Profit sharing method based on weighted Shapley value under government regulation

L L Yu¹, T T Li¹, W X Liu¹, P Yuan¹, H B Shao¹, Y Wang¹, Z Q Wang²,³ and S C Zhou²

¹Henan Economic Research Institute, State Grid Corporation of China, Henan, 450052, China
²Key Laboratory of Control of Power Transmission and Conversion (SJTU), Ministry of Education, Shanghai, 200240, China

E-mail: 141887981@qq.com

Abstract. With the diversification of power market users, reasonable profit distribution among members becomes the focus of government regulation. Under the background of demand-side liberalization, with the introduction of "peak-regulating device" represented by battery, the member operation characteristics of small and medium-sized power users become more and more complex, and the traditional method of profit allocation based on power generation assessment is no longer applicable. In order to solve this problem, this paper proposes a profit-sharing method based on weighted Shapley value, which takes the contribution of marginal conditional value-at-risk under the participation of small and medium-sized users as the weight to improve the traditional Shapley value method. An example is given to illustrate the feasibility and rationality of the improved method.

1. Introduction

With the proposal of new electricity reform, the focus of our government's supervision on the power industry has changed to supervision on the construction of electricity market, the reform of transmission and distribution price, the reform of power selling side and the establishment and regulation of power trading institutions [1]. The government regulators supervise the power market economy, maintain the stability of the market order, safeguard the legitimate rights and interests of market participants, and ultimately realize the optimal allocation of resources in the power industry and the benign competition in the power market. With the diversification of social capital entering the distribution market, the government regulators pay more attention to how to make a reasonable profit distribution among members, stimulate the participation of members, so as to promote the healthy development of the power industry.

In recent years, under the supervision of the government, distributed energy has received a lot of policy support. Distributed generators and energy storage devices are connected to the power grid in large quantities, and the power generation pattern of the traditional power system has been broken. According to the requirements of the document "Some Opinions on Further Deepening the Reform of Electric Power System" issued by the Central Committee of the Communist Party of China, it is clearly proposed that power users who meet certain conditions can trade with power generation companies or power selling companies. Demand-side resources include active load, energy storage equipment and distributed generation, and other small and medium-sized user resources. They can
participate in the operation of the electricity market through different ways and strategies, so that various types of demand-side resources can effectively participate in the operation of the electricity market. Reference [2] verifies that renewable energy participates in power market dispatching and achieves excess revenue. Reference [3] proposes a source-load interaction model considering the resources of small and medium-sized users, and establishes a resource market operation model for small and medium-sized users with the active load as the invoking object. Combining with the power selling company, the distributed energy and active load are optimized, and an optimal scheduling model is established aiming at maximizing the profit of the independent power selling company in the reference [4]. Market participants such as renewable energy generators and demand-side response can participate in the electricity market and achieve a win-win situation between the generation and the electricity side through trading strategies [5,6].

However, with the introduction of energy storage devices, it is not clear how to reasonably assess the market role of various types of electricity purchasers and sellers and how to allocate reasonable profits. Taking energy storage device as an example, the role of energy storage in power system and the corresponding profit allocation method have always been the difficult points in academic research and practical operation. If the energy storage device participates in the resources of small and medium-sized users, its function is similar to that of peak-shaving and valley-filling device in the power system, which ensures the maximum benefit of the system through time-sharing charging and discharging strategy. However, the dual characteristics of "user-power" make it difficult for the system to distribute its profits reasonably. For the research in the field of profit allocation, reference [7] and [8] propose a risk-based profit allocation method for virtual power plants based on cooperative game, which allocates profits among the members of the virtual power plants.

The above method only considers the traditional profit allocation problem, but does not consider the subjective satisfaction of market participants and the market contribution of each participant. Moreover, the traditional profit allocation method is not very robust, and will face the problem of not reaching the income balance in the actual operation. In order to solve these problems, the paper [9] based on the firefly algorithm improves the traditional profit allocation method, Shapley value method, by using the profit fine-tuning coefficient and stability index, so that the cooperative game can satisfy the assumption of individual rational constraints. Reference [10] presents a profit allocation method for virtual power plant members based on their marginal contribution and power prediction accuracy. By calculating their marginal contribution and evaluating their market performance, Shapley value method is used to allocate benefits to cooperative game alliances.

As for the income allocation of small and medium-sized users participating in electricity market transactions after they form aggregated entities, this paper combines the risk contribution theory to improve the traditional Shapley value method and formulate a profit sharing mechanism with multi-agent participation. This method has strong universality and can effectively avoid the situation that traditional methods may not meet the rational constraints.

