Economical Optimal of Virtual Power Plant with Source, Load and Storage

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***Abstract*—As an emerging form of energy aggregation, virtual power plant (VPP) can reduce the impact of the uncertainty of the output power of new energy sources such as wind power and photovoltaics on the grid security and improve the reliability of power supply. It is the future development of new energy grid-connected direction. In order to improve the scheduling flexibility of VPP, reduce power generation costs, and obtain better benefits for VPP, based on previous studies, considering the impact of load on VPP, a VPP economic optimization scheduling model considering source-load-storage joint operation is constructed in order to reduce forecast errors and increase VPP revenue, the scheduling model adopts multi-period scale optimization and multi-market profit model. Finally, particle swarm algorithm is used to solve the model and optimize the energy output in VPP. The simulation example analyzes the VPP internal power supply and the VPP output optimization situation, and compares and analyzes the interruptible load participation in the VPP scheduling and the impact of the change in the proportion on the VPP revenue, as well as the economic differences of the VPP under the four different operating modes. The simulation results show that the flexibility and economy of VPP can be improved by aggregating an appropriate proportion of interruptible loads and adopting a reasonable operation mode.**

Keywords: VPP; distributed energy; time-of-use electricity price; optimal dispatch; operation strategy.

I. INTRODUCTION

In recent years, fossil energy reserves have been declining, and environmental pollution has become more and more serious. With the support of national policies and the increase of people's awareness of environmental protection, the installed capacity of wind power, photovoltaics and other renewable energy sources has increased year by year. As the penetration rate of renewable energy in the power system continues to increase, the safe and stable operation of the power grid is affected to a certain extent [1]. Taking wind power and photovoltaic renewable energy as examples, their volatility and uncontrollability will cause random volatility impacts on the grid, which increases the difficulty of power grid dispatching and operation, and increases the cost of power grid operation [2]. The emergence of virtual power plant (VPP) provides new ideas for solving this problem. VPP can effectively integrate distributed new energy sources of different types and regions, and realize the overall controllability of VPP's external output through the energy management system [3], so that it has similar operating functions as conventional power plants, and participates in power market transactions and system scheduling [4]. VPP aggregated distributed energy has not changed its grid connection mode, but by making full use of advanced technical means such as network communication, intelligent measurement, data processing, and intelligent decision-making, it realizes the collaborative management and control of multiple distributed energy sources, thereby reducing The impact of the volatility of new energy output such as small wind power and photovoltaics on the power grid improves the reliability of power supply [5].

VPP aggregates a variety of distributed energy sources, which can improve the flexibility of its own scheduling, and thus obtain greater benefits. At present, relevant research has been carried out on the optimization of VPP aggregated renewable energy and its internal power sources. Literature [6] mainly considers that VPP uses a controllable power supply and energy storage system to stabilize the output of new energy, so as to realize the controllability of VPP output and maximize the benefits. Literature [11] aggregates distributed power sources such as wind power, photovoltaics, gas turbines, energy storage, etc., and proposes a VPP operation strategy based on time-of-use electricity prices to achieve optimal scheduling of VPP, but the article does not consider the impact of load on VPP scheduling , And has not optimized VPP with multiple time scales.

In order to improve the scheduling flexibility of VPP, reduce the cost of power generation, and make VPP obtain better benefits, this paper establishes a virtual power plant optimization model based on previous studies, considering the joint participation of source, load, and storage. Based on a centralized scheduling model, participating in system scheduling under the VPP scheduling strategy will benefit from the power and reserve markets. In the model, wind power, photovoltaics, gas turbines, energy storage batteries, pumped storage, and interruptible loads are aggregated. The objective function is to maximize the benefits of VPP in each period, and the particle swarm algorithm is used to solve the problem to obtain the output of each distributed power source in different periods. The controllable load's participation in virtual power plant scheduling and the influence of its proportion change on the virtual power plant's revenue are analyzed, and the economics of virtual power plants under four different operating modes are compared and analyzed. The simulation results show that the built model is reasonable,

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and the joint participation of source, load and storage in virtual power plant scheduling is beneficial to improve the flexibility and economy of the virtual power plant.

