Two-Layer Optimization Model for Virtual Power Plants Participating in Node-Based Spot Market

Zheng Zhao(✉), Shijun Tian, and Chenghui Tang

State Grid Energy Research Institute Co., Ltd, Beijing 102209, China
zhaozheng@sgeri.sgcc.com.cn

Abstract. Virtual power plants (VPP) can aggregate decentralized resources that are small in scale and lack the ability to optimize management, and follow the market price to enhance the flexible regulating ability of the system. At present, there are few cases of virtual power plants participating in the market in China, and the relevant rules are still in the process of improvement. After the large-scale development of virtual power plants, they face the situation where the same power plant resources are distributed at different nodes and exhibit different operating characteristics. In this study, a two-layer coordination optimization model for multi-types of VPPs to participate in the node-based spot market is proposed, and simulation cases verified the effectiveness of the method, which is able to improve the interaction ability between virtual power plants and the power grid, and optimize market operating costs and efficiency.

Keywords: virtual power plants · spot market

1 Introduction

With the deepening of the new power system and the large-scale development of renewable energy, its randomness and volatility have put forward higher requirements for the system's balance ability. The imperative of "coal reduction and electrification" will lead to a reduction in traditional regulatory resources. Virtual power plants (VPP) can aggregate all kinds of decentralized resources that are small in scale and lack the ability to optimize management, form a market entity with a certain scale and the ability to respond to regulation, and can use the market price incentive mechanism to more fully tap the system regulation potential on the load side.

Although China has currently carried out spot market pilot projects, establishing a two-level market structure of inter-provincial and intra-provincial, and establishing a medium-long term and spot electricity energy market and ancillary service market, its participation in emerging market entities such as VPP is relatively limited. In addition, VPPs differ from traditional power resources in that their resources may be distributed at different nodes of the system. In some nodes, they may exhibit power generation characteristics, while in others, they may exhibit load characteristics. Therefore, virtual

S. H. B. D. M. Zailani et al. (Eds.): ICMSEM 2023, 259, pp. 1379–1388, 2024.
https://doi.org/10.2991/978-94-6463-256-9_139

power plants cannot adopt an offer and bid method similar to traditional power resources, and need to distinguish between resource types, node locations, etc.

Foreign scholars have conducted extensive research on the scheduling mode of virtual power plants. Reference [1] adopts a static scheduling mode to independently formulate power generation plans for each time period, compares the effectiveness of several simple control strategies in HOMER software and control strategies under ideal prediction conditions, and analyzes the applicable scenarios of different strategies. Reference [2] adopts a dynamic scheduling mode, and introduces a linear model of batteries in the scheduling model of microgrids (virtual power plants), considering the coupling of economic scheduling periods. Reference [3] considers the power generation cost and environmental protection cost of microgrids (virtual power plants), establishes an economic scheduling model for microgrids (virtual power plants) with the minimum operating cost, and solves it using chaotic quantum genetic algorithm. Reference [4] proposed the optimal operation strategy and cost optimization scheme for microgrids (virtual power plants), with the objective function of minimizing the operating cost of microgrids, taking into account both operation and maintenance costs and pollution discharge costs, and using the MSDS algorithm to solve. At present, research on the economic operation of virtual power plants and microgrids mostly focuses on the economic operation models and algorithms of virtual power plants [4–9]. In fact, virtual power plants and microgrids can proactively respond to grid demand in a friendly manner, providing reliable and clean electricity during peak periods of tight power supply in the large grid, alleviating transmission congestion, and reducing the operating costs of the main grid, as well as investment in power system power planning and expansion planning, which is of great significance. This part of research is currently relatively weak.

This study combines the actual situation of China's electricity spot market, focuses on complex types of VPPs including power resources, controllable loads, energy storage, and fully considers the dynamic decision-making behaviour of energy storage. It proposes a two-layer coordination optimization model for virtual power plants to participate in the spot market, improve the interaction ability between virtual power plants and the power grid, and optimize market operating costs and efficiency. The two-layer coordination optimization model includes internal and external competition models, external participation in the spot market, and internal optimization of internal resources based on system boundary conditions such as meteorological information and load forecasting, to determine the regulatory capacity and price of participating in the market.

