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Stackelberg Game Model of Wind Farm and Electric Vehicle Battery Switch Station

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Abstract. In this paper, a cooperation method between wind farm and Electric vehicle battery switch station (EVBSS) was proposed. In the pursuit of maximizing their own benefits, the cooperation between wind farm and EVBSS was formulated as a Stackelberg game model by treating them as decision makers in different status. As the leader, wind farm will determine the charging/discharging price to induce the charging and discharging behavior of EVBSS reasonably. Through peak load shifting, wind farm could increase its profits by selling more wind power to the power grid during time interval with a higher purchase price. As the follower, EVBSS will charge or discharge according to the price determined by wind farm. Through optimizing the charging /discharging strategy, EVBSS will try to charge with a lower price and discharge with a higher price in order to increase its profits. Since the possible charging /discharging strategy of EVBSS is known, the wind farm will take the strategy into consideration while deciding the charging /discharging price, and will adjust the price accordingly to increase its profits. The case study proved that the proposed cooperation method and model were feasible and effective.

1. Introduction

With the increasing of wind power integration, the impact of its uncertainty and anti-peak characteristic on the grid is becoming more and more serious. Power system dispatching is facing a series of challenging problems [1-3]. In order to mitigate the negative impact of wind power on the grid, corresponding energy storage system (ESS) are constructed to improve the operational characteristics of wind power [4]. However, the ESS is too costly to be applied in large scale [5].

Electric vehicle battery switch station (EVBSS) could provide service as ESS through uniform management of charging and discharging of batteries, which provides a new approach to solve the above problems [6]. Through utilizing EVBSS as energy storage system, unit commitment model and economic dispatch model of power system containing wind farm and EVBSS are proposed respectively in [7] and [8]. In [9,10], wind farm and EVBSS are proposed to collaborate, working together as an integrated system. The study on the generation schedule of the integrated system has been carried out in [9], and three operating indices of the integrated system have been proposed. In order to improve the operation indices, a two-stage multi-objective optimization model for collaborative scheduling of the integrated system were proposed in [10]. Utilizing the complementary efficiency between wind farm and EVBSS, a synergistic benefit could be achieved. For one thing, EVBSS could reduce the charging cost, for another, wind power can utilize EVBSS as ESS to increase revenue. However, the above studies assumed that wind farm and EVBSS belong to an integrated system and the profits redistribution between them was not involved. In fact, since the wind farm and EVBSS are usually independent to each other, it is difficult to dispatch them uniformly in the form of an integrated system.

This paper focused on the collaboration between wind farm and EVBSS. Compared with [7-10], the following contributions of this study can be highlighted:

1) Wind farm could indirectly affect the charge and discharge process of EVBSS by setting the charging/discharging price in advance. It is not necessary to dispatch wind farm and EVBSS uniformly in the form of an integrated system.

2) Since wind farms and EVBSS are independent of each other, in the proposed game model, they only need to pursue their own benefits, and do not need to pay attention to each other's income, which is more in line with the actual situation. Therefore, the proposed cooperation method is more feasible.

3) The cooperation between wind farm and EVBSS was formulated as the Stackelberg game model by treating them as decision makers in different status. When the game reaches the Nash equilibrium, the profits of both sides are maximized. Moreover, the model can also provide guidance for the study of demand response management.

2. Description of the game problem between Wind farm and EVBSS

EVBSS and wind farm made a contract with each other. On one hand, EVBSS could charge by wind power which is much cheaper than charging from the power grid. On the other hand, EVBSS could sell its stored energy back to the wind farm to earn a benefit.

After the day-ahead purchase price of wind power are given, the wind farm will determine the charging/discharging prices for EVBSS in advance. In fact, Wind farm treats EVBSS as a special energy storage system. Although wind farm cannot directly intervene charge and discharge process of EVBSS, it can indirectly adjust the charge and discharge process of EVBSS by setting charging/discharging prices reasonably. Besides, the peak load shifting of wind power is realized at the same time, which could increase the profits of the wind farm by selling more wind power to the power grid during time interval with a higher purchase price.

