An Optimal Dynamic Pricing and Schedule Approach in V2G

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Abstract—**Smart Grid (SG) can greatly improve the efficiency and reliability of traditional grid. As a promising feature of future SG, the Vehicle-to-Grid (V2G) technique exhibits great potential to balance the supply and demand of electrical power as well as integrate renewable energy. Recently, some V2G-based schemes have been proposed to leverage the energy-storage capability of electric vehicles (EVs) to effectively reduce energy loss caused by supply-demand mismatches. However, most of the existing schemes rely on the assumption that the charge station is profit-neutral, lacking of adequate incentive to the charge stations for wide deployment. In this paper, we investigate a scenario where the charge station is modelled as an entity driven by its own profit. We formulate the interactions between the charge station and multiple EVs as a game, in which two kinds of EVs, cooperative EVs and selfish EVs, are considered. Regarding the intelligence of selfish EVs, a dynamic pricing over multiple time slots is developed from the charge station's perspective to maximize its own profit. Both theoretical analysis and simulation results show that through our scheme of dynamic pricing for selfish EVs and charging scheduling for cooperative EVs, the charge station can maximize its profit while EVs maximize their utilities.**

I. INTRODUCTION

Due to the shrinkage of fossil fuels supply, exacerbation of environment pollution and other economic reasons, EVs have emerged as a promising alternative in recent years that use electricity to replace a significant fraction of fossil fuels consumption [1], [2]. The fuel conversion efficiency of EVs is estimated as 22.5%-45% [3], [4], while that of the conventional vehicles is only about 20%. Therefore, the usage of EVs are growing dramatically recently. Commercial plug-in hybrid electric vehicles (PHEVs) have been produced by a few automobile manufacturers such as Cooper, Nissan, Tesla, etc.. Moreover, the first generation of PHEVs have emerged into the market in 2011 [5]. It is estimated by Oak Ridge National Laboratories that almost 30% of the vehicles in the European Union will be PHEVs by 2020 [6]. Similar study done by the German Federal Government showed that there would be one million EVs on Germany's road by 2020 [7].

The large-scale deployment of EVs has drawn great attentions from researchers in power grid and smart grid [8]-[10]. In [8], Kempton and Letendre analyzed in details vehicle battery storage by comparing three EV configurations over various driving requirements and electric utility demand conditions. Mi studied in [9] the design of EV including topology, control, battery management, etc., while Turker et al. in [10] conducted research on the impact of EVs on electric grids and investigate the energy management for Vehicle-to-Grid (V2G).

The widely deployment of EVs may cause sever impact on the power grid such as power losses and voltage deviations without coordination of the charging of EVs. For example, Hadley performed a thorough analysis of EV penetration into the regional power grid [11], and reported that quick charging EVs during the evening hours could create much higher new peaks without proper coordination. To tackle such challenges, the author in [12] proposed a coordinate charging scheme to minimize the power losses and maximize the main grid load factor while the authors in [13] used quadratic programming to regulate the frequency in the grid. The effects of the grid-connected EVs on bulk power systems were investigated in [14], where a smart storage scheme was proposed to maintain the quality of power frequency under a large number of EVs.

By using EVs' batteries as distributed storages, V2G can assist the power grid to embrace the potential economic and environmental benefits that are not possible before [15]-[19]. In [16], V2G is used to stabilize the grid by compensating the mismatch in supply and demand. In [19], the authors proposed an advanced smart charging communication protocol to match domestic load demand with the intermittent decentralized power supply. As shown in [18], with a proper scheduling scheme, V2G can help reduce the peak demand by 70%. V2G can also be utilized to integrate renewable energy [20]-[23]. In [21], V2G is investigated to integrate the wind power. Later in [23], Islam and Pota proposed a feed forward compensating control strategy to smooth power variation in wind farm.

One key problem in V2G is how to control the charging/discharging process of EVs [24]-[26]. In [24], the authors proposed a distributed approach to schedule the charging and discharging process of EVs to compensate the mismatch between load demand and power supply. However, there is no justification about the reason that EVs would obey the scheme. Similarly, the authors in [25] failed to provide a valid reasoning that residential load would cooperate. In [26], EVs are assumed to be intelligent who would minimize their own charging cost. By proper setting the real-time selling price, rational EVs that minimize their own charging cost can help balance the load and supply. Nevertheless, the charge stations were assumed to be profit-neutral, and thus lacking of adequate incentive to the charge station for wide deployment.

