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Distributed optimal active power dispatch with energy storage units and power flow limits in smart grids[☆]

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ABSTRACT

Dynamic optimal active power dispatch with energy storage units and power flow limits is an important problem in smart grids. This problem is usually described as a convex optimization model. In our model, not only the conventional equality and inequality constraints, energy storage units' constraints and power flow constraints are considered, but also the energy storage units' operational costs and the power price of the main grid are considered in the total costs. To solve this problem, a fully distributed algorithm based on the alternating direction method of multipliers (ADMM), the projected gradient method and the average consensus is proposed. The proposed algorithm can obtain the optimal output power settings of the energy storage units, distributed generators and the main grid for different demand loads with different initial states. In the proposed algorithm, firstly, the dispatch problem is decomposed into multiple subproblems on the basis of the alternating direction method of multipliers; then the subproblems can be solved according to the projected gradient method and the average consensus algorithm. In order to apply the projected gradient method, every bus is equipped with a bus agent which is responsible for information communication and the output power optimization calculation. Simulation studies demonstrate the effectiveness of the proposed algorithm. .

1. Introduction

Optimal active power dispatch (OAPD) is an important question which aims at obtaining the minimum operational costs by setting up the optimal output power references of distributed energy resources (DER) (including distributed generators (DGs) and energy storage units (ESUs)) under various physical constraints [1]. DER and loads can compose an autonomous power grid which can operate in the main grid connected mode or the islanded mode [2–5]. In the main grid connected mode, the system can sell/purchase electrical power to/from the main grid according to the actual demand. Accordingly, the electrical price of the main grid is an essential factor which needs to be considered. There are two types of algorithms which can solve the OAPD problem, i.e., the analytical algorithms (e.g. gradient search [6] and lambda iteration [7]) and heuristic algorithms (e.g. particle swam optimization [8] and genetic algorithm [9]).

With more and more renewable DER penetrating in the next generation of power grids [10], the traditional centralized algorithms require more complicated communication networks and a central controller with stronger processing capacity, which greatly limits computational efficiency and increases operational costs. Also, the centralized algorithms cannot ensure the timeliness because of the communication latency and the complicated operation calculations [11]. In comparison with the centralized algorithms, distributed algorithms have many advantages, e.g. lower computation complexity and lower operational cost, which can efficiently avoid single-point failures [12]. By the distributed algorithms, the OAPD problem can be divided into multiple subproblems which can be solved, independently and effectively. For example, based on the distributed optimization, the authors of [13–17] studied the distributed economic dispatch problem.

In practical power grid, the demand loads are time-varying, so the ramp rate constraints of DER need to be considered in the economic dispatch which is regarded as the dynamic optimal active power dispatch (DOAPD) [18]. The renewable DGs (e.g. the wind and solar power generators) penetrated in power grids are intermittent. The features of renewable DGs will greatly influence the stability of an

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autonomous power grid. To counteract the uncertainty and intermittency of renewable DGs, it is necessary to use ESUs in the power grid [19]. The ESUs' operational costs should be included in the total operational cost and the ESUs' boundary constraints also need to be considered, which greatly increases the difficulty of the optimization problem. The authors in [20] proposed a distributed algorithm based on the alternating direction method of multipliers (ADMM) for DOAPD with ESUs' boundary constraints, but the ESUs' operational costs weren't considered. In [21], the dynamic economic dispatch with ESUs' operational costs was solved via the dynamic programming algorithm. However, the discharging costs and charging costs were regarded as the same, which differs from the practical situation. Also, to ensure the safety and reliability of the power transmission, the active power flow through transmission lines is limited, the power flow constraints need to be considered. The authors in [22] studied the OAPD problem with the DC power flow constraints and proposed a fully distributed algorithm. However, the ESUs were not considered in the model in [22]. To the best of the authors' knowledge, no distributed algorithms have been designed to solve the DOAPD problem with ESUs and power flow constraints.

In this paper, a fully distributed algorithm is proposed to solve the DOAPD problem, which includes the conventional equality and inequality constraints (the supply and demand balance constraint, boundary constraints and ramp constraints of DGs), ESUs' constraints and power flow constraints. Also, the ESUs' different discharging and charging costs are considered in the total cost. In the proposed algorithm, firstly, the DOAPD problem is decomposed into multiple subproblems on the basis of the ADMM algorithm; then the subproblems can be solved according to the projected gradient method and average consensus algorithm. In order to apply the projected gradient method, every bus is equipped with a bus agent which is responsible for information communication and the output power optimization calculation. By the proposed algorithm, the optimal output power settings of DER and the main grid can be obtained.