Once the charging/discharging prices are determined, EVBSS will optimize its charge and discharge schedule, combined with the battery swapping demand. During the lower price period, EVBSS will charge the batteries to satisfy the battery swapping demand and to store energy. During the high price period, EVBSS will discharge and sell energy back to the wind farm to earn a benefit. Taking the so called “low-price charging and high-price discharging” strategy, EVBSS could increase its profits.

The wind farm has already known the next day's battery swapping demand and the EVBSS's charge and discharge strategies for different charging/discharging prices. Therefore, the wind farm will dynamically correct the charging/discharging prices accordingly to maximize its own profits.

It can be seen that the wind farm and EVBSS are in a leader-follower relationship, which could be formulated by Stackelberg game mode. On the one hand, the determination of charging/discharging prices of wind farm will affect the charging and discharging strategy of EVBSS. On the other hand, the charging and discharging strategy of EVBSS will in turn affect the wind farm sales revenue, and the wind farm should adjust its charging/discharging prices accordingly.

3. System model

3.1. Charging/discharging pricing scheme model of wind farm

The objective function of the charging/discharging pricing scheme model is to maximize the profits of the wind farm.

$$\max \sum_{t=1}^{N_t} (P_{\mathrm{w}}^t - P_{\mathrm{c}}^t + P_{\mathrm{d}}^t)\pi_{\mathrm{w}}^t \Delta t + \sum_{t=1}^{N_t} P_{\mathrm{c}}^t \pi^t \Delta t - \sum_{t=1}^{N_t} P_{\mathrm{d}}^t \pi^t \Delta t \tag{1}$$

The expression of the wind farm profit is given in equation (1), which consists of three parts. The first part is the income of selling electric power to the power grid. The second part is the income of selling electric power to the EVBSS. And the third part is the cost of purchasing electric power from EVBSS.

The decision variables $\{\pi^t, \forall t\}$ are the charging/discharging prices determined by the wind farm. P_{w}^t is the wind power at time *t*. P_{c}^t and P_{d}^t are the charge and discharge power of EVBSS at time *t*. π_{w}^t is the pool purchase price of wind power for the power grid at time *t*, which is already known when determining π^t. Δt is the length of a single time interval.

To make it more clearly, equation (1) can be converted into equation (2):

$$\max \ \sum_{t=1}^{N_t} P_{\mathrm{w}}^t \pi_{\mathrm{w}}^t \Delta t + \sum_{t=1}^{N_t} (P_{\mathrm{d}}^t - P_{\mathrm{c}}^t)(\pi_{\mathrm{w}}^t - \pi^t)\Delta t \tag{2}$$

The first part of equation (2) stands for the income of the wind farm without cooperation with EVBSS. The second part is the additional profits that wind farms get through cooperation with EVBSS.

The constraints of the model include equation (3) and equation (4):

$$\pi_{\min}^t \le \pi^t \le \pi_{\max}^t, \ \forall t \tag{3}$$

$$\sum_{t=1}^{N_t} (P_{\mathrm{d}}^t - P_{\mathrm{c}}^t)(\pi_{\mathrm{w}}^t - \pi^t)\Delta t \ge 0, \ \forall t \tag{4}$$

Equation (3) stands for the constraints of charging/discharging price. $\pi_{\max}^t$ and $\pi_{\min}^t$ are the highest and the lowest price, respectively.

Equation (4) indicates that the wind farm can generate additional benefits by cooperating with EVBSS. Only when equation (4) is met, the wind farm has the motivation to cooperate with EVBSS.

