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Collaborative Pricing Strategy of Distribution Network and Electric Vehicle Aggregator Based on Integral System

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Abstract. Scaled EVs as a new type of load have great potential to participate in the standby market. However, the uncertainty of EV users' participation in aggregator regulation affects the optimal strategy for aggregators to participate in the market. Aiming at the uncertainty of users' willingness and the conflict of interest between aggregators and the distribution network, this paper proposes an optimal scheduling strategy of master-slave game for EV aggregators to improve users' willingness with a point system. First, the second-order cone optimal current model of the distribution network is established, and then the distribution network node marginal tariff is obtained. Second, the aggregator revenue model with energy storage is established, and the price-guided demand response model is proposed, while the aggregator point system is established to guide the charging behavior of EV users, so that the cooperative operation optimization problem between the distribution grid and the aggregator can be solved, and the economic interests among EV users, EV aggregators and distribution grid operators can be effectively balanced.

Keywords: electric vehicles, user willingness, master-slave game, reserve market.

1. Introduction

Under the background of the global energy crisis and the depletion of oil resources, the industrial structure of the national economy is constantly changing, and the new energy industry is thriving. Due to the transformation of clean energy, such as solar energy, wind energy, and nuclear energy, and the rapid advancement of technologies, such as electric vehicles, global energy-related carbon dioxide emissions in 2023 will increase less than in 2022 [1]. Large-scale access to the electric vehicle (EV) has become the main development trend.

EV is a flexible power load, with the advantages of low driving noise, high energy utilization rate, zero exhaust emission, and less pollution compared with traditional fuel vehicles [1]. It is also a distributed energy storage unit, so it has great potential as a demand response resource to help the power grid cut peaks. However, a single EV has the characteristics of “small capacity, strong randomness, and high self-interest”, and allowing it to access the power grid in disorder will lead to a huge impact on the power grid and a waste of resources such as transformers [2].

The distribution network is gradually changing from a power network that simply accepts and distributes electric energy to users to a power network with integrated interaction of source, network, load, and storage [3]. The electric vehicle aggregator (EVA), which buys user-side demand response resources and provides charging and discharging guidance services for EV users, has gradually become an important independent subject of the power market, which plays a transition role in the “vehicle-network interaction”. It has the ability to participate in the electricity market bidding and provide auxiliary services such as peak cutting to the power grid that a single EV does not have, which improves the safety and reliability of power supply in the power grid, effectively reduces the operating cost of the power grid and creates conditions for electric vehicle users to participate in the demand response market.

The ultimate goal of load aggregators is to make profits and formulate electricity price strategies to guide users’ behavior. The existing research mostly adopts game theory and considers the interests of aggregators and electric vehicle users. This study [5] used the master-slave game theory to solve the problem of mutual profit-seeking pricing between electric vehicle load aggregators and users. Based on the principle of the master-slave game, this study [6] established a general model of incentive price customization for load aggregators, which was suitable for managing various types of demand response resources and provided references for load aggregators to carry out demand response. In this research [7], the aggregation optimization model and pricing strategy optimization model of electric vehicle load adjustability are established to respond to market demand in stages. In order to make full use of the V2G game relationship between EVA and users to get the optimal EVA power pricing and EV charging and discharging strategy, this study [8] took into account the maximization of both parties' income and improved the negative impact of EV load on the power grid. As different stakeholders, users of DSO, EVA, and EV have different optimization objectives in their decision-making process. These studies [9-11] have analyzed the problem of multi-agent and multi-objective optimization power. The above-mentioned studies have investigated the game optimization of load aggregators from different perspectives, but none of them consider the influence of the change of willingness to participate in regulation on the aggregation ability of aggregators from the user level. Moreover, the charging price in the above-mentioned documents is aimed at maximizing the aggregators or considering the user's income, ignoring the influence of EV load on the distribution network, which may lead to the impact of matching schemes on power grid security and increase its operating cost burden.

This research [12] introduced the fixed point theorem and investigated the cooperative pricing strategy of multi-microgrid and distribution networks. This study [13] proposed a method for distribution network operators to set the interactive price of electric energy by using bi-level optimization to coordinate the energy transaction of multi-microgrid systems. This study [14] not only considered the master-slave game relationship between the distribution network and microgrid but also adopted the Nash negotiation theory to solve the cooperative operation problem of the IEM alliance. This research [15] introduced the carbon trading mechanism and a variety of flexible resources, including EV, to participate in ADN economic low-carbon scheduling while establishing the game model. The existing research from the distribution network side mostly considers the coordinated optimization of the distribution network and integrated energy microgrid, and there is little research on the optimization of electric vehicle aggregators participating in dispatching.