2 Situation of the VPP Participation in China's Electricity Market

Since the implementation of Document No. 9, in accordance with the work deployment of the NDRC and the NEA, the scope of provincial-level spot pilot projects in China has been continuously expanding. The first batch of provincial spot pilot projects (Guangdong, Mengxi, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, Gansu) have continuously extended the settlement cycle, and some pilot projects have been transferred to non-stop settlement trial operation. The second batch of provincial spot electricity pilot projects (Shanghai, Jiangsu, Anhui, Liaoning, Henan, Hubei) have all started trial operation work. China's provincial spot pilot projects generally adopt the medium-long term contract for difference (CFD), plus full power spot model. The power generation side make offer and bid in the market, and some pilot power users do not bid in the market. The market clearing adopts the Locational Marginal Pricing (LMP) mechanism.

At present, VPPs are in the early stages of participating in the market in China, and some VPPs only participate in the ancillary service market and demand side management, and have not yet participated in the spot market. State Grid Jibei Electric Power Co., Ltd. carried out the pilot practice of VPP in 2019, and officially put it into commercial operation on December 12, 2019, with a total capacity of 358 MW and a maximum regulation capacity of 204 MW. It participated in the market clearing of peak regulating ancillary services in North China. The "load type" VPP can bid the upper and lower limits of next day power load and the decreasing “power-price” curve in Shanxi spot pilot rules, however, no VPPs have actually participated yet.

With the promotion of the dual carbon goal, the electricity installation structure mainly based on coal power cannot meet the requirements of the rapid development of renewable energy for flexible resource regulation in the system. The introduction of VPPs will further enhance the flexible regulation ability of the power system, which is of great significance for building a new type of power system. In the future, with the expansion of the scale of virtual power plants, the VPP type will be expanded from the current “load type” to “power generation type”, “hybrid type” and other types, and will be applied more widely. The sub-resources of the same VPP may be distributed in different nodes, which will bring challenges to system balancing and market clearing.

3 Double Layer Coordinated Optimization Model for Virtual Power Plants

3.1 Virtual Power Plant Participation in the Spot Market Process

i) Preparation stage: Virtual power plant agents should determine and submit their own resource composition information, including resource name, resource capacity, connection nodes, and node resource types (Supply/Demand/Hybrid), as shown in Fig. 1. The spot market needs to complete preparations such as verifying unit parameters, determining organizational methods, releasing transaction times, and setting grid operation boundary conditions.

ii) Day-ahead market stage: Virtual power plant agents should report the bidding plan based on the day ahead distributed energy prediction results, and develop internal flexible resource operation plans and pricing methods. The electricity market will collect all market participants bidding data, and conduct market clearing, and then release day-ahead market clearing results to all market participants.

iii) Real-time market stage: Virtual power plant agents conduct real-time distributed resource forecasting, submit real-time bidding plan, and develop internal flexible resource operation schedule. The spot market will collect all market participants bidding data, and conduct market clearing, and then release real-time market clearing results to all market participants.

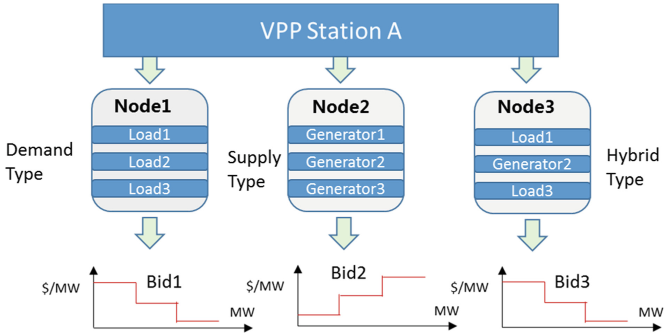

Fig. 1. Different type of VPP sub-resources connected to different market nodes

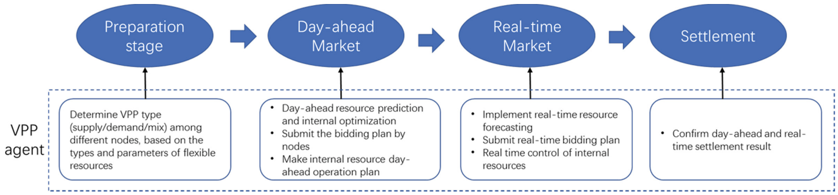

Fig. 2. Schematic diagram of virtual power plant participation in the spot market process

iv) Settlement stage: The spot market settles virtual power plant agents based on day-ahead and real-time settlement results, and the virtual power plant agents confirm the settlement results.