2. Traditional Shapley value method

Usually, a cooperative game is defined as [11]:

For each player \((N, v)\), there exists a unique \(u_i\) value, defined as Shapley value, at which time the income \(u_i\) allocated to player \(i\) is:

\[
u_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-S-1)!}{n!} [v(S) - v(S \cup \{i\})]
\]

(1)

Where: \(S \subseteq N \setminus \{i\}\) denotes that the set \(S\) contained in \(N\) does not contain player \(i\); \(|S|\) is the number of all players in alliance \(S\). \(S\) is a coalition, \(v(S)\) is called the characteristic function of coalition \(S\).

For cooperative games \((N, v)\), \(N = \{1, 2, ..., n\}\), for each player \(i \in N\), a real parameter \(u_i\) is given to form \(n\)-dimensional vector and it satisfies
\[ u_i \geq v(\{i\}), \quad v(N) = \sum_{i=1}^{N} u_i \]  
\[
(2)
\]

If so, the \( u_i \) is said to be an allocation scheme for alliance \( S \).

For each Shapley value division, three rational constraints need to be satisfied:

- **Individual Rational Constraint**
  \[ u_i \geq v(\{i\}), \forall i \in N \]  
\[
(3)
\]

Guarantee that members of the alliance will get no less profit than when they bid alone.

- **Alliance Rational Constraint**
  \[ \sum_{i \in S} u_i \geq v(S), \forall S \subseteq N \]  
\[
(4)
\]

Guarantee that the profit of alliance is not less than that of any real subset of alliance participating in the market.

- **Global Rational Constraint**
  \[ \sum_{i \in N} u_i = v(N) \]  
\[
(5)
\]

Guarantee that the alliance game is the global optimal solution.

Based on Shapley value method, according to the contribution of each player to the cooperative alliance, the initial profit allocation can ensure that each player can get no less than the profit when he does not join the alliance while maximizing the profit of the alliance.

3. **Problems and solutions of Shapley value method**

3.1. **Problem of Shapley value method**

Firstly, the Shapley value does not satisfy the rational constraints, which has been described in detail in the reference [9,10]. In addition, according to the formula definition of Shapley value method, it can be found that all the members involved in profit allocation are "anonymous members", that is, the operational and physical characteristics of members are not considered. In addition, the Shapley value only considers the contribution of members’ marginal revenue, but does not consider the risks that members may bring to their operation. Therefore, this method has no practical significance in power system operation, especially in the system with intermittent energy sources such as wind power and photovoltaic.

3.2. **Weighted Shapley value method based on contribution degree of marginal risk value**

Marginal risk contribution represents the marginal utility of a single risk to the total risk of the system. The traditional value of risk and conditional value of risk satisfy the condition of continuous differentiability, and the sensitivity of the system risk to the single risk factor can be calculated. The expression formula of marginal risk contribution is as follows:

\[ C_{i,MC} = \left. \frac{d\rho}{d\varepsilon} (L + \varepsilon L_i) \right|_{\varepsilon=0} = \frac{d\rho(L)}{d\omega_i} \]  
\[
(6)
\]

Where: \( i \) represents a risk factor; \( MC \) represents marginal contribution; \( \rho(\cdot) \) represents a risk evaluation function; \( \varepsilon \) represents a small marginal increment; \( L \) represents the sum of risks caused by individual risk factors; \( L_i \) represents the risk caused by this risk factor; \( \omega_i \) represents the total amount of risk factors \( i \) in the system.

For small and medium-sized users participating in electricity market transactions, distributed generation contributes more to the profits of the alliance, but it is also the main risk source of the
alliance. Therefore, this paper introduces conditional risk value (VaR) to define the marginal risk contribution that members may bring to the alliance.

According to the potential risks brought by different decision variables, the contribution degree of marginal conditional risk value of each member, $VaRMC_i$, is calculated.

$$VaRMC_i = \frac{VaR(N) - VaR(N \setminus i)}{VaR(N)}$$

(7)

Based on the improved Shapley value method in reference [9], the income fine-tuning coefficient $\Delta \lambda_i$ is introduced, and its constraint is as follows:

$$\sum_{i=1}^{n} \Delta \lambda_i = 0$$

(8)

The sum of fine-tuning coefficients is 0, which means that adjusting the profits among the members of the alliance will not affect the total profits of the alliance.

