








Distributed Energy Resource Coordination Over Time-Varying Directed Communication Networks

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Abstract—In this paper, we consider the optimal coordination problem for distributed energy resources (DERs), including distributed generators and energy storages. We first propose an algorithm based on the push-sum and gradient method to solve the optimal DER coordination problem in a distributed manner. In the proposed algorithm, each DER only maintains a set of variables and updates them through information exchange with a few neighboring DERs over a time-varying directed communication network. We show that the proposed distributed algorithm with appropriately chosen diminishing step sizes solves the optimal DER coordination problem if the time-varying directed communication network is uniformly jointly strongly connected. Moreover, in order to improve the convergence speed and to reduce the communication burden, we propose an accelerated distributed algorithm with a fixed step size. We show that the new proposed algorithm exponentially solves the

optimal DER coordination problem if the cost functions satisfy an additional assumption and the selected step size is less than a certain critical value. Both proposed distributed algorithms are validated and evaluated using the IEEE 39-bus system.

Index Terms—Distributed coordination, energy storage (ES), multiagent systems, multistep optimization, push-sum and gradient method, smart grid.

I. INTRODUCTION

THE infrastructure that defines the U.S. power grid is based largely on predigital technologies developed in the first part of the 20th century. In subsequent decades, grid development has evolved through emphasis on safety, accessibility, and reliability to security and resiliency. The past few years have witnessed acceleration in the deployment and integration of digital smart grid sensing, communication, and control technologies that improve electric grid reliability, security, and efficiency of existing power systems at both transmission and distribution levels. Focusing on the distribution system, a great effort has been made in developing distributed generation (DG) and energy storage (ES) technology. DG and ES are important elements of the emerging smart grid paradigm. For ease of reference, these resources are often referred to as distributed energy resources (DERs) [2]. DERs are smaller, highly flexible, and can be aggregated to provide power necessary to meet regular demand. As the electricity grid continues to be modernized, DER such as distributed generators and ESs can help facilitate the transition of the present power grid to a smarter one.

At the high deployment level, DERs can collectively become a valuable system asset if coordinated with system needs and control processes, as they can respond very fast and are close to the loads. In order to achieve an effective deployment among DERs, one needs to properly design the coordination and control mechanism among them. One approach is through a completely centralized control strategy, where a single control center accesses the entire network's information and provides control signals to the entire system. This centralized control framework may not be effective for large-scale power networks due to performance limitations, such as a single point of failure, high communication and computational burden, limited flexibility, and lack of privacy.

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Recently, an alternative distributed approach has been proposed to overcome these limitations. In particular, each DER makes a local decision based on the information received from a few neighboring DERs over the underlying communication network. Most existing distributed DER coordination studies focused on a single type of DERs. On the one hand, for DG coordination, various distributed algorithms have been proposed, among which discrete-time algorithms were given in [3]–[11] and continuous-time algorithms were presented in [12]–[14]. On the other hand, cooperative management for a network of ESs has been considered in [15] and [16].

However, only a few studies considered the optimal distributed coordination of distributed generators with ESs [17]–[21]. To coordinate DGs and ESs over multiple time periods, the authors of [17] proposed a distributed discrete-time algorithm based on the consensus and innovation method, and the authors of [21] developed a distributed continuous-time algorithm based on the Laplacian gradient dynamics and dynamic average consensus. In the above studies, the charging/discharging efficiencies of ESs were not modeled. As shown in [22] and other existing studies, the optimal charging/discharging operation and the corresponding benefits from a storage device could vary significantly with its efficiencies. The authors of [18] and [19] developed distributed DER coordination strategies, where charging/discharging losses have been taken into consideration.

Note that existing studies [17]–[21] focused on the case where the communication network is time-invariant (fixed). However, in practice, the communication network topology may vary due to unexpected loss of communication links. Thus, in this paper, we consider the optimal DER coordination problem over time-varying and directed networks.

The main contributions of this paper are summarized as follows.

- 1) Inspired by the push-sum and gradient method [23], we first propose a distributed algorithm with diminishing step sizes and show that the proposed distributed algorithm with the properly chosen step sizes is capable of achieving the optimal DER coordination if the time-varying directed communication network is uniformly jointly strongly connected. Compared with existing distributed DER coordination studies for undirected connected topologies [17]–[20] and strongly connected and weight-balanced directed topologies [21], this requirement is much more general, since the network can be disconnected at any time instant as long as the joint graph over a period of time is strongly connected but not necessarily weight balanced.
- 2) The distributed algorithm proposed above, however, can be rather slow due to the diminishing step sizes. In order to improve the convergence speed, we further develop an accelerated distributed algorithm with a fixed step size and show that the new algorithm exponentially solves the optimal DER coordination problem if the fixed step size is less than a certain critical value and the cost functions satisfy some additional properties. Compared with other existing algorithms with diminishing step sizes [17]–[19], the new proposed algorithm solves the optimal DER coordination problem faster. Our proposed algorithms are

discrete time by design and readily to be implemented, while the algorithm proposed in [21] is continuous time and requires discretization for the implementation.

The remainder of this paper is organized as follows. Section II introduces some preliminaries on graph theory and convex analysis and notations. In Section III, we formulate the optimal DER coordination problem. In Section IV, a distributed algorithm with diminishing step sizes and an accelerated distributed algorithm with a fixed step size are developed. Section V presents case studies and simulation results. Concluding remarks are offered in Section VI.

II. PRELIMINARIES

In this section, we first present some background on graph theory [24], which is needed to describe the communication network among DERs. Let $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ denote a directed graph (digraph) with the set of nodes (agents) $\mathcal{V} = \{1, \dots, N\}$ and the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. A directed edge from node i to node j is denoted by $(i, j) \in \mathcal{E}$. For notational simplicity, we assume that the digraph does not have any self-loop, i.e., $(i, i) \notin \mathcal{E}$ for all $i \in \mathcal{V}$ although each node i has access to its own information. A directed path from node i_1 to node i_k is a sequence of nodes $\{i_1, \dots, i_k\}$ such that $(i_j, i_{j+1}) \in \mathcal{E}$ for $j = 1, \dots, k-1$. If there exists a directed path from node i to node j , then node j is said to be reachable from node i . A digraph \mathcal{G} is said to be strongly connected if every node is reachable from every other node.