The major contributions of this paper are summarized as:

(1) The DOAPD problem with the supply and demand balance constraint, boundary constraints and ramp constraints of DER and line flow constraints is modeled as a convex optimization problem, and the algorithm based on combinational tools from ADMM, the projected gradient method and average consensus is proposed to solve this problem in a fully distributed manner.
(2) The ESUs' charging costs are included in the total operational costs, which is more accordant with practical circumstances.
(3) The dynamic optimal power exchange with the main grid is obtained by the proposed algorithm.

The rest of the paper is organized as follows. Section 2 introduces some formulations about the network theory and the adopted algorithm. Section 3 presents the establishment of the DOAPD model and problem formulation. In Section 4, the algorithm based on ADMM, projected gradient method and average consensus is proposed to solve the DOAPD problem. Simulation studies and the conclusion of this paper are provided in Section 5 and Section 6.

2. Preliminaries

In this section, the graph theory, the average consensus algorithm and the ADMM algorithm are introduced as the theoretical foundations of the proposed algorithm.

The distributed algorithm can be performed effectively on the basis of the distributed network communication. In this paper, the communication network is modeled by an undirected graph $G = (V, E)$ where $V = [1, \cdots, n]$ denotes the nodes' set and E denote the communication links' set. For an undirected graph G, $e_{ij} \in E$ indicates the information can be transmitted between the i-th node and the j-th node, i.e., $e_{ij} \in E$ is equivalent to $e_{ji} \in E$. For the node $i \in V$, its neighbor nodes set can be denoted by $N_i = \{j \in V - \{i\} | e_{ij} \in E\}$ and its neighbor nodes number can be denoted by deg_i.

The distributed computation is based on the communication network among neighbor agents, which implies the consensus problem need to be solved firstly.

The basic consensus algorithm was proposed in [23]:

$$z_i^{\kappa+1} = z_i^{\kappa} + \sum_{j \in N_i} a_{ij}(z_i^{\kappa} - z_j^{\kappa}), \tag{2.1}$$

where κ represents the κ-th iteration, z_i and z_j are the states of the i-th agent and j-th agent, a_{ij} represents the communication weight between the i-th agent and j-th agent.

(2.1) can be rewritten as:

$$Z^{\kappa+1} = WZ^{\kappa}, \tag{2.2}$$

where $Z = [z_1, \cdots, z_n]^{\top}$, W is the weight matrix, which can be defined as [24]:

$$w_{ij} = \begin{cases} \frac{1}{max(deg_i, deg_j) + 1} & j \in N_i, \\ 1 - \sum_{j \in N_i} w_{ij} & j = i, \\ 0 & \text{otherwise}. \end{cases} \tag{2.3}$$

According to (2.3), the weight matrix W is row and column stochastic matrix, so the states z_i will converge to the same value [25]:

$$\lim_{\kappa \to \infty} z_i^{\kappa} = \left(\sum_{j=1}^{n} z_j^0 \right) / n, \tag{2.4}$$

where z_j^0 is the initial value of z_j.

Also, the DOAPD problem is a large scale optimization problem. In order to realize the distributed computation, it's necessary to decompose the DOAPD problem into multiple subproblems. The ADMM algorithm is a computational framework for large scale convex optimization problems. By the ADMM algorithm, the large scale global problem can be decomposed into multiple local subproblems which can be solved easily. Then the solution of the global problem can be obtained by coordinating the solutions of these subproblems. According to the features, the ADMM algorithm is introduced for the DOAPD problem.

Take the following optimization model into consideration:

$$\begin{cases} \min\limits_{x,y} & f(x) + g(y), \\ s.\ t. & Ax + By = c, \end{cases} \tag{2.5}$$

where x, y and c are $n \times 1$, $m \times 1$ and $p \times 1$ dimensional vectors, A and B are $p \times n$ and $p \times m$ dimensional matrices.

For the problem in (2.5), make two assumptions about the functions f, g and coefficient matrix A, B, described as follows [26]:

Assumption 1. The (extended-real-valued) functions f: $\mathbf{R}^n \to \mathbf{R} \cup \{+\infty\}$ and g: $\mathbf{R}^m \to \mathbf{R} \cup \{+\infty\}$ are closed, proper and convex.

Assumption 2. The matrices A and B have full column ranks.