3.2. Charging/discharging schedule model of EVBSS

The objective function of the charging/discharging schedule model is to maximize the profits of EVBSS.

$$\max \ \sum_{t=1}^{N_t} \pi_{\mathrm{EV}} Q_{\mathrm{d}}^t + \sum_{t=1}^{N_t} P_{\mathrm{d}}^t \pi^t \Delta t - \sum_{t=1}^{N_t} P_{\mathrm{c}}^t \pi^t \Delta t \tag{5}$$

The expression of the EVBSS profit is given in equation (5), which consists of three parts. The first part is the income of replacing the batteries for the electric vehicles. The second part is the income of selling electric power to the wind farm. And the third part is the cost of charging the batteries. The decision variables are $\{P_{\mathrm{c}}^t, P_{\mathrm{d}}^t, \forall t\}$, which stand for the charge and discharge power of EVBSS in the following day, respectively. π_{EV} is the price of swapping battery for electric vehicles. Q_{d}^t is the battery swapping demand at time *t*.

Charging/discharging schedule model is subject to equation (6) to equation (13).

- Constraints on Charging/discharging Power

$$0 \le P_{\mathrm{c}}^t \le U_{\mathrm{c}}^t P_{\mathrm{c}}^{\max}, \ \forall t \tag{6}$$

$$0 \le P_{\mathrm{d}}^t \le (1 - U_{\mathrm{c}}^t) P_{\mathrm{d}}^{\max}, \ \forall t \tag{7}$$

$$P_{\mathrm{c}}^t - P_{\mathrm{w}}^t \le 0, \ \forall t \tag{8}$$

As binary variable, U_c^t stands for the charging and discharging status of EVBSS at time *t*. $P_c^{\max}$ and $P_d^{\max}$ are the maximum charge and discharge power of the EVBSS, respectively. Equation (8) indicates that EVBSS could only use wind power to charge the batteries.

- Constraint on Storage Capacity of the EVBSS

$$Q^{\min} \le Q_{ev}^t \le Q^{\max}, \ \forall t \tag{9}$$

Where $Q^{\max}$ and $Q^{\min}$ are maximum and minimum energy storage of the EVBSS. The expression for stored energy Q_{EV}^t of EVBSS at time *t* can be expressed as

$$Q_{ev}^t = Q_{ev}^{t-1} + P_c^t \eta_c \Delta t - P_d^t \Delta t / \eta_d \text{-} Q_d^t, \ \forall t \tag{10}$$

Where η_c and η_d denotes the efficiency of charging and discharging, respectively.

- Constraint on Energy Storage at the End of Decision-making Cycle of EVBSS

$$Q_{ev}^{N_t} \ge Q^{end} \tag{11}$$

Where Q^{end} refers to the minimum energy storage of the EVBSS required at the end of the decision-making cycle.

- Constraint on Energy Storage Reserve for Battery Swapping Demand

$$Q_{ev}^t \ge Q^{\min} + (1+\gamma) Q_d^t, \ \forall t \tag{12}$$

Where γ is the reserve rate for the battery swapping demand.

- Constraint on the Profit of EVBSS

$$\sum_{t=1}^{N_t} (P_d^t - P_c^t) \pi^t \Delta t \ge -\sum_{t=1}^{N_t} Q_d^t \pi_d \tag{13}$$

Where π_d is the price of charging from the power grid directly for EVBSS. Equation (13) indicates that the profits of EVBSS in cooperation with the wind farm are greater than those when EVBSS charge the batteries directly from the grid. EVBSS has the motivation to cooperate with the wind farm only when equation (13) is satisfied.

3.3. Stackelberg game model

In the pursuit of maximizing their own benefits, the cooperation between wind farm and EVBSS was formulated as the Stackelberg game model by treating them as decision makers in different status. The game structure is shown in figure 1.

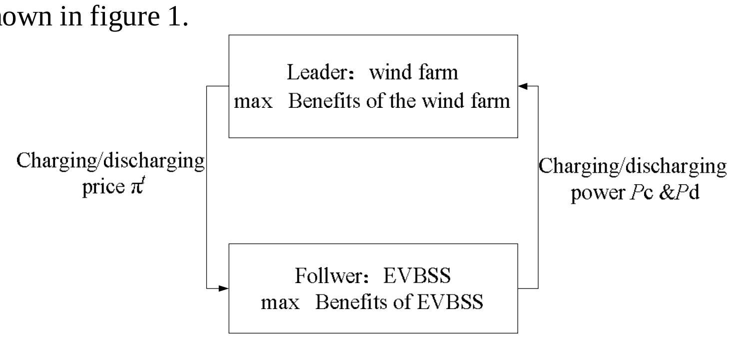

Figure 1. Stackelberg game structure of wind farm and EVBSS.