Then redefine the profits made by the members of the alliance:

$$u_i(v)' = u_i(v) + \Delta \lambda_i \sum_{i=1}^{n} u_i(v)$$

(9)

Similar to Formula (8) and Formula (9), the income fine-tuning factor $\Delta \lambda_i$ is introduced, and the relative return rate is used as an index to measure members' satisfaction with profit distribution. Relative return rate is defined as:

$$\beta_i = \omega_i \frac{u_i(v)'}{u_i(v)}$$

(10)

In order to ensure the equilibrium of the alliance's income distribution, the relative return rate of all members should tend to be close before and after the redistribution. The income center is defined as:

$$\bar{\beta} = \frac{\sum \beta_i}{N}$$

(11)

Taking the closest relative income of members as the optimization objective, the objective function is as follows:

$$\min \sum_{i=1}^{N} |\beta_i - \bar{\beta}|$$

(12)

The constraints are formula (8), formula (3~5) and

$$\omega_i = \frac{VaRMC_i}{\sum_{i \in N} VaRMC_i}$$

(13)

4. Case study

4.1. Model solution and data base

First, the system dispatch will calculate the load power that small and medium-sized users need to reduce in each period according to the load reduction curve submitted by the current load and the small and medium-sized users' resources. Then the small and medium-sized users' resources will send load reduction requirements to their respective power sources and users. Because the power supply and users' time-sharing output and power consumption characteristics are different, energy storage
devices may be required to participate in the system dispatch response, in order to ensure that small and medium-sized user resources from the power grid to maximize the benefits. After gaining daily revenue, the incomes of small and medium-sized user resources are redistributed according to the method of weighted Shapley value to ensure that members of the system can obtain relatively reasonable revenue according to their own characteristics. To sum up, the pre-day scheduling and weighted Shapley value algorithm in the model are mixed integer optimization models with 0-1 variables, which can be solved by commercial software CPLEX 12.5.

The example used in this paper is a small and medium-sized user alliance composed of three members: wind turbine, energy storage battery and load in a certain area of Henan Province. Each member’s normalized contribution of marginal conditional risk value is shown in table 1.

| Member              | Contribution Degree of Marginal Conditional Risk Value (VaRMC) |
|---------------------|-------------------------------------------------------------|
| Wind turbine        | 0.71                                                         |
| Energy storage battery | 0.04                                                     |
| Load                | 0.25                                                         |

And when the small and medium user members in this area do not form an alliance, that is, the actual operation of the current stage, the running results of each member are shown in figure 1. Figure 1 shows the output and load reduction of each member of the system. The interruptible load and energy storage device specifies load reduction and charging and discharging strategies according to the system price and retail price. The members seek to maximize their own revenue. However, it can be seen that the difference between the output and dispatch value of the power station will be reduced by abandoning the wind to avoid system penalty (red bar chart). This causes a huge waste of resources and affects the economic operation of the system. This approach is also inconsistent with the national policy of preferential consumption of renewable energy. At this time, the system's comprehensive income is 790,000 yuan.

4.2. Case analysis
Firstly, the dispatching results when an alliance is formed or not are analysed and compared.

In the process of solving the example, it is found that when the small and medium-sized user resources form an alliance, the overall revenue of the system has been improved, and the operation characteristics of uncertain power sources such as wind power have also been improved. Figure 2 is the most intuitive description of the problem.

Figure 2 shows the dispatching situation of each member in the joint optimal dispatching situation after alliance formation. Compared with figure 1, it can be clearly seen that interruptible load and energy storage devices ensure that the system does not abandon the wind phenomenon through joint
dispatching, and at the same time, the system will not be punished by output fluctuation. At this time, the system's comprehensive income is 840,000 yuan. It can be seen that after joining the alliance, the overall revenue of small and medium-sized users has changed from 790,000 yuan to 840,000 yuan, and the overall profit has increased.

Next is the analysis of profit sharing among members of the alliance. If the traditional Shapley value method is used, the result of profit allocation is shown in Table 2. At this time, the profit of the "battery" members is less than that of the non-participating alliance model. That is to say, the result of profit allocation does not satisfy the individual rationality hypothesis of Shapley value method.

Table 2. Comparison of member profits under traditional Shapley value apportionment.

| Scene                      | Not joining the Alliance | Traditional Shapley Method |
|----------------------------|--------------------------|----------------------------|
| Wind power revenue/ Ten thousand yuan          | 57                        | 58                        |
| Battery revenue/ Ten thousand yuan             | 4                         | 3.8                       |
| Load revenue/ Ten thousand yuan                | 18                        | 18.2                      |
| Comprehensive benefits/ Ten thousand yuan     | 79                        | 80.4                      |

According to the improved Shapley value method proposed in reference [9], that is, considering the situation where the overall stability coefficient of the alliance is the largest, the results of the example are shown in Table 3. Then, through the example, it can be seen that in order to maximize the stability
coefficient of the alliance, the excess revenue of the system participating in the alliance is transferred to the "battery" of the member with the smallest profit.

