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Research on virtual power plant market trading model under decentralized trading mechanism based on nonlinear programming

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Abstract With a large number of distributed energy storage accessed by virtual power plants, the market trading model based on traditional two-stage stochastic planning faces problems such as large computational volume and single decision result. Therefore, considering the different decision risk preferences of different decision makers, this paper introduces the decentralized trading theory, combines the nonlinear planning theory, and optimizes it through the mixed integer optimization model, thus forming a set of market trading models applicable to complex situations. Taking 8MW distributed wind turbines as the research object for example analysis, the results show that in the middle and late stages of the transaction, as the transaction continues, the total social welfare and the number of transactions under the decentralized trading model based on nonlinear programming gradually reach the optimal value under the ideal state. Compared with other trading models, the value of the increase in the total social welfare of this paper's model in the peak hour, the normal hour, and the valley hour is more than 15%. This shows that the model in this paper can reduce the cost of electricity and improve the comprehensive social benefits.

Index Terms virtual power plant, nonlinear programming, decentralized trading, integer optimization, comprehensive social benefits

I. Introduction

With the decreasing fossil energy, environmental pollution and climate change problems are becoming more and more serious, decentralized deepening and greening of clean energy will be rapidly developed in the context of energy supply side reform. As the cost of new energy generation continues to decline, driven by smart grid and energy Internet technology, and facilitated by the continuous improvement of the power market trading mechanism, it has become an inevitable trend for a large number of distributed power sources to participate in power market trading [1]-[4]. However, distributed power generation resources are often the layout of decentralized wind power and photovoltaic and other new energy resources, its installed capacity is small, it is difficult to fully participate in the power market competition [5], [6]. In addition, due to the uncertainty of its own output, there are many technical difficulties in the grid operation of new energy, unable to play the expected role of new energy power generation in the power system, so in order to alleviate the above negative impacts, and promote the participation of distributed power supply in the market transactions, the virtual power plant has gradually come into the public's view [7]-[9].

Virtual power plant (VPP), refers to the information, control, communication and other technologies through the energy management system and its control of a smaller scale of distributed energy aggregation of a class of integrated power plants, can be realized for the decentralized distribution of a large number of new energy projects to effectively connect to the grid and participate in the market transactions. Among them, distributed energy mainly includes small-scale power equipment, demand response resources and related energy storage facilities connected to the power system by the distribution grid [10]. VPP can aggregate multiple distributed resources in a certain area and realize coordinated control of them, so as to obtain better scheduling characteristics [11].

With the vigorous development of ubiquitous power IoT, the owners of virtual power plants can directly participate in power market transactions and bring benefits to themselves. In the context of the current power market reform and advocating the development of distributed energy, the virtual power plant can effectively manage decentralized distributed energy sources, can aggregate multiple distributed energy sources on the demand side to form a special power plant to participate in the power market transactions, and can also promote the consumption of distributed energy sources while participating in the market operation and harvesting profits [12]-[15]. In this context, some power distribution enterprises with decentralized power supply have gradually started to explore and study a series of issues such as how to make decisions on their participation in virtual power plant market transactions.

In order to solve the shortcomings of the traditional two-stage stochastic planning theory's virtual power plant market trading model, such as large computational volume, single decision-making result and non-selectivity. In this paper, the decentralized trading theory is combined with the nonlinear planning theory to construct a decision model for virtual power plant participation in market trading that contains multiple energy networks, energy storage units, distributed units, demand response and other resources. Then the model is optimized and solved using the mixed integer optimization model and Matlah software to provide different decision-making scenarios for virtual power plant operators with different risk preferences. A distributed wind turbine with a rated power of 8MW is selected as the research object, and the reliability of this paper's methodology is verified by comparing the decentralized and centralized trading models, and analyzing in depth their comprehensive benefits and day-ahead decisions.

