Multi-agent revenue distribution model of VPP based on game theory

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Abstract. VPP contain multiple investment entities. There are cooperation and competition relationships among different entities. It is necessary to study the problem of income distribution among multiple entities. Firstly, the multi-agent investment income model of VPP is analyzed, and the VPP income function is determined. Secondly, based on cooperative game theory, the Shapley value method is used to construct a multi-agent revenue model allocation model for VPP. Finally, select typical scenarios for measurement and analysis to verify the validity of the model.

1. Introduction

In order to alleviate environmental degradation and resource shortages, DG have developed rapidly in recent years. In order to make DG actively participate in system operation management, countries such as Europe and the United States have proposed the concept of VPP [1-5]. Conceptually, the VPP realizes the aggregation of different types of DER (DER) such as DG, energy storage system and controllable load through advanced technologies such as control, measurement and communication, and realizes more through the energy management system. The coordinated and optimized operation of energy sources is conducive to the rational development of different resources [6]. Functionally, VPP act like traditional power plants in power systems and markets [7].

When there are different DG investment entities within the virtual power plant, each investment entity may have a profit conflict due to the fixed electricity price or centralized control within the virtual power plant. Some DGs may lack the willingness to actively participate in the standby adjustment due to the decrease in profits. Therefore, in view of the existence of multiple investment entities within VPP, only the operation strategy of DGs with different ownership rights within VPP is clarified. Without intervening in its independent operation rights, it is guaranteed that each DG can obtain the maximum benefit by joining the virtual power plant. Ensure that virtual power plants can be more practical in the future. Therefore, in order to encourage more DG to actively join the virtual power plant, promote the healthy development of the virtual power plant, pay attention to the internal operation mechanism of the multi-agent virtual power plant, and ensure that each DG can obtain the corresponding economic value, which has certain research significance.

The distribution of income is the core issue of the incentive mechanism of multi-investment VPP [8], designing a reasonable benefit distribution mechanism, giving full play to the complementary role of the main advantage, and realizing the efficient operation and win-win of the VPP. In the research method
of multi-subject income distribution, different modeling methods are usually selected according to different industries and alliance categories. Operational and optimization methods and probabilistic methods are considered as standard modeling methods for income distribution. The applications of cybernetics and game theory are extensive, and they are often used in conjunction with mathematical programming and optimization methods. Among them, the research on supply chain alliance mostly adopts game theory or game theory theory and mathematical planning. For example, based on Shapley value method, dynamic alliance benefit distribution, based on nucleolar theory, network loss allocation, Gao and Yang et al. [9] proposed a profit distribution scheme based on the study of uncertain alliance game.

This paper tries to solve the problem of VPP revenue distribution of multi-investment entities. According to the cooperative game theory, the scheme of solving the problem of VPP revenue distribution is proposed. A case study is performed based on typical scene data to verify the validity of the model.

2. VPP revenue mode

2.1. Basic composition and income model

The VPP consists of a variety of market entities, consisting of distributed power generators, virtual plant operators, grid operators, and users. The decentralized control mode is applicable to the VPP with multi-agent mode. In the decentralized control mode, the VPP is divided into autonomous subsystems that communicate with each other, and the control is delegated to each distributed power agent, and each agent can pass the communication network obtains other agent part information, and decides whether the distributed power source participates in market competition, participates in the electric energy market or the standby market, and the bidding strategy according to the change of the external information. The control center is simplified into a data exchange and data processing center, and each agent exchanges information with the data exchange center and each agent. Since the decisions between the subsystems interact with each other under this structure, the power generation scheme of each unit may require several iterations of communication negotiation and decision-making processes to be finalized. The decentralized control VPP is more suitable for multi-agent mode, and also meets the requirements of market openness, competition, and coordination.

