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Benefit Allocation Model for Distributed Electric Vehicle Using a Shapley-Value Approach

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Abstract. This paper proposes a benefit allocation model for distributed electric vehicle. It considers the cooperative relationships between the stakeholders innovatively. The stakeholders consist of vehicles, charging piles, and power grids. The benefit of each stakeholder is calculated using the shapley-value approach. Based on the order of decision-making among stakeholders, the benefit allocation model includes inner layer and outer layer. The benefits of vehicles and charging piles are calculated by inner layer. The benefits of power grids are calculated by outer layer. Then, the computational flow of the model is presented according to the nested relationships in proposed benefit **allocation** model. Case studies validate the feasibility of the proposed model. Result shown that the proposed model can increase the gain of trolley compared to conventional.

Keywords. Benefit allocation, shapley-value, electric vehicle, bi-layer

1. Introduction

The number of electric vehicles (EVs) has grown rapidly in recent years in response to low-carbon and green energy requirements [1]. In the electricity market, an EV can act not only as energy consumers (energy storage system) but also as energy providers (electrical load) [1,2]. Based on this, existing studies have shown that the cooperative model helps to maximize benefits [2]. In the context of V2V (EV-to-EV) technology, several studies have established benefit allocation model between EVs as energy consumers and EVs as energy providers [2]. With the development of V2G (Vehicle-to-Grid) technology, EVs as energy providers can provide energy to the grid during peak power consumption, effectively improving the stability of the grid [3]. The grid, as a stakeholder in the new model, seeks to maximize the benefits from the collaboration. However, existing studies have not explored the distribution of benefits among V2Gs, charging pile managers, and the grid.

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Against this background, this paper focuses on benefit allocation between stakeholders. A benefit allocation model that considers cooperation among stakeholders is first proposed in this paper. Based on cooperative game theory, the shapley-value approach is adopted in the proposed benefit allocation model to describe benefit-sharing process. Then, a case is implemented to verify the effectiveness of the proposed model.

2. Shapley value approach

The Shapley value method is an axiomatic method in cooperative game, which defines a rule for allocating the benefit obtained by the grand coalition [4]. The Shapley value method allocates benefit according to the marginal benefit of each player to the coalition [4-5]. It is mostly used to solve distributional problems.

In the Shapley value approach, $[I, V]$ denote a game where I is a set of N individuals, and $V(S)$ denotes the eigenfunction through which the gains from cooperation of coalition S are obtained when $S \subseteq I$.

Four conditions are used to determine the uniqueness of the allocation scheme as follows where v is an allocation scheme for the coalition N:

Effectiveness: $\sum_{i=1}^{|N|} x_i = v(N)$.

Symmetry: if $x_i = x_j$, then $v(S \cup \{i\}) = v(S \cup \{j\})$ where a coalition S does not contain i and j.

Additivity: $(N, v1 + v2) = (N, v1) + (N, v2)$ where $(N, v1)$ and $(N, v2)$ are two cooperative games and $(v1 + v2)(S) = v1(S) + v2(S)$.

In addition, if the $v(S \cup \{i\}) = v(S), \forall S \subset N$, the gain for non-contributors is zero.

3. Design benefit allocation model based on Shapley value approach

3.1 Description of benefit allocation problem

(1) Subjects of benefit allocation problem
EVs, charging piles, and power grids are the main participants in V2G networks, and cooperation among them requires reasonable benefit incentives. Therefore, EVs, charging piles, and power grids are selected as the game subjects. Then, the benefit allocation problem among them is descripted.
(2) Problem description

Without cooperation, the EV acts as an energy consumer, and its cost C_{ev} equals to the cost of charging (Eq. 1).

$$C_{ev} = p_{ev}q_{ev} + p_{ev}q_{ev}\beta \tag{1}$$

where p_{ev} is the unit price of electricity from the grid, q_{ev} represents the charging time of the EV, and β represents the rate charged to EV by the charging pile manager. In this scenario, grid revenues C_g are related to power trading revenues and grid operating costs, as shown in Eq. 2.

$$C_g = p_{ev}q_{ev} - p_{ev}q_{ev}\alpha - \varepsilon C_{op} - C_{cg} \tag{2}$$

where α represents the rate charged to grid by the charging pile manager. When not cooperating, ε denotes the stability of grid operations, C_{op} stands the cost of grid operations, and C_{cg} denotes the cost of electricity generation. When not cooperating, the benefit of the charging pile manager C_{cp} posts come from fees collected during the charging process of EV, as shown in Eq. 3.

$$C_{cp} = p_{ev}q_{ev}\beta + p_{ev}q_{ev}\alpha \quad (3)$$

where p_{cp} represents the average price of charging through a charging post, q_{cp} stands for charging time through the charging post, and γ stands for the rate of user fees charged by the charging post manager.

When cooperating in the situation, EV's as energy providers take advantage of time-sharing tariff policies to spend less cost. Although this will reduce the revenue of the grid, it can improve the stability and security of grid operation. In addition, more distributed energy can be consumed through rational charging and discharging management of EVs, thus increasing source-side revenues.