II. Market trading mechanisms for the participation of virtual power plants

The continuous development and improvement of the power market has a positive role in promoting the construction of virtual power plants. On the one hand, the continuous improvement of the market mechanism for the construction of the virtual power plant provides a policy guarantee, which is conducive to the participation of virtual power plants in the power market fairness. On the other hand, the development of the power market for the virtual power plant to participate in more types of market transactions to provide the possibility of virtual power plants in more types of markets to create opportunities for profitability, a greater extent to play the advantages of the virtual power plant. The types of existing virtual power plant participation in power markets at home and abroad are shown in Table 1. This section focuses on the transaction mode of virtual power plants participating in the electricity spot market and the FM auxiliary service market [16].

Table 1: The type of virtual power plant involved in the power market

Market type	The advantages of virtual power plants
Power spot market	With strong adjustment potential, flexible adjustment
Auxiliary service market FM service Standby service Reactive service	Coordinate the response advantages of multiple resources and improve the overall response performance
Long-term bilateral and centralized trading markets	With strong adjustment potential, complementary and complementary complementarity can be achieved through coordinated optimization
Green card trading, financial trading market	Gain market advantage with the ability to adjust and predict

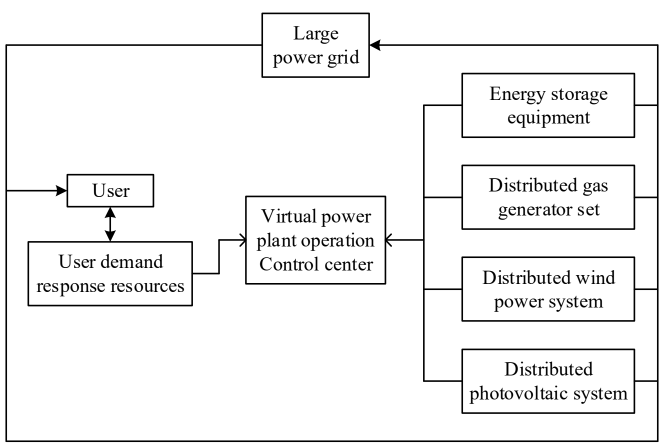


Figure 1: Schematic diagram of the virtual power plant structure

II. A. Transaction Mechanisms for VPP Participation in Electricity Spot Markets

VPP should not be narrowly defined as a collection of various distributed resources, but based on the ideas of “communication” and “aggregation”, the distributed new energy power plants, combined heat and power (CHP) systems, controllable loads and energy storage devices, etc., which are dispersed and connected to different levels of the grid, are brought together [17]. Through the energy management system (EMS) coordination and optimization control to complete the market operation, in the realization of power trading at the same time to optimize the use of resources, improve the reliability of power supply of a complex, its internal structure is shown in Figure 1.

The Basic Rules of Electricity Spot Market (Draft for Public Comments) issued by the National Energy Administration (NEA) explicitly proposes to “promote the participation of emerging market players such as energy storage, distributed power generation, load aggregators, virtual power plants and new energy microgrids in the transaction”. This provides a guarantee for virtual power plants to “ride” on the spot electricity market. The traditional unit declares an incremental power generation price curve based on its own operating data, with each segment declaring the starting point of the output interval, the end point of the output interval, and the energy price of the interval. Similar to the way traditional power producers participate in the spot market, virtual power plants that have obtained access qualifications participate in the spot market through the form of “quoting” to balance the power supply, and independently decide on the volume and price curves under the declared power generation status as well as the upper limit of the power generation operating capacity, which serves as the basis for the clearing of the entire 24-hour participation in the electricity spot market. The power dispatching organization will be based on the declared information of market members as well as the grid operation boundary conditions and operation constraints on the operation day, and will aim at maximizing the social welfare to clear to get the trading results of the electric energy market. On the one hand, the virtual power plant aggregates renewable energy sources such as wind and light, which reduces the generation cost of the virtual power plant. On the other hand, the virtual power plant aggregates different types of resources, compared with the traditional power producers in the process of declaring the amount of electricity and tariffs can be more strategic, in order to hedge the risk of obtaining high profits. When the virtual plant predicts that the price of electricity will be relatively high during a certain period of time, the aggregated resources can be incentivized to increase their output, for example, by encouraging the discharge of energy storage systems and the participation of flexible loads in demand response. When the virtual plant predicts a relatively low price for a certain period of time, the aggregated resources are encouraged to reduce their output, e.g., storage systems are charged at this time, and flexible loads are increased in electricity consumption.