The VPP contains multiple investment entities, that is, the DER inside the VPP is owned by the independent operator. The VPP operator is only the third-party inherited operator that obtains market access, and only contracts with the independent operator to fix The electricity price allows DER to join the VPP to centrally dispatch power generation, and does not grasp the technical details of the power generation cost of DER. The efficiency of the VPP operator is realized by the difference between the external market and the internal contract price, and the benefits of the DER independent operator are passed. Contract electricity price and power generation cost are realized.

2.2. Revenue function expression

VPP coordinates the energy flow between internal elements, including adjusting the output of DG, charging and discharging ESS, and cutting off IL. At the same time, as a whole, it conducts electricity trading with the electricity market, selling and purchasing electric energy.

The revenue function of a VPP can be expressed as:

\[
\begin{align*}
\max \text{ profit} & = f_{\text{out}} + f_{\text{in}} \\
f_{\text{out}} & = E_s - C_b \\
f_{\text{in}} & = E_1 - SUC_{DG} - SDC_{DG} - OC_{DG} - OC_{ESS} - C_{cl}
\end{align*}
\]

Where: \( f_{\text{out}} \) is the revenue of VPP trading in the unified market; \( E_s \) is the total revenue from the sale of electricity under the unified market; \( C_b \) is the total purchase cost under the unified market; \( f_{\text{in}} \) is the internal retail income of VPP; \( E_1 \) is the internal user of VPP. The proceeds from the sale of electricity; \( SUC_{DG} \) is the DG boot fee; \( SDC_{DG} \) is the DG shutdown fee; \( OC_{DG} \) is the DG operating cost; \( OC_{ESS} \) is the
energy storage system operation and maintenance cost; $C_{cl}$ is the cutoff interruptible load. The compensation fee paid.

### 3. VPP revenue distribution model

#### 3.1. Formatting author affiliations

Combined with the research content of this paper, this paper mainly studies the establishment of market mechanism in multi-agent VPP. The game of alliance and cooperation among various controllable resource investors participating in market competition is in line with the characteristics of cooperative game theory. Therefore, this paper applies cooperative game theory to establish a multi-agent VPP revenue distribution model. The distribution methods of cooperative income include Nucleolus, Shapley, etc., in which Sharpe value method is the most commonly used method to solve public profit distribution problem. This chapter uses this method to study VPP and power distribution company. Income distribution.

When the VPP cooperates with the power distribution company, the VPP gives up the priority dispatching right, resulting in loss of its own revenue, and the distribution company pays less to other power sources. Therefore, it is necessary to distribute the cooperative income to the VPP and the power distribution company. The text of your paper should be formatted as follows:

#### 3.2. cooperative game feature function

According to the cooperative game idea, the alliance h assigns the cooperative income based on the value generated by the alliance, also known as the characteristic function $v(h)$, which has:

$$v(h) = B(h) - \sum_{x \in h} B(x)$$  \hspace{1cm} (2)

Where: B is the income function of each participant set.

V1, V2, ..., VM and distribution company D can form alliances such as {D}, {V_m}, {V_1, V_2, ..., V_m} and {D, V_1, ..., V_m}, alliance features The function is:

$$v(\{V_m\}) = 0$$ \hspace{1cm} (3)

$$v(\{D\}) = 0$$ \hspace{1cm} (4)

$$v(\{V_1, V_2, ..., V_m\}) = B(\{V_1, V_2, ..., V_m\}) - \sum_{x \in \{V_1, V_2, ..., V_m\}} B(x)$$ \hspace{1cm} (5)

$$v(\{D, V_1, ..., V_m\}) = B(\{D, V_1, ..., V_m\}) - \sum_{x \in \{D, V_1, ..., V_m\}} B(x)$$ \hspace{1cm} (6)

In the formula, if X takes $V_m$ in the set{V_1, V_2, ..., V_m}, then B{V_m} represents the benefit of the VPP m separately optimized operation; X takes D in the set{D, V_1, ..., V_m}, at this time B{D} represents the profit of the distribution company D when the VPP is separately optimized for operation; B{V_1, V_2, ..., V_m} is the VPP M alliance income; B{D, V_1, ..., V_m} is the alliance of distribution company D and M.