In this paper, an agent is assigned to each distributed generator and ES in the power system. These agents exchange information according to the topology of the communication network, which may be different from the physical network, and is modeled as a time-varying directed graph $\mathcal{G}(k) = (\mathcal{V}, \mathcal{E}(k))$, where the edge set changes over time due to unexpected loss of communication links. All nodes that can transmit information to node i directly at time k are said to be its in-neighbors and belong to the set $\mathcal{N}_i^{\text{in}}(k) = \{j \in \mathcal{V} \mid (j, i) \in \mathcal{E}(k)\}$. The nodes that receive information from agent i at time k belong to the set of its out-neighbors, denoted by $\mathcal{N}_i^{\text{out}}(k) = \{j \in \mathcal{V} \mid (i, j) \in \mathcal{E}(k)\}$. The cardinality of $\mathcal{N}_i^{\text{out}}(k)$ is called its out-degree at time k and is denoted by $d_i(k) = |\mathcal{N}_i^{\text{out}}(k)|$. The joint graph of $\mathcal{G}(k)$ in the time interval $[k_1, k_2]$ with $k_1 < k_2 \leq \infty$ is denoted as $\mathcal{G}([k_1, k_2]) = \cup_{k \in [k_1, k_2]} \mathcal{G}(k) = (\mathcal{V}, \cup_{k \in [k_1, k_2]} \mathcal{E}(k))$. A time-varying directed network $\mathcal{G}(k)$ is said to be *uniformly jointly strongly connected* if there exists an integer $B > 0$ such that $\mathcal{G}([k_0, k_0 + B])$ is strongly connected for any $k_0 \in \mathbb{Z}_+$, where \mathbb{Z}_+ is the set of nonnegative integers.

We now provide some background on basic convex analysis [25]. A function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is *convex* if $f(\theta x + (1 - \theta)y) \leq \theta f(x) + (1 - \theta)f(y)$ for all $x, y \in \mathbb{R}^n$ and for all $\theta \in (0, 1)$. If the inequality holds for all $x \neq y$, then the function is *strictly convex*. A continuously differentiable function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is *strongly convex* if there exists a constant $\exists \mu > 0$ such that $f(y) \geq f(x) + \nabla f(x)'(y - x) + \frac{\mu}{2} \|y - x\|^2$ for all $x, y \in \mathbb{R}^n$. A continuously differentiable function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is *smooth* if it has a Lipschitz continuous gradient, i.e., there exists a constant $L > 0$ such that $\|\nabla f(y) - \nabla f(x)\| \leq L \|y - x\|$ for all $x, y \in \mathbb{R}^n$.

Notations: Given a matrix A , A' denotes its transpose, and A_{ij} denotes its (i, j) th entry. A column vector $x \in \mathbb{R}^n$ will be denoted by $x = (x_1, x_2, \dots, x_n)'$.

III. PROBLEM FORMULATION AND MOTIVATION

Consider a power network of $N + M$ DERs, where the first N agents are distributed generators and the last M agents are ESs. The objective of optimal coordination is to minimize the total cost on the premise that all DERs collectively meet a given demand profile during a finite-time horizon $\mathcal{T} = \{1, \dots, T\}$, where T is the number of time periods.

The total cost is the sum of DERs' costs over a number of time periods:

$$\sum_{t=1}^T \sum_{i=1}^{N+M} C_i(p_{i,t}) \quad (1)$$

where $C_i(p_{i,t})$ is the cost function of DER i during the period t and $p_{i,t}$ is the power from the generator or storage i during period t . The power from storage is measured at the grid coupling point and is positive when injecting power into grid, i.e., using generator convention.

Compared to most existing studies [1], [17]–[19], where cost functions are assumed to be quadratic, this paper considers general convex cost functions that satisfy the following assumption.

Assumption 1: For each $i = 1, \dots, N + M$ and each $t \in \mathcal{T}$, the cost function $C_i(p_{i,t}) : \mathbb{R} \rightarrow \mathbb{R}_+$ is strictly convex and continuously differentiable.

The power from the DGs and ESs together need to meet a given demand over a period of T , i.e.,

$$\sum_{i=1}^{N+M} p_{i,t} - D_t = 0 \quad \forall t \in \mathcal{T} \quad (2)$$

where D_t is the given total demand of period t .

For each DG $i \in \mathcal{N} := \{1, \dots, N\}$, there are two constraints due to physical limits. The first one is the capacity limit on how much power DG i can generate at each time period.

$$p_i^{\min} \leq p_{i,t} \leq p_i^{\max} \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{N} \quad (3)$$

where p_i^{\min} and p_i^{\max} for $i \in \mathcal{N}$ are the lower and upper power limits of generator i , respectively. The second constraint is ramping up/down constraints

$$\Delta p_i \leq p_{i,t} - p_{i,t-1} \leq \Delta \bar{p}_i \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{N} \quad (4)$$

where Δp_i and $\Delta \bar{p}_i$ are the lower and upper bounds of ramping rates of generator i , respectively.

For each ES $i \in \mathcal{M} := \{N + 1, \dots, N + M\}$, since ES cannot be charged and discharged at the same time, we define

$$p_{i,t} = p_{i,t}^+ - p_{i,t}^- \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \quad (5)$$

where

$$0 \leq p_{i,t}^+ \leq p_i^{\max}, 0 \leq p_{i,t}^- \leq p_i^{\max} \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \quad (6)$$

and $p_i^{\max} > 0$ is the upper bound of the power limit of ES i .

Note that due to the charging/discharging efficiencies, the rate of change of energy stored in ES is given by

$$p_{i,t}^{\text{batt}} = \frac{1}{\eta_i^+} p_{i,t}^+ - \eta_i^- p_{i,t}^- \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \quad (7)$$

where $p_{i,t}^{\text{batt}}$ is the rate of change of energy stored in ES i at the end of period t , and $\eta_i^+, \eta_i^- \in (0, 1)$ are discharging and charging efficiency of ES i , respectively.

The energy stored in ES i evolves according to the following dynamics:

$$E_{i,t} = E_{i,t-1} - p_{i,t}^{\text{batt}} \Delta T \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \quad (8)$$

where $E_{i,t}$ is the energy stored in ES i at the end of time period t and ΔT is the size of period.

The energy stored in ES i needs to be within the storage capacity, i.e.,

$$0 \leq E_{i,t} \leq E_i^{\max} \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \quad (9)$$

where E_i^{\max} is the energy capacity of ES i .

The energy stored in ES i at the end of the scheduling period is set to be equal to the initial energy state as

$$E_{i,T} = E_{i,0} \quad \forall i \in \mathcal{M} \quad (10)$$

but can also be set to other feasible values.

With the above model, the optimal DER coordination problem can be formulated as the following convex optimization problem:

$$\mathbf{PP} : \min_{p_{i,t}} \sum_{t=1}^T \sum_{i=1}^{N+M} C_i(p_{i,t}) \quad (11)$$

subject to (2)–(10). For the feasibility of **PP** and for reliable power system operation, we make the following assumption.

Assumption 2: Assume that the demand can be served solely by generators, i.e.,

$$\sum_{i=1}^N p_i^{\min} \leq D_t \leq \sum_{i=1}^N p_i^{\max} \quad (12)$$

Remark 1: Note that since a physical storage device cannot be charged and discharged at the same time, we need to ensure that either $p_{i,t}^+$ or $p_{i,t}^-$ needs to be zero, i.e.,

$$p_{i,t}^+ p_{i,t}^- = 0 \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M}.$$

However, when $\eta_i^+ \eta_i^- < 1$, there is no need to add this nonconvex constraint into the optimization problem (11), as shown in [19, Th. 1].

