THE TWO-LAYER OPTIMIZATION MODEL OF VIRTUAL POWER PLANTS BASED ON THE ELECTRIC ENERGY - PEAK SHAVING MARKET

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Abstract

This paper aims at the current participation status and insufficient economic viability of virtual power plants (VPP) in the electric energy market and peak shaving market, and establishes a two-layer optimization model for virtual power plants to participate in the joint electric energy - peak shaving market. The upper-level model aims to minimize the clearing cost of the electricity market, while the lower-level model aims to minimize the total internal cost of the virtual power plant, and is solved through iterative optimization. Through the analysis of numerical examples, the validity and scientificity of the model were verified, providing a theoretical basis for the optimal quotation and dispatching plan of virtual power plants in the market, which is conducive to improving the economy and market participation enthusiasm of virtual power plants.

1 Introduction

With the large-scale grid connection of renewable energy sources such as wind power and photovoltaic power, the peak shaving pressure on the power grid has significantly increased[1,2] . As a flexible resource, virtual power plants can aggregate resources such as distributed energy, energy storage and controllable loads to provide peak shaving support for the power grid[3] . However, at present, virtual power plants have the problem of insufficient economy in market operation, which leads to their low enthusiasm for participating in the market[4]. Therefore, it is urgently necessary to balance the profits of virtual power plants in the electricity energy market and the peak shaving market through optimizing the model. Virtual power plants should formulate the optimal quotations and dispatching plans in the day-ahead and intraday markets to adapt to market changes and improve their economic efficiency.

Many scholars have conducted research on the participation of virtual power plants in the market. Zhong et al. [5] scholars, from the perspective of the development trajectory of domestic VPP, expounded on the development process and current situation of domestic VPP, and summarized the current development status of domestic VPP from five aspects: policy, platform, regulation, business, and market. Scholars Shen et al. [6] proposed a differentiated quotation mechanism for different power supply equipment in virtual power plants to reasonably guide virtual power plants to participate in market optimization. Scholars Wang et al. [7] proposed a VPP optimization operation method considering the active recovery of the remaining available regulation capacity for the VPP optimization operation problem under the normal and continuous regulation of the market. Scholars Li et al. [8] proposed a bidding strategy for virtual power plant clusters to participate in the electricity energy and frequency regulation markets in order to solve the problem of resource allocation in multimarket coupling decision-making of clusters and take into account both electrical energy and frequency regulation benefits. Li et al. [9] scholars proposed a low carbon optimization scheduling method for VPP considering the collaboration of resources on multiple user sides in a market environment. However, no in-depth research has been conducted on how to balance the benefits of virtual power plants in the electric energy market and the peak shaving market.

Therefore, this paper systematically analyzes the current participation status of virtual power plants in the electric energy market and peak shaving market, constructs a two layer optimization model, and verifies the validity of the model through numerical examples, providing theoretical support and practical guidance for the market operation of virtual power plants.

2 VPP Participates in the Analysis of the Current Market Situation

At present, the national unified power trading market is gradually maturing. The business model of virtual power plants is gradually shifting towards participating in power market transactions, and the market mechanism is constantly improving. Local policies support the development of virtual power plants. For instance, Jiangsu, Tianjin, Shanghai and other places have issued specific compensation standards for virtual power plants to participate in peak shaving and demand response.

From the perspective of market size, by 2025, the investment and construction market size of virtual power plants will exceed 30 billion yuan, with an average annual investment and construction scale reaching 10.5 to 20 billion yuan, and the maximum power load will reach 1.63 billion kilowatts. If the peak load demand of 5% is met, only 50 to 60 billion yuan needs to be invested through virtual power plants, while 400 billion yuan is required through thermal power plants.

From the perspective of participating in the market, the subsidy price for virtual power plants participating in the peak shaving market is 0.1 yuan /kWh, and the subsidy electricity price for participating in the demand response market is 2.4 yuan /kWh. For instance, virtual power plants predict the spot market price of electricity and adjust the controllable load of users, adjusting the user's load from the high spot price period to the low spot price period, thereby increasing the spot profit of electricity sales companies, with an average revenue of 0.274 yuan per kilowatt-hour.

3 Establish a Joint Market Optimization Model for VPP Participation in Electric Energy and Peak Shaving

3.1 Joint Architecture

In the joint market of electricity energy and peak shaving involving VPP, the upper level entities are the electricity market, while the lower-level entities include multiple independently operating VPP and thermal power units, as shown in Fig. 1.

