



Research on the revenue distribution method of virtual power plant considering the contributions of participants

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Abstract. Virtual power plant can effectively integrate various types of distributed energy resources as a whole to participate in the power market, however, how to reduce the deviation between the day-ahead clearing of the virtual power plant and the real-time power, enhance the consumption rate of distributed energy resources, and improve the stability of the power system still needs to be studied. In this paper, a virtual power plant operation optimisation model is constructed for multiple types of distributed flexibility resources such as source, load and storage. The two-stage optimisation model of virtual power plant operation is constructed with the goal of maximising the revenue of the virtual power plant and the goal of minimising the deviation of the output power of the virtual power plant from the day-ahead to the real-time scheduling. Finally, the proposed model is analysed by examples to verify that the proposed model has good advantages in improving the revenue of virtual power plants and enhancing the consumption of new energy resources.

Keywords: power system; virtual power plant; deviation assessment.

1 Introduction

Distributed renewable energy power generation has been developing rapidly and is one of the largest new power sources in the world in recent years. Distributed energy resources (DERs) such as photovoltaic and wind power have become an important part of China's adaptation to climate change and energy security.^[1] However, due to the random, volatile and geographically dispersed power output, the access of DERs poses a challenge to the safe, reliable and economic operation of the power grid. Virtual power plant (VPP) is a new generation of intelligent control technology and interactive business model that integrates the clean development of "source-load-storage", and is capable of aggregating all kinds of resources scattered in the grid, such as distributed power generation, energy storage, load, etc., for coordinated and optimised operation control and market transaction.^[2-3] Currently, the virtual power plant project in Shanxi Province is being implemented in an orderly manner, with two batches of virtual power plant pilot projects with a total of ten enterprises, regulating capacities ranging from 20 to 90 MW. However, how to perfect the construction of virtual power plants and maximize the revenue is still a challenge. Currently, most of

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the research on VPP focuses on the generation coordination optimisation of DERs within VPP. HAO Jianhong establishes a multi-objective economic optimization scheduling model for virtual power plants that takes into account the interests of power suppliers and cooling/heat suppliers;^[4] Fernández-Muñoz presents a suite of two optimisation models for the short-term self-scheduling and redispatch of a virtual power plant (VPP) composed of a wind farm and a Li-ion battery, that participates in the day-ahead energy and secondary regulation reserve markets of the Spanish power system.^[5]

2 Modelling of participants in the virtual power plant

The wind-solar output model is shown in equations (1) and (2), and the initial construction cost of wind-solar power generation is ignored in the operation process, which can be approximated as zero power generation cost.

$$\bar{P}_{w,t} = \begin{cases} 0 & v_t \leq v_{cut-in} \\ \frac{1}{2} \rho \pi R^2 C_p v_t^3 & v_{cut-in} \leq v_t \leq v_{rated} \\ P_{w,rated} & v_{rated} \leq v_t \leq v_{cut-out} \\ 0 & v_{cut-out} \leq v_t \end{cases} \quad (1)$$

$$\bar{P}_{r,t} = \eta_r S_r \varphi_{r,t} \quad (2)$$

Here: $\bar{P}_{w,t}$ for the predicted output power of wind turbines; $\bar{P}_{r,t}$ for the predicted output power of photovoltaic power generation; v_t for the actual wind speed; v_{cut-in} for the cut-in wind speed; $v_{cut-out}$ for the cut-out wind speed; v_{rated} for the rated wind speed; $P_{w,rated}$ for the rated power of the wind turbine; ρ for the air density; R for the radius of the wind turbine; C_p for the actual use of wind energy coefficients; η_r for the photovoltaic power conversion efficiency; S_r for the area of the photovoltaic array; $\varphi_{r,t}$ for the light intensity per unit area in the moment t.