Remark 2: Compared with existing studies for optimal DG coordination [3]–[14], the optimal coordination problem of both DGs and ESs is more challenging. Since there is only limited energy that can be stored in a storage, the operations of storages in different periods are interdependent. It is thus indispensable to formulate the optimization problem over multiple periods concurrently as given in (11). A similar problem formulation has been studied in [17] and [21]. In these problem formulations, the physical constraints such as transmission line loss and power flow and transmission line flow constraints have not been considered. As discussed in [21], the design of distributed

algorithms for such a problem is already challenging; therefore, we leave the extension to handle other physical constraints as a future research direction.

Remark 3: Compared to [17] and [21], the charging and discharging losses are considered in our problem formulation. These losses introduce nonlinearity to the dynamics of ESs, which makes the optimization problem nonconvex. By introducing two lifted variables $p_{i,t}^+$ and $p_{i,t}^-$ for ESs in (5), we convert the nonconvex optimization problem to its convex equivalency (11).

The existing studies on DER coordination focused on fixed communication networks [17]–[21]. However, in practice, the communication network topology may vary due to unexpected loss of communication links [23]. This motivates the study in this paper. In particular, the communication topology for DERs is modeled as a time-varying directed graph $\mathcal{G}(k) = (\mathcal{V}, \mathcal{E}(k))$, where the agent set is $\mathcal{V} = \{1, 2, \dots, N + M\}$, in which the first N agents correspond to DGs, while the last M agents correspond to ESs, and the edge set $\mathcal{E}(k)$ models communication links among DERs, which may change over time due to unexpected loss of communication links.

We make the following mild assumption regarding the communication network.

Assumption 3: The time-varying directed communication network $\mathcal{G}(k)$ is uniformly jointly strongly connected, i.e., the joint communication network $\mathcal{G}([k_0, k_0 + B])$ is strongly connected for any $k_0 \in \mathbb{Z}_+$ with some integer $B > 0$.

Note that the above assumption is a mild condition on the connectivity of communication topologies, since the network can be disconnected at any time instant as long as the joint graph over a period of time is strongly connected.

IV. MAIN RESULTS

In this section, we first present the Lagrangian-based approach for the optimal DER coordination in Section IV-A. In Section IV-B, we propose a distributed algorithm with diminishing step sizes and show that the proposed distributed algorithm asymptotically achieves the optimal DER coordination if the time-varying directed communication network is uniformly jointly strongly connected and the cost functions are strictly convex. To improve the slow convergence due to the diminishing step sizes, in Section IV-C, we develop a distributed algorithm with a fixed step size and show that the new proposed algorithm exponentially realizes the optimal DER coordination under an additional assumption on the cost functions.

A. Lagrangian-Based Approach

For problem **PP** (11), we denote $\Omega_{\mathcal{N},i}$ as the set of all $p_i \in \mathbb{R}^T$ for which (3) and (4) are satisfied, where $i \in \mathcal{N}$ and $p_i = (p_{i,1}, p_{i,2}, \dots, p_{i,T})'$. We also denote $\Omega_{\mathcal{M},i}$ as the set of all $p_i^+, p_i^- \in \mathbb{R}^T$ for which (6)–(10) are satisfied, where $i \in \mathcal{M}$, $p_i^+ = (p_{i,1}^+, p_{i,2}^+, \dots, p_{i,T}^+)$, and $p_i^- = (p_{i,1}^-, p_{i,2}^-, \dots, p_{i,T}^-)$. Note that both sets $\Omega_{\mathcal{N},i}$ and $\Omega_{\mathcal{M},i}$ are convex polyhedra since all constraints are affine. Moreover, the objective function in (11) is also strictly convex given Assumption 1. Therefore, the primal problem **PP** (11) has a unique minimizer, for which we

denote as p_i^* . Moreover, there is zero duality gap, and the dual optimal set is nonempty [26].

In order to solve the optimal DER coordination problem **PP** in (11), we can instead solve its dual problem with respect to constraint (2), which couples the operations of all DERs. Following the similar analysis as those in [1], [10], [27], and [28], it is not hard to obtain the dual problem of **PP** as follows:

$$\mathbf{DP} : \max_{\lambda \in \mathbb{R}^T} \sum_{i=1}^{N+M} \Phi_i(\lambda) \quad (13)$$

where $\lambda = (\lambda_1, \dots, \lambda_T)'$ and λ_i for $i \in \mathcal{T}$ are dual variables associated with the power balance constraints (2)

$$\Phi_i(\lambda) = \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda'(p_i - D^i), \quad i \in \mathcal{V} \quad (14)$$

where $\Omega_i = \Omega_{\mathcal{N},i}$ for $i \in \mathcal{N}$, and $\Omega_i = \{p_i = p_i^+ - p_i^- | \{p_i^+, p_i^-\} \in \Omega_{\mathcal{M},i}\}$ for $i \in \mathcal{M}$.

Note that $D^i \in \mathbb{R}^T$ are virtual local demands at DER i for all the periods such that $\sum_{i=1}^{N+M} D^i = D$, where $D = (D_1, \dots, D_T)'$. One choice is that $D^i = \frac{1}{N+M} D$ for all $i \in \mathcal{V}$. Note that D^i s have no physical meaning. The purpose of introducing these parameters is to convert the dual problem into the maximization problem of $N + M$ local functions as shown in (13) such that distributed algorithms can be developed to solve the dual problem.

Under Assumption 1, for any given λ , the right-hand side of (14) has a unique minimizer given by

$$p_i(\lambda) = \arg \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda' p_i, \quad i \in \mathcal{V}. \quad (15)$$

Furthermore, there exists at least one optimal solution to the dual problem (13), and the unique optimal solution of the primal problem (11) can be obtained by solving the local optimization problem (14), which is given by

$$p_i^* = p_i(\lambda^*) = \arg \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda^{*'} p_i, \quad i \in \mathcal{V} \quad (16)$$

where $\lambda^* = (\lambda_1^*, \dots, \lambda_T^*)'$ is any dual optimal solution.

Note that $C_i(\cdot)$ is strictly convex and the constrained set is a bounded polyhedron; it then follows from [29, p. 669] that the function $\Phi_i(\lambda)$ is continuously differentiable, and the gradient is given by

$$\nabla \Phi_i(\lambda) = -(p_i(\lambda) - D^i). \quad (17)$$

In this paper, we aim to solve the DER coordination problem (11) by solving its dual problem (13) in a distributed manner. Compared with the existing literature [17]–[21], which focused on fixed communication networks, we aim to develop distributed algorithms for solving the DER coordination problem over time-varying directed networks.

B. Distributed Push-Sum and Gradient-Based Algorithm

To address the challenges of time-varying directed networks, we propose a distributed algorithm based on the push-sum and (sub)gradient method developed recently in [23].