Therefore, the distributable profit in the case of cooperation is shown in Eq. 4.

$$B_{co} = C_{co} - C_{ev} - C_g - C_{cp} \quad (4)$$

where C_{co} denotes the sum of the profits of all three in the case of cooperative.
In the issue of benefit distribution, the interests of vehicle owners are considered first. The smooth operation of the distribution network is the ultimate requirement to ensure its stability. On this basis, the charging pile utilizes distributed energy to cooperate with electric vehicle charging and discharging, so that the distribution network is in an optimal operating state.

3.2 Shapley value of subjects

The VE, charging piles, and power grids serve as distributed devices of V2G networks. They are treated as nodes in the network. Therefore, the number of nodes determines the number of networks. For example, if the number of nodes is N, the number of networks that can be formed amounts to 2^N. In the Shapley value approach, these networks are treated as sub-coalitions. The vehicles, charging piles, and power grids constitute a grand coalition. The benefit gained by each device can be denoted by their Shapley value in coalitions.

Owners of the EV adopt a time-of-use tariff policy. Cost minimization is their goal. Depending on the owner's objective, the benefit of vehicle ve is calculated as follows [4].

$$\zeta_{ve}^{Shapley}(c) = \sum_{s \in S_i} \frac{(|s|-1)!\,(N-|s|)!}{N!} \times [c(s) - c(s\,\backslash\{ve\})] \quad (5)$$

Where $\zeta_{ve}^{Shapley}(c)$ represents the benefit gained by the vehicle ve. s denotes the sub-coalition including devices, consisting of vehicles, charging piles, and power grids. $|s|$ denotes the number of devices in sub-coalition. $c(s)$ denotes the benefit function of sub-coalition. $c(s\,\backslash\{v\})$ denotes the sub-coalition consists of devices, consisting of vehicles, charging piles, and power grids, but except ve. Thus, the marginal benefit of device v is represented as $c(s) - c(s\,\backslash\{v\})$. c denotes the cost of vehicle v. Note that the above benefit function relates to the cost c.

Charging piles are distributed energy. Their goal is minimization of composite mean squared error. Thus, the benefit of charging pile pi is calculated as follows.

$$\zeta_{pi}^{Shapley}(e) = \sum\nolimits_{s \in S_i} \frac{(|s|-1)!\,(N-|s|)!}{N!} \times [e(s) - e(s \setminus \{pi\})] \tag{6}$$

Where $\zeta_{pi}^{Shapley}(e)$ represents the benefit gained by charging pile pi. $e(s)$ denotes the benefit function of sub-coalition. $s \setminus \{pi\}$ denotes the sub-coalition consists of devices, consisting of vehicles, charging piles, and power grids, but except charging pile p. $e(s \setminus \{pi\})$ denotes the marginal benefit of device charging pile pi. Note that the above benefit function relates to the composite mean squared error e.

The stability of the distribution system is important to power grids. The objective of power grids is minimizing their net loss. Therefore, the benefit of power grid g is calculated as follows.

$$\zeta_{g}^{Shapley}(l) = \sum\nolimits_{s \in S_i} \frac{(|s|-1)!\,(N-|s|)!}{N!} \times [l(s) - l(s \setminus \{g\})] \tag{7}$$

Where $\zeta_{g}^{Shapley}(l)$ represents the benefit gained by power grid g. $l(s)$ denotes the benefit function of sub-coalition. $s \setminus \{g\}$ denotes the sub-coalition consists of devices, consisting of vehicles, charging piles, and power grids, but except power grid g. $l(s \setminus \{g\})$ denotes the marginal benefit of power grid g. Note that the above benefit function relates to the net loss l.

3.3 Establishment of benefit allocation model

According to the problem description in Section 3.1, the order of decision-making exists in vehicles, charging piles, and power grids. Therefore, the order of decision-making is taken into account in the distribution of benefits. Depending on the importance of the participants, the order of decision-making is VE→charging pile→power grid.

The benefit allocation model is shown in Eq.8.

$$\begin{cases} f(g) = \zeta_{g}^{Shapley}(l) \\ \quad \begin{cases} f(ve) = \zeta_{ve}^{Shapley}(c) \\ f(pi) = \zeta_{pi}^{Shapley}(e) \end{cases} \end{cases} \tag{8}$$

Where $f(pi)$ denotes the benefit of charging pile pi, $f(ve)$ denotes the benefit of vehicle ve, and $f(g)$ denotes the benefit of power grid g.

A simple example is conducted to describe the cooperation profits of VE, charging pile, and power grid, as shown in Fig. 1. In the Fig. 1, the cooperation process consists of inner layer and outer layer. The computational results from the inner layer model are applied as initial values in the outer layer model. Similarly, the computational results of the outer layer model affect the computation of the inner layer model. This iteration goes on and on. When the termination condition is satisfied, the optimization iteration ends and the optimal result is output.

