Cooperative game trading mode of virtual power plant group

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Abstract. Considering the complementarity of wind energy and light energy, this paper puts forward the cooperative game of virtual power plant with different clean energy output. Through real-time information exchange, the cooperative game transaction mode of virtual power plant group is proposed based on the original traditional virtual power plants directly trading with the distribution network. In the virtual power plant cooperative alliance, the virtual power plant with more electric power and the virtual power plant with less electric power could share electric power, thus obtaining higher overall profits. The nucleolus theory is used to distribute the benefits of the alliance. The validity of the model is verified by simulation.

1. Introduction
With the continuous reform of the power market, the market environment of the power-selling side is gradually open; the virtual power plant (VPP) participates in the trading of the power market with a new operating mode that integrates distributed power, load and energy storage[1]. In the new environment, how virtual power plants develop their own business models in the new round of power sales competition is particularly important[2].

At this stage, the academic research on the participation of virtual power plants in market competition focuses on the energy management, optimization scheduling, and bidding mechanism of virtual power plants. Literature [3] proposed a distributed daily economic dispatch optimization model for wind power grid-connected systems of virtual power plants. Through load transfer to achieve peak-shaving and valley filling, wind power consumption was promoted. In the literature [4], considering the wind power output characteristics and the uncertainty of small and medium user load, a virtual power plant coordinated scheduling model based on revenue maximization is constructed. Literature [5] proposed an optimization decision model for the virtual power plant how to maximize the profit of wind power-photovoltaic-load-storage combined operation. The influence of distributed energy output on the bidding strategy under this model is analyzed. Literature [6] proposed a two-layer coordinated interaction mechanism involving multiple virtual power plants, and established a two-layer optimization model for multiple virtual power plants. Through multi-scale rolling optimization of multiple virtual power plants, the maximum profit was realized.

On the whole, most of these documents have studied the bidding strategy of virtual power plants and the scheduling optimization model of the day before and during the day[7]. There are few literatures to study the participation of multiple virtual power plants in the electricity market[8-9]. Therefore, this paper proposes a cooperative game model of virtual power plant group[10-11]. This
paper focuses on the analysis and research of the trading mode of virtual power plant cooperative game.

2. System structure and trading mode
In this paper, energy hub concept modeling is used to obtain data of various energy loads in real time by using two-way communication system and smart meter to ensure transactions between virtual power plants.

The system structure of the interconnected virtual power plant group is shown in Figure 1.

![Figure 1. System structure diagram of multiple virtual power plants.](image)

![Figure 2. Multiple power plant transaction mode diagram.](image)

Each virtual power plant consists of load, clean power, and energy storage. It is connected to the distribution network through the energy hub. The clean energy output preferentially meets its own load demand, and exchanges energy with the distribution network when there is demand. Each virtual power plant processes its own data transmission with an information processing center, feeds it back to each virtual power plant, and finally trades. Since the load and clean energy output of each virtual power plant is different, the net load of each virtual power plant is different. At some point, virtual power plants with lots of electricity can sell excess power to the distribution network; For power-hungry virtual power plants, they can buy electricity from the distribution network. In general, the purchase price of the power distribution network is lower than the sale price. Therefore, if the virtual power plant with excess electricity and the virtual power plant with shortage of electricity cooperate, the electricity cost can be reduced and the overall income can be increased.

As shown in Figure 2, this paper first establishes a market model for direct trading between each virtual power plant and the grid. Then a cooperative model between multi-virtual power plants based on cooperative game theory is proposed.

3. Model

3.1. Direct trading model of virtual power plant
Suppose there are n virtual power plants in an area, and divide it into 1–24 time periods by one day. In the kth period, the load power of the virtual power plant i is \( L_i(k) \); the clean energy output is \( P_i(k) \).

For the surplus power plant i, the profit \( M_i(k) \) at this time is:

\[
M_i(k) = m_1
\]

\[
m_1 = p_i(k) \ast (P_i(k) - L_i(k))
\]

For the power-deficient virtual power plant i, the profit at this time is:

\[
M_i(k) = 0
\]

Electricity purchase expenditure \( E_i(k) \) is:

\[
E_i(k) = m_2
\]

\[
m_2 = p_d(k) \ast (L_i(k) - P_i(k))
\]
Where: $m_1$ represents the profit from the sale of excess electricity to the power distribution network; $m_2$ represents the expenditure of purchasing electricity from the large power grid by a virtual power plant with insufficient power.