More specifically, at each iteration $k \in \mathbb{Z}_+$, each DER (agent) $i \in \mathcal{V}$ maintains five vectors, namely, $w_i(k)$, $y_i(k)$, $\lambda_i(k)$, $p_i(k)$, $v_i(k) \in \mathbb{R}^T$, where $w_i(k)$, $y_i(k)$, and $v_i(k)$ are auxiliary vectors, and $p_i(k)$ and $\lambda_i(k)$ are agent i 's estimations of the primal solution (optimal generations of DGs and ESSs) and the dual optimal solution (optimal incremental cost), respectively. For example, $\lambda_i = (\lambda_{i,1}, \dots, \lambda_{i,T})'$, where $\lambda_{i,t}$ for $i \in \mathcal{V}$ and $t \in \mathcal{T}$ is agent i 's estimate of the optimal incremental cost (marginal price) for period t . At each iteration $k \in \mathbb{Z}_+$, each agent $i \in \mathcal{V}$ updates its vectors according to the following:

$$w_i(k+1) = \sum_{j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\}} \frac{v_j(k)}{d_j(k)+1} \quad (18a)$$

$$y_i(k+1) = \sum_{j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\}} \frac{y_j(k)}{d_j(k)+1} \quad (18b)$$

$$\lambda_i(k+1) = \frac{w_i(k+1)}{y_i(k+1)} \quad (18c)$$

$$p_i(k+1) = \arg \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda_i(k+1)' p_i \quad (18d)$$

$$v_i(k+1) = w_i(k+1) - \alpha(k+1)(p_i(k+1) - D^i) \quad (18e)$$

where the division in (18c) operates entrywise. The algorithm is initialized with an arbitrarily assigned vector $v_i(0) \in \mathbb{R}^T$ and $y_i(0) = \mathbf{1}$ for all $i \in \mathcal{V}$.

The step size $\alpha(k+1)$ satisfies the following decaying (diminishing) conditions:

$$\begin{aligned} \sum_{k=1}^{\infty} \alpha(k) &= \infty, \quad \sum_{k=1}^{\infty} \alpha^2(k) < \infty \\ \alpha(k) &\leq \alpha(s) \text{ for all } k > s \geq 1. \end{aligned} \quad (19)$$

A typical choice for a sequence $\alpha(k)$ satisfying (19) is $\alpha(k) = \frac{a}{k+b}$, where $a > 0$ and $b \geq 0$.

The proposed algorithm (18) is inspired by the push-sum and (sub)gradient method developed in [23]. Note that it follows from (17) that the term $-(p_i(k+1) - D^i)$ in the update (18e), where $p_i(k+1)$ is given by (18d), is the gradient of the function $\Phi_i(\lambda_i(k+1))$. The update (18) without the gradient term is called the push-sum algorithm [30]–[32], or the ratio consensus algorithm [33]–[35] in the literature. In these algorithms, all $\lambda_i(k)$ converge to the average of initial values as $k \rightarrow \infty$. The inclusion of the gradient term in the update is to ensure that all $\lambda_i(k)$ converge to a dual optimal solution λ^* .

Remark 4: In algorithm (18), at each iteration $k \in \mathbb{Z}_+$, each agent (DER) i sends the quantities $\frac{v_i(k)}{d_i(k)+1}$ and $\frac{y_i(k)}{d_i(k)+1}$ to all the agents j in its out-neighbors set and receives the corresponding messages from its in-neighbors. In order to implement the algorithm, each agent i needs to know its out-degree $d_i(k)$, which is necessary if agents are not aware of their unique identifier (ID) as shown in [36]. However, this may be impractical when agents use a broadcast-based communication [36]–[38]. To overcome the case that some agents are not aware of their out-degrees, the authors of [37] developed a strategy, where each agent also transmits to its out-neighbors one extra running sum along with its unique identifier. By assuming that each agent knows its unique

identifier, the authors of [38] proposed a distributed optimization algorithm with row stochastic matrices, which is easier to construct since each agent could assign edge weights to its in-neighbors. Note that the analyses in [37] and [38] are applicable to fixed graphs. It is an interesting future research direction to extend their results to time-varying graphs.

The following theorem establishes the convergence result of algorithm (18).

Theorem 1: Suppose that Assumptions 1–3 hold. The distributed algorithm (18) with the step size $\alpha(k)$ satisfying conditions in (19) asymptotically solves the optimal DER coordination problem (11), i.e., $p_i(k) \rightarrow p_i^*$ and $\lambda_i(k) \rightarrow \lambda^*$ as $k \rightarrow \infty$ for all $i \in \mathcal{V}$.

Proof: Note that the dual problem **DP** (13) has the same form as the distributed optimization problem considered in [23]. The difference is that the dual problem (13) is a maximization problem for the sum of concave functions, while the problem in [23] is a minimization problem for the sum of convex functions. Therefore, in what follows, we verify that the sufficient conditions given in [23, Th. 1] are indeed satisfied.

The first condition that the graph is uniformly jointly strongly connected holds due to Assumption 3. The second condition also holds, since each function $\Phi_i(\lambda)$ in the maximization problem (13) is concave and the optimal set is nonempty, due to Assumption 1. Finally, the gradient of each function $\Phi_i(\lambda)$ given by (17) is uniformly bounded, since the constrained set is bounded and the virtual local demand is also bounded. Hence, it follows from [23, Th. 1], whose proof is somewhat involved, that $\lambda_i(k) \rightarrow \lambda^*$ as $k \rightarrow \infty$ for all $i \in \mathcal{V}$.

To be self-contained, here, we briefly provide the essential idea of the proof, which contains two steps. In the first step, it can be shown that $\lambda_i(k)$ for $i \in \mathcal{V}$ converges to the average process $\bar{v}(k)$ defined as

$$\bar{v}(k) = \frac{1}{N+M} \sum_{i=1}^{N+M} v_i(k) \quad (20)$$

increasingly well as iteration goes on, i.e., $\lambda_i(k) \rightarrow \bar{v}(k)$ as $k \rightarrow \infty$. In the second step, it can be shown that the average process converges to a dual optimal solution λ^* , i.e., $\bar{v}(k) \rightarrow \lambda^*$ as $k \rightarrow \infty$.

Finally, it follows from the update equation (18d) and the zero duality between the primal problem (11) and the dual problem (13) that $p_i(k) \rightarrow p_i^*$ as $k \rightarrow \infty$ for all $i \in \mathcal{V}$. ■

C. Accelerated Distributed Algorithm

In the previous section, we have developed a distributed algorithm with the diminishing step sizes for solving the optimal DER coordination problem. However, the convergence of algorithm (18) is rather slow due to the diminishing step sizes. In order to speed up the convergence, motivated by the recent advances in distributed optimization [39]–[43], in this section, we develop an accelerated distributed algorithm with a fixed step size.