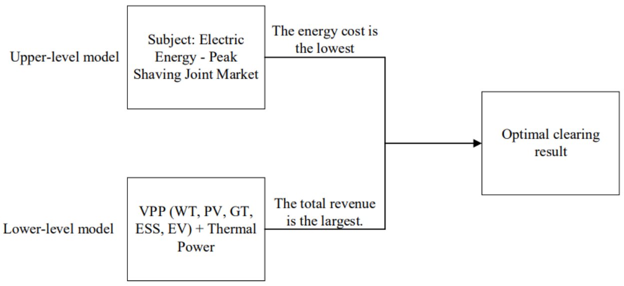

Fig. 1 Two-layer junction architecture

As can be seen from Figure 1, in the transaction clearing stage of the upper-level model, the electricity market aims to minimize the clearing cost and conducts clearing with the day-ahead market load curve as the constraint condition. During the transaction declaration stage of the lower-level model, all resources with power supply capacity within the VPP declare electricity prices and electricity volumes to the VPP operators. Gas turbine units additionally declare peak shaving electricity prices and peak shaving electricity volumes to the VPP operators. Each VPP operator coordinates the declaration parameters of internal units and reports them to the power market.

3.2 Two-layer optimization model

3.2.1 Upper-level optimization model

(1) Objective function

With the goal of minimizing the clearance cost, the following expression is expressed:

$$\begin{aligned} \min F_{upper} &= \min \sum\nolimits_{t=1}^{T} (C_{DG}^1(t) + C_{GT}^1(t) + \\ & C_{ES}^1(t) + C_{EV}^1(t))(P_{DG}^1(t) + P_{GT}^1(t) + P_{ES}^1(t) + \\ & P_{EV}^1(t)) + (C_{DG}^2(t) + C_{GT}^2(t) + C_{ES}^2(t) + \\ & + C_{EV}^2(t))(P_{DG}^2(t) + P_{GT}^2(t) + P_{ES}^2(t) + P_{EV}^2(t)) \end{aligned} \tag{1}$$

In the formula, $C_{DG}^1(t)$、$C_{GT}^1(t)$、$C_{ES}^1(t)$、$C_{EV}^1(t)$、$C_{DG}^2(t)$、$C_{GT}^2(t)$、$C_{ES}^2(t)$、$C_{EV}^2(t)$ represents the clearing price and peak shaving price of units such as new energy, gas, energy storage and electric vehicles at t time respectively; $(P_{DG}^1(t)$、$P_{GT}^1(t)$、$P_{ES}^1(t)$、$P_{EV}^1(t)$、$P_{DG}^2(t)$、$P_{GT}^2(t)$、$P_{ES}^2(t)$、$P_{EV}^2(t)$ respectively represent the clearing power and peak shaving power of units such as new energy, gas, energy storage and electric vehicles.

(2) Constraint conditions

The balance constraint of electric power demand is expressed as follows:

$$\begin{cases} \sum\nolimits_{n=1}^{N} (P_{DG}^1(t) + P_{GT}^1(t) + P_{ES}^1(t) + P_{EV}^1(t)) = P_{dem,1}^1 \\ \sum\nolimits_{n=1}^{N} (P_{DG}^2(t) + P_{GT}^2(t) + P_{ES}^2(t) + P_{EV}^2(t)) = P_{dem,1}^2 \end{cases} \tag{2}$$

In the formula, $P_{dem,1}^1$、$P_{dem,1}^2$ represents the electric power demands of the electric energy market and the peak shaving market at time respectively.

3.2.2 Lower-level optimization model

(1) Objective function

With the goal of minimizing the total cost, a quotation model for multiple VPPS at the lower level to participate in the joint market of electric energy and peak shaving is established:

$$\begin{aligned} \min F_{lower} &= \min \sum\nolimits_{t=1}^{T} (C_{op}(t) + C_{DR}(t) \\ & + C_{cut}(t) + R_m(t)) + C_{ZJ} \end{aligned} \tag{3}$$

$$\begin{cases} C_{op}(t) = C_{DG}(t) + C_{GT}(t) + C_{ES}(t) + C_{EV}(t) \\ C_{DR}(t) = \gamma_{SL} P_{SL}(t) + \gamma_{IL} P_{IL}(t) \\ C_{cut}(t) = \gamma_{cut} P_{cut}(t) \\ C_{ZJ}(t) = \dfrac{\theta_{ES}(1+\theta_{ES})}{(1+\theta_{ES})^n - 1} \times \dfrac{\rho_{ES} V_{ES}}{365} \end{cases} \tag{4}$$

In the formula, F_{lower} represents the total cost of the lower-level optimization model; $C_{op}(t)$、$C_{DR}(t)$、$C_{cut}(t)$、$R_m(t)$ represents the total operating cost, demand response cost, curtailment cost and revenue of each device participating in the market at t time. C_{ZJ} represents the depreciation cost of the energy storage device at t time. $C_{DG}(t)$、$C_{GT}(t)$、$C_{ES}(t)$、$C_{EV}(t)$ is the operating cost of units such as new energy, gas, energy storage and electric vehicles at t time; γ_{SL}、γ_{IL} is the time-of-use electricity price and interruptible load compensation price at t time. P_{SL}、$P_{IL}(t)$ represents the operating power and interruptible output power at t time . γ_{cut} is the penalty coefficient for power curtailment; θ_{ES} is the annual interest rate for investment loans in energy storage equipment. ρ_{ES} represents the construction cost required for energy storage devices; V_{ES} represents the rated capacity of energy storage.