Wind farms and EVBSS are not making decisions at the same time. In fact, as the leader, the wind farm will determine the charging/discharging price at first. As the follower, EVBSS will develop the optimal charging and discharging strategy based on the prices set by wind farm. Since the possible charge and discharge strategies of EVBSS is known, the wind farm could adjust its price accordingly while making the decision.

The Stackelberg game model of wind farm and EVBSS is as follows:

$$\begin{array}{ll} \text{Leader} & \begin{cases} \max \sum_{t=1}^{N_t} P_{\mathrm{w}}^t \pi_{\mathrm{w}}^t \Delta t + \sum_{t=1}^{N_t} (P_{\mathrm{d}}^t - P_{\mathrm{c}}^t)(\pi_{\mathrm{w}}^t - \pi^t)\Delta t \\ \text{s.t. } (3)-(4) \end{cases} \\ \text{follower} & \begin{cases} \left\{P_{\mathrm{c}}^t, P_{\mathrm{d}}^t, \forall t\right\} \in \arg\max \sum_{t=1}^{N_t} \pi_{\mathrm{EV}} Q_{\mathrm{d}}^t + \sum_{t=1}^{N_t} P_{\mathrm{d}}^t \pi^t \Delta t - \sum_{t=1}^{N_t} P_{\mathrm{c}}^t \pi^t \Delta t \\ \text{s.t. } (6)-(9),(11)-(13) \end{cases} \end{array} \tag{14}$$

The follower part in the Stackelberg game model is a mixed-integer linear programming model, which can be solved by CPLEX, the mature business software. The Stackelberg game model as a whole can be solved by genetic algorithm (GA).

4. Simulation analysis

Multiple wind farms and a number of EVBSSs in the model can be equivalent to one wind farm and one EVBSS. Equivalent wind farm data and EVBSS parameters are selected from [9]. In figure 2, the day-ahead predicted value of wind power is presented. The battery swapping demand is presented in figure 3. The capacity of the equivalent EVBSS is 55MW•h. The initial electric quantity stored by EVBSS is 27.5MW•h. The parameters of the equivalent EVBSS are shown in Table 1.

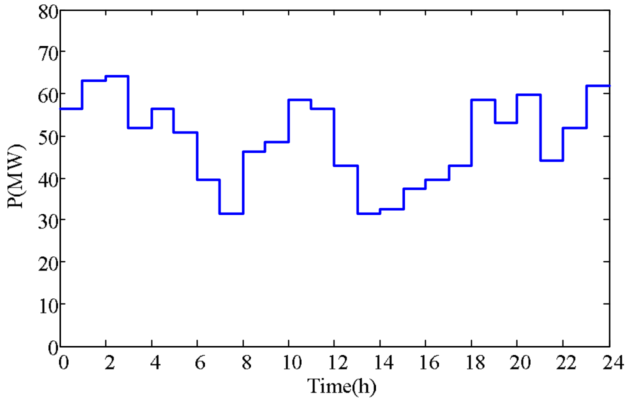

Figure 2. Day-ahead wind power prediction of the wind farm.

The decision-making cycle is 24 hours of the next day; besides, each hour serves as one time interval.

The pool purchase price of wind power is shown in figure 4. Through setting reasonable pool purchase price of wind power, the power grid could effectively guide the wind farm to increase output power in the peak periods of the load and to decrease output power in the valley periods of the load.

The upper and lower limit of charging/discharging price are presented in figure 5. Battery swapping price π_{EV} is 380￥/MW•h. π_{d}, the price of charging from the power grid directly for EVBSS, is 550￥/MW•h.

