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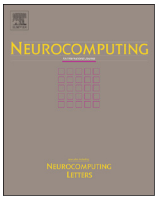

Bi-level optimal dispatch in the Virtual Power Plant considering uncertain agents number

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ABSTRACT

In smart grid, virtual power plant (VPP) is a novel solution to Distributed Energy Resources (DER) in the power grid. Same for traditional power plants, VPP should provide electricity generation to power grid according to the command electricity generation coming from power grid control center. Different from traditional power plants, VPP controls geographically distributed DER agents, which aggregate various local DER, such as small-scale engines, turbines or storages. Moreover, the number of DER Agents in VPP probably changes in pace with DER Agents plug in and plug out. In this paper, a distributed optimization algorithm is projected to solve VPP bi-level optimal dispatch considering uncertain agents number. Simulation results show that the proposed algorithm can effectively solve bi-level optimal dispatch with changing lower agents.

1. Introduction

The global climate challenges are recognized internationally and have led to the penetration of Distributed Energy Resources (DER) growing fast all over the world. In general, Virtual Power Plant (VPP) is a concept to assemble a number of DER with various operating patterns and availability that connected to various points in the power grid. With the same visibility, controllability and functionality as the conventional power plants, VPP optimal operation and control display the necessity of research. Currently, VPP projects [1] are mainly concentrated in Europe and the United States, which focuses on interactive information architecture [2], frequency control [3], auxiliary services [4] and VPP energy management optimization scheduling [5].

VPP energy management schedule is optimal coordination among VPP member agents. VPP has large numbers of DER with different types and different features, so the VPP energy management became more complex than traditional power plants. From the point of optimal goal, the VPP optimal dispatch mainly concerns on costs minimum or profits maximum. Researchers have researched various possibilities of VPP combination form. Matteo [6] considers electric vehicles into VPP optimal model so as to participate in short-term power market, aiming to sell electricity during peak electricity and storage energy during valley electricity. VPP model, constructed by Shropshire [7], contains a coastal wind farm and a small medium scaled nuclear power plant. Michiel [8] appends a micro-gas turbine into VPP to balance the volatility of wind generation. From the perspective of demand side, Mohammadi [9] compensates flexible loads for the uncertainty of wind generation.

In VPP construction, the group of DER units connected on site of the power grid will be aggregated as a DER Agent, so as to organize VPP hierarchical structure. Based on this structure, Hrvoje [10] and Edmund [11] built a VPP two-stage stochastic optimization model. Multi-level programming problems (MLPP) initiate long term research interesting since Norton and Candler [12] firstly presented. If hierarchical optimization problems have only two decision layers, it is known as BLPP. Hajinassiry [13] uses integer coded genetic algorithm (GA) to solve the upper level problem and a chaotic simulated annealing technique to deal with lower level. Kuo [14] proposes a hybrid method based on GA and PSO, better stability than GA and PSO, which is already applied to solve BLPP in supply chain model. Aviso [15] presents a bi-level fuzzy optimization method to solve BLPP while exploring the effect of decentralized decision-making to optimize the water exchange networks in an eco-industrial park. Mojica-Nava [16] discussed a hierarchical microgrid control strategy based on dynamic population games, which could consider the task sharing among homogenous agents as well as the dynamic maximization of the microgrid utility. In some circumstances, BLPP is transformed into multi-objective optimization problem (MOP) based on Lagriange KKT conditions. There are a variety of algorithms to solve MOP. Cheng [17]

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proposes an improved particle swarm optimization to obtain the optimal integration of DER into the distribution system.

VPP consists of certain DER Agents, within which a number of Distributed Energy Resources (DERs) are aggregated. So VPP can be considered as a bi-level system, where VPP is upper level and each DER Agent is lower level. In smart grid, DER agent could vary its operation state according to the dynamics of DERs, changing from plug-in to plug-out, or, conversely, from plug-out to plug-in. Therefore, the VPP dispatch is bi-level optimization with uncertain agent number. However, scarcely any investigation on BLPP with variable structure has been published.

This paper makes the following contributions that, to the best of author's knowledge, have not been exploited yet:

- Distributed optimization algorithm to solve dispatch optimization mathematic model with variable structure is implemented through the concept of VPP with uncertain agent number.
- The proposed algorithm is examined through different communication topologies among agents. The communication topology is modeled by a directed graph (digraph). Each DER Agent requires its own information and the information of its neighbors on the digraph.
- The influence of different communication topologies on optimization results and converge process is discussed.

This paper is organized as follows: Section 2 builds the VPP hierarchical dispatch architecture. In Section 3, the VPP bi-level optimization mathematics model is constructed. In Section 4, distributed algorithm to solve hierarchical distributed optimization is presented based on distributed primal-dual sub-gradient algorithm. The proposed algorithm is verified in Section 5 on different communication topologies and agent number cases. Section 6 concludes the paper.