(2) Constraint conditions

The power balance constraints of each device participating in the market in the lower level model are expressed as follows:

$$\begin{aligned} &P_{wt}(t)+P_{pv}(t)+P_{GT}(t)+P_{ESS}^{dis}(t)+P_{EV}^{dis}(t)+P_{IL}(t)= \\ &P_{cut}(t)+P_{ESS}^{chr}(t)+P_{EV}^{chr}(t)+P_{SL}(t)+P^{1}(t)+P^{2}(t) \end{aligned} \tag{5}$$

In the formula, $P_{wt}(t)$、$P_{pv}(t)$ represents the output power of wind power and photovoltaic power at time t .

The constraint conditions of new energy units are expressed as follows:

$$\begin{aligned} &P_{wt}^{\min}(t)\le P_{wt}(t)\le P_{wt}^{\max}(t) \\ &P_{pv}^{\min}(t)\le P_{pv}(t)\le P_{pv}^{\max}(t) \end{aligned} \tag{6}$$

In the formula, $P_{wt}^{\min}(t)$、$P_{wt}^{\max}(t)$、$P_{pv}^{\min}(t)$、$P_{pv}^{\max}(t)$ represents the maximum and minimum output power of wind power and photovoltaic power respectively at time t .

The constraint conditions of the gas turbine unit are expressed as follows:

$$P_{GT}^{\min}(t)\le P_{GT}(t)\le P_{GT}^{\max}(t) \tag{7}$$

In the formula, $P_{GT}^{\min}(t)$、$P_{GT}^{\max}(t)$ represents the maximum and minimum output power of the gas unit at time respectively.

The constraint conditions of energy storage equipment are expressed as follows:

$$0\le P_{ES}^{ch}(t)\le U_{ES}P_{ES}^{ch}(t) \tag{8}$$

$$0\le P_{ES}^{dis}(t)\le (1-U_{ES})P_{ES}^{dis}(t) \tag{9}$$

In the formula, U_{ES} represents the charging and discharging state of the energy storage device and is a variable ranging from 0 to 1.

The constraint conditions of electric vehicles are expressed as follows:

$$0\le P_{EV}^{ch}(t)\le U_{EV}P_{EV}^{ch}(t) \tag{10}$$

$$0\le P_{EV}^{dis}(t)\le (1-U_{EV})P_{EV}^{dis}(t) \tag{11}$$

In the formula, U_{EV} represents the charging and discharging state of the electric vehicle equipment and is a variable ranging from 0 to 1.

4 Case Study Analysis

4.1 Data information

In order to verify the validity and scientificity of the model, this paper selects a demonstration project of a certain virtual power plant for empirical analysis. The output power of new energy units such as wind power and photovoltaic power, as well as gas units, is shown in Fig. 2.

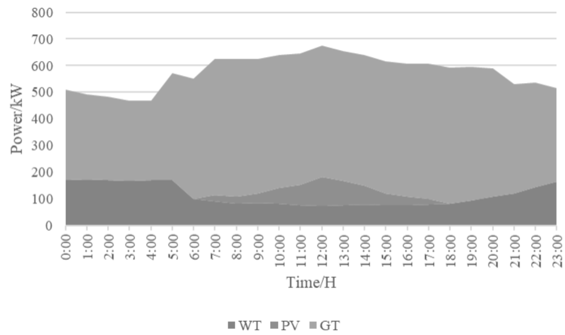

Fig. 2 Output situation of the unit

The initial charging load requirement for electric vehicles is 1000kW, and the charging and discharging efficiency is 95%.

4.2 Result discussion and analysis

4.2.1 Iterative result analysis: To enhance the practicality of the two-layer model, the upper limit of the number of quotations for each device within the VPP is 6, that is, the iteration terminates after 6 times, as shown in Fig. 3.