In this paper, we consider a more realistic scenario where both EVs and charge station are intelligent. On one hand, EVs will dynamically adjust their charging scheme to maximize

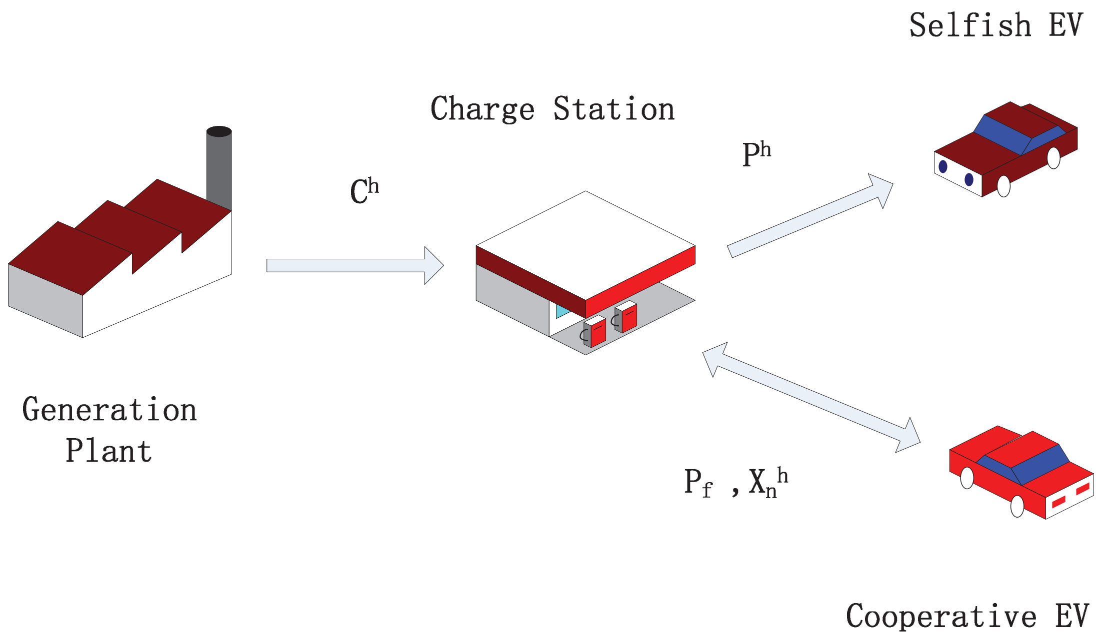

Fig. 1. System Model

their own utilities according to the real-time selling price. On the other hand, the charge station would set up the optimal real-time price to maximize its own profit instead of the social welfare by taking into account the response of EVs. In such a case, the charge station would not set up a very high real-time selling price to avoid the situation that there is not many EVs, nor would it set up the price too low to reduce the profit. The simulation results show that the proposed scheme can maximize both the charge station's profit and EVs' utilities.

The reminder of paper is organized as follows. We describe in details the system model in Section II. The optimal strategy of selfish EVs is analyzed in Section III while the optimal strategy of the charge station is discussed in Section IV. Finally, we show the simulation results in Section V and draw conclusions in Section VI.

II. SYSTEM MODEL

Consider the system in Fig 1. It consists of four main components: cooperative EV, selfish EV, charge station and generation plant. The charge station buys electricity from generation plant at the price c^h, and then sells the electricity to two kinds of EVs: selfish EVs at the real-time selling price p^h and cooperative EVs at a fixed price p_f. We assume that c^h, p_f and the number of selfish EVs and cooperative EVs remain the same in H time slots.

A. Generation Plant

We assume that generation plant announces the generation price c^h every H time slots. Here, the time scale H is relatively small since it would be difficult for the generation plant to announce a valid price for a long period in the future. We further assume that the generation plant always have enough electricity to support all EVs to be charged, i.e., there would be no blackout. Last, discharging back from the charge station is not allowed.

B. Charge Station

As discussed above, the charge station would buy electricity from the generation plant at c^h and charge selfish EVs at the real-time selling price p^h and cooperative EVs at a fixed price p_f. The goal of the charge station is to maximize its own profit by dynamically setting p^h and properly scheduling the charging process of cooperative EVs according to c^h. We further assume that the numbers and feature parameters of both kinds of EVs are known to the charge station and would remain unchanged in H time slots.