The schematic diagram of virtual power plant participation in the spot market process is shown in Fig. 2.

3.2 A Two-Level Optimization Model for Virtual Power Plants

The process of virtual power plant participating in the spot market is divided into two levels of optimization scheduling, which are external and internal competitions. External competition refers to participating in the spot market or ancillary service market organized by market operator. Internal competition refers to virtual power plants optimizing internal resources based on system boundary conditions such as meteorological information and load forecasting, and determining the power volume and price to participate in the market.

(1) External competition optimization model

In external competition model, the objective function is to minimize the sum of the generation costs of all generators and the virtual power plant, expressed as follows

$$min \sum_{t\in T}\sum_{i\in G^t} C_i^{trans}\left(pg_{i,t}^{trans}\right) + \sum_{t\in T}\sum_{k\in DIST}\sum_{i\in G^{dist,k}} C_i^{dist,k}\left(pg_{i,t}^{dist,k}\right)$$

In which, set T represents the set of scheduling time intervals, set G represents the node set where the generator set is located, and set DIST represents the VPP number set.

In the transmission network, the output of the generator set needs to meet the following constraints:

(1) Power balance constraints

$$\sum_{i \in G^{trans}} pg_{i,t}^{trans} = \sum_{i \in B^{trans}} pb_{i,t}^{trans} + \sum_{i \in D^{trans}} PD_{i,t}^{trans}, \forall t \in T$$

(2) Line transmission capacity constraints

$$-PL_j^{trans} \le \sum_{i \in G^{trans}} SF_{j-i}^{trans} pg_{i,t}^{trans} - \sum_{i \in B^{trans}} SF_{j-i}^{trans} pb_{i,t}^{trans} - \sum_{i \in D^{trans}} SF_{j-i}^{trans} PD_{i,t}^{trans} \le PL_j^{trans}, \forall j \in L^{trans}, \forall t \in T$$

(3) Spinning reserve constraints

$$0 \le ru_{i,t}^{trans} \le RU_i^{trans} \Delta t, ru_{i,t}^{trans} \le \overline{PG}_i^{trans} - pg_{i,t}^{trans}, \forall i \in G^{trans}, \forall t \in T$$

$$0 \le rd_{i,t}^{trans} \le RD_i^{trans} \Delta t, rd_{i,t}^{trans} \le pg_{i,t}^{trans} - \underline{PG}_i^{trans}, \forall i \in G^{trans}, \forall t \in T$$

$$\sum_{i \in G^{trans}} ru_{i,t}^{trans} \ge SRU_t^{trans}, \sum_{i \in G^{trans}} rd_{i,t}^{trans} \ge SRD_t^{trans}, \forall t \in T$$

(4) Unit ramping constraints

$$-RD_i^{trans} \Delta t \le pg_{i,t+1}^{trans} - pg_{i.t}^{trans} \le RU_i^{trans} \Delta t, \forall i \in G^{trans}, \forall t \in T$$

(5) Unit power output constraints

$$\underline{PG}_i^{trans} \le pg_{i,t}^{trans} \le \overline{PG}_i^{trans}, \forall i \in G^{trans}, \forall t \in T$$

(2) Internal Competition Optimization Model

In internal competition model, the goal is only to minimize power generation costs of internal resources:

$$min \sum_{i \in G^{VP}} \sum_{t \in T} C_i^{VP}\left(pg_{i,t}^{VP}\right) = \sum_{i \in G^{VP}} \sum_{t \in T} a_i^{VP}\left(pg_{i,t}^{VP}\right)^2 + b_i^{VP}\left(pg_{i,t}^{VP}\right) + c_i^{VP}$$

The generation cost of each generator set in the virtual power plant is expressed by a quadratic function, where $pg_{i,t}^{VP}$ is the output of generator i in the virtual power plant during scheduling interval t, G^{VP} is the set of generator units within the virtual power plant range, T is the set of scheduling periods, and function C_i^{VP} is the generation cost function of generator i, parameter a_i^{VP} 、 b_i^{VP} 、 c_i^{VP} is the power generation cost coefficient of generator i.