With respect to the limitations of existing research, this paper proposes a collaborative pricing strategy between distribution networks and electric vehicle aggregators. Firstly, the second-order cone optimal power flow model of the distribution network is established, the dual model of the second-order cone programming problem is derived, and then the marginal price of distribution network nodes is obtained. Secondly, the income model of aggregators with energy storage is established, and the demand response model guided by price is put forward. At the same time, the pricing system of aggregator integral is established to guide the charging behavior of electric vehicle users.

2. Master-slave Game Model Framework

In reality, distribution networks and electric vehicle aggregators, as different stakeholders, have different optimization objectives in their respective decision-making processes [16]. On the one hand, each subject independently optimizes its own goals. On the other hand, they are influenced by each other's behaviors, forming a complex interest-game relationship. Therefore, the distribution network is the main body, and the method of combining master-slave games with optimization is adopted to formulate the optimal electricity price strategy to maximize the interests of both parties.

In the market environment, the aggregator of electric vehicles makes demand decisions according to the transaction price announced by the connected distribution network, while the distribution network makes pricing decisions according to the strategy reported by the aggregator. This price-demand closed loop essentially constitutes a Stackelberg game problem. The specific master-slave game model framework is shown in Figure 1. The distribution network is the leader in the game, which formulates an electricity price strategy according to the current electricity demand situation and transmits it to aggregators. There are M aggregators in the market who act as followers in the game together, make their own optimal operation decisions according to the transaction price, and report the adjustment of trading strategy to the superior distribution network. It should be pointed out that in order to focus on the interaction between the distribution network and aggregators, the interaction between aggregators is not considered in this paper.

3. Optimal Power Flow Model of Distribution Network

As the leader of the game, the main goal of the distribution network is to optimize the operation cost and set the transaction price. Considering the radial distribution network, the following Distflow model [17] is adopted to model it:

$$\min \alpha_1 \sum_{t=1}^{T} \sum_{g=1}^{G} D_{g,t}^{P} P_{g,t}^{P} + \alpha_2 \sum_{t=1}^{T} \sum_{l=1}^{L} P_{l,t}^{PL} \tag{1}$$

T is the optimization period, G is the number of generator sets, and $P_{g,t}^{P}$ represents the active output plan of generator set G in the T period. $D_{g,t}^{P}$ is the active cost of generator set G, and $P_{l,t}^{PL}$ represents the active network loss of transmission line l in the T period. Because the former part is the cost of power purchase and the latter part is the active power loss, and the dimensions of the two parts are different, the price coefficient sums α_1 and α_2 are introduced.

The constraints considered in the proposed economic dispatch model with embedded network losses include network transmission constraints, transmission capacity constraints of transmission lines, and output characteristics constraints of generator sets [17].

Constraints:

a. Network transmission constraints, including node active and reactive power balance, voltage relationship, and line active and reactive power loss relationship.

$$\text{relation.}\begin{cases} P_{b,t}^{D} + \sum_{l\in b} P_{l,b,t}^{C} = \sum_{g\in b} P_{g,t}^{P} & (2) \\ Q_{b,t}^{D} + \sum_{l\in b} Q_{l,b,t}^{C} = \sum_{g\in b} Q_{g,t}^{P} & (3) \\ V_{b2,t}^{2} = V_{b1,t}^{2} + 2(r_l P_{l,b1,t}^{C} + x_l Q_{l,b1,t}^{C}) + (r_l^2 + x_l^2)\frac{(P_{l,b1,t}^{C}{}^{2} + Q_{l,b1,t}^{C}{}^{2})}{V_{b1,t}^{2}} & (4) \\ P_{l,t}^{PL} = \frac{(P_{l,b1,t}^{C}{}^{2} + Q_{l,b1,t}^{C}{}^{2})}{V_{b1,t}^{2}} r_l & (5) \\ Q_{l,t}^{PL} = \frac{(P_{l,b1,t}^{C}{}^{2} + Q_{l,b1,t}^{C}{}^{2})}{V_{b1,t}^{2}} x_l & (6) \\ V_{b,t} = 1 & (7) \end{cases}$$