Since only one charge station is considered in our system, we assume that the charging prices lie between p_{min} and p_{max} to avoid monopoly. The fixed price p_f is usually lower than p^h since the cooperative EVs would obey the charging scheme controlled by the charge station. On the other hand, we assume that the selfish EVs are not allowed to discharge back to the station since they are not directly controlled by the charge station.

C. Cooperative EV and Selfish EV

We assume that there are N_1 cooperative EVs and N_2 selfish EVs in next H time slots. Let us denote $\mathbf{N}_1 = \{1, \ldots, N_1\}$

and $\mathbf{N}_2 = \{N_1+1, \ldots, N_1+N_2\}$ as the indices of cooperative EVs and selfish EVs, respectively. Let a_n and d_n be the arrival time and departure time of EV n, respectively. Let $\mathbf{x}_n = \{x_n^1, \ldots, x_n^H\}$ be the energy consumption profile of EV n during the H time slots. Denote x_n^{exp} as the expected charging amount, x_n^o as the initial battery state, and x^{max} and x^{min} as the maximal charging amount and discharging amount per time slot, respectively.

1) Cooperative EV: For cooperative EV n, x_n^h stands for the charging/discharging amount at time slot h, where $h \in [a_n, d_n]$. x_n^h can be positive, i.e., charging amount, or negative, i.e., discharging amount. Denote SOC_{min} and SOC_{max} as the minimal and maximal required battery state, respectively.

To be charged at a lower price, cooperative EVs are directly controlled by the charge station. On the other hand, the charge station has to satisfy some requirements set by the cooperative EVs, e.g., the battery needs to be charged by x_n^{exp} when leaving the charge station, while the battery state should always lie in SOC_{min} and SOC_{max}.

Therefore, the consumption profile $\mathbf{x}_n$ of cooperative EV n should satisfy the following constraints, denoted as $\mathbf{X}_n^{CO}$,

$$\begin{array}{l}
x^{min} \leq x_n^h \leq x^{max} \quad \forall n \in \mathbf{N}_1 \quad \forall h \in \{1, \ldots, H\} \\
x_n^h = 0 \quad \forall n \in \mathbf{N}_1 \quad \forall h \notin \{a_n, \ldots, d_n\} \\
x_n^o + x_n^h + \sum_{m=1}^{h-1} x_n^m \geq SOC_{min} \quad \forall n \in \mathbf{N}_1 \quad \forall h \in \{1, \ldots, H\} \\
x_n^o + x_n^h + \sum_{m=1}^{h-1} x_n^m \leq SOC_{max} \quad \forall n \in \mathbf{N}_1 \quad \forall h \in \{1, \ldots, H\} \\
\sum_{h=1}^{H} x_n^h = x_n^{exp} \quad \forall n \in \mathbf{N}_1
\end{array} \tag{1}$$

2) Selfish EV: Different from cooperative EVs, selfish EVs are not directly controlled by the charge station. Instead, they can decide their own charging schemes with the objective of maximizing their own utilities. On the other hand, selfish EVs are not allowed to discharge power back to the charge station, i.e., x_n^h of selfish EV n will always be non-negative.

The charging strategy of selfish EVs is related to the real-time selling price. We assume that there is a minimal charging requirement, i.e., the selfish EV n should be charged at least up to $1-\alpha$ of x_n^{exp}, where α is a constant reflecting the flexibility of selfish EVs. After meeting the minimal requirement, a selfish EV will determine its charging amount by maximizing its own utility by taking into account the real-time selling price. The utility function of selfish EV would be discussed in later sections.

Therefore, the consumption profile $\mathbf{x}_n$ of selfish EV n should satisfy the following constraints, denoted as $\mathbf{X}_n^{SC}$,

$$\begin{array}{l}
0 \leq x_n^h \leq x^{max} \quad \forall n \in \mathbf{N}_2 \quad \forall h \in \{1, \ldots, H\} \\
x_n^h = 0 \quad \forall n \in \mathbf{N}_2 \quad \forall h \notin \{a_n, \ldots, d_n\} \\
x_n^{exp}(1-\alpha) \leq \sum_{h=1}^{H} x_n^h \leq x_n^{exp} \quad \forall n \in \mathbf{N}_2
\end{array} \tag{2}$$

The whole process of the system can be summarized as follows:

- The generation plant announces the selling price c^h for next H time slots.
- The charge station sets up the fixed price p_f. Then there will be N_1 cooperative EVs and N_2 selfish EVs in next H time slots. The feature parameters of EVs such as arrival time, departure time and expected charging amount are collected by the charge station.
- The charge station sets up the real-time selling price for selfish EVs and the charging schedule for cooperative EVs. In order to maximize its profit, the charge station has to take into account the response of intelligent selfish EVs when determining p^h and the charging scheme for cooperative EVs.
- Based on the real-time selling price, selfish EVs determine their charging scheme by maximizing their own utilities.