According to the method in this paper, i.e. the method of seeking relative equilibrium of alliance income after risk weighting, the result of profit sharing is shown in Table 4. According to the contribution degree of marginal conditional risk value given in Table 1, we can know that wind power contributes the most to the alliance risk. Correspondingly, the profit growth rate of wind power after participating in the alliance is the lowest, that is to say, the profit allocation scheme of the alliance obtained at this time is relatively reasonable and fair. Each member obtains the corresponding excess return after participating in the alliance according to their own contribution characteristics and contribution to the alliance revenue.

Table 4. Weighted Shapley value method based on marginal risk contribution.

| Scene                          | Not joining the Alliance | Weighted Shapley Method | Profit Growth Rate |
|-------------------------------|--------------------------|-------------------------|-------------------|
| Wind power revenue/ Ten thousand yuan | 57                       | 57.1                    | 0.18%             |
| Battery revenue/ Ten thousand yuan | 4                        | 4.4                     | 10.00%            |
| Load revenue/ Ten thousand yuan | 18                       | 18.9                    | 5.00%             |
| Comprehensive benefits/ Ten thousand yuan | 79                       | 80.4                    | /                 |

5. Conclusions
Under the supervision of the government, with the continuous promotion of the policy of liberalization of electricity sales side, small and medium-sized users are facing the problem of multi-subject profit sharing. A reasonable profit sharing mechanism is conducive to the sustainable development of small and medium-sized users. Therefore, from the perspective of small and medium-sized user alliance, this paper analyses the potential risks and benefits of renewable energy units, energy storage devices and active load to the system, and carries out weighted evaluation calculation on the strategies of different members participating in the market. Through the calculation of practical examples, the reasonable income distribution method of alliance members' game under different methods is obtained.

Based on the relative return rate, the profit allocation method can reasonably distribute the profits of the small and medium-sized user alliance participating in the electricity market exchange, so that the profits of the members depend not only on their own load output, but also on the peak shaving and compensation role in the alliance. It is an important means to ensure the stability of the alliance to ensure that the relative return of each member is balanced.

Acknowledgments
This research was financially supported by the Science and Technology Project of State Grid Corporation Headquarters, and the project name is Research on Evaluation System and Development Strategy Optimizing of Power Grid Development under the New Background of Government Supervision (52170018000X).

References
[1] Yuan Y and Wang W 2017 Current situation, problems and countermeasure of electricity supervision under new electricity reform Science & Technology Vision 2017 137-138 (in Chinese)
[2] Mashhour E and Moghaddas-Tafreshi S M 2011 Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: Problem formulation IEEE T. Power Syst. 26 949-956
[3] Wen G, Weng W H, Zhao Y et al 2017 A bi-level optimal dispatching model considering
source-load interaction integrated with load aggregator *Power Syst. Technol.* 12 (in Chinese)

[4] Gu W, Ren J Y, Gao J, *et al* 2017 The Optimal scheduling model of power sales company considering distributed generation and adjustable load *Autom. Electr. Power Syst.* 41 37-44 (in Chinese)

[5] Kang S Y, Li J L, Li Y S *et al* 2016 Multi-objective generation scheduling model of source and load considering the strategy of TOU price *Power Syst. Prot. Contr.* 44 83-9 (in Chinese)

[6] Tang Y, Lu Z Z and Fu X Y 2015 Demand response strategies for promoting consumption of distributed power generation with residential active load *Autom. Electr. Power Syst.* 39 49-55 (in Chinese)

[7] Bialek J and Kattuman P 2004 Proportional sharing assumption in tracing methodology *IEE Proceedings-Generation, Transmission and Distribution* 151 526-32

[8] Dabbagh S R and Sheikh-EL-Eslami M K 2015 Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative Game theory *Electr. Power Syst. Res.* 121 368-78

[9] Wang J, Wang Z L, Chen J Y *et al* 2014 A game model for DGs-loads in microgrid based on firefly algorithm and its analysis *Autom. Electr. Power Syst.* 21 7-12 (in Chinese)

[10] Cheng Y, Fan S, Ni J *et al* 2015 An innovative profit allocation to distributed energy resources integrated into virtual power plant *P. Int. Conf. Renew. Power Gener.* (17-18 Oct. 2015)

[11] Xiong Y J 2010 *The Basis of Modern Game Theory* (Beijing, China: National Defense Industry Press)