More specifically, at each iteration $k \in \mathbb{Z}_+$, each DER (agent) $i \in \mathcal{V}$ maintains five vectors $u_i(k)$, $v_i(k)$, $\lambda_i(k)$, $p_i(k)$, $y_i(k) \in \mathbb{R}^T$, where $u_i(k)$, $v_i(k)$, and $y_i(k)$ are auxiliary vectors, and $p_i(k)$ and $\lambda_i(k)$ are agent i 's estimations of the primal solution

(optimal generations of DGs and ESs) and the dual optimal solution (optimal incremental cost), respectively. These vectors are updated as follows:

$$u_i(k+1) = \sum_{j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\}} \frac{u_j(k) + \alpha y_j(k)}{d_j(k) + 1} \quad (21a)$$

$$v_i(k+1) = \sum_{j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\}} \frac{v_j(k)}{d_j(k) + 1} \quad (21b)$$

$$\lambda_i(k+1) = \frac{u_i(k+1)}{v_i(k+1)} \quad (21c)$$

$$p_i(k+1) = \arg \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda_i(k+1)' p_i \quad (21d)$$

$$y_i(k+1) = \sum_{j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\}} \frac{y_j(k)}{d_j(k) + 1} - (p_i(k+1) - p_i(k)). \quad (21e)$$

The algorithm is initialized with any $\lambda_i(0) = u_i(0) \in \mathbb{R}^T$, $v_i(0) = \mathbf{1}$, $p_i(0) = \arg \min_{p_i \in \Omega_i} \sum_{t=1}^T C_i(p_{i,t}) - \lambda_i(0)' p_i$, and $y_i(0) = -(p_i(0) - D^i)$.

The proposed algorithm (21a) is inspired by the algorithm recently proposed in [41], which uses a distributed inexact gradient method and employs the push-sum protocol for gradient tracking (termed as Push-DIGing). Intuitively, the update (21a) is a distributed inexact gradient method, where the variable $y_j(k)$ is used instead of the average gradient, and in the update (21e), $y_j(k)$ tracks the average gradient by employing dynamic average consensus [44]. The updates (21b) and (21c) are based on the push-sum method to handle the time-varying directed graphs. Note that the implementation of the algorithm also requires each agent to know its out-degree.

Remark 5: Note that it follows from (17) that the term $-(p_i(k+1) - p_i(k))$ in (21e) is equal to $-(\nabla \Phi_i(\lambda_i(k+1)) - \nabla \Phi_i(\lambda_i(k)))$, which is the new information contained in the most recent gradient evaluation. This idea has also been used in other recent studies to accelerate the convergence speed, among which [39]–[42] focused on undirected graphs and [41] studied directed graphs. Here, we propose algorithm (21a) based on Push-DIGing developed [41], since it is applicable to time-varying directed graphs.

To establish convergence of algorithm (21a), we make the following assumption on the cost functions.

Assumption 4: For each $t \in \mathcal{T}$, the cost function $C_i(p_{i,t})$ or $C_i(p_{i,t}^+, p_{i,t}^-)$ is increasing and twice continuously differentiable over $p_i \in \Omega_{\mathcal{N},i}$ for $i \in \mathcal{N}$ and $\{p_i^+, p_i^-\} \in \Omega_{\mathcal{M},i}$ for $i \in \mathcal{M}$, respectively. Moreover, there exist two positive constants α_i and β_i , such that $\frac{1}{\alpha_i} \leq \nabla^2 C_i(p_{i,t}) \leq \frac{1}{\beta_i}$ for $p_i \in \Omega_i$.

It is easy to see that when Assumption 4 is satisfied, each cost function $C_i(\cdot)$ is strongly convex for $p_i \in \Omega_i$ since $\nabla^2 C_i(p_{i,t}) \geq \frac{1}{\alpha_i}$ for $p_i \in \Omega_i$. Therefore, $C_i(\cdot)$ is strictly convex over $p_i \in \Omega_i$, that is, Assumption 1 is satisfied for $p_i \in \Omega_i$. However, when the cost functions satisfy additional properties as given in Assumption 4, compared with algorithm (18), which asymptotically solves the optimal DER coordination problem,

the new algorithm (21a) exponentially achieves the optimal DER coordination as shown in the following theorem.

Theorem 2: Suppose that Assumptions 2–4 hold. Then, there exists a constant $\bar{\alpha} > 0$, such that the distributed algorithm (21a) with any fixed step size $0 < \alpha < \bar{\alpha}$ exponentially solves the optimal DER coordination problem (11), i.e., $\lambda_i(k) \rightarrow \lambda^*$ and $p_i(k) \rightarrow p_i^*$ as $k \rightarrow \infty$ for all $i \in \mathcal{V}$ with a linear convergence rate.

Proof: We first show that the each estimate $\lambda_i(k)$ for $i \in \mathcal{V}$ converges to the dual optimal solution λ^* exponentially (R-linearly in the language of optimization theory). We show this by verifying that all the sufficient conditions of [41, Th. 5.9] are satisfied.

1) First, we show that each local dual function $\Phi_i(\lambda)$ given in (14) is strongly concave and smooth.

Note that it follows from (15) that

$$p_i(\lambda) = \text{proj}_{\Omega_i}(\nabla \tilde{C}_i^{-1}(\lambda)) \quad (22)$$

where $\tilde{C}_i(p_i) = \sum_{t=1}^T C_i(p_{i,t})$, and $\nabla \tilde{C}_i^{-1}(\lambda)$ is the inverse function of $\nabla \tilde{C}_i(p_i)$, which exists over its argument domain since each function $\nabla C_i(p_{i,t})$ is continuous and $C_i(p_{i,t})$ is strictly increasing in its argument domain due to Assumption 4, and $\text{proj}_{\Omega_i}(\cdot)$ denotes the projection to the set Ω_i . It then follows from the standard property of the derivative of the inverse function that

$$\frac{\partial p_i}{\partial \lambda}(\lambda) = \begin{cases} \frac{1}{\tilde{C}_i''(p_i(\lambda))}, & \text{if } p_i \in \Omega_i \\ 0 & \text{otherwise.} \end{cases} \quad (23)$$

Next, from (17), we have

$$\nabla^2 \Phi_i(\lambda) = -\frac{\partial p_i}{\partial \lambda}(\lambda).$$

This together with (23) implies that

$$\nabla^2 \Phi_i(\lambda) = \begin{cases} -\frac{1}{\tilde{C}_i''(p_i(\lambda))}, & \text{if } p_i \in \Omega_i \\ 0, & \text{otherwise.} \end{cases}$$

Finally, it follows from the fact that $\frac{1}{\alpha_i} \leq \nabla^2 C_i(p_{i,t}) \leq \frac{1}{\beta_i}$ from Assumption 4 that, when exists,

$$-\frac{\alpha_i}{T} \leq \nabla^2 \Phi_i(\lambda) \leq -\frac{\beta_i}{T}. \quad (24)$$

The second inequality of (24) implies that the local dual function $\Phi_i(\lambda)$ given in (14) for any $i \in \mathcal{V}$ is strongly concave. This also ensures that the dual problem (13) has a unique optimal solution λ^* .

Also note that it follows from the first inequality of (24) and [27, Lemma 3] that the local dual function $\Phi_i(\lambda)$ has a Lipschitz continuous gradient. Thus, the local dual function $\Phi_i(\lambda)$ is smooth.

2) Next, the time-varying directed graph is uniformly jointly strongly connected by Assumption 3.

3) Finally, it is easy to see that the weight mixing matrix of algorithm (21a) given by

$$A_{ij}(k) = \begin{cases} \frac{1}{d_j(k)+1}, & \text{if } j \in \mathcal{N}_i^{\text{in}}(k) \cup \{i\} \\ 0, & \text{otherwise} \end{cases}$$

is column stochastic for all $k \in \mathbb{Z}_+$.