The problem of finding the optimal strategy for the charge station can be formulated as a Stackelberg Game. First, the charge station needs to derive the selfish EVs' response given the real-time selling price, i.e., the selfish EVs' charging scheme can be expressed as a function of the real-time selling price. Then, by substituting such a charging scheme, the profit of the charge station becomes a function of the real-time selling price and the schedule policy of cooperative EVs. Therefore, by maximizing the profit of the charge station, we can derive the optimal real-time selling price for selfish EVs and the optimal schedule policy for cooperative EVs. In the following sections, this paper will first examine the optimal charging scheme of selfish EV in Section III. Then the optimal real-time selling price and schedule of cooperative EVs will be explored in Section IV.

III. OPTIMAL STRATEGY OF SELFISH EV

Since selfish EVs can determine their own charging scheme according to the real-time selling price, their utility function can be define as follows:

$$U_n(\mathbf{x}_n) = -\sum_{h=1}^{H} x_n^h p^h - \lambda_n \left(\sum_{h=1}^{H} x_n^h - x_n^{exp}\right)^2 \tag{3}$$

where the first term $\sum_{h=1}^{H} x_n^h p^h$ represents the charging cost while the second term $(\sum_{h=1}^{H} x_n^h - x_n^{exp})^2$ stands for the cost of failing to be charged by x_n^{exp}. The λ_n is a constant reflecting the urgency of selfish EV n to be charged by x_n^{exp}. The larger λ_n, the more likely selfish EV n would be charged by x_n^{exp}.

As discussed before, selfish EV n would choose its charging amount from the interval $[x_n^{exp}(1-\alpha), x_n^{exp}]$ and schedule its charging scheme to maximize its own utility by taking into account the real-time selling price.

Therefore, considering the utility function in (3) and the constraint of the energy consumption profile for selfish EVs in (2), the problem of finding the optimal strategy for selfish EVs can be formulated as follows:

$$\begin{aligned} \underset{\mathbf{x}_n}{\text{maximize}} \quad & U_n(\mathbf{x}_n) = -\sum_{h=1}^{H} x_n^h p^h - \lambda_n \Big(\sum_{h=1}^{H} x_n^h - x_n^{exp}\Big)^2 \\ \text{subject to} \quad & \mathbf{x}_n \in \mathbf{X}_n^{SC}, \quad \forall n \in \mathbf{N}_2 \end{aligned} \tag{4}$$

Suppose all selfish EVs have to stay at least one time slot to satisfy the minimal charging requirement, i.e., $x_n^{exp}(1-\alpha) \geq x^{max}$, $\forall n \in \mathbf{N}_2$. Then, the way to find the optimal charging scheme for selfish EVs is as follows. Selfish EV n would first sort the order of time slots inside $[a_n, d_n]$ based on the corresponding real-time selling price. Then, it will be charged at the maximal speed x^{max} at the time slots that the real-time selling prices are relatively low until the minimal charging requirement is satisfied. After that, selfish EVs would check the utility function to decide whether to be further charged.

Define $k_n = \left\lfloor \frac{x_n^{exp}(1-\alpha)}{x^{max}} \right\rfloor$. Since the total consumption of selfish EV n has to be no less than $x_n^{exp}(1-\alpha)$, selfish EV n would be charged at the maximal charging speed x^{max} at k_n time slots when the real-time selling prices are relatively low. At the (k_n+1)th time slot, since the minimal charging requirement has been satisfied, the charging amount depends on the utility function. Since the function is concave, we can easily derive the corresponding optimal charging amount at this time slot. Starting from the (k_n+2)th time slot, the real-time selling price becomes so high that selfish EV would choose not to be charged to avoid the degradation of the utility. In summary, the optimal charging scheme of selfish EV n is:

$$\text{Define } h_n^i \in [a_n, d_n] : p^{h_n^i} \leq p^{h_n^j} \; if \; i \leq j.$$