The cost of energy storage equipment consists mainly of marginal operating costs.

$$C_{s,t} = a_s (|P_{s,t}^-| + |P_{s,t}^+|) \Delta t \quad (3)$$

$$E_{s,t} = E_{s,t-1} + E_{s,t}^- - E_{s,t}^+ \quad (4)$$

$$E_{s,t}^- = \eta_m P_{s,t}^- \Delta t \quad (5)$$

$$\eta_{out} E_{s,t}^+ = P_{s,t}^+ \Delta t \quad (6)$$

Here: a_s is the cost of kWh of energy storage device; $P_{s,t}^-$, $P_{s,t}^+$ respectively, is the charging and discharging power of energy storage; $E_{s,t}$ is the power of energy storage

device s at time t ; $E_{s,t}^-$ is the charging power of energy storage device s at time t ; $E_{s,t}^+$ is the discharging power of energy storage device s at time t ; η_{in} is the charging efficiency; η_{out} is the discharging efficiency.

When a VPP makes a call on its internal adjustable resources, it is required to pay a compensation fee based on the capacity of the call.

$$C_{DR,t} = \sum_{i=1}^{N_{DR}} C_{DR_i,t} \quad (7)$$

$$C_{DR_i,t} = r_{DR_i} Q_{DR_i,t} \quad (8)$$

$$Q_{DR_i,t} = |z_{i,t} P_{DR_i,t} \cdot \Delta t| \quad (9)$$

Here: $C_{DR_i,t}$ is the cost of calling the i th adjustable load; r_{DR_i} is the compensation price of the i th adjustable load; $Q_{DR_i,t}$ is the response power of the i th adjustable load at time t ; $P_{DR_i,t}$ is the adjustment of the power of the i th adjustable load at time t ; N_{DR} is the number of adjustable loads; and $z_{i,t}$ is a 1-0 variable indicating whether or not adjustable load i is called.

VPP participates in the unified market clearing on T-1, and operates on T day according to the clearing result of the previous day, and when the actual curve of VPP deviates from the clearing result, it will face deviation assessment. Therefore, with the premise of maximising the consumption of wind power and PV, VPP gives priority to calling its internal flexible adjustable resources for adjustment according to the operating characteristics of the energy storage equipment and adjustable loads, and formulates real-time optimised operation strategies to reduce the cost of deviation power assessment and maximise the real-time revenue.

The subjects within the VPP are modelled as follows:

$$C_{s,t} = a_s (|P_{s,t}^-| + |P_{s,t}^+|) \Delta t \quad (10)$$

$$E_{s,t} = E_{s,(t-1)} + E_{s,t}^- - E_{s,t}^+ \quad (11)$$

$$E_{s,t}^- = \eta_{in} P_{s,t}^- \Delta t \quad (12)$$

$$\eta_{out} E_{s,t}^+ = P_{s,t}^+ \Delta t \quad (13)$$

$$SOC_{s,t} = \frac{E_{s,t}}{E_{s,max}} \quad (14)$$

$$C_{DR,t} = \sum_{i=1}^{N_{DR}} C_{DR_i,t} \quad (15)$$

$$C_{DR_i,t} = r_{DR_i} Q_{DR_i,t} \quad (16)$$

$$Q_{DR,i,t} = |z_{i,t} P_{DR,i,t} \cdot \Delta t| \quad (17)$$

Here: a_s is the cost of kWh of the energy storage device s ; $P_{s,t}^-$, $P_{s,t}^+$ are the charging and discharging power of the energy storage respectively; $E_{s,t}$ is the power of energy storage device s at time t ; $E_{s,t}^-$ is the charging power of energy storage device s at time t ; $E_{s,t}^+$ is the discharging power of energy storage device s at time t ; η_{in} is the charging efficiency; η_{out} is the discharging efficiency; $E_{s,max}$ is the maximum capacity of the energy storage device; $C_{DR,i,t}$ is the call cost of the i th adjustable load; $r_{DR,i}$ is the compensation price of the i th adjustable load; $Q_{DR,i,t}$ is the response power of the i th adjustable load at time t ; $P_{DR,i,t}$ is the adjustment amount of the power of the i th adjustable load at time t ; N_{DR} is the number of adjustable loads; $z_{i,t}$ is a 1-0 variable indicating whether adjustable load i is called or not.