$P_{b,t}^{D}$ and $Q_{b,t}^{D}$ are the active and reactive power of any node, respectively. $P_{g,t}^{P}$ and $Q_{g,t}^{P}$ are the active and reactive power of generator set g. $l \in b$ and $g \in b$ represent all transmission lines connected to nodes and all generator sets connected to nodes, respectively. $P_{l,b,t}^{C}$ and $Q_{l,b,t}^{C}$ are the active and reactive power sent by the node. The nodes on both sides of the transmission line are defined as b1 and b2, respectively. The squares of the voltage amplitudes of the nodes on both sides are $V_{b1,t}^{2}$ and $V_{b2,t}^{2}$, respectively. Power flows sent by transmission line l at node b1 and node b2 are $P_{l,b1,t}^{C}+\mathrm{j}Q_{l,b1,t}^{C}$ and $P_{l,b2,t}^{C}+\mathrm{j}Q_{l,b2,t}^{C}$, respectively. The active and reactive losses of transmission line l are $P_{l,t}^{PL}$ and $Q_{l,t}^{PL}$, respectively, and its impedance is $r_l+\mathrm{j}x_l$. The equations are node active power balance, node reactive power balance, voltage relation, line active power loss relation, and line reactive power loss relation in turn.

b. Transmission capacity constraints of transmission lines.

$$P_{l,b1,t}^{C}{}^{2} + Q_{l,b1,t}^{C}{}^{2} \le S_{l}^{C}{}^{2} \tag{8}$$

S_l^C is the transmission capacity limit of transmission line l.

c. Constraints on output characteristics of generator set.

$$\begin{cases} P_g^{P,min} \le P_{g,t}^P \le P_g^{P,max} & (9) \\ Q_g^{P,min} \le Q_{g,t}^P \le Q_g^{P,max} & (10) \\ {P_g^{P,min}}^2 \le {Q_{g,t}^P}^2 \le {P_g^{P,max}}^2 & (11) \\ P_g^{PC,min} \le P_{g,t}^P - P_{g,t-1}^P \le P_g^{PC,max} & (12) \end{cases}$$

The four constraints are active power constraint, reactive power constraint, gross power constraint and climbing rate constraint in turn. $P_g^{P,min}$ and $P_g^{P,max}$ are the upper and lower limits of the active output of generator set g, $Q_g^{P,min}$ and $Q_g^{P,max}$ are the upper and lower limits of reactive power of generator set g, and $P_g^{PC,min}$ and $P_g^{PC,max}$ are the upper and lower limits of climbing rate of generator set g.

d. The relationship between active output and load.

$$\sum_{t=1}^{T}(\sum_{g=1}^{G} P_{g,t}^{P} - \sum_{l=1}^{L} P_{l,t}^{PL}) = \sum_{k=1}^{K}\sum_{t=1}^{T}(E_t^{k-} + E_t^{k+}) \tag{13}$$

4. Aggregator Revenue Modeling

As a follower, the electric vehicle aggregator makes independent optimization according to the given price of the distribution network. This paper considered that the aggregator is composed of a charging pile, an energy storage unit, and an elastic load. The objective function of the aggregator operation includes the cost of purchasing electricity from the superior power grid, the cost of generating electricity by the gas turbine, the cost of charging and discharging energy storage, and the penalty of photovoltaic reduction. It is worth noting that the objective function contains the node marginal price variable, which needs to be given by the distribution network.

$$\max \sum_{t=1}^{T}\sum_{1}^{N} C_{k,t}E_{k,t,n}^{EV} + \sum_{t=1}^{T}(C_t^- E_t^- - C_t^d E_t - C_t^+ E_t^+) \tag{14}$$