The virtual power plant $i$ benefits in one day is:

$$M_i = \sum_{k=1}^{24} M_i(k)$$

$$M_i(k) = \begin{cases} m_1, & L_i(k) - P_i(k) < 0 \\ 0, & L_i(k) - P_i(k) \geq 0 \end{cases}$$

The expenditure of the virtual power plant $i$ in one day is:

$$E_i = \sum_{k=1}^{24} E_i(k)$$

$$E_i(k) = \begin{cases} m_2, & L_i(k) - P_i(k) \geq 0 \\ 0, & L_i(k) - P_i(k) < 0 \end{cases}$$

For this model, the large grid is traded separately with each virtual power plant. When the virtual power plant has excess power, it calculates the revenue from selling electricity, and when the virtual power plant has less power, it calculates the electricity purchase cost.

### 3.2. Cooperative game model

The cooperative game in game theory refers to the fact that the players of the game form alliances through a certain constraint agreement to obtain a better trading strategy. In the cooperative game, we pay attention to the overall interests and emphasize efficiency, fairness and justice. The cooperative game requires the overall income to be greater than the sum of the benefits of each member when operating separately; For the profit distribution, the profit of each alliance participant is not less than the profit of the member's individual operation.

In a multi-virtual power plant system, each virtual power plant belongs to a single entity, and each of the virtual power plants has different clean energy sources, and there is complementarity, which makes the virtual power plant cooperation have the possibility of additional revenue. Each virtual power plant forms an alliance with each other and uses excess power and then trades with the large power grid. This avoids the sale of excess power to the large grid at a lower price and the purchase of electricity from the grid at a higher price.

Because of the complementarity between wind and light energy, at some point the cooperative alliance has the mutual use of electricity, which is sold to internal use at a price lower than the grid sales price, thus reducing the purchase cost, which is the cooperative income. Through the reasonable distribution of cooperative income, the benefits of surplus power and power shortage virtual power plants have been increased respectively, so there is a driving force for forming cooperative alliances between virtual power plants.

The benefits of cooperation between virtual power plants are shown in Figure 3:

![Figure 3. Cooperation income.](image)

Suppose there are $n$ virtual power plants in a certain area that are willing to alliance, and form alliance $S$ to trade with the power grid. Defining the net load $Q_i(k) = L_i(k) - P_i(k)$ of the virtual power plant $i$ at time $k$, then the profit $V(S)$ of the alliance $S$ is:

$$V(S) = \sum_{i=1}^{n} \sum_{k=1}^{24} M_i(k) + U \ast \left( p_d(k) - p_i(k) \right)$$

$$U = \sum_{k=1}^{24} \min \left\{ \sum_{i \in P_k} Q_i(k), \sum_{i \in Q_k} Q(k) \right\}$$

$$V(S) = \sum_{i=1}^{n} \sum_{k=1}^{24} M_i(k) + U \ast \left( p_d(k) - p_i(k) \right)$$

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$$\sum_{k=1}^{24} \min \left\{ \sum_{i \in P_k} Q_i(k), \sum_{i \in Q_k} Q(k) \right\}$$
$$M_i(k) = \begin{cases} \frac{m_1}{m_2} & L_i(k) - P_i(k) < 0 \\ \frac{m_1}{m_2} & L_i(k) - P_i(k) > 0 \end{cases}$$

(12)

Where: at k time, $P_k, Q_k$ are the collection of all the multi-electric virtual power plants and the virtual power plants lacking electricity, and $U$ is the sum of the mutual electricity consumption in the cooperative alliance.

### 3.3. Profit distribution model

An important issue in cooperative game solving is to find one or a group of assignments, so that each person in the bureau gets their payment according to this group of assignments, and everyone has no opinion. Among the various solutions of cooperative games, only the nucleolus solution must exist, and is unique, and has symmetry, which satisfies the individual's rationality and overall rationality[12-13]. Therefore, the nucleolar algorithm can always give users a reasonable profit distribution. The idea of the nucleolar algorithm is to prioritize the most dissatisfied alliances, choose the allocation method to minimize the dissatisfaction; consider the second dissatisfied alliance, and choose the allocation method to make the dissatisfaction as small as possible. This cycle until all the league's dissatisfaction is as small as possible.

Suppose $Y = \{y_1, y_2, ..., y_n\}$ represents the set of profits of each virtual power plant under cooperative game, $X = \{x_1, x_2, ..., x_n\}$ represents the set of returns of profits of each virtual power plant, $v(S)$ represents the profit from the alliance S cooperation. In order to ensure the fairness of the profit distribution of cooperative games, Y should satisfy the core distribution theory of cooperative games:

1. **Overall rational constraints:**
   $$\sum_{i \in S} y_i = v(N)$$
   (13)

2. **Individual rational constraints:**
   $$\sum_{x \in S} y_i \geq v(S)$$
   (14)

3. **Non-negative constraints:**
   $$y_i \geq 0$$

The solution can be expressed as:

$$\min \max_{x \in X} e(S, x)$$

Where: $e(S, x)$ is the excess value of Union S for x, which usually indicates the degree of dissatisfaction of the Alliance participants with the allocation scheme. $e(S, x) = v(S) - x(S)$. Let $V(S) = v(S) - \sum_{i \in S} v(i)$, $V(S)$ means: the excess profit generated by the cooperative alliance of the participants.

