Coordination of Distributed Energy Resources for Provision of Ancillary Services: Architectures and Algorithms

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Abstract

We discuss the utilization of distributed energy resources (DERs) to provide active and reactive power support for ancillary services. Though the amount of active and/or reactive power provided individually by each of these resources can be very small, their presence in large numbers in power distribution networks implies that, under proper coordination mechanisms, they can collectively provide substantial active and reactive power regulation capacity. In this article, we provide a simple formulation of the DER coordination problem for enabling their utilization to provide ancillary services. We also provide specific architectures and algorithmic solutions to solve the DER coordination problem, with focus on decentralized solutions.

Keywords: Distributed Energy Resources (DERs), Ancillary Services, Distributed Algorithms, Consensus.

1 Introduction

On the distribution side of a power system, there are many distributed energy resources (DERs), e.g., photovoltaic (PV) installations, plug-in hybrid electric vehicles (PHEVs) and thermostatically-controlled loads (TCLs), that can be potentially used to provide ancillary services, e.g., reactive power support for voltage control (see, e.g., [1] and the references therein), and active power up and down regulation for frequency control (see, e.g., [2] and the references therein). To enable DERs to provide ancillary services, it is necessary to develop appropriate control and coordination mechanisms. One potential solution relies on a centralized control architecture in which each DER is directly coordinated by (and communicates with) a central decision maker. An alternative approach is to distribute the decision making, which obviates the need for a central decision maker to coordinate the DERs. In both cases, the decision making involves solving a *resource allocation* problem for coordinating the DERs to collectively provide a certain amount of a resource (e.g., active or reactive power).

In a practical setting, whether a centralized or a distributed architecture is adopted, the control of DERs for ancillary services provision will involve some aggregating entity that will gather together and coordinate a set of DERs, which will provide certain amount of active or reactive power in exchange for monetary benefits. In general, these aggregating entities are the ones that interact with the ancillary services market, and through some market-clearing mechanism they enter a contract to provide some amount of resource, e.g., active and/or reactive power over a period of time. The goal of the aggregating entity is to provide this amount of resource by properly coordinating and controlling the DERs, while ensuring that the total monetary compensation to the DERs for providing the resource is below the monetary benefit that the aggregating entity obtains by selling the resource in the ancillary services market.

In the context above, a household with a solar PV rooftop installation and a PHEV might choose to offer the PV installation to a renewable aggregator so it is utilized to provide reactive power support (this can be achieved as long as the PV installation power electronics-based grid interface has the correct topology [3]). Additionally, the household could offer its PHEV to a battery vehicle aggregator to be used as a controllable load for energy peak shaving during peak hours and load-leveling at night [4]. Finally, the household might choose to enroll in a demand response program in which it allows a demand response provider to control its TCLs to provide frequency regulation services [2]. In general, the renewable aggregator, the battery vehicle aggregator, and the demand response provider can be either separate entities or they can be the same entity. In this article, we will refer to these aggregating entities as *aggregators*.

2 The Problem of DER Coordination

Without loss of generality, denote by x_j the amount of resource provided by DER i without specifying whether it is active or reactive power. [However it is understood that each DER provides (or consumes) the same type of resource, i.e., all the x_i's are either active or reactive power.] Let $0 < \underline{x}_i < \overline{x}_i$, for $i = 1, 2, \ldots, n$, denote the minimum ($\underline{x}_i$) and maximum ($\overline{x}_i$) capacity limits on the amount of resource x_i that node i can provide. Denote by X the total amount of resource that the DERs must collectively provide to satisfy the aggregator request. Let $\pi_i(x_i)$ denote the price that the aggregator pays DER i per unit of resource x_i that it provides. Then, the objective of the aggregator in the DER coordination problem is to minimize the total monetary amount to be paid to the DERs for providing the total amount of resource X while satisfying the individual capacity constraints of the DERs. Thus, the DER coordination problem can be formulated as follows:

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^{n} x_i \pi_i(x_i) \\ \text{subject to} \quad & \sum_{i=1}^{n} x_i = X \\ & 0 < \underline{x}_i \le x_i \le \overline{x}_i, \ \forall j. \end{aligned} \tag{1}$$

By allowing heterogeneity in the price per unit of resource that the aggregator offers to each DER we can take into account the fact that the aggregator might value classes of DERs differently. For example, the down regulation capacity provided by a residential PV installation (which is achieved by curtailing its power) might be valued differently from the down regulation capacity provided by a TCL or a PHEV (both would need to absorb additional power in order to provide down regulation).

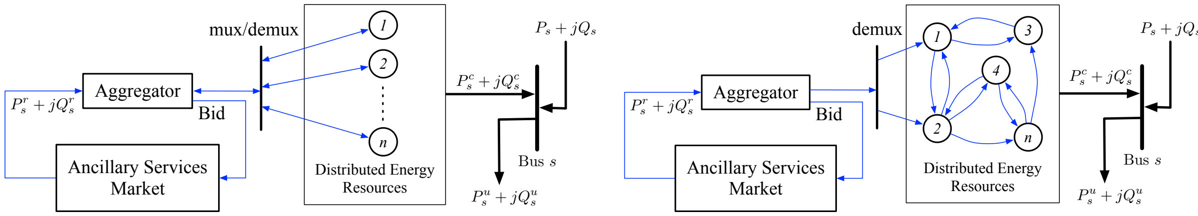
It is not difficult to see that if the price functions $\pi_i(\cdot), \ i = 1, 2 \ldots, n$, are convex and non-decreasing, then the cost function $\sum_{i=1}^{n} x_i \pi_i(x_i)$ is convex; thus, if the problem in (1) is feasible, then there exists a globally optimal solution. Additionally, if the price per unit of resource is linear with the amount of resource, i.e., $\pi_i(x_i) = c_i x_i, \ i = 1, 2, \ldots, n$, then, $x_i \pi_i(x_i) = c_i x_i^2, \ i = 1, 2, \ldots, n$, and the problem in (1) reduces to a quadratic program. Also, if the price per unit of resource is constant, i.e., $\pi_i(x_i) = c_i, \ i = 1, 2, \ldots, n$, then, $x_i \pi_i(x_i) = c_i x_i, \ i = 1, 2, \ldots, n$, and the problem in (1) reduces to a linear program. Finally, if $\pi_i(x_i) = \pi(x_i) = c, \ i = 1, 2, \ldots, n$, for some constant $c > 0$, i.e., the price offered by the aggregator is constant and the same for all DERs, then, the optimization problem in (1) becomes a feasibility problem of the form

$$\begin{aligned} \text{find} \quad & x_1, x_2, \ldots, x_n \\ \text{subject to} \quad & \sum_{i=1}^{n} x_i = X \\ & 0 < \underline{x}_i \le x_i \le \overline{x}_i, \ \forall j. \end{aligned} \tag{2}$$

If the problem in (2) is indeed feasible (i.e., $\sum_{l=1}^{n} \underline{x}_l \le X \le \sum_{l=1}^{n} \overline{x}_l$), then there is an infinite number of solutions. One such solution, which we refer to as *fair-splitting*, is given by

$$x_i = \underline{x}_i + \frac{X - \sum_{l=1}^{n} \underline{x}_l}{\sum_{l=1}^{n} (\overline{x}_l - \underline{x}_l)} (\overline{x}_i - \underline{x}_i), \ \forall i. \tag{3}$$

The formulation to the DER coordination problem provided in (2) is not the only possible one. In this regard, and in the context of PHEVs, several recent works have proposed game-theoretic formulations to the problem [5, 6, 7]. For example, in [7], the authors assume that each PHEV is a decision maker and can freely choose to participate after receiving a request from the aggregator. The decision that each PHEV is faced with depends on its own utility function, along with some pricing strategy designed by the aggregator. The PHEVs are assumed to be price anticipating in the sense that they are aware of the fact that the pricing is designed by the aggregator with respect to the average energy available. Another alternative is to formulate the DER coordination problem as a scheduling problem [8, 9], where the DERs are treated as tasks. Then, the problem is to develop real-time scheduling policies to service these tasks.