Intraday real-time returns are shown below:

$$\max C_{VPP}^T = \max \left(\sum_{t=1}^T C_{sell,t}^T - \sum_{t=1}^T (C_{s,t} + C_{DR,t} + C_{p,t}) \right) \quad (18)$$

$$C_{sell,t}^T = c_{sell,t} (P_{w,t}^T + P_{r,t}^T - P_{s,t}^- + P_{s,t}^+ - \sum_{i=1}^{N_{DR}} P_{DR,i,t}) \quad (19)$$

$$C_{sell,t}^T = c_{sell,t} (P_{w,t}^T + P_{r,t}^T - P_{s,t}^- + P_{s,t}^+ - \sum_{i=1}^{N_{DR}} P_{DR,i,t}) \quad (20)$$

$$C_{p,t} = c_{f,t} |\Delta P_t| \quad (21)$$

$$\Delta P_t = P_{w,t}^D + P_{r,t}^D - P_{w,t}^T - P_{r,t}^T + P_{s,t}^- - P_{s,t}^+ - \sum_{i=1}^{N_{DR}} P_{DR,i,t} \quad (22)$$

Here: $c_{sell,t}$ for the VPP and grid real-time clearing interactive tariff at time t ; $P_{w,t}^T$ and $P_{r,t}^T$ for the actual output of wind power and PV; for the VPP deviation appraisal tariff; $c_{f,t}$ for the declared deviation power, ΔP_t which is positive when the actual power is greater than the clearing power in the previous day.

Definition of deviation assessment tariff As shown in equation (14), the positive deviation assessment tariff is lower and the negative deviation assessment tariff is higher during peak load hours, and vice versa during low load hours, in order to incentivise the VPP to improve its own regulation capability and reflect the value of scarce regulation resources.

$$c_{f,t} = \begin{cases} c_p + m_1 (1 + e^{\frac{100}{C_{sell,t}^T}}) c_{sell,t}^T, \Delta P_t \geq 0 \\ c_p + m_2 (1 - e^{\frac{100}{C_{sell,t}^T}}) c_{sell,t}^T, \Delta P_t < 0 \end{cases} \quad (23)$$

Here: c_p is the basic deviation assessment tariff; m_1, m_2 is the positive and negative deviation assessment coefficient.

3 Numerical results

This paper takes a virtual power plant in Shanxi as an example, aggregating multiple wind, storage and load resources to form a VPP with a total of 20MW wind, 10MW PV, 1MW/2MWh storage and 30MW load, of which the share of adjustable load is 10%. The base deviation assessment tariff is RMB 400/MWh.

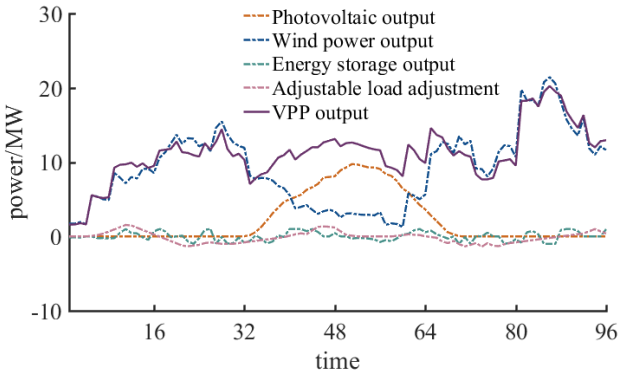


Fig. 1. Real-time operational results of the virtual power plant.

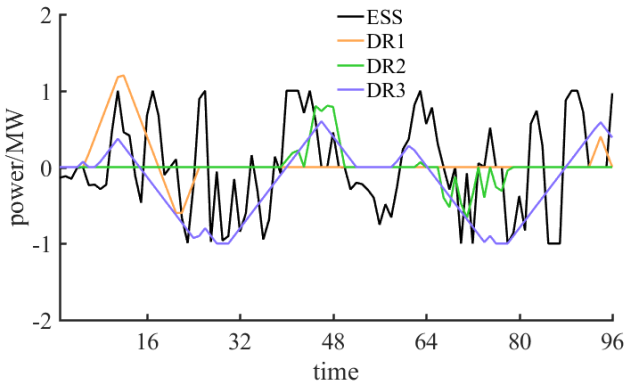


Fig. 2. Adjustable adjustments for real load and energy storage.