Solve the above formula using linear constraints:

$$\begin{cases}
\min \varepsilon \\
\text{s. t} \quad V(S) = \sum_{i \in S} x_i \\
\quad v(S) - \sum_{i \in S_1} x_i \leq \varepsilon
\end{cases}$$

(16)

Where: $\varepsilon$ is an arbitrarily small real number, representing the degree of dissatisfaction of the Alliance participants in the allocation scheme.$S$ is a cooperative alliance of all participants. $S_1$ is a subset of $S$.

Ultimately, the profit of each participant in the major league should be the sum of the combined profits of the participants and the profits created by the participants when they operate separately. which is:

$$y_i = x(i) + v(i)$$

(17)

### 4. Case analysis

#### 4.1. Basic data

The article takes a multi-virtual power plant system consisting of three virtual power plants in a region as an example. The clean energy output of the three virtual power plants is predicted as shown in Figure 4. (The interval is 1 hour, divided into 24 time slots). The virtual power plant 1 energy comes
from high-power photovoltaic power generation; the virtual power plant 2 energy comes from wind power generation; The virtual power plant 3 energy comes from low-power photovoltaic power generation; The required load of each virtual power plant is shown in Figure 5. Photovoltaic and wind power costs are shown in Table 1.

![Figure 4. Clean energy output.](image1)

![Figure 5. Load.](image2)

**Table 1. Cost data.**

| Types            | Power lower limit/kw | Power cap/kw     | Operating costs/(¥/kWh) |
|------------------|----------------------|------------------|-------------------------|
| Power grid       | 0                    | ∞                | Peak and valley electricity price |
| Wind Turbine     | 0                    | Predictive value | 0.35                    |
| Photovoltaic     | 0                    | Predictive value | 0.45                    |

The electricity price of the power grid uses the peak and valley electricity prices, and the peak period is 10:00~15:00 and 18:00~21:00; The electricity price for electricity is 0.83 ¥/kWh, and the purchase price is 0.65 ¥/kWh; The flat time is 7:00~10:00, 15:00~18:00, 21:00~24:00, the electricity price is 0.53 ¥/kWh, and the purchase price is 0.38 ¥/kWh; The valley time is from 0:00 to 7:00, the electricity price is 0.22 ¥/kWh, and the electricity price is 0.17 ¥/kWh. The maximum power of the tie line between virtual power plants is 40kw.

### 4.2. Simulation result analysis

**Table 2. Results under different trading methods.**

| Types                      | Virtual power plant 1 | Virtual power plant 2 | Virtual power plant 3 | total    |
|---------------------------|-----------------------|-----------------------|-----------------------|----------|
| Direct trading mode (¥)   | 16.0                  | 49.9                  | 2.6                   | 115.9    |
| Cooperative trading mode (¥) | 45.5                | 89.1                  | 30.7                  | 165.3    |
| Difference value:         | 183%                  | 78.4%                 | 1088%                 | 42.5%    |

As shown in Table 2, the revenue of the virtual power plant in the cooperative alliance is 42.56% higher than that of the direct transaction, and the revenue of each virtual power plant is higher than the single income. Especially when the virtual power plant's clean energy complementarity is stronger, its income is higher.

The comparison of the profit of the three virtual power plants in different modes at each moment is as follows (When the profit is negative at this moment, it indicates the expenditure of the virtual power plant to purchase electricity):
Figure 6. Comparison of the revenue of virtual power plant 1.

Figure 7. Comparison of the revenue of virtual power plant 2.

Figure 8. Comparison of the revenue of virtual power plant 3.

As shown in Figures 6, 7, and 8, it can be clearly seen that the three cooperative virtual power plants have significantly increased their revenues during most of the time, and the expenditures have been significantly reduced; Only in the absence of electricity in the three virtual power plants at a certain moment, the benefits and expenditures will not change. The simulation proves that the cooperation model of this paper can effectively improve the benefits of different virtual power plants, and at the same time, it can be seen that the complementarity of different clean energy sources such as wind and light.

5. Conclusions
The multi-virtual power plant cooperative game model established in the paper uses the nucleolus distribution method to distribute the benefits of each virtual power plant. Through the example, the following conclusions are obtained: 1. The cooperative transaction of multiple virtual power plant groups obtains more profits than the direct transaction model as a whole. 2. The nucleolus theory is used to distribute the profits, so that the income of each virtual power plant is improved; the electricity sales revenue of the multi-power virtual power plant becomes larger, and the power purchase expenses of the virtual power plant lacking electricity become less.

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