II. VPP STRUCTURE AND BASIC PRINCIPLES

Renewable energy such as wind power and photovoltaic can be aggregated in VPP. Considering the uncertainty of the output power of these energy sources. VPP in the model includes controllable unit (gas turbine), uncontrollable unit (wind turbine and photovoltaic unit), energy storage system (energy storage battery and pumped storage) and load (interruptible load), and unified control and management are carried out through the internal energy management system of VPP.VPP can participate in the reserve market as well as the power market.The controllable power supply, energy storage and interruptible load in VPP can cooperate with the output of wind power and photovoltaic units to meet the VPP power generation plan. The remaining interruptible load and the reserve capacity of controllable power supply can participate in the reserve market.

III. VPP OPTIMIZATION SCHEDULING MODEL

The VPP optimal scheduling model adopts multi-time scale optimization and multi-market profit model, which reduces the prediction error of VPP output and improves the revenue of VPP as much as possible. Multi-time scale optimization considers the optimization mode combining day-ahead scheduling and day-ahead scheduling, and reduces the prediction error of VPP output step by step through optimization at different time scales. The multi-market profit model considers that VPP can participate in the power and reserve market under the scheduling policy.

A. Objective Function

1) Day-ahead Scheduling Objective Function

VPP scheduling needs to predict the output of wind turbines and photovoltaic units, and then formulate a VPP output plan for the next day based on the predicted wind and photovoltaic output. The formulation of the VPP output plan should maximize the benefits of VPP on the basis of ensuring the priority use of new energy. The day-ahead scheduling objective function is used to optimize the output of VPP's internal controllable power sources in each period, and combined with the predicted output of wind power and photovoltaics, the output plan for each period of the VPP on the next day can be obtained. The scheduling period of the VPP optimization scheduling model is 24 h, and its objective function is as follows:

$$\max\ f_{kvppjh} = \sum_{K=1}^{24}\left(S_K^{vppjh} - C_K^{gljh} - C_K^{rljh} - C_K^{gdjh} - C_K^{bcjh}\right) \tag{1}$$

In the formula: K is the day-ahead time series, with 1 hour as 1 time period, a total of 24 time periods; S_K^{vppjh} is the planned revenue of VPP participating in the electric energy market and the reserve market during the K period; C_K^{gljh} is the management cost of the VPP internal operation plan during the K period; C_K^{rljh} is The planned fuel cost of the gas turbine in the K period; C_K^{gdjh} is the planned power purchase cost of the energy storage system in the K period in the grid; C_K^{bcjh} is the planned compensation cost of the interruptible load within the VPP in the K period.

2) Intraday Scheduling Objective Function

Day-ahead scheduling provides VPP output plans for each period of the next day. Intra-day scheduling aims to maximize the net income of each period of VPP, and optimizes the output of various controllable power sources in VPP at different time periods based on the real-time wind power and photovoltaic output of the next day. The scheduling period of the VPP intraday optimization scheduling model is 24 h, and its objective function is as follows:

$$\max\ f_{kvpp} = \sum_{K=1}^{96}\left(S_k^{vpp} - C_k^{gl} - C_k^{rl} - C_k^{gd} - C_k^{bc} - C_k^{cf}\right) \tag{2}$$

In the formula: k is the intraday time series, with 15 min as 1 time period, a total of 96 time periods; S_k^{vpp} is the income of VPP participating in the electric energy market and backup market during k period; C_k^{gl} is the internal operation and management cost of VPP during k period; C_k^{rl} is k period The fuel cost of the gas turbine; C_k^{gd} is the electricity purchase cost of the energy storage system in the k period; C_k^{bc} is the compensation cost of the interruptible load in the VPP in the k period; C_k^{cf} is the penalty cost of the VPP in the k period.

The expressions of day-ahead scheduling are similar to those of day-ahead scheduling. This section uses day-ahead scheduling as an example to explain the specific expressions of each part.

The benefits of VPP's participation in the electric energy market and standby market during period k are as follows:

$$S_k^{vpp} = \lambda_k^{em} P_k^{em} + \lambda_k^{by} R_k^{by} \tag{3}$$

In the formula: λ_k^{em} and λ_k^{by} are the electricity prices in the electric energy market and the reserve market during the k period, respectively; P_k^{em} and R_k^{by} are the electricity sales of the VPP in the electric energy market and the reserve capacity sold in the reserve market during the k period, respectively.