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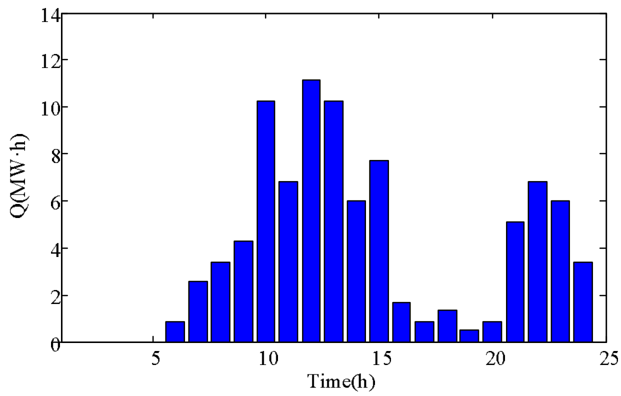

Figure 3. Battery swapping demand.

Table 1. Parameters of EVBSS.

Q^{max} (MW·h)	Q^{min} (MW·h)	Q^{end} (MW·h)	P_c^{max} (MW)	P_d^{max} (MW·h)	γ	η_c	η_d
55	5.5	27.5	11	7	0.1	0.95	0.92

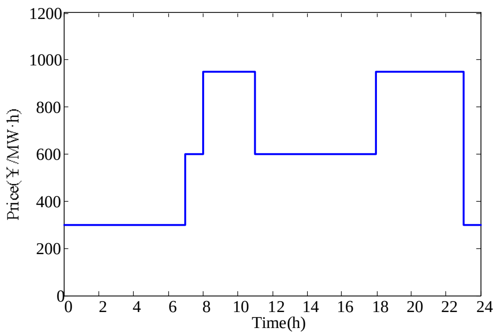

Figure 4. Pool purchase price of wind power.

According to the above conditions, the Nash equilibrium point of the proposed Stackelberg game was figured out. At the Nash equilibrium, the charging/discharging price determined by wind farm is shown in figure 6, and the charging/discharging power of EVBSS is shown in figure 7, where charging power is positive and discharging power is negative.

In figure 6, it is clearly found that the variation of charging/discharging price basically follow the trend of wind power purchase price. In the period of low wind power purchase price, such as time interval 0-6, wind farm develops a lower charging/discharging price to guide EVBSS charge and store wind power. Similarly, in the period of high wind power purchase price, such as time interval 8-10, the wind farm will set a higher charging/discharging price to attract EVBSS discharge, in order to obtain more benefits.

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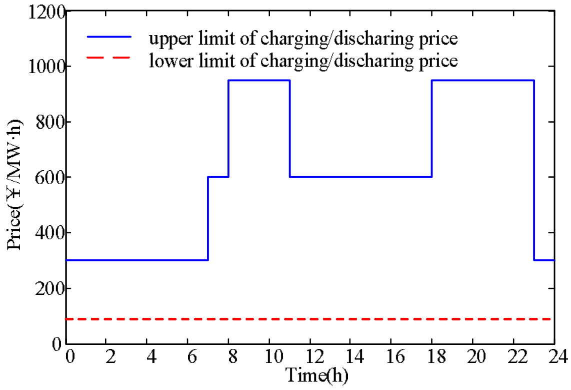

Figure 5. Upper and lower limit of charging/discharging price.

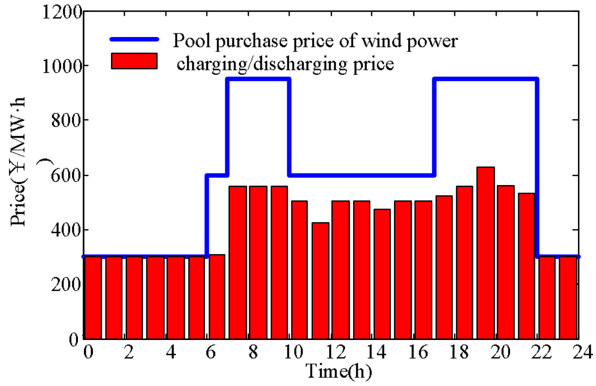

Figure 6. Charging/discharging price at the Nash equilibrium point.