(a) Centralized architecture.

(b) Decentralized architecture.

Figure 1: Control architecture alternatives.

3 Architectures

Next, we describe two possible architectures that can be utilized to implement the proper algorithms for solving the DER coordination problem as formulated in (1). Specifically, we describe a centralized architecture that requires the aggregator to communicate bi-directionally with each DER, and a distributed architecture that requires the aggregator to only unidirectionally communicate with a limited number of DERs, but requires some additional exchange of information (not necessarily through bidirectional communication links) among the DERs.

3.1 Centralized Architecture

A solution can be achieved through the completely centralized architecture of Fig. 1(a), where the aggregator can exchange information with each available DER. In this scenario, each DER can inform the aggregator about its active and/or reactive capacity limits and other operational constraints, e.g., maintenance schedule. After gathering all this information, the aggregator solves the optimization program in (1), the solution of which will determine how to allocate among the resources the total amount of active power P_s^r, and/or reactive power Q_s^r that it needs to provide. Then, the aggregator sends individual commands to each DER so they modify their active and or reactive power generation according to the solution of (1) computed by the aggregator. In this centralized solution however, it is necessary to overlay a communication network connecting the aggregator with each resource, and to maintain knowledge of the resources that are available at any given time.

3.2 Decentralized Architecture

An alternative is to use the decentralized control architecture of Fig. 1(b), where the aggregator relays information to a limited number of DERs that it can directly communicate with each DER being able to exchange information with a number of other close-by DERs. For example, the aggregator might broadcast the prices to be paid to each type of DER. Then, through some distributed protocol that adheres to some communication network interconnecting the DERs, the information relayed by the aggregator to this limited number of DERs is disseminated to all other available DERs. This dissemination process may rely on flooding algorithms, message-passing protocols, or linear-iterative algorithms as proposed in [10, 11]. After the dissemination process is complete and through a distributed computation over the communication network, the DERs can solve the optimization program in (1) and determine its active and/or reactive power contribution.

A decentralized architecture like the one in Fig. 1(b) may offer several advantages over the centralized one in Fig. 1(b), including the following. First, a decentralized architecture may be more economical because it does not require communication between the aggregator and the various DERs. Also, a decentralized architecture does not require the aggregator to have a complete knowledge of the DERs available. Additionally, a decentralized architecture can be more resilient to faults and/or unpredictable behavioral patterns by the DERs. Finally, the practical implementation of such decentralized architecture can rely on inexpensive and simple hardware. For example, the testbed described in [12], which is used to solve a particular instance of the problem in (1), uses Arduino microcontrollers (see [13] for a description) outfitted with wireless transceivers implementing a ZigBee protocol (see [14] for a description).

4 Algorithms

Ultimately, whether a centralized or a decentralized architecture is adopted, it is necessary to solve the optimization problem in (1). If a centralized architecture is adopted, then solving (1) is relatively straightforward using, e.g., standard gradient-descent algorithms (see, e.g., [15]). Beyond the DER coordination problem and the specific formulation in (1), solving an optimization problem is challenging if a decentralized architecture is adopted (especially if the communication links between DERs are not bi-directional); this has spurred significant research in the last few years (see, e.g., [15, 16, 17, 18, 19] and the references therein).

In the specific context of the DER coordination problem as formulated in (1), when the cost functions are assumed to be quadratic and the communication between DERs is not bi-directional, an algorithm amenable for implementation in a decentralized architecture like the one in Fig 1(b) has been proposed in [12]. Also, in the context of Fig 1(b), when the communication between DERs are bi-directional, the DER coordination problem, as formulated in (1), can be solved using an algorithm proposed in [20].