Taking the trading rules for the implementation of the electricity spot market in Shanxi Province as a reference, it introduces the trading process for virtual power plants to participate in the electricity spot market.

(1) Before 8:30 on the bidding day, the market operating organization releases the relevant information of the operation day: load forecast curve and other trading parameters to the relevant market members through the power market trading system.

(2) From 8:30 to 9:30 on the bidding day, market participants declare the volume and price curves, the upper and lower limits of generation output and other trading information for the operating day.

(3) Before 17:30 on the bidding day, the power dispatching organization conducts market clearing in the day before the bidding day based on the information declared by the market participants as well as the marginal conditions of grid operation on the day of operation, and obtains the trading results of the power market in the day before the bidding day, and releases the results openly to the market.

(4) On the operation day, the power dispatching organization updates the ultra-short-term load forecast 1-4 hours before the actual operation time, and the market participants declare the ultra-short-term volume and price curves.

(5) The Power Dispatchers will conduct rolling clearing every 15 minutes and announce the clearing result of that period 30 minutes before the actual operating moment.

II. B.Trading mechanisms for VPP participation in the FM ancillary services market

In order to accelerate the construction of the auxiliary service market and establish a special working mechanism for the power auxiliary service market, it is necessary to continuously promote the marketization of FM, standby and other varieties, and continuously guide the participation of virtual power plants, new energy storage and other new subjects in the regulation of the power system [18]. Therefore, the virtual power plant can provide FM services by flexibly controlling internal high-quality resources, such as energy storage and electric vehicles, making the overall external characteristics track the automatic generation control signals issued by the dispatch center. Since virtual power plant can aggregate high-quality FM resources, it has higher comprehensive FM performance and is more competitive than traditional FM units. In the FM auxiliary service market, the supplier of FM auxiliary service of virtual power plant needs to comply with the relevant technical standards of FM auxiliary service, and meet the requirements of regulation performance and metering accuracy. Each participant needs to make synchronized declarations of FM capacity and FM mileage as well as FM capacity price and FM mileage price in the FM market. The power control center organizes the FM market clearing according to the adjustable capacity demand of each time period, and arrives at the winning capacity and mileage of each participant, as well as the relevant clearing price.

Based on the implementation rules of Shanxi Provincial Electricity Auxiliary Service Market, the transaction process of virtual power plant participating in the FM auxiliary service market is given.

(1) Before 8:30 on the bidding day, the power control center releases the opening information of the FM market for each time slot, including: market players for FM market access, FM market demand for each time slot on the following day, load forecast curve, and the range of declared prices in the FM market.

(2) From 8:30 to 9:30 on the bidding day, FM service providers declare FM capacity, FM mileage price and FM capacity price.

(3) From 9:30 to 10:30 on the Bidding Day, the Electricity Regulation and Control Center carries out the calculation of FM market clearing for each time slot. Based on the FM demand in each time slot in the FM market, the data declared by FM service providers and historical FM performance indicators, etc., and with the goal of minimizing the cost of supplying FM services, the FM market will be centrally cleared. It is worth noting that in the current Shanxi FM auxiliary service market, the price of FM capacity does not need to be declared by market players but is priced in a uniform manner. In order to further reflect the advantages of virtual power plants in the FM auxiliary service market, this paper modifies this and sets the FM service providers to declare both FM capacity price and FM mileage price when participating in the FM market.