2. VPP hierarchical dispatch architecture

Theoretically, VPP contains certain DER Agents, which assemble a variety of distributed generation energies, such as batteries, and wind and photovoltaic generation, and controllable generations such as fuel cell and diesel generator, as well as batteries undertaking energy storage. The single DER Agent just determines optimal operation strategy and control energy balance itself interior. While as the VPP, coordinated operation among the multiple DER Agents should be considered, such as coordinated frequency control, voltage control and economic dispatch. Considering the characteristics of multiple decision makers in VPP, this paper proposed a two layer hierarchical structure for the VPP coordinated operation. These two layer hierarchical structure would synthetically integrate global aims with local aims of each DER Agent. In other words, the decision makers in upper and lower layers can interact with each other. The upper decision makers guide the lower decision makers by their own decisions but do not interfere with the lower decision directly, while the decision makers in lower layer only need to take the upper decisions as an argument, and then make their own decisions within the scope of freedom. Based on the hierarchical structure we can build a bi-level programming for VPP with different objective functions [18–20].

The VPP hierarchical structure in this paper is shown in Fig. 1. The upper layer contains several DER Agents and different DER Agents communicate with adjacent DER Agents based on the communication links. In this paper, undirected communication is considered. That means the same information transfers between mutual connecting sides. The upper layer operates in accordance to distributed coordinated mode among each DER Agent, where there is no upper control center. In the lower layer, each DER Agent was managed by inside control center, as shown in Fig. 1.

3. VPP bi-level optimization mathematics model

The upper layer aims to minimize VPP total costs of the output power from DER Agents in the VPP to the power grid, with the constraints of power output and transmission line limits. The objectives of the lower layer are minimal costs of Distributed Energy Resources in each DER Agent, with the output constraints of Distributed Energy Resources.

3.1. VPP bi-level optimal model

The general bi-level optimization model can be described as follows:

$$\begin{aligned}&\min_{\mathbf{x}} F_0(\mathbf{x},\mathbf{y})\, s.t. \quad \mathbf{g}(\mathbf{x},\mathbf{y}) \ge \mathbf{0}\\ &\min_{\mathbf{y}} F_{1i}(\mathbf{x},\mathbf{y}) \quad i=1,2,\ldots,n\, s.t. \quad \mathbf{h}(\mathbf{x},\mathbf{y}) \ge \mathbf{0}\end{aligned} \tag{1}$$

where $\mathbf{x} \in R^{n_x}$ is the decision variable in upper layer, $\mathbf{y} \in R^{n_y}$ is the decision variable in lower layer. $F_0 : R^{n_x} \times R^{n_y} \to R$ is the objective function in upper layer, $\mathbf{g} : R^{n_x} \times R^{n_y} \to R^{n_g}$ is the constraint in upper layer. $F_{1i} : R^{n_x} \times R^{n_{yi}} \to R$ is the objective function in lower layer at agent i, $\mathbf{h} : R^{n_x} \times R^{n_{yi}} \to R^{n_{hi}}$ is the constraint in lower layer at agent i.

3.2. Upper layer of VPP bi-level model

3.2.1. Objective function

$$\begin{aligned}\min F_0(\mathbf{P}_{upper}) &= \min \sum_{i=1}^{N} f_{0i}\left(P_{upper}^{i}\right)\\ &= \min \sum_{i=1}^{N} \left(\alpha_i \left(P_{upper}^{i}\right)^2 + \beta_i \left(P_{upper}^{i}\right) + \gamma_i\right)\end{aligned} \tag{2}$$

where F_0 expresses the total costs of multiple DER Agents. n means the number of DER Agents in VPP. $f_{0i}(\cdot)$ indicates the output power costs function from DER Agent i to the power grid. P_{upper}^{i} is the decision variable in upper layer, which determines the power output of DER Agent i to the main grid. α_i, β_i, and γ_i are the coefficients of the cost function in DER Agent i.

3.2.2. Constraints

3.2.2.1. The upper and lower bound constraints of the exchange power.

$$\mathbf{g}_{bound} : P_{upper,\min}^{i} \le P_{upper}^{i} \le P_{upper,\max}^{i} \quad i=1,2,\ldots,N \tag{3}$$

where $P_{upper,\min}^{i}$ and $P_{upper,\max}^{i}$ represent the lower and upper bounds of the output power between the main power grid and DER Agent i, respectively.

3.2.2.2. Power grid command constraint.

$$g_{command} : \sum_{i=1}^{N} P_{upper}^{i} = P_{command} \tag{4}$$

where $P_{command}$ is the command generation from the power grid, which requires the VPP meet the demand of a certain amount of power generation $P_{command}$.

3.2.2.3. Power lines flow constraints.

$$\mathbf{g}_{flow}^{+} : \sum_{i=1}^{N} \eta_{i-m} P_{upper}^{i} \ge -T_m \quad m=1,2,\ldots,M \tag{5}$$