Management costs include the management costs of k period wind turbines, photovoltaic units, gas turbines, pumped storage, energy storage batteries, and interruptible loads:

$$C_k^{gl}=K^w g_k^w+K^{pv} g_k^{pv}+K^{mt} g_k^{mt}+K^{chou}\left(g_k^{chou}+g_k^{fang}\right)$$
$$+K^{es}\left(g_k^{esc}+g_k^{esd}\right)+K^{el} g_k^{el} \tag{4}$$

In the formula: g_k^w, g_k^{pv}, g_k^{mt} are respectively the output of wind turbines, photovoltaic units and gas turbines in period k; g_k^{chou} and g_k^{fang} are the charging and discharging capacities of pumped storage in period k; g_k^{esc} and g_k^{esd} respectively refer to the charging amount and discharge quantity of the storage battery in period k; g_k^{el} is the load interruption of the interruptible load in the k period; K^w, K^{pv}, K^{mt}, K^{chou}, K^{es}, K^{el} are respectively wind power, photovoltaic, gas turbine, pumped energy storage, energy storage battery and interruptible load Operational management coefficient.

The fuel cost of the gas turbine in period k is

$$C_k^{rl}=P_{mt} g_k^{mt} \tag{5}$$

In the formula: P_{mt} is the fuel cost per unit of gas turbine power generation; P_{NG} is the price of natural gas; η_e is the power generation efficiency of the gas turbine; L_{NG} is the low calorific value of natural gas.

The power purchase cost of the energy storage system in the power grid during the k period is

$$C_k^{gd}=\lambda_k^{gd} g_k^{gd} \tag{6}$$

In the formula: λ_k^{gd} is the price of electricity sold in the power grid during the k period; g_k^{gd} is the electricity purchased by the energy storage system in the power grid during the k period.

The compensation cost for interruptible load is

$$C_k^{bc}=\sum_{m=1}^{M}\left(\lambda_m^{el} g_k^{el}\right) \tag{7}$$

In the formula: m is the interruption level, with a total of M levels; λ_m^{el} is the m-level interruptible load compensation coefficient, and different interruption levels have different compensation coefficients.

The VPP's daily dispatch output needs to be in line with the previously declared output plan, and the penalty cost is considered in the objective function to ensure that the VPP will output according to the output plan. The penalty cost of VPP in k period is

$$C_k^{cf}=\lambda_k^E\left|G_k-P_k^{em}\right|+\lambda_k^B\left|R_k-R_k^{by}\right| \tag{8}$$

B. Restrictions

The constraints of day-ahead scheduling and intra-day scheduling are similar. The constraints mainly include: power balance constraints, gas turbine constraints, pumped storage capacity and power generation/pumping constraints, battery capacity and charge and discharge constraints, interruptible load constraints, and reserve constraints. Here, intraday scheduling is used as an example to explain the constraints.

1) The power balance constraint is as follows:

$$\sum_{k=1}^{96}\left(g_k^w+g_k^{pv}+g_k^{mt}+g_k^{fang}+g_k^{esd}-g_k^{chou}-g_k^{esc}-g_k^{elo}-g_k^{fh}\right)=P_k^{em} \tag{9}$$

In the formula: g_k^{elo} is the interruptible load and the remaining uninterrupted load; g_k^{fh} is the fixed load.

2) The gas turbine constraints are as follows:

$$g_k^{mt}\geq g_{\min}^{mt} \tag{10}$$

$$g_k^{mt}+R_k^{mt}\leq g_{\max}^{mt} \tag{11}$$

$$R_k^{mt}\leq\gamma^u t \tag{12}$$

$$-\gamma^d\leq g_k^{mt}-g_{k-1}^{mt}\leq\gamma^u \tag{13}$$

In the formula: $g_{\min}^{mt}$ and $g_{\max}^{mt}$ are the minimum output and maximum output of the gas turbine, respectively; R_k^{mt} is the remaining reserve capacity of the gas turbine in period k; γ^d and γ^u are the downward and upward ramp rates of the gas turbine, respectively; t is the standby time.