$$x_n^{h_n^1} = x_n^{h_n^2} = \ldots = x_n^{h_n^{k_n}} = x^{max}$$

$$x_n^{h_n^{k_n+1}} = \begin{cases} x_n^{exp}(1-\alpha) - k_n x^{max}, \\ \text{if } \frac{p^{h_n^{k_n+1}}}{2\lambda_n} > x_n^{exp} - (k_n+1)x^{max} \\ \\ x^{max}, \\ \text{if } \frac{p^{h_n^{k_n+1}}}{2\lambda_n} \leq x_n^{exp} - (k_n+1)x^{max} \\ \quad (k_n+1)x^{max} \leq x_n^{exp} \\ \\ x_n^{exp} - k_n x^{max}, \\ \text{if } \frac{p^{h_n^{k_n+1}}}{2\lambda_n} \leq x_n^{exp} - (k_n+1)x^{max} \\ \quad (k_n+1)x^{max} > x_n^{exp} \end{cases} \tag{5}$$

$$x_n^{h_n^{k_n+2}} = x_n^{h_n^{k_n+3}} = \ldots = 0$$

From (5), we have the following remarks about the strategies of selfish EVs:

- The charging amount of selfish EVs tends to decrease when the real-time selling price becomes higher.
- The larger λ_n is, the more likely selfish EV n would be further charged.
- Setting all p^h to be p_{max} is not an optimal choice for the charge station since in such a case, selfish EVs may decrease their charging amount, which results in a decrease of the charge station's profit.

IV. OPTIMAL STRATEGY OF CHARGE STATION

In the previous section, we derive the optimal charging scheme for selfish EVs for any given real-time selling price. In this section, we will discuss how the charge station sets the optimal real-time selling price and controls the charging process of cooperative EVs to maximize the profit.

Denote $\mathbf{p} = \{p^1, \ldots, p^H\}$ and $\mathbf{x}^{CO} = \{\mathbf{x}_n \in \mathbf{X}_n^{CO} : \forall n \in N_1\}$ as the real-time selling price vector and scheduling set for cooperative EVs, respectively. The problem can be formulated as follows:

$$\begin{aligned} \underset{\mathbf{p} \quad \mathbf{x}^{CO}}{\text{maximize}} \; R(\mathbf{p}, \mathbf{x}^{CO}) &= p_f \sum_{n \in N_1} x_n^{exp} + \sum_{h=1}^{H} p^h \sum_{n \in N_2} x_n^h \\ &\quad - \sum_{h=1}^{H} c^h \sum_{n \in N} x_n^h \end{aligned}$$

$$\begin{aligned} \text{subject to} \qquad & \\ \mathbf{x}_n \in \mathbf{X}_n^{SC}, &\quad \forall n \in \mathbf{N}_2 \\ \mathbf{x}_n \in \mathbf{X}_n^{CO}, &\quad \forall n \in \mathbf{N}_1 \\ p_{min} \leq p^h \leq p_{max}, &\quad \forall h \in \{1, \ldots, H\} \\ \sum_{n \in N} x_n^h \geq 0, &\quad \forall h \in \{1, \ldots, H\} \end{aligned}$$

where $N = N_1 \bigcup N_2$.

The first term in the objective function is fixed since both p_f and the expected charging amount of all cooperative EVs are fixed. As discussed in the previous section, the charging amount of all selfish EVs $\sum_{n \in N_2} x_n^h$ at each time slot h is a function of $\mathbf{p}$. The optimal charging scheme for selfish EV n is determined by the order of real-time selling price and $p^{h_n^{k_n+1}}$. Given a specific order of the real-time selling price and the value of $p^{h_n^{k_n+1}}$, $\sum_{n \in N_2} x_n^h$ is a constant and the problem becomes a linear optimization problem, which can be easily solved. Since we need to go through all possible price order permutations and all possible $p^{h_n^{k_n+1}}$, it is NP-hard to find the optimal solution to the optimization problem. Nevertheless, the problem is still solvable due to the following reasons:

- Since $h_n^{k_n+1}$ generally may be the same for different selfish EVs, there may exist contradict constraints about $p^{h_n^{k_n+1}}$, which reduces a lot of combinations of price order and constraints about $p^{h_n^{k_n+1}}$.
- The H in our model is general small since the generation plant is unlikely to announce the selling price c^h for a long period in the future, and EVs would not stay at the charge station for a long time if they could be fully charged in 3-5 time slots. With a small H, the number of EVs in H time slots would not be large neither, which means that the scale of the optimization problem is small.

V. SIMULATION RESULTS

In the section, some simulations are conducted to demonstrate the proposed real-time selling price and charging schedule scheme are optimal, i.e., maximizing the profit of the charge station. We also draw some general conclusions on how the charge station could enlarge its maximal profit.