Hence, it follows from [41, Th. 5.9] that if $\alpha < \bar{\alpha}$, where $\bar{\alpha}$ is a constant depending on the parameters of the communication network and cost functions, then each estimate $\lambda_i(k)$ for $i \in \mathcal{V}$ converges to the unique optimal solution λ^* exponentially (R-linearly in the language of optimization theory). That is, there exist some constants $C > 0$ and $0 < \rho < 1$ such that

$$\|\lambda_i(k) - \lambda^*\| \leq C\rho^k \quad \forall k \in \mathbb{Z}_+. \quad (25)$$

Next, we show that the estimate $p_i(k)$ for each $i \in \mathcal{V}$ converges to the optimal generation p_i^* exponentially.

Note that from (16) and (22), for all $k \in \mathbb{Z}_+$, we have

$$\begin{aligned} & \|p_i(k) - p_i^*\| \\ &= \left\| \text{proj}_{\Omega_i}(\nabla \tilde{C}_i^{-1}(\lambda_i(k))) - \text{proj}_{\Omega_i}(\nabla \tilde{C}_i^{-1}(\lambda^*)) \right\| \\ &\leq \left\| \nabla \tilde{C}_i^{-1}(\lambda_i(k+1)) - \nabla \tilde{C}_i^{-1}(\lambda^*) \right\| \\ &\leq \left\| \nabla^2 \tilde{C}_i^{-1}((1-c)\lambda_i(k+1) + c\lambda^*) \right\| \\ &\quad \times \|\lambda_i(k+1) - \lambda^*\| \\ &\leq \frac{\alpha_i C}{T} \rho^k \end{aligned} \quad (26)$$

for some constant $0 < c < 1$, where the first inequality follows from the standard nonexpansiveness property of the projection operator [25], the second inequality follows from the mean value theorem, and the last inequality follows from $\nabla^2 C_i(p_{i,t}) \geq \frac{1}{\alpha_i}$ and (25). Therefore, (26) implies that $p_i(k)$ converges to the optimal generation p_i^* with the same R-linear rate $O(\rho^k)$ as the convergence of $\lambda_i(k)$ to λ^* . Hence, algorithm (21a) achieves the optimal DER coordination exponentially (R-linearly). ■

Remark 6: Note that the complicated closed-form expressions for $\bar{\alpha}$ and the convergence rate ρ can be derived by following the worst-case analysis given in [41, Th. 5.9]. However, such an upper bound on fixed step sizes is often conservative, and larger values can be chosen in the numerical experiments. Nevertheless, it ensures the distributed algorithm to have provable convergence guarantees.

Remark 7: Compared to algorithm (18) with diminishing step sizes, algorithm (21a) uses a fixed step size and solves the optimal DER coordination problem faster. In order to establish faster convergence of (21a), the local cost functions $C_i(p_{i,t})$ for $i \in \mathcal{V}$ and $t \in \mathcal{T}$ need to satisfy more properties, as given in Assumption 4. Therefore, depending on the properties of cost functions, we may choose different algorithms to solve the optimal DER coordination problem. If only Assumption 1 is satisfied, we use algorithm (18) to solve the optimal DER coordination problem. If Assumption 4 is satisfied, we can use algorithm (21a) to solve the optimal DER coordination problem with a faster convergence rate.

V. CASE STUDIES

In this section, we validate and evaluate the performance of algorithm (18) with diminishing step sizes and algorithm (21a) with a fixed step size for optimal DER coordination using the IEEE 39-bus system modified from [45]–[47] shown in Fig. 1, where Buses 30–39 are connected with DGs, and Buses 27 and

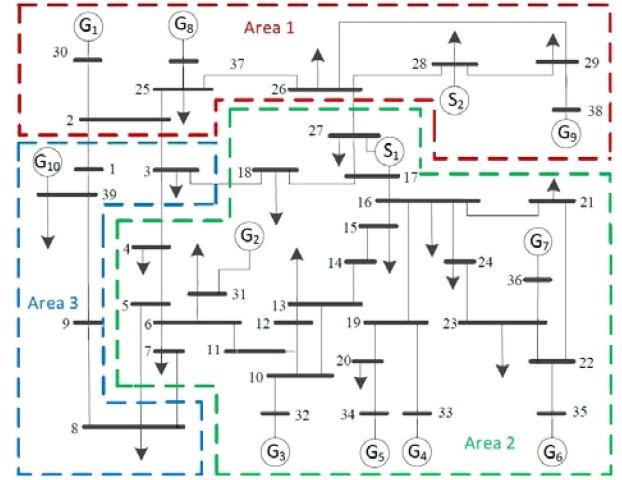


Fig. 1. IEEE 39-bus system.

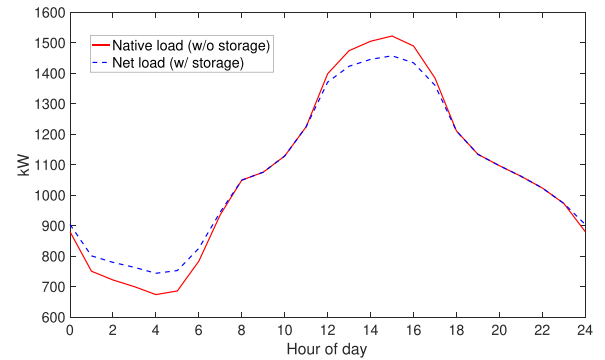


Fig. 2. Native load versus net load.

TABLE I
GENERATOR PARAMETERS

Unit	a_i (\$/kW ² h)	b_i (\$/kWh)	c_i (\$/h)	Range (kW)
1	0.00024	0.0267	0.38	[30,60]
2	0.00052	0.0152	0.65	[20,60]
3	0.00042	0.0185	0.4	[50,200]
4	0.00031	0.0297	0.3	[20,140]
5	0.000248	0.0156	0.3312	[50,300]
6	0.000199	0.0116	0.4969	[110,500]
7	0.00028	0.0195	0.32	[40,250]
8	0.00028	0.0195	0.32	[40,250]
9	0.00042	0.0185	0.4	[50,200]
10	0.00031	0.0297	0.3	[20,140]

28 are connected to ESs. The demand during a 24-h is plotted in red in Fig. 2.

The cost functions of DGs are given by $C_i(p_{i,t}) = a_i^2 p_{i,t} + b_i p_{i,t} + c_i$ for all $i \in \{30, 31, \dots, 39\}$ and for $t \in \{1, 2, \dots, 24\}$. The cost functions of ESs are given by $C_i(p_{i,t}) = a_i^2 p_{i,t}$ for $i \in \{27, 28\}$ and for $t \in \{1, 2, \dots, 24\}$. The parameters of DGs and ESs are given in Tables I and II, respectively. Note that the cost functions satisfy both Assumptions 1 and 4.