III. Modeling of transactions in the virtual power plant market

Nonlinear programming is an important branch of operations research, which studies mathematical planning problems with nonlinear functions in the objective function and/or constraints. For different nonlinear planning problems, there is no universally applicable solution. So far, it is a general step to apply nonlinear planning by proposing and planning special algorithms, testing the results obtained by applying these algorithms to the problem of interest and constructing some better algorithms based on these experiences [19]. The traditional two-stage stochastic programming theory seeks the set of solutions that maximize the expectation of the objective function as the optimal day-ahead declared output for the virtual power plant to participate in the spot market in all scenarios consisting of different joint tariff scenarios and scenarios of the respective outputs of wind and light. Stochastic programming has the advantages of being easy to understand and model, but it also has drawbacks such as large computation, single decision result, and non-selectivity. Therefore, this paper introduces the decentralized trading theory, combines with the nonlinear planning theory to further modify the model, and provides virtual power plant operators with different risk preferences with the option of day-ahead declared output based on their risk preferences. Finally, the effectiveness of the virtual power plant market trading model proposed in this paper is examined by comparing the advantages and disadvantages of the decentralized and centralized trading models through specific example data.

III. A. Objective function

VPP costs are as follows:

$$C_{VPP}=\sum_{t=1}^{T}\left(\sum_{i=1}^{N_{Gi}}C_{Gi,t}+\sum_{j=1}^{N_{Wj}}C_{Wj,t}+\sum_{j=1}^{N_{Wj}}C_{Wj,t}^{c}+\sum_{k=1}^{N_{PV}}C_{PVk,t}+\sum_{k=1}^{N_{PV}}C_{PVk,t}^{c}+C_{BESSt}+C_{GRt}\right) \tag{1}$$

$$C_{Gi,t}=a_iP_{Gi,t}^2+b_iP_{Gi,t}+c_i \tag{2}$$

$$C_{Wj,t}=\lambda_W P_{Wj,t} \tag{3}$$

$$C_{PVk,t}=\lambda_{PV}P_{PVk,t} \tag{4}$$

$$C_{Wj,t}^{c}=\rho_W(P_{Wj,t}^{pr}-P_{Wj,t}) \tag{5}$$

$$C_{PVk,t}^{c}=\rho_{PV}(P_{PVk,t}^{pr}-P_{PVk,t}) \tag{6}$$

$$C_{BESSt}=\kappa_{BESS}(P_{BESSt}^{ch}+P_{BESSt}^{dch}) \tag{7}$$

$$C_{GRt}=\gamma_b P_{GRt}^{b}-\gamma_s P_{GRt}^{s} \tag{8}$$

VPP gains are as follows:

$$R_{VPP}=\sum_{t=1}^{T}(R_{Ct}+R_{Ct}+R_{Vt}) \tag{9}$$

$$R_{Gt} = \xi_s \left(\sum_{i=1}^{N_c} P_{Gi,t} + \sum_{j=1}^{N_w} P_{Wj,t} + \sum_{k=1}^{N_w} P_{PVk,t} + P_{BESSt}^{dch} - P_{BESSt}^{ch} \right) \tag{10}$$

$$R_{Ct} = \delta_c (E_{Ct}^{re} - E_{Ct}) \tag{11}$$

$$E_{Ct}^{re} = \omega_{re} \left(\sum_{i=1}^{N_G} P_{Gi,t} + \sum_{j=1}^{N_W} P_{Wj,t} + \sum_{k=1}^{N_W} P_{PVk,t} + P_{BESSt}^{dch} - P_{BESSt}^{ch} \right) \tag{12}$$