The internal operating constraints are also considered as below.

(1) Load flow constraints

$$\sum_{i:i\rightarrow j}\left(p_{i\rightarrow j,t}^{VP}-l_{i\rightarrow j,t}^{VP}\right)+p_{j,t}^{VP}=\sum_{m:j\rightarrow m}p_{j\rightarrow m,t}^{VP},\forall j\in N^{VP},\forall t\in T$$

(2) Line constraints

$$-PL_{i\rightarrow j}^{VP}\leq p_{i\rightarrow j,t}^{VP}\leq PL_{i\rightarrow j}^{VP},\forall(i\rightarrow j)\in L^{VP},\forall t\in T$$

(3) Unit power output constraints

$$\underline{PG}_i^{VP}\leq pg_{i,t}^{VP}\leq\overline{PG}_i^{VP},\forall i\in G^{VP},\forall t\in T$$

4 Case Study

A hybrid-type virtual power plant is used in this study. This VPP contains microturbine, fuel cell, wind turbine, photovoltaic, energy storage and the loads. The topology of the VPP and forecasting market price are shown in Fig. 3.

Scenario 1: Demand Type. When the peak load is high and more than VPP max generating limit, the VPP works as demand, and make optimal strategy purchasing power from gird. The load curve and scheduling curve of different resources in VPP are shown in Fig. 4. It can be found that the ESS stores energy bought from the main grid when the electricity price is low (3 am to 6 am; 1 pm; and 5pm to 8 pm), and consumes the stored energy within the VPP when the electricity price in main grid is high (9 am to 12 pm; 2 pm to 3pm; and 9 pm). Hence, the ESS is able to store the cheap energy and discharge it when the energy in main grid is expensive, thus reduces the total cost.

Scenario 2: Supply Type. If the peak load is lower than VPP max generating limit, the VPP will have opportunity selling power to grid. The load curve and scheduling curve of different resources in VPP are shown in Fig. 5. It can be seen that the ESS stores energy when the electricity price in main grid is low (2 am to 9 am; 1 pm; and 5pm to 8 pm), while discharges energy and sends to the main grid when the electricity price is high (10 am to 12 pm; 2 pm to 4pm; and 9 pm). Indeed, the performance of ESS helps the VPP maximize the profits.