3) Pumped storage capacity and power generation/pumping constraints. The storage capacity of the upper reservoir of the pumped storage reservoir is limited, and the capacity of the lower reservoir is relatively large. Therefore, the capacity of the upper reservoir needs to be restricted, as shown in the following formula:

$$V_{\min}^{up}\leq V_k^{up}\leq V_{\max}^{up} \tag{14}$$

$$V_k^{up}=V_{k-1}^{up}+\Delta t\left(\lambda_k^{chou} g_k^{chou}\eta_p-\lambda_k^{fang} g_k^{fang}/\eta_t\right) \tag{15}$$

$$\lambda_k^{chou}+\lambda_k^{fang}\leq 1 \tag{16}$$

$$g_{\min}^{fang}\leq g_k^{fang}\leq g_{\max}^{fang} \tag{17}$$

$$g_k^{chou}=g_0^{chou} \tag{18}$$

In the formula: V_k^{up} is the upper reservoir capacity in period k; $V_{\min}^{up}$ and $V_{\max}^{up}$ are the minimum and maximum capacities of the upper reservoir respectively; λ_k^{chou} and λ_k^{fang} are the state variables of the reservoir charging and discharging respectively; $g_{\min}^{fang}$ and $g_{\max}^{fang}$ are the minimum and maximum of the pumped storage system, respectively output; Δt is a period of time; η_p is the pumping efficiency; η_t is the power generation efficiency.

IV. VIRTUAL POWER PLANT OPERATION STRATEGY

A. *VPP Scheduling Policy*

1) VPP day-ahead dispatching According to the predicted wind power and photovoltaic output of the next day, taking into comprehensive consideration the power generation costs of all DG in VPP and aiming at maximizing VPP revenue, the VPP output plan of 24 periods of the next day is obtained, and the next-day output plan is reported to the distribution network.

2) After confirming the output plan declared by VPP, the distribution network shall arrange the output of VPP and other generating units in the region.

3) VPP intra-day scheduling is combined with the daily declaration output plan and the real-time output of wind power photovoltaic to carry out economic optimization scheduling and adjust the output of internal DG to meet the power generation plan.

B. *Output Strategy of Distributed Power Supply in VPP*

1) In order to improve the utilization rate of wind power and photovoltaic output and reduce the phenomenon of abandoning wind and light, the use of wind power and photovoltaic output should be given priority in VPP.

2) Gas turbines generate power according to VPP dispatching requirements, and the remaining capacity participates in the standby market transaction.

3) On the basis of stabilizing the deviation of VPP output, the energy storage system can purchase and store electricity from the grid during the period of low electricity price according to the change of power price of the grid, and sell electricity to the grid through VPP during the period of high electricity price, so as to improve the revenue of VPP.

4) Interruptible load is interrupted according to VPP scheduling needs, and the remaining interruptible capacity participates in standby market transactions.

V. ANALYSIS OF EXAMPLES

A. *Model Parameter*

The VPP considered in the model consists of three wind farms, two photovoltaic power stations, two gas turbines, one energy storage battery, one pumped storage power station and 120 MW load. The total capacity of the wind farm is 320 MW, and the operation management coefficient is 30.0 yuan/(MW·h). The total capacity of the photovoltaic power station is 160 MW, and the operation management coefficient is 10.5 yuan/(MW·h). The total capacity of the gas turbine is 120 MW, the operation management coefficient is 43.5 yuan/(MW·h), and the fuel coefficient is 68.6 yuan/(MW·h). The maximum capacity of energy storage battery is 75 MW, and the operation management coefficient is 34.3 yuan/(MW·h).

B. *Calculation Method*

Particle swarm optimization (PSO) is used to solve the VPP economic optimization scheduling model. Particle swarm optimization algorithm adopts velocity position model to optimize the whole space, and each particle performs iterative operation to update its velocity V and position X.