Figure 1 shows the VPP real-time operation results and Figure 2 shows the real-time adjustments of adjustable loads. As shown in Figures 1 and 2, the adjustment quantities of the four participants, namely, energy storage equipment, DR1, DR2 and DR3, are about 46:12:8:38. The three adjustable loads generally reduce their own power consumption during the periods from 0 to 17, 39 to 54 and 87 to 96, which is reflected in the external expression of "giving out" power; and increase their power

consumption according to the dispatch information during the periods from 18 to 38 and 66 to 86, which is reflected in the external expression of "absorbing" power, so as to achieve the goal of "absorbing" power in the period of 0 to 17, 39 to 54 and 87 to 96. The three adjustable loads generally reduce their own power consumption during 0 to 17, 39 to 54 and 87 to 96, which is reflected as "sending" power; and increase power consumption during 18 to 38 and 66 to 86 according to the dispatch information, which is reflected as "absorbing" power, so as to achieve the goal of following the VPP operator's control instructions, reducing the power deviation between the VPP's real-time and day-ahead clearing, and thus reducing the cost of the VPP's deviation assessment, and maximizing the VPP's overall revenue.

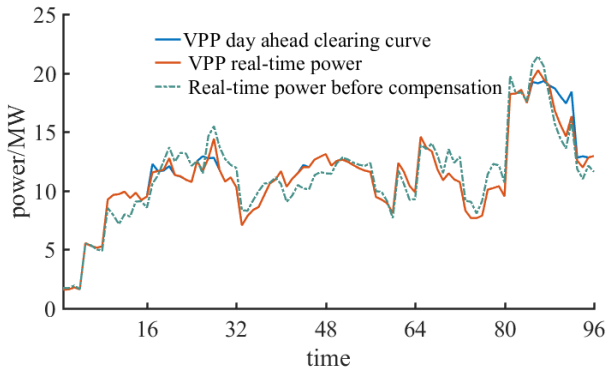


Fig. 3. VPP Real Time - Day Ahead Output Deviation.

Figure 3 shows the VPP real-time - day-ahead capacity deviations. When the energy storage equipment and the three adjustable loads are involved in the real-time operation of VPP, except for the 10 to 29 hours and 89 to 95 hours when the deviation cannot be completely eliminated due to the excessive deviation of the wind and the limitation of the adjustable resource's adjusting capacity, the rest of the hours can be adjusted through the flexibility of the energy storage and the adjustable loads, which can make the real-time operation of the VPP basically close to the previous day's clearing curve, and reduce the overall operating cost of the VPP.

4 Conclusions

In this paper, we construct a virtual power plant system structure model containing distributed wind turbines, energy storage devices, and dispatchable loads, and optimise the scheduling with revenue maximization as the day-ahead scheduling objective, and minimization of day-ahead-real-time virtual power plant output power deviation as the real-time scheduling objective. The results show that the strategy proposed in this paper can effectively reduce the deviation of virtual power plant operation, enhance the consumption rate of distributed energy and improve the stability of the power system.

References

1. BP. (2022) Statistical Review of World Energy 2022.
2. Hongchao G, Tai J, Cheng F, et al. Review of virtual power plant operations: Resource coordination and multidimensional interaction[J]. *Applied Energy*, 2024, 357:122284-.
3. KANG Chongqing, CHEN Qixin, SU Jian, et al. Scientific problems and research framework of virtual power plant with large-scale flexible resources in new power system[J]. *Automation of Electric Power Systems*, 2022, 46(18):3-14.
4. HAO Jianhong, HUANG Ting, et al. Multi-objective optimal scheduling strategy for virtual power plants with multiple energy suppliers[J]. *Distribution & Utilization*, 2023, 40(12): 32-42. DOI: 10.19421/j.cnki.1006-6357.2023.12.005.
5. Fernández-Muñoz Daniel; Pérez-Díaz Juan I., Optimisation models for the day-ahead energy and reserve self-scheduling of a hybrid wind–battery virtual power plant[J]. *Journal of Energy Storage*, 2023. DOI: 10.1016/J.EST.2022.106296.

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