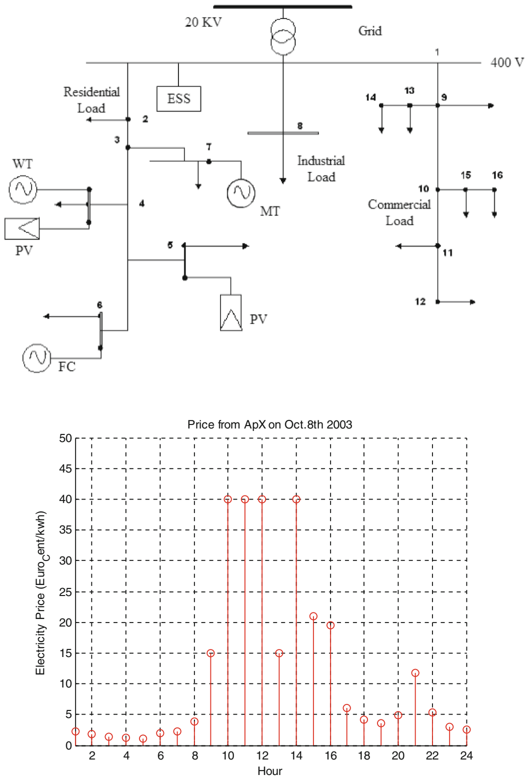

Fig. 3. VPP configuration and forecasting market price

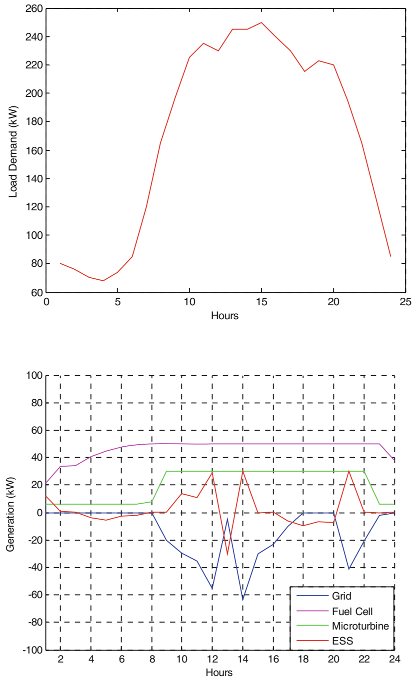

Fig. 4. Load curve and VPP resource scheduling curve in demand scenario

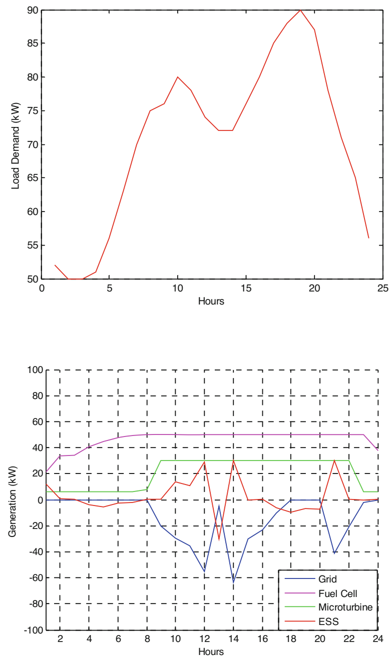

Fig. 5. Load curve and VPP resource scheduling curve in supply scenario

5 Conclusions

This study proposes an interactive coordination optimization method between virtual power plants and power grids, covering multiple time scales including real-time, intraday, and intraday. This method fully considers the characteristics of China's existing spot market rules and proposes a virtual power plant based on node declared resource types, electricity price curves, etc. Through a double layer optimization of the main grid virtual power plant, it ensures that market results can be executed, which helps to improve the safety margin of the power grid, improve power supply reliability, safety, and grid friendliness.

Acknowledgments. This work is funded by SGERI Young Talents Project "Research on Market Mechanism and Operation Simulation of Comprehensive Multi-Energy System".

References

1. Dennis B C, Byron W C. Optimal dispatch strategy in remote hybrid power systems. Solar Energy, 58(4–6): 165–179.
2. Xiao P L, Ming D, Jiang H H, et al. Dynamic economic dispatch for microgrids including battery energy storage. 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems, IEEE, 2010: 914–917.
3. Lia G C. Solve environmental economic dispatch of smart microgrid containing distributed generation system: using chaotic quantum genetic algorithm. Electrical Power and Energy Systems, 2012, 43(1): 779–787.
4. Mohamed F A, Koivo H. System modelling and online optimal management of microgrid using mesh adaptive direct search. International Journal of Electrical Power and Energy Systems, 2010, 32(5): 398–407.
5. Mao M Q, Ji M H, et al. Multi-objective economic dispatch model for a microgrid considering reliability. 2010 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems, 2010: 993–998.
6. Gu W, Wu Z, Yuan X. Microgrid economic optimal operation of the combined heat and power system with renewable energy. Proceedings of IEEE Power and Energy Society General Meeting, 2010:1–6.
7. 8. Peik-Herfeh M, Seifi H, Sheikh-El-Eslami M K. Decision making of a virtual power plant under uncertainties for bidding in a day-ahead market using point estimate method. International Journal of Electrical Power & Energy Systems, 2013, 44(1):88–98.
8. Griffin T, Tomsovic K, Secrest D, et al. Placement of dispersed generations systems for reduced losses. IEEE Proceedings of the 33nd Hawaii International Conference on System Sciences. Hawaii, USA: IEEE, 2000: 1–9.
9. Celli G, Pilo F. Optimal distributed generation allocation in MV distribution networks. Proceedings of 22nd IEEE Power Engineering Society International Conference on Power Industry Computer Applications. Sydney, Australia: IEEE, 2001: 81–86.