As mentioned earlier, when the price offered by the aggregator is constant and identical for all DERs, the problem in (1) reduces to the feasibility problem in (2). One possible solution to this feasibility problem is the fair splitting solution in (3). Next, we describe a linear-iterative algorithm—originally proposed in [10, 11] and referred to as *ratio consensus*—that allows the DERs to individual determine its contribution so that the fair splitting solution is achieved.

4.1 Ratio Consensus: A Distributed Algorithm for Fair Splitting

We assume that each DER is equipped with a processor that can perform simple computations, and can exchange information with neighboring DERs. In particular, the information exchange between DERs can be described by a directed graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V} = \{1, 2, \dots, n\}$ is the vertex set (each vertex—or node—corresponds to a DER), and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of edges, where $(i, j) \in \mathcal{E}$ if node i can receive information from node j. Let $\mathcal{L}^+ \subseteq \mathcal{V}$, $\mathcal{L}^+ \neq \emptyset$ denote the set of nodes that the aggregator is able to communicate with. We require $\mathcal{G}$ to be *strongly connected*, i.e., for any pair of vertices l and l', there exists a path that starts in l and ends in l'.

The processor of each DER i maintains two values y_i and z_i, which we refer to as internal states, and updates them (independently of each other) to be, respectively, a linear combination of DER i's own previous internal states, and the previous internal states of all nodes that can possibly transmit information to node i (including itself). In particular, for all $k \geq 0$, each node i updates its two internal states as follows:

$$y_i[k+1] = \sum_{j \in \mathcal{N}_i^-} \frac{1}{\mathcal{D}_j^+} y_j[k], \tag{4}$$

$$z_i[k+1] = \sum_{j \in \mathcal{N}_i^-} \frac{1}{\mathcal{D}_j^+} z_j[k], \tag{5}$$

where $\mathcal{N}_i^- = \{j \in \mathcal{V} : (i, j) \in \mathcal{E}\}$, i.e., all nodes that can possibly transmit information to node i (including itself); and $\mathcal{D}_i^+$ is the out-degree of node i, i.e., the number of nodes to which node i can possibly transmit information (including itself). Then, if the initial conditions in (4) are set to $y_i[0] = X/m - \underline{x}_i$ if $i \in \mathcal{L}^+$, and $y_i[0] = -\underline{x}_i$ otherwise; and the initial conditions in (5) are set to $z_i[0] = \overline{x}_i - \underline{x}_i$. Then, as shown in [11], as long as $\sum_{l=1}^n \overline{x}_l \leq X \leq \sum_{l=1}^n \overline{x}_l$, each DER i can asymptotically calculate its contribution as

$$x_i = \underline{x}_i + \gamma(\overline{x}_i - \underline{x}_i) \tag{6}$$

where

$$\gamma = \lim_{k \to \infty} \gamma_i[k] = \lim_{k \to \infty} \frac{y_i[k]}{z_i[k]} = \frac{X - \sum_{l=1}^n \underline{x}_l}{\sum_{l=1}^n (\overline{x}_l - \underline{x}_l)}. \tag{7}$$

It is important to note that the algorithm in (4)–(7) also serves as a primitive for the algorithm proposed in [12], which solves the problem in (1) when the cost function is quadratic. Also, the algorithm in (4)–(7) is not resilient to packet-dropping communication links or imperfect synchronization among the DERs, which makes it difficult to implement in practice; however, there are robustified variants of this algorithm that address these issues [21], and have been demonstrated to work in practice [12].

Cross References

[1] "Averaging algorithms and consensus"

[2] "Distributed optimization"

[3] "Network Games"

[4] "Control of networked systems, Overview"

[5] "Flocking in Control of Networked Systems"

[6] "Graphs for modeling networked interactions"

[7] "Power System Voltage Control, Hierarchical Structures in"

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