#### 3.3. Cooperative Game Reaching Stable Distribution Conditions

The basis of the cooperative game is that the distribution strategy needs to satisfy individual rationality and overall rationality. Assuming that the VPP and distribution company cooperative income distribution plan is $x_{V1}, x_{V2}, ..., x_{V_m}$, D, the overall rationality is:

$$x_D + x_{V1} + \cdots + x_{V_m} = v(\{V_1, ..., V_m\})$$ \hspace{1cm} (7)

Individual rationality is that the income cannot be lower than the single-day income, namely:

$$x_D \geq V(\{D\}) \quad x_{V_m} \geq V(\{V_m\})$$ \hspace{1cm} (8)

The above two formulas only indicate the allocation range that can be accepted by the cooperative participants. This section specifically uses the Shapley value method for specific allocation.

#### 3.4. Income distribution based on Shapley value

The Shapley value satisfies individual rationality, overall rationality and uniqueness, and is the most common method for solving cooperative game problems. When using the Shapley value, the cooperative benefit of the participant m is:
\[ x_m = \sum_n \frac{(|h|-1)!(n-|h|)!}{n!} [v(h) - v(h - \{m\})] \]  

(9)

Here \( H \) is the set of all participating unions \( h \), \(|h|\) is the number of individuals in \( h \); \( n \) is the total number of individuals participating in the allocation.

4. Example analysis

4.1. Cooperative income distribution

This example is based on the Yunnan Distributed Power Demonstration Project. The project data is shown in the table.

| Constant name                          | Constant value |
|----------------------------------------|----------------|
| PV plant maximum output power/MW       | 4.50           |
| Wind farm rated output power/MW        | 6.50           |
| Single hydro unit capacity/MW          | 9.00           |
| Number of hydropower units             | 2.00           |
| Reservoir capacity ceiling/million (m³)| 207.30         |
| Reservoir capacity lower limit/million (m³)| 20.00        |
| Maximum power generation flow/(m³/s)   | 42.00          |
| Maximum power generation flow/(m³/s)   | 3.00           |

4.2. Multi-VPP cooperation model solution analysis

When multiple VPP are coordinated with the distribution company, the cooperative benefits need to be distributed among multiple VPP and distribution companies. Assume that the distribution company's load is doubled, and a cooperative windwater VPP \( V_2 \) is added. Its water flow \( J_1=20.7 m^3/s \). The weathering prediction data is shown in the table. The parameters of the ARMA simulation model are the same as \( V_1 \), and the scene generation and The reduction technology generates \( V_2 \).

| Time | Wind power forecast | Photovoltaic power forecast | Time | Wind power forecast | Photovoltaic power forecast |
|------|---------------------|-----------------------------|------|---------------------|-----------------------------|
| 1    | 4.31                | 0                           | 13   | 1.97                | 1.85                        |
| 2    | 3.91                | 0                           | 14   | 2.39                | 1.82                        |
| 3    | 4.14                | 0                           | 15   | 2.60                | 0.77                        |
| 4    | 4.33                | 0                           | 16   | 2.67                | 1.01                        |
| 5    | 3.42                | 0                           | 17   | 2.98                | 0.28                        |
| 6    | 3.35                | 0                           | 18   | 3.70                | 0.06                        |
| 7    | 2.29                | 0.01                        | 19   | 3.37                | 0.01                        |
| 8    | 3.14                | 0.08                        | 20   | 3.03                | 0                           |
| 9    | 2.57                | 0.43                        | 21   | 3.08                | 0                           |
| 10   | 2.38                | 0.98                        | 22   | 3.04                | 0                           |
Table 2 shows the benefits of each alliance. The results show that the two VPP alliances have increased revenue. The distribution company's cooperation with two VPP is more profitable than the cooperation with a single VPP. The former is due to the fact that although the proportion of capacity is basically unchanged, the number of units has increased, complementing each other, reducing the amount of abandoned wind and standby demand. Since Virtual Power V1, V2 and Power Distribution Company D contribute differently to their respective cooperative alliances, The Shapley value method is used to reasonably distribute the cooperative income according to their respective contributions: VPP: \( x_v^1 = 11000 \) yuan; \( x_v^2 = 14900 \) yuan; distribution company: \( x_d = 25300 \) yuan.