As can be seen from figure 7, the EVBSS is charged at a time when the charge/discharge price was low, and was discharged during the high charge/discharge price period. EVBSS could increase its profits by the "low-price charging and high-price discharging" strategy.

Figure 8 presents the optimized output power of wind farm. Compared to its predicted value, the optimized output power is reduced during valley periods of the load, such as time interval 0-6, and the output power of the wind farm is increased during the peak periods of the load, such as time interval 19-21. This shows that the proposed model can weaken the anti-peak characteristic of wind power, correspondingly, the peak regulation pressure of the grid will be reduced.

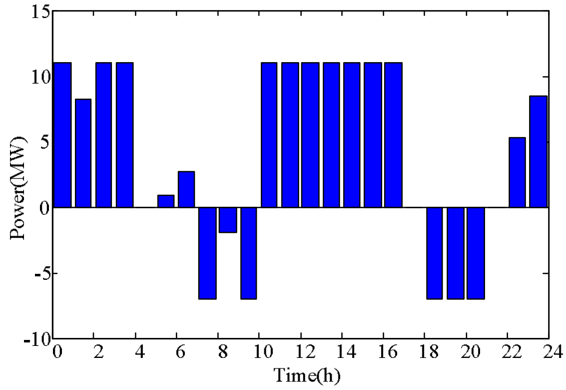

Figure 7. Charging/discharging power of EVBSS at the Nash equilibrium point.

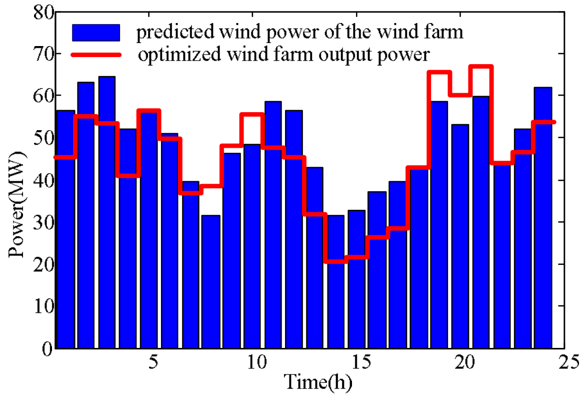

Figure 8. Optimized output power of wind farm.

Table 2 compares the profits of wind farm and EVBSS within cooperative and non-cooperative modes. Compared to the non-cooperation situation, the profits of the wind farm and EVBSS in the proposed model have both increased. Therefore, the wind farm and EVBSS have the motivation to cooperate.

Table 2. Comparison of wind farm and EVBSS in different modes.

Modes	**Profit of wind farm (¥)**	**Profit of EVBSS (¥)**
cooperative	710,017	15,440
non-cooperative	705,493	15,300

5. Conclusion

This paper presented a method of cooperation between wind farm and EVBSS based on Stackelberg game model. Through the analysis of case study, this paper validated the model and obtained the following conclusions:

(1) Wind farm and EVBSS do not need to be dispatched uniformly as an integrated system. On the contrary, they are independent, though wind farm could induce the charging and discharging behavior of EVBSS by formulating proper charging /discharging price.

(2) In order to get the Nash equilibrium of the Stackelberg game mode, wind farm and EVBSS only need to maximizing their own economic benefits. At the Nash equilibrium point, the profits of the wind farm and the EVBSS are both higher than those in the non-cooperative situation, which providing motivation for their cooperation.

(3) Through the cooperation between wind farm and EVBSS, under the premise of ensuring the economic benefits of both sides, the anti-peak characteristic of the wind farm is mitigated, which is beneficial to reduce the peak regulation pressure of the power grid as well.

It should be pointed out that the prediction error of wind power and battery swapping demand was not considered in this paper. In the future, the feasibility of EVBSS providing reserve for wind farms to mitigate wind power fluctuations will be studied and the uncertainties of wind power and battery swapping demand will be taken into consideration as well.

Acknowledgments

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