$$E_{Ct} = \sum_{i=1}^{N_G} E_{Gi,t} + E_{GRt}^{b} \tag{13}$$

$$R_{Vt} = \delta_G (P_{Vt}^{re} - P_{Rt}) \tag{14}$$

where: C_{VPP} is the total VPP operating cost. $C_{Gi,t}$ is the gas unit operating cost. $C_{Wj,t}$ is the wind power cost. $C_{Wj,t}^{c}$ is the cost of wind abandonment. $C_{PVk,t}$ is the photovoltaic cost. $C_{PVk,t}^{c}$ is the cost of abandoned light. C_{BFSSt} is the storage battery operating cost. C_{GRt} is the main grid cost. a_i, b_i, c_i are the cost coefficients of gas-fired unit generation. $P_{Gi,t}$ is the gas unit output. λ_W is the wind power generation cost coefficient. $P_{Wj,t}$ is the wind turbine output. λ_{PV} is the photovoltaic power generation cost coefficient. $P_{PVk,t}$ is the PV output. ρ_W is the wind abandonment cost factor. $P_{Wj,t}^{pr}$ is the wind power forecast output. ρ_{PV} is the PV cost factor. $P_{PVk,t}^{pr}$ is the PV forecast output. κ_{BESS} is the storage battery generation cost factor. $P_{BESSt}^{ch}, P_{BESSt}^{dch}$ are the storage battery charging and discharging power, respectively. R_{Gt}, R_{Ct}, R_{Vt} are the VPP unit, carbon trading, and green certificate trading revenues, respectively. ξ_s is the VPP generation revenue coefficient. δ_c is the carbon trading revenue coefficient. E_{Ct}^{re} is the carbon emission allowance. E_{Ct} is the actual value of carbon emissions. ω_{re} is the quota factor. E_{GRt}^{b} is the electricity purchased from the main grid. δ_G is the green certificate revenue factor. P_{Vt}^{re}, P_{Rt} are the renewable energy generation dispatch and quota values, respectively.

III. B. Constraints

Supply and demand balance constraints:

$$\sum_{i=1}^{N_G} P_{G,t} + \sum_{j=1}^{N_W} P_{Wj,t} + \sum_{k=1}^{N_W} P_{PVk,t} + P_{BESSt}^{dch} - P_{BESSt}^{ch} + P_{GRt}^{b} - P_{GRt}^{s} = P_{Lt} \tag{15}$$

Unit generation constraints:

$$P_{G\min i} \le P_{Gi,t} \le P_{G\max i} \tag{16}$$

Unit Climbing Constraints:

$$P_{Gi,t} - P_{Gi,t-1,s} \le R_{U\max i} \tag{17}$$

$$P_{Gi,t-1} - P_{Gi,t} \le R_{D\max i} \tag{18}$$

Energy storage operational constraints:

$$P_{\min i}^{dch} \le P_{BESSt}^{dch} \le P_{\max i}^{dch} \tag{19}$$

$$P_{\min i}^{ch} \le P_{BESSt}^{ch} \le P_{\max i}^{ch} \tag{20}$$

Battery capacity constraints:

$$E_{BESSt+1} = E_{BESSt} + \Delta t (P_{BESSt}^{ch} \eta_i^{ch} - \frac{P_{BESSt}^{dch}}{\eta_i}) \tag{21}$$

$$E_{BESS\min i} \le E_{BESSt} \le E_{BESS\max i} \tag{22}$$

Exchange power constraints with the main network:

$$P^{b}_{\min t} \le P^{b}_{t} \le P^{b}_{\max t} \tag{23}$$

$$P^{s}_{\min t} \le P^{s}_{t} \le P^{s}_{\max t} \tag{24}$$

Distributed Power Output Constraints:

$$0 \le P_{wj,t} \le P^{pr}_{Wj,t\max} \tag{25}$$

$$0 \le P_{PVk,t} \le P^{pr}_{PVk,t\max} \tag{26}$$

where: $R_{U\max i}, R_{D\max i}$ are the upper and lower limits of the unit climbing output constraint, respectively. $P_{1,t}$ is the load demand. $\eta_i^{ch}, \eta_i^{dch}$ are the charging and discharging efficiencies, respectively. $E_{BESS\min i}, E_{BESS\max i}$ are the lower and upper battery capacity limits, respectively.

III. C. Participation of virtual power plants in market trading processes

In this paper, we consider a virtual power plant participating in the day-ahead and real-time markets, and the real-time market includes standby service transactions. Before the day-ahead market closes on day N, the virtual plant forecasts the available output of distributed power sources (mainly PV and wind) and then submits bids to the independent system operator (ISO) for each time slot during the 24-hour period on day N+1. As a result, virtual power plants often need to predict their actual output 1224 hours in advance, which makes it difficult for virtual power plants to control the deviation between their bidding output and actual output.