Assume that the V2 wind power prediction accuracy of the VPP is improved, and the normal white noise of the ARMA model is reduced to \( \sigma = 1.5 \), and the wind power classic scene is generated, and the scenes are shown as the probability and the table. At this time, the Shapley value method is used to distribute the cooperative income: VPP: \( x_v^1 = 10900 \) yuan; \( x_v^2 = 20100 \) yuan; distribution company: \( x_d = 30800 \) yuan. From the table to further analyze the various alliances, we can see that improving the accuracy of scenery prediction increases the profit of virtual power and wide-band, and increases the cooperation revenue when participating in each alliance. Therefore, the improvement of prediction accuracy affects the cooperative income allocated to VPP.

Table 3. Income of VPP / Other Power Supply.

| Alliance classification | VPP revenue | Other power revenue |
|-------------------------|-------------|--------------------|
| \{D\},{V_1\},{V_2\}   | \( V_1:94200 \); \( V_2:87600 \) | 627600             |
| \{D,V_1\},{V_2\}      | \( V_1:92000 \); \( V_2:87600 \) | 606000             |
| \{D,V_2\},{V_1\}      | \( V_1:94200 \); \( V_2:86300 \) | 587700             |
| \{V_1,V_2\},{D}       | \( V_1,V_2: 182200 \) | 628100             |
| \{V_1,V_2,D\}         | \( V_1,V_2: 179000 \) | 565800             |

5. Conclusion

This paper studies the basic structure of VPP, ie, the income model, in the context of multi-investment entities participating in VPP. The income function of VPP is proposed. Based on the cooperative game theory, the distribution method of VPP revenue is analyzed, and the VPP revenue distribution model based on Shapley value method is constructed. After a typical case study, the income distribution model of Shapley value method is applicable to the distribution of VPP revenue, which provides a quantitative basis for researching and optimizing the income distribution of various participating entities in VPP.

References

[1] Pudjianto D., Ramsay, C. and Strbac, G. (2008) Microgrids and VPP: Concepts to support the integration of DER resources[J], Power and Energy, 222(7):731-741.
[2] Pudjianto, D., Ramsay, C. and Strbac, G. (2007) VPP and system integration of DER resources[J], Transmission Distribute., 1(1):10-16.
[3] Djapic, P., Ramsay, C., Pudjianto, D., Strbac, G., Mutale, J., Jenkins, N. and Allan, R. (2007) Taking an active approach[J], IEEE Power Energy Mag, 5(4):68-77.
[4] Yang, Z.G., Liu, J., Suresh, B., (2010) Enabling renewable energy and the future grid with advanced electricity storage[J], Minerals, Metals, Materials Society, 62(8):14-23.
[5] Strbac, G., Jenkins, N., Green, T., et al. (2006) Review of Innovative Network Concepts[J], DG-GRID project report.
[6] Asmus, P., Microgrids, (2010) VPP and our DER future[J]. The Electricity Journal, 23(10):72-82.

[7] Stjepan, S., Tomislav, D., Tomislav, C., et al. (2011) Economic dispatch of VPP in an event-driven service-oriented framework using standards-based communications[J]. Electric Power Systems Research, 81(12):2108-2119.

[8] Waters, C. D. (2009) An Introduction to Supply Chain Management[M]. London: Palgrave MacMillan.

[9] Gao, J., Yang, X. (2016) Uncertain Shapley Value of Coalitional Game With Application to Supply Chain Alliance[J]. Applied Soft Computing, 3:18-25.