untapped resource in the power grid. According to National Energy Technology Laboratory, with only 10% customer participation, the potential nationwide value of demand dispatch could be several billion dollars per year in reduced energy costs [6]. The deployment of DERs and DR will not only defer infrastructure investments in the power grid, but also meet additional reserve requirements from renewable generation. Although the deployment of DR and DERs can lead to more economic and reliable system operation, it requires proper coordination between DERs and DR to harvest their potential benefits.

The coordination problem can be solved in a completely centralized manner, where a single control center accesses states of potentially thousands of devices and broadcasts control signals to them. Such a centralized control strategy is often subject to several disadvantages, such as high requirement and cost in communication, substantial computational burden, limited flexibility and scalability, and disrespect of privacy [7,8]. As an alternative, a distributed control strategy has been proposed, where each control agent maintains a set of variables and updates them through information exchange with a few neighboring agents. During the past few years, many studies have been dedicated to distributed approaches that can be applied to DER coordination. The authors of [9] applied the leader-follower consensus algorithm to economic dispatch problem, where the incremental cost is chosen as the consensus variable and the leader collects the mismatch between system generation and demand, and then leads the updated of

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marginal cost in the system. To avoid the requirement of the leader, the authors later proposed the two-level consensus algorithm in [10], where the upper level executes the consensus and gradient algorithm, and the lower level executes the classical consensus algorithm. In [11], a strategy based on the local replicator equation was presented for DG coordination. In [12], the authors designed a distributed algorithm for DER coordination. In addition to the consensus term, the proposed algorithm uses an innovation term to ensure the balance between system generation and demand. Notice that the aforementioned distributed algorithms only apply to the case where the information exchange among DERs are undirected. However, in the communication networks, the communication links could be unidirectional due to the nonuniform communication power levels. Therefore, the distributed coordination algorithms have been developed for directed communication networks. For example, the authors of [13] proposed a distributed algorithm based on the consensus and bisection method. The authors of [14] developed a minimum-time consensus algorithm which optimal coordination problem within provable minimum time steps. The common assumption of the above cited papers is that the communication network is reliable, i.e., the communication links are fixed and are not subject to time-delays and packet drops. However, the communication network may vary due to unexpected loss of communication links and the communication links may suffer from time-delays. Motivated by these facts, coordination problem over communication networks with imperfect communication links have been considered. The authors of [15] developed a distributed algorithm that is resilient against potential packet drops and applied the algorithm to DER coordination. In [16], the authors proposed a nonnegative-surplus based distributed algorithm for DER coordination over time-varying directed communication networks but without time delays. In [17], the authors developed a distributed algorithm that integrates consensus algorithm and optimal control algorithm, which is robust to communication failures and adaptive to topology changes. The authors of [18] proposed a distributed algorithm based on the push-sum and gradient method for DER coordination over time-varying communication networks with arbitrarily large but bounded time-delays. Note that in the aforementioned work, the transmission lines are assumed to be lossless. Recently, there are also studies that incorporated power losses into the distributed algorithm design [19,20].

Although useful insights regarding DER and DR coordination have been reported in these papers, the existing results cannot be directly extended and applied to practical applications. This is because the controllable loads were simply modeled as a “generator” with negative generation, where the load characteristics and dynamics were totally ignored. Furthermore, the studies did not address the issue of designing real-time load control strategies to achieve optimal power consumption. This paper proposes a hierarchical control framework with two layers to achieve integrated coordination of DERs and DR. The underlying control strategy accounts for the detailed characteristics and dynamics of controllable loads, and addresses the issue of designing real-time control strategies.

The rest of this paper is organized as follows. In Section 2, the major challenges of integrated coordination between DERs and DR are first discussed in detail, and then the proposed hierarchical control framework is briefly introduced with main contributions highlighted. The top layer of the proposed framework is described in Section 3, where a general coordination problem between DERs and DR is formulated and solved using a distributed approach. The bottom layer of the proposed framework is described in Section 4, where the device aggregation and real-time control are presented and illustrated using air conditioners (ACs). In Section 5, various case studies along with detailed simulation results are provided to demonstrate the effectiveness of the proposed framework. Finally, concluding remarks are given in Section 6.

2. Problem statement and proposed framework

Power system operation requires instantaneous power balance between generation and demand that is constantly varying. Balancing is achieved through energy scheduling and real-time control. In this paper, we consider the short-term scheduling and operation problems for DGs and controllable loads in an active distribution system. A practical problem is how to optimally coordinate these resources to meet the desired total power consumption without violating operating constraints of individual resources. In a grid-connected distribution system, the desired power consumption can be set to follow the day ahead purchase or load following signal. At the scheduling stage, the optimal resource allocation problem is formulated and solved between DGs and DR at each scheduling period (e.g., every 5 min), where the real-time dynamics of controllable loads must be captured. At the operation stage, real-time control is carried out so that DGs and controllable loads follow optimal power generation and consumption, respectively.

2.1. Technical challenges

Although many results regarding DER and DR coordination have been presented in the literature, there are still several technical gaps that are significant enough to prohibit practical application of these existing results.

First, the cost functions of DGs and the utility functions of controllable loads are required to formulate and solve the optimal coordination problem or clear the market. Existing studies such as [12,17] assume that those functions are available and can be directly used in the proposed distributed approaches. However, it is not straightforward to construct the utility functions of power for controllable loads as the cost functions of power for DGs. For instance, the utility of using an AC is directly related to the comfort an individual customer perceives at different indoor air temperatures rather than the power consumption. Therefore, it is required in practice to extract the utility functions and capture the underlying economics based on the preferences of individual customers.

Second, it is required for practical applications to consider the operation stage as well. After the coordination problem is solved at the scheduling stage, individual resources are expected to follow optimal generation or consumption through real-time control. It is straightforward for DGs to meet this expectation because their generation level can be continuously adjusted with existing generator controllers. However, this is often not the case for controllable loads. Some controllable loads such as thermostatically controllable loads have not been designed with the capability to continuously adjust their power consumption. Furthermore, their power consumption cannot be directly controlled and is usually indirectly affected by other control variables. For example, the thermostat of an AC receives the temperature setpoint as the control input and then automatically switches the compressor on and off to maintain the indoor air temperature around the setpoint. Therefore, a real-time load controller has to be designed for individual controllable loads using the locally acceptable control input while capturing the underlying economics.

Effectively coordinating and controlling DERs and DR for short-term scheduling and real-time control cannot be realized by simply adding one coordination algorithm to another load control approach. A systematic method is needed to capture the underlying economics and dynamics of controllable load synthetically in both scheduling and real-time control. The proposed framework herein