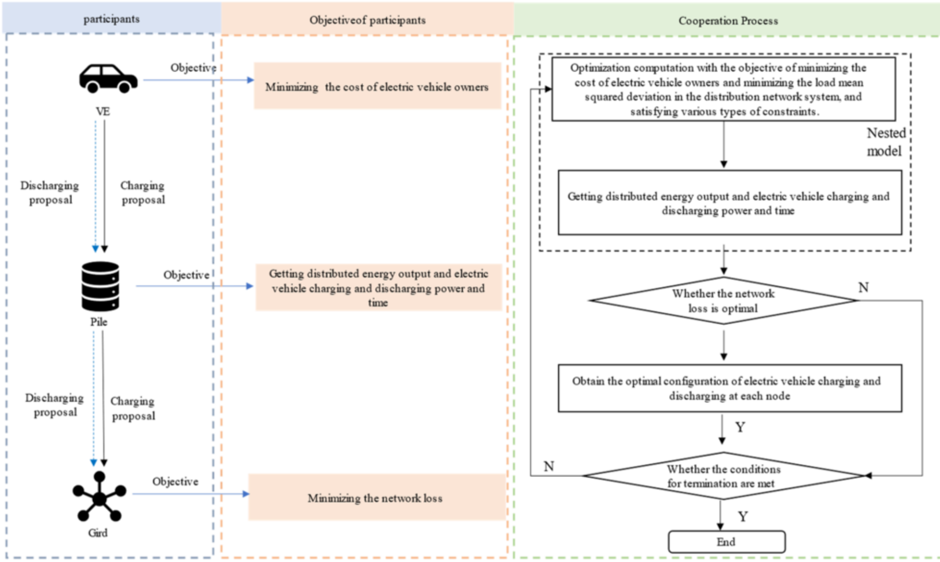

Fig. 1 Example of participant cooperation in a VE charge/discharge situation

4. Case study

To evaluate the effectiveness of the proposed benefit allocation model, a case study was conducted. The case includes 5 VEs (V_1, V_2, V_3, V_4, and V_5), 3 charging piles (P_1, P_1, and P_1), and 1 power grid (G). Each VE makes decisions independently. Each charging post operates independently. The data for the charging piles are obtained from the usage records of three public charging piles in a residential neighborhood.The data for the VEs are selected from the VEs that use the three selected charging piles with the highest frequency. The data for the grid are obtained from the unit price of electricity in the province in which the residential neighborhood is located. The data for the grid are obtained from the unit price of electricity in the province in which the residential neighborhood is located.

MATLAB R2022b codes the benefit allocation model of this case. Then, the solving of the model is implemented in MATLAB R2022b.

Allocation result is obtained by benefit allocation model, as shown in Fig. 2. When the non-cooperative model is used, VE needs to pay for charging fees and charging post usage fees. When the cooperative model is used, the revenues of VEs, charging piles, and power grid are all significantly increased. Among them, VE's revenue increases most significantly, mainly because the additional revenue in the cooperative mode depends on A's discharge decision. In summary, the proposed model can increase the benefit of each VE, charging pile, and power grid.

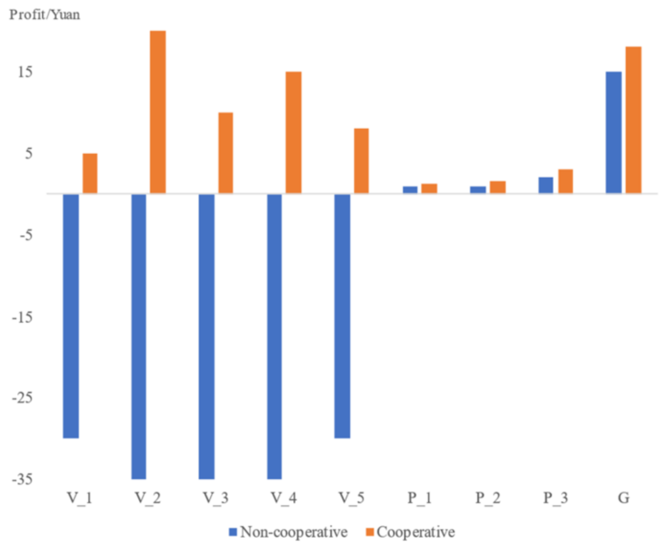

Fig. 2 Profits of Stakeholders where VEs act as not only consumer but also provider

5. Conclusion

This paper offers a feasible solution to solve grid-connected issues. Firstly, vehicles, charging piles, and power grids are selected as subjects in this paper, and then the problem of benefit allocation is descripted. Based on this, a benefit allocation model is established based on cooperative game theory where the benefit is calculated according to Shapley value. The model is characterized by an inner model and an outer model. The inner model is used to optimize the benefits to vehicles and charging piles; the outer model can optimize the benefits of power grids. They interact and iterate. Subsequently, solving process of the proposed benefit allocation model is designed. Finally, a case study is implemented, and verify the effectives of the proposed benefit allocation model. The proposed model can increase the benefit of each vehicle by Comparing with previous strategy.

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