The IEEE 39-bus system has been partitioned into three areas, as shown in Fig. 1. Within each area, the communication links among DERs are bidirectional. The communication links between different areas maybe unidirectional. More specifically,

TABLE II
 STORAGE PARAMETERS

Unit	α_i (\$/kWh)	E_s (kWh)	p_{\max} (kW)	η_+	η_-
1	0.0001	500	50	0.8	0.8
2	0.0001	400	40	0.88	0.88

the communication links between Area 1 and Area 3 are (2, 1) and (2, 3), and the communication link between Area 1 and Area 2 is (27, 26). The communication network is modeled as a time-varying directed network switching among two fixed topologies. More specifically, we have

$$\mathcal{G}(k) = \begin{cases} \mathcal{G}_1, & \text{if } k \in [0, 1) \cup [2, 3) \cdots \cup [2s, 2s + 1) \cdots \\ \mathcal{G}_2, & \text{if } k \in [1, 2) \cup [3, 4) \cdots \cup [2s + 1, 2s + 2) \cdots \end{cases}$$

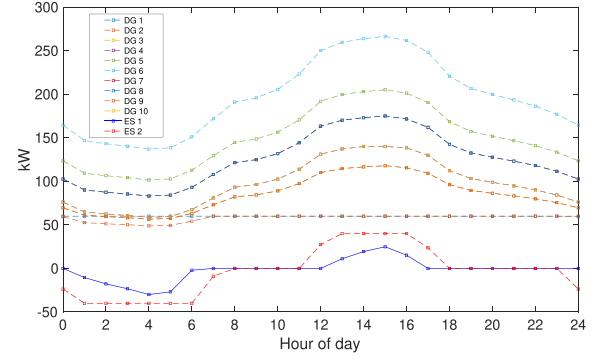
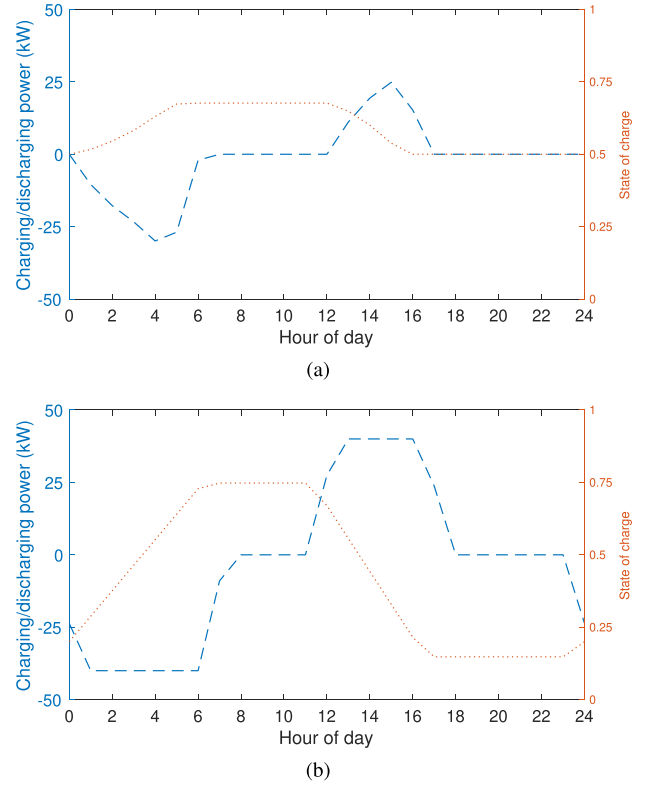
where $s \in \mathbb{Z}_+$, \mathcal{G}_1 is the directed graph obtained by disconnecting Area 1 and Area 3, that is, by removing the links (2,1) and (2,3), and \mathcal{G}_2 is the directed graph obtained by disconnecting Area 1 and Area 2, that is, by removing the link (27,26). It is easy to check that each of the fixed topologies \mathcal{G}_1 and \mathcal{G}_2 is not connected. For example, in the directed graph \mathcal{G}_1 , there is no directed path from agents in Area 1 to agents in Area 2 and Area 3. However, the time-varying directed graph $\mathcal{G}(k)$ is uniformly jointly strongly connected, since the joint graph $\mathcal{G}([k_0, k_0 + B))$ is strongly connected for any $k_0 \geq 0$ with $B = 2$. Thus, Assumption 3 is satisfied with $B = 2$. According to Theorems 1 and 2, algorithm (18) with properly chosen diminishing step sizes and algorithm (21a) with a fixed step size less than a certain critical value solve the optimal DER coordination problem, which will be verified in the following subsections, respectively.

A. Algorithm With Diminishing Step Sizes

We start by evaluating algorithm (18). We have verified that algorithm (18) with the diminishing step size $\alpha(k) = \frac{0.005}{k}$, which satisfies the conditions in (19) converges to the optimal generation roughly in 10 000 steps and the computation time is 61.7079 s. The blue curve in Fig. 2 is the resulting net load (load minus storage). Fig. 2 shows how two ESs are coordinated to cut the peak and fill the valley. In particular, they are discharged during peak hours when the energy price is high and charged during off-peak hours when the energy price is low.

The obtained optimal generations for ten DGs and two ESs over 24 h are plotted in Fig. 3. The power output and state of charge (SOC) for both storages are provided in Fig. 4. For each storage, SOC is the same at the beginning and end of the scheduling period, but the total charging energy (area between the negative blue curve and the x -axis) is more than the discharging energy (area between the positive blue curve and the x -axis) due to charging and discharging losses. ESs are idle when the energy price is not high (or low) enough to make the discharging (or charging) profitable considering the round-trip efficiency. In particular, ES 1 is idle during Hour 6–12 and 17–24 because of its low charging/discharging efficiency, while ES 2 is engaged more often due to its higher charging/discharging efficiency.

In order to show the convergence more clearly, the simulation results for Hour 1 are given in Fig. 5. Fig. 5(a) plots the evolutions of the estimates $\lambda_{i,1}(k)$ all for $i \in \mathcal{V}$, which shows that


Fig. 3. Optimal power generations for DGs and ESs over 24 h.

Fig. 4. Charging (negative) and discharging (positive) power and SOC. (a) ES 1. (b) ES 2.

all $\lambda_{i,1}(k)$ converges to 0.0716 \$/kWh, which is roughly equal to the optimal incremental cost $\lambda_1^* = 0.0699$ \$/kWh. In order to clearly show the convergence process for power generations, in Fig. 5(b), we have only included the evolutions for the power generation for DGs 1, 5, 6, 8, and 10, and ESs 1 and 2. They all converge to the corresponding optimal generations. Fig. 5(c) plots the evolution of the total generation in comparison with the total demand, which clearly shows that the total generation meets the total demand for Hour 1, i.e., $D_1 = 750.9792$ kW.