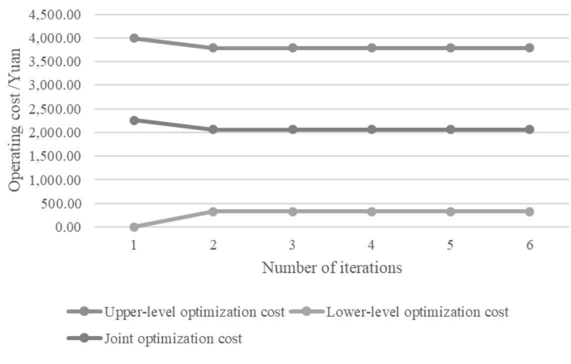

Fig. 3 Iterative results of the optimization model

It can be known from Fig. 3 that, first, with the continuous increase of the number of iterations, the joint operation cost of establishing a two-layer optimization model shows a downward trend. Among them, the operating cost of the upper model is 3,788.36 7 yuan, the operating cost of the lower model is 328.59 yuan, and the joint operating cost is 2,058.48 yuan. Second, after the model iteration is completed, the optimal solution can be achieved. Thirdly, after the 6th iteration of the double-layer optimization model, a joint optimal solution emerged, and the solution time was 1.32 seconds. From the analysis of the above results, it can be seen that the costs of the upper and lower layer optimization models show a constantly fluctuating state, mainly affected by the quotations of each unit in the lower layer model.

4.2.2 Analysis of optimization results: Since the double-layer optimization model is greatly influenced by the operation plans and operating costs of each unit at the lower level. Set the operation plans and operating costs of each unit as fixed, and the results are shown in Fig. 4.

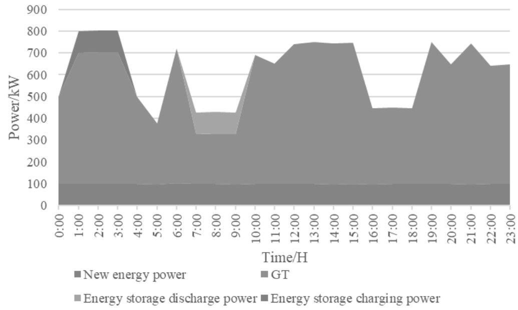

Fig. 4 Operation plans for each device

As can be seen from Fig.4, the price of new energy is relatively stable, ranging from 0.5 yuan to 0.7 yuan. The price of gas turbine units is higher than that of other power supply equipment, fluctuating greatly, ranging from 0.6 yuan to 1.3 yuan. Moreover, from 14:00 to 16:00, the load is at its peak. By increasing the output of gas turbine units, the economic operation can be maintained. During the night period, energy storage devices start charging by consuming the electricity generated by new energy units, thereby alleviating the power supply pressure at other times. Therefore, in practical applications, appropriately increasing the quotation of gas units can reduce risks, and appropriately lowering the quotation of new energy units can enhance the consumption level of new energy and maintain the economic operation of the system.

4.2.3 Analysis of clearing results: In the two-layer optimization model, each unit at the lower level quotes to the upper power market, and the upper power market quotes based on the quotations of each unit, as shown in Fig. 5.

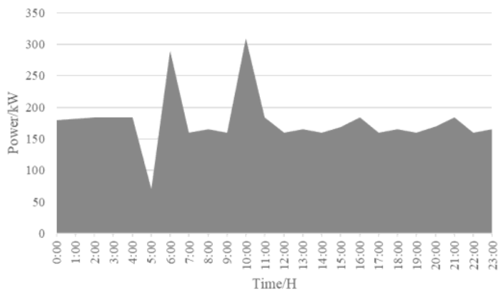

Fig. 5 Clearance plan

As can be seen from Fig. 5, the power clearance of thermal power units mainly occurs between 8:00 and 18:00. Although the power of wind and solar power generation is relatively high, due to its own load demand, the overall system will increase the quotations of each equipment, thereby reducing the overall market load power shared by the power. Second, the upper-level power market gives priority to choosing equipment with lower peak shaving prices to participate in peak shaving.

5 Conclusion

This paper analyzes the economic issues of virtual power plants in the market by establishing a two-layer optimization model for virtual power plants to participate in the joint market of electric energy and peak shaving. The research results show that:

1) The double-layer optimization model can effectively reduce the joint operation cost of the virtual power plant. After 6 iterations, the optimal solution is reached, with a solution time of 1.32 seconds. It has high practicability and convergence.
2) By optimizing the quotations and operation plans of each device, the economic viability of virtual power plants in the electric energy market and peak shaving market has been significantly enhanced.
3) The electricity market gives priority to equipment with low peak shaving prices to participate in peak shaving, and thermal power units undertake the main peak shaving tasks during peak load periods.

In the future, it is suggested that the policy mechanism for virtual power plants to participate in the market be further improved, the subsidy standards be raised, and the market transaction rules be optimized to promote the healthy development and largescale application of virtual power plants.

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