$$s.t. C_{t,min} \le C_{k,t} \le C_{t,max} \tag{15}$$

$$\sum_{t=1}^{T} C_{k,t}/T = C_{av} \tag{16}$$

$$\sum_{t=1}^{T}\sum_{1}^{N} E_{k,t,n}^{EV} = E_{k,T}^{MG} \tag{17}$$

$$E_t \ge 0, 0 \le E_t^+ \le Mz_t \tag{18}$$

$$0 \le E_t^- \le r_t^-(1 - z_t) \tag{19}$$

$$W_{k,t}^{MG} + r_t^+ - r_t^- = E_t + E_t^+ - E_t^- \tag{20}$$

$$0 \le r_t^+ \le u_t R_m^+, 0 \le r_t^- \le (1 - u_t)R_m^- \tag{21}$$

In the above formula, $C_{k,t}$ is the charging unit price of polymerization quotient k in t period; E_t is the contract electricity quantity of t period in the current market; E_t^+ and E_t^- are the electricity purchased and sold from the real-time market during t period; r_t^+ and r_t^- are the charge and discharge amount of energy storage equipment in t period; z_t is a Boolean variable, which indicates the energy transaction state in time t; u_t is a Boolean variable, which indicates the state of the energy storage device in time t; $E_{k,t,n}^{EV}$ is the charging amount of the nth electric vehicle at the aggregator k during the t period; C_t^+ and C_t^- are the real-time market purchase and sale price for t period; C_t^d is the market contract electricity price of t period in the current market; $C_{t,min}$ and $C_{t,max}$ are the lowest and highest electricity prices in t period; C_{av} is the daily average electricity price; is the maximum charging and discharging power of energy storage equipment; R_m^+ and R_m^- are the charging and discharging efficiency of energy storage equipment; T is the total number of time periods; M M is a normal number large enough to be taken as the maximum trading power in the real-time market.

In the above formula, the objective function (14) maximizes the profit of the aggregator. The profit of the aggregator consists of four parts, of which the first item represents the income from selling electricity to electric vehicles, the second item is the income from selling electricity to the real-time market, the third item is the cost of purchasing electricity in the previous market, and the fourth item is the cost of purchasing electricity in the real-time market.

It is assumed that the electricity price in the current market is lower than that in the real-time market. The constraint formula (15) is the upper and lower bounds of pricing, and formula (16) is the average price constraint. Constraints (17)-(19) together constitute a power balance condition. Among them, the integer variable z_t in formula (18) and (19) limits that among E_t^+ and E_t^- , at most, one of them can be strictly greater than 0. Because the amount of electricity sold by retailers to the real-time market is limited by the capacity of energy storage equipment, that is $\mathrm{E}_\mathrm{t}^- \leq \mathrm{r}_\mathrm{t}^-$. Considering the complementary relationship between E_t^+ and E_t^- , there are constraints (18) and (19). In fact, influenced by the maximum charging power of energy storage devices and electric vehicles, it must be less than the sum of the maximum charging power of all electrical equipment. Therefore, the parameter M in formula (18) can also be taken as the sum of the maximum charging power of all electrical equipment. It should be pointed out that, in general, because the real-time market electricity price is higher than the current market electricity price at the same time, the aggregator will not directly purchase electricity from the real-time market in the optimal charging strategy. Constraint (21) limits the charging and discharging rate of the energy storage device and an integer variable u_t limits that among r_t^+ and r_t^-, at most, one of them is strictly greater than 0. That is, the energy storage device cannot be in the charged and discharged at the same time.

The marginal price of nodes is used as the selling price of the distribution network. According to the knowledge of the power market, LMP is equivalent to a Lagrange multiplier with an active power balance constraint $\lambda_{t,b}$. N is the number of electric vehicles charged by the aggregator in the optimization period, and $\sum_{t=1}^{T} E_{k,t,n}^{EV}$ is the charging amount of electric vehicles n in the k aggregator in the optimization period.

The charging price of electric vehicles in China consists of two parts: electricity fee and service fee. $C_{k,t}$ is the electricity price of aggregator k in t period.

$$C_{k,t} = \lambda_{t,b} + C_{k,t}^{cre}$$

$\lambda_{t,b}$: the regional electricity price of node b during the t period.

$C_{k,t}^{cre}$: charging a service fee of aggregator k in t period under the influence of credit score.

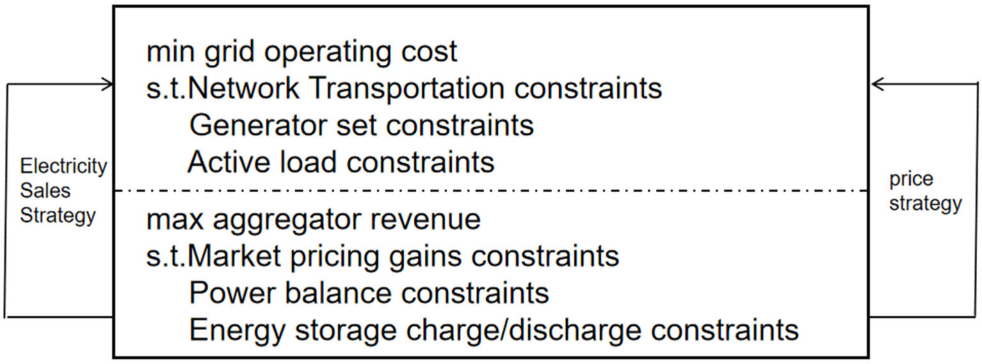

Figure 1. Two-level game model framework

5. Aggregator Integral System

The essence of the appointment mechanism is a binding contract [18].