B. Algorithm With a Fixed Step Size

To accelerate the convergence, we next apply algorithm (21a). We have checked that algorithm (21a) with the fixed step size $\alpha = 5 \times 10^{-5}$ solves the optimal DER coordination problem

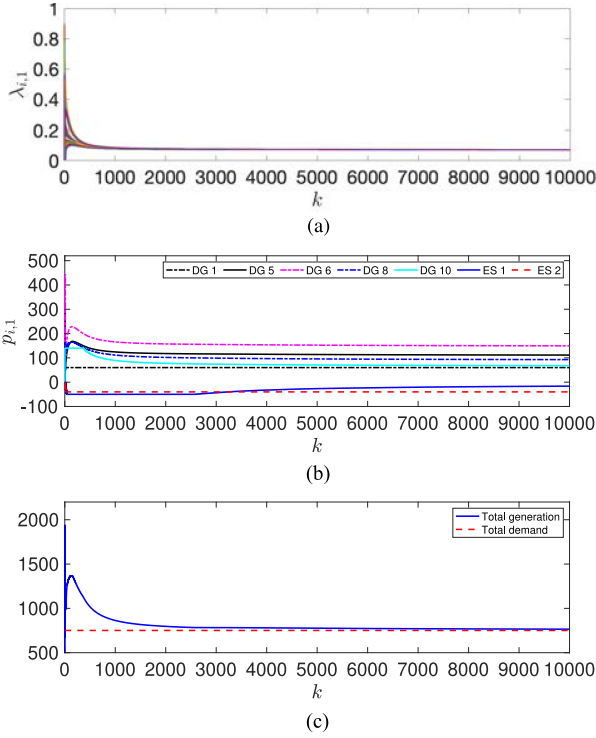


Fig. 5. Results of algorithm (18) with the diminishing step size $\alpha(k) = \frac{0.005}{k}$. (a) Incremental cost (\$/kWh). (b) Generation (kW). (c) Total generation versus total demand (kW).

roughly in 1000 steps and the computation time is 6.1681 s. The simulation results for Hour 1 are given in Fig. 6. Fig. 6(a) shows that all estimates $\lambda_{i,1}(k)$ converge to the optimal incremental cost $\lambda_1^* = 0.0699$ \$/kWh. The evolutions of power generations for DGs 1, 5, 6, 8, and 10, and ESs 1 and 2 are plotted in Fig. 6(b), which shows that they converge to the corresponding optimal generations. Fig. 6(c) plots the evolution of the total generation in comparison with the total demand, which clearly shows that the total generation meets the total demand for Hour 1, i.e., $D_1 = 750.9792$ kW.

Compared with the simulation results of algorithm (18) with the diminishing step sizes shown in Fig. 5, the convergence of algorithm (21a) with the fixed step size is much faster. For example, at time step $k = 1000$, the estimates $\lambda_{i,1}(k)$ are all roughly equal to optimal incremental cost $\lambda_1^* = 0.0699$ \$/kWh, while using algorithm (18) with the diminishing step sizes $\alpha(k) = \frac{0.005}{k}$, at the same time step, all estimates $\lambda_{i,1}(k)$ are in the range of $[0.0746, 0.0830]$, which are in the neighborhood of the optimal incremental cost with 18.7% error.

To make the comparison more explicit, we have also plotted the total generations of these two algorithms together with the demand for Hour 1 in Fig. 7. As can be seen, the total generation by running algorithm (21a) with $\alpha = 5 \times 10^{-5}$ converges to the total demand roughly at the time step $k = 400$, while the convergence of algorithm (18) with the diminishing step sizes $\alpha(k) = \frac{0.005}{k}$ is not achieved even at the time step $k = 1000$. Hence, the convergence of algorithm (21a) with a fixed step size is faster.

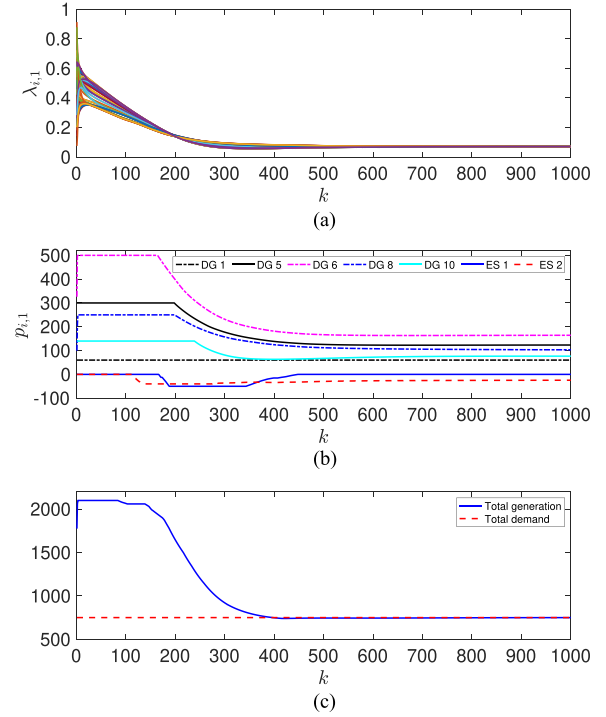


Fig. 6. Results of algorithm (21a) with the fixed step size $\alpha = 5 \times 10^{-5}$. (a) Incremental cost (\$/kWh). (b) Generation (kW). (c) Total generation versus total demand (kW).

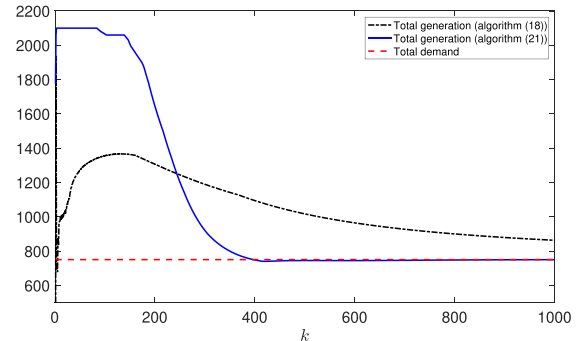


Fig. 7. Comparison of algorithm (18) and algorithm (21a).

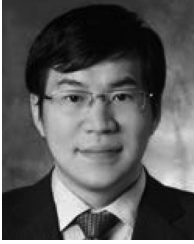
VI. CONCLUSION

In this paper, we have considered the optimal coordination problem of DERs, including DGs and ESs. In the problem formulation, storage charging/discharging efficiencies were explicitly modeled. We first proposed a distributed algorithm with diminishing step sizes and showed that the proposed algorithm with an appropriately chosen step size asymptotically solves the optimal DER coordination problem over time-varying directed communication networks that are uniformly jointly strongly connected. To accelerate the convergence, we next developed a distributed algorithm with a fixed step size and showed that the new proposed algorithm exponentially solves the optimal DER coordination problem if the cost function satisfies additional properties. The performances of the proposed algorithms have been tested on the IEEE 39-bus system. One future research direction is to extend the proposed distributed algorithms

to accommodate other communication effects, such as time delays and packet drops. Another interesting research direction is to extend the proposed distributed algorithms to accommodate additional physical constraints, such as those relevant to transmission line loss, power flow, and transmission line flow.

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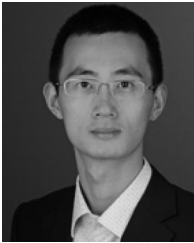


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