In this paper, it is assumed that the virtual power plant participates in the market transaction as a price taker, and only needs to make a market offer based on the forecast, so as to ensure that all of the virtual power plant's internal bidding power is utilized, and to realize the support of the market transaction. The actual bidding of new energy units is related to the forecasted output results, and the bidding output is arranged according to the time-accurate forecast results continuously. There is still a certain time interval from the closure of the day-ahead market to the opening of the real-time market, therefore, although the output forecast is more accurate at this time, there is still a certain prediction error. In the real-time market, virtual power plants can utilize their own energy storage units, distributed units, demand response and other resources to smooth out the output deviation of wind power and PV between the actual operation and the day-ahead declared plan, and bid for the excess power after satisfying the day-ahead plan as standby service power in the real-time market. The transactions in this paper are settled on an hourly basis, clearing for specific transaction results, and announced to the market.

III. D. Solution tools

In this paper, a mixed integer optimization model is developed and the Matlah software is used to solve the model, specifically the Gurobi solver in the YALMIP toolbox.

IV. Analysis of examples

IV. A. Basic data

In order to validate the nonlinear planning decision model constructed in this paper, a distributed wind turbine with a rated power of 8MW and a maximum output power of 10MW is selected, and a distributed photovoltaic (PV) turbine with a rated power of 5MW and a maximum output power of 7MW is selected, and the maximum storage capacity of the storage battery is 10MW·h and the minimum storage capacity is 1MW·h. The initial capacity is 5MW·h, and the maximum charging power is 1.5MW·h and the maximum discharging power is 2MW·h, an initial capacity of 5MW·h, a maximum charging power of 1.5MW·h, and a maximum discharging power of 2MW·h. The incentive-based demand response cost is 500 yuan/MW, and the maximum directly controlled load power is not more than 20% of the customer's load, and the gas unit startup and shutdown cost is 1000 yuan once, the rated output power of the gas unit is 5MW, the climbing speed is 1MW·h, the minimum output power is 1MW, and the penalty factor θ is taken as 0.4.

IV. B. Presentation and analysis of calculation results

Matlab2016b software is applied to calculate the model in ten electricity price scenarios to get the decision-making results of the virtual power plant's in participating in spot market transactions as follows:

IV. B. 1) Analysis of the previous day's decisions

The volatility of photovoltaic power generation is smaller than that of wind power generation, which is that photovoltaic power generation does not generate power at 0-6 moments and 19-24 moments, and does not have volatility, and the scenario simulation shows that the wind power generation and photovoltaic power generation are complementary, and the wind power generates more power during the night time when the wind speed is high. The wind power generates more power at night when the wind speed is high, and generates less power during the daytime, which is concave, and the photovoltaic power generation is opposite to the wind power, the unit only generates power during the daytime, and its power generation curve is convex, which proves that containing wind and solar power units at the same time can suppress the power output volatility of the whole system. The optimal daytime output curve is shown in Figure 2, which shows that the daytime declared output curve of the virtual power plant can be divided into three stages: the first stage is from 0:00 to 8:00 p.m. This stage is due to the fact that the system only has wind power at night, so the declared amount is less. The second stage is from 09:00 to 15:00, this stage with the distributed PV gradually power generation, the joint declaration of the system gradually increases. The third stage is from 16:00 to 23:00, as the peak of electricity consumption approaches, the market price rises a few days ago, the joint declaration of the system reaches the highest value.