5.1. Characterization of charging behavior of electric vehicles

(1) Defining a selection vector of charging station

$$A_{n,t}^{EV}=\left[CS_{n,t}^{1},CS_{n,t}^{2},\cdots,CS_{n,t}^{I},\cdots,CS_{n,t}^{K}\right]$$

$$T_{n,t}^{EV}=\left[TCS_{n,t}^{1},TCS_{n,t}^{2},\cdots,TCS_{n,t}^{I},\cdots,TCS_{n,t}^{K}\right]$$

$$W_{n,t}^{EV}=\left[WCS_{n,t}^{1},WCS_{n,t}^{2},\cdots,WCS_{n,t}^{I},\cdots,WCS_{n,t}^{K}\right]$$

$$L_{n,t}^{EV}=\left[LCS_{n,t}^{1},LCS_{n,t}^{2},\cdots,LCS_{n,t}^{I},\cdots,LCS_{n,t}^{K}\right]$$

$$\sum_{\forall K}CS_{n,t}^{I}=1$$

$CS_{n,t}^{I}$ indicates whether EV user n chooses to go to charging pile I for charging at the time t; if yes, it is 1, otherwise, it is 0.

$TCS_{n,t}^{I}$ represents the driving time spent by EV user n to charging pile I at the time t.

$WCS_{n,t}^{I}$ represents the distance of EV user n from charging pile I at the time t.

$LCS_{n,t}^{I}$ represents the queuing time spent by EV user n waiting for charging after arriving at charging pile I at the time t.

(2) Description of reservation situation

If the electric vehicle is charged and reserved for charging, the advance time and the reserved charging pile can be selected.

$$\Delta t_{n,ar}=\begin{cases}0\sim5\ min\\5\sim20min\\\geq 20min\end{cases}$$

$$t_c=\begin{cases}t_{peak}=-1\\t_{low}=1\end{cases}$$

$\Delta t_{n,ar}$ is the time difference between the time when the electric car n arrives at the reserved charging station and the reserved time. When $\Delta t_{n,ar}\geq 20min$, it is automatically canceled, and the system records this $\Delta t_{n,ar}$ =30min. t_c is the time period to which the appointment time belongs.

$$K_{n,t}=\begin{cases}I_{re}\\I_{els}\end{cases}$$

$$I_{re}=[I_1,I_2,I_3]=1$$

$$I_{els}=[I_4,I_5,\cdots,I_K]=-1$$

$K_{n,t}$ is the appointed selected charging station for electric vehicle n at the time t.

I_{re} is the recommended charging station for comprehensive charging congestion and distribution cost of the system.

I_{els} represents other charging stations.

5.2. Integral definition

$$gra_t^k = \sum_1^N \sum_1^C e^{-\varphi \Delta t_{n,ar,c}} + K_{n,t,c} + \mu t_c$$

C is the cumulative charging times of electric vehicle n in t period, φ is the penalty coefficient for breach of contract, and μ is the peak-valley coefficient.

5.3. Relationship between integral and service fee

$$C_{k,t}^{cre} = \varepsilon_t^k e^{-gra_t^k}$$

ε_t^k is the integral electricity price coefficient of aggregator k in t period.

$$C_{k,min}^{cre} \leq C_{k,t}^{cre} \leq C_{k,max}^{cre}$$

(In order to further reduce the market power of agents, the upper bound of the average retail electricity price can be limited to ensure the interests of users.)

6. Conclusion

In terms of the uncertainty of electric vehicle users' willingness to participate in regulation and the conflict of interests between electric vehicle aggregators and distribution networks, this paper established a master-slave game model of distribution networks considering users' willingness. On the distribution network side, the Distflow model with second-order cone relaxation is used to describe the optimal power flow problem on the distribution network side. On the aggregator side, the simplified model is used for interactive iterative calculation with distribution network operators, which greatly improves the calculation efficiency. Meanwhile, considering the uncertainty of users' willingness to participate in dispatching, the integration system is added to guide users' charging choices, which provides the optimal strategy for aggregators to participate in power market decision-making and realize benign interactive incentives with electric vehicle users. This is of great significance to the reliable operation of the power grid and the promotion of multi-social benefits.

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