C. *Optimization results and Comparative Analysis*

1) Analysis of the Influence of Interruptible Load Capacity Change on VPP Economy

Intra-VPP aggregation interruptible loads can participate in intra-VPP scheduling. The total load in VPP is set as 120MW, in which the proportion of interruptible load can be adjusted. The influence of interruptible load on scheduling flexibility and net revenue of VPP at different proportions is considered here. Table 1 shows the penalty costs and net benefits of VPP under different proportions of interruptible loads. As can be seen from Table Ⅰ, with the increase of interruptible load, the penalty cost of VPP decreases gradually, and the net revenue of VPP increases first and then decreases. This indicates that with the increase of interruptible load, THE internal scheduling capability of VPP is stronger and the scheduling flexibility is improved. Meanwhile, the increase of interruptible load also brings greater operation and maintenance costs and compensation costs to VPP. Therefore, when the interruptible load reaches a certain proportion, the net revenue of VPP starts to decrease.

TABLE I. PENALTY COST AND NET BENEFIT OF VPP UNDER DIFFERENT INTERRUPTIBLE LOADS

Interruptible load size/MW	**VPP penalty cost/yuan**	**VPP net income per yuan**
0	303850	1843604
25	274692	1929579
50	252091	1971517
100	238811	1930421

In order to minimize the cost of interruptible load to VPP and improve the net revenue of VPP, the interruptible load is considered to participate in the standby market, and the remaining interruptible capacity of the interruptible load on the basis of meeting the VPP scheduling is considered to participate in the standby market transaction. Table Ⅱ shows the penalty costs and net benefits of VPP after participation in the standby market. By comparing Table 1 and TableⅡ, it can be seen that the penalty cost of VPP decreases and the net benefit of VPP increases after the interruptible load participates in the standby market. The comparison results show that the participation of interruptible load in the standby market can further improve the scheduling flexibility of VPP and the net profit of VPP.

TABLE II. PENALTY COST AND NET BENEFIT OF VPP AFTER INTERRUPTIBLE LOAD PARTICIPATES IN STANDBY

Interruptible load size/MW	Interruptible load standby revenue/yuan	VPP penalty cost/yuan	VPP net income per yuan
0	0	303850	1843615
25	14504	232292	1945100
50	24297	220045	2009732
100	52345	218578	1987525

2) The effect of VPP behavior on revenue

In order to measure the influence of VPP's participation in the reserve market and energy storage system's participation in peak load shifting on THE revenue of VPP, the following four schemes are constructed, in which the interruptible load size is 50 MW. The scheme Settings and calculation results are shown in Table Ⅲ and Table Ⅳ respectively.

TABLE III. FOUR DIFFERENT VPP CONSTRUCTION SCHEMES

Package number	VPP participates in the standby market	Energy storage system in VPP participates in peak and valley filling
1	√	√
2	×	√
3	√	×
4	×	×

TABLE IV. RESULTS OF THE FOUR SCHEMES WERE COMPARED

Project	Cost/yuan			
	Plan 1	*Plan 2*	*Plan 3*	*Plan 4*
VPP operating costs	1738037	1755560	1646330	1641325
Electricity market profit	3844721	3876940	3711930	3678495
Reserve market profit	123059	0	112750	0
Participate in peak filling profit	78110	82560	0	0
Penalty cost	220065	319988	239119	424250
VPP net income	2009730	1801388	1939226	1612911

As can be seen from the comparison results in Table Ⅳ, the net revenue of VPP when VPP only participates in the standby market or only participates in peak load shifting is lower than that when VPP participates in both the standby market and peak load shifting. Compared with Option 1, option 2 does not participate in the reserve market and Option 3 does not participate in peak filling, so the penalty cost of VPP is higher and the net benefit of VPP is lower. Option 4, which does not participate in either the reserve market or peak filling, has the highest penalty cost and the smallest net VPP benefit.The results show that the participation of VPP in reserve market and peak load shifting can improve the scheduling flexibility and net profit of VPP.

VI. CONCLUSION

From the point of view of improving the flexibility of VPP scheduling and net income, this paper establishes a VPP optimal scheduling model considering the joint participation of source, charge and storage, solves the modeling problem of simultaneous aggregation of source, charge and storage in VPP, and provides a new model for THE benefit of VPP by using multi-market profit.

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