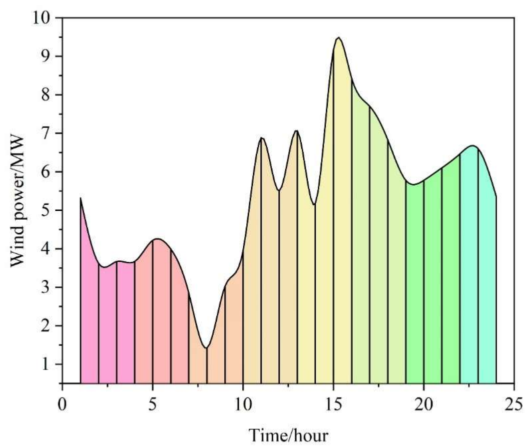
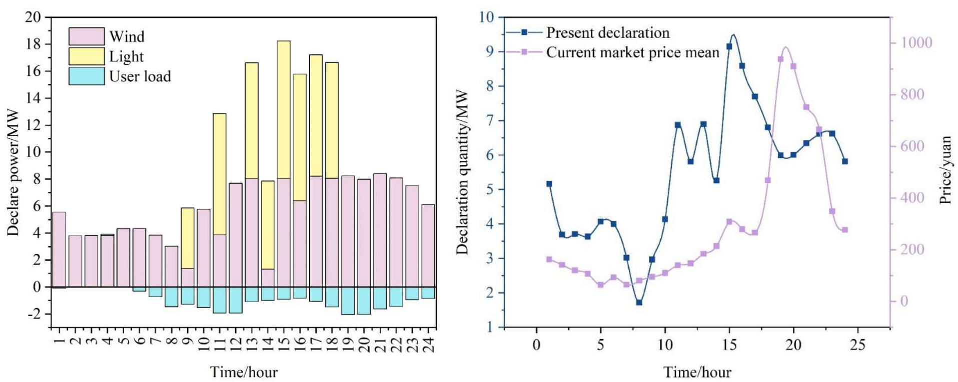


Figure 2: the optimal output curve



(a) Declaration

(b) Current market price mean and declaration quantity

Figure 3: Virtual power plant joint declaration output curve

The joint declared output curve of virtual power plants is shown in Figure 3. In addition, it can be seen from the figure that the declaration curve of wind power is more in the night time and noon time, which is because on the one hand, in the noon time and night time, the customer is in the peak period of electricity consumption, and wind power needs to declare more power to meet the customer's load demand. On the other hand, the supply-demand relationship in the night time makes the price in the day-ahead market increase, so the virtual plant operator needs to declare more power in the night time in order to get more revenue from the day-ahead market. Finally, from the figure, we can get the virtual power plant joint declared power curve and the day-ahead market price curve, the virtual power plant declares lower power in the 0-8 time period, the wind power is the main unit in this time period, and after the 8 time period, the joint declared power increases with the increase of PV unit power and maintains at the high declared power level, and after the 18 time period, the declared power decreases with the decrease of PV unit power. With the increase of wind power output during the night, the joint declared power of virtual power plants remains at a high level.

IV. B. 2) Decentralized versus centralized trading models

Under the centralized trading model, the clearing is carried out by the trading center based on the offers of the trading parties with the objective of maximizing social welfare. Since the trading center cannot grasp the cost information of each thermal power unit and shared energy storage, the market clearing result is only the optimal value based on the current offer. Ideally, assuming that the trading center can grasp the cost information of all market players, social welfare can be maximized. The number of thermal power units and shared energy storage in the market is set to be 4/20, and the transactions are simulated in three modes of decentralized trading, centralized trading and ideal state respectively, in which it is assumed that both shared energy storage and thermal power units are quoted the middle price of the price range in the centralized trading mode and cleared out based on this price.

The total social welfare under the three models is shown in Figure 4. The market efficiency under the decentralized trading model is the lowest at the beginning of the transaction, but as the transaction continues, the total social welfare and the number of transactions under the decentralized trading model gradually exceeds that of the centralized trading market with a single offer, and eventually converges to the optimal value under the ideal state. Under the decentralized trading considering the information disclosure mechanism, the shared energy storage and thermal power units fully interact with each other in terms of price information through continuous price negotiation and default optimization. Compared with the centralized trading model with single offer, the shared energy storage is able to discover price information in a timely manner and achieve higher total social welfare than the centralized trading model.

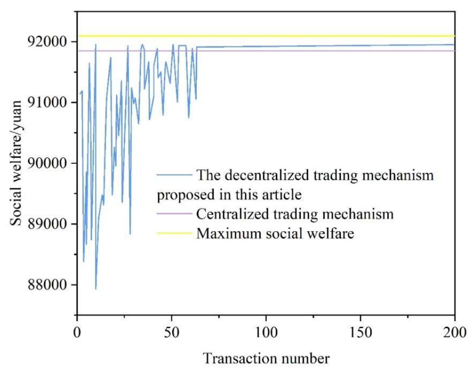


Figure 4: Decentralized trading and centralized trading

IV. B. 3) Comprehensive benefits analysis

Comprehensive benefit analysis as shown in Table 2, from the previous analysis results can be seen, the overall comprehensive social benefits and power supply compensation cost coefficient is negatively correlated, so this paper selects a smaller power supply compensation cost coefficient. It can be seen that when the power supply compensation cost coefficient is 0.1, the social comprehensive benefit achieved is the largest. By analogy, the relationship also tends to be the same in weekdays and valley hours. In the following, we analyze the VPP, the revenue of the power supply company and the comprehensive social benefits when the power supply compensation cost coefficient is 0.1. It can be seen that the VPP and the price of electricity sold by the power supply company are reduced, and the amount of electricity supplied by the power supply company is also relatively reduced, so that the total income of the power supply company from electricity sales is reduced despite the compensation cost for the supply of VPP. From the relationship curve between the social comprehensive benefit and the coefficient of power supply compensation cost, it can be seen that when the coefficient of power supply compensation cost is 0.1, the social comprehensive benefit achieved is the largest. The decentralized trading model based on nonlinear planning reduces the total revenue of the power supply company by 17.65% in the peak hours, 20.65% in the normal hours, and 18.18% in the valley hours, but the comprehensive social benefits are significantly increased by 19.27%, 22.53%, and 15.02%, respectively. This result shows that the decentralized trading model based on nonlinear programming can reduce the cost of electricity consumption, improve the efficiency, and also enhance the comprehensive social benefits. It can also better promote the healthy development of enterprises. The optimized adjustment of differential tariffs provides a useful reference for the formulation of reasonable tariff policies and effectively promotes the rapid development of society.

Table 2: The efficiency of the compensation fee is 0.16

	Total revenue of the power supply company / 10^8 yuan		VPP/10^8 yuan
	A centralized trading model based on traditional two-stage stochastic programming	A decentralized trading model based on nonlinear programming	
Peak time	1.592	1.311	0.252
Normal segment	1.150	0.9125	0.1947
Valley time	0.6022	0.4927	0.1639
	Social comprehensive benefit / 10^8 yuan		
	A centralized trading model based on traditional two-stage stochastic programming	A decentralized trading model based on nonlinear programming	Increase/%
Peak time	3.483	4.154	19.27%
Normal segment	2.517	3.084	22.53%
Valley time	1.518	1.746	15.02%

V. Conclusion

In this paper, we mainly use decentralized trading theory and nonlinear programming theory to establish a virtual power plant market trading model under decentralized trading mechanism based on nonlinear programming. The mixed integer optimization model and Matlah software are used to solve it. In order to verify the validity of the model in this paper, the distributed wind turbine with rated power of 8MW is selected as the example object for research, and the following conclusions are obtained:

(1) Distributed wind turbines are in the peak period of electricity consumption during the night time hours and midday hours, with more declarations.

(2) Simulating the transaction under the three modes of decentralized trading, centralized trading and ideal state, it can be found that the model of this paper has the lowest market efficiency in the early stage of the transaction, but in the middle and late stage of the road transaction, the decentralized trading mode is gradually converging to the optimal value under the ideal state.

(3) The comprehensive social benefits of the decentralized trading model based on nonlinear programming increase by more than 15% in all cases. Therefore, it can reduce the cost of electricity, improve efficiency and promote the healthy development of enterprises.

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