A. *Optimality*

The real-time selling price and the generation price are assumed to be hour-based. As discussed before, only small time scale scenario is practical. Here H is set to be 5, i.e., it is a 5-hour schedule scenario. The number of EVs that arrive at and leave the charge station during 5 hours should not be large. In all simulations, we assume that there are 10 cooperative EVs and 15 selfish EVs whose feature parameters are various and known to the charge station. In practice, the maximal charging speed of EVs should be large enough to allow the charge station to give a more flexible schedule for cooperative EVs. We assume that all EVs have the same maximal charging speed $x^{max} = 0.3$, while the maximal discharging speed for cooperative EVs is $x^{min} = -0.3$. The generation price is assumed to be Gaussian. It is reasonable to set the fixed charging price lower than p_{max} to attract cooperative EVs. We set $p_{min} = 0, p_{max} = 60$ and $p_f = 45$. The parameter α for selfish EVs is set to be 0.7. In such a case, selfish EVs have a flexible decision on their total consumptions, i.e., they can be charged by any value between $0.3x_n^{exp}$ and x_n^{exp}.

Given a specific set of parameters, i.e., x_n^{exp}, x_n^o, a_n, d_n and λ_n, of all 25 EVs in Table I as well as the generation price $55.69, 49.54, 28.93, 40.88, 19.25$ over 5 hours, the optimal total charging amount of 10 cooperative EVs is shown in Fig. 2. From Fig.2, we can see that 10 cooperative EVs in total would optimally be charged by $0, 0.3, 2.2, 0.7, 0.6$ over these 5 hours. In general, the lower the generation price is, the larger amount the cooperative EVs are charged. Through such kind of scheduling, the charge station could enlarge its profit. However, it is not always true as shown in the figure. The generation price is the lowest at the last time slot while the charging amount is not the highest. The reason for this phenomenon is that only two cooperative EVs are at the charge station at the last time slot, which can be seen from Table I. Therefore, the total charging amount could not exceed 0.6, i.e., the largest charging amount of two cooperative EVs per time slot. The phenomenon also implies that the availability of cooperative EVs may be one factor to further enlarge the profit of the charge station.

The optimal real-time selling price is $24.00, 60.00, 59.99, 59.98, 59.97$ and corresponding optimal total consumption of 15 selfish EVs in total is $0.3, 0, 1, 0, 2.7$ over 5 hours as shown in Fig. 3. The profit of the charge station is 183.8062. In general, the lower the real-time selling price is, the larger amount that selfish EVs would be charged. However, one has to take into account the availability and expected charging amount of selfish EVs. For instance, the charging amount is only 0.3 at the first time slot, when the real-time selling price is the lowest. The reason behind such a phenomenon is that there is only one selfish EV at the charge station at the first time slot.

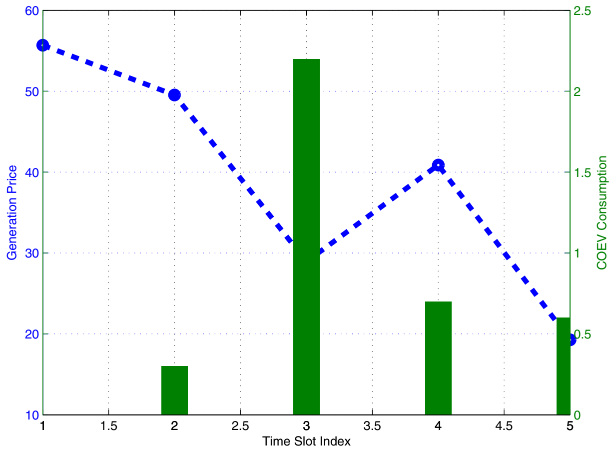

Fig. 2. optimal total consumption of cooperative EVs

TABLE I
PARAMETERS OF EVS

n	a_n	d_n	x_n^o	x_n^{exp}	λ_n
1	1	3	0.2	0.6	55
2	2	4	0.6	0.4	60
3	3	4	0.8	0.2	60
4	1	3	0.2	0.6	55
5	4	5	0.3	0.2	58
6	2	4	0.6	0.4	60
7	4	5	0.3	0.2	58
8	3	4	0.8	0.2	60
9	2	4	0.6	0.4	60
10	1	3	0.2	0.6	55
11	1	3	0.5	0.5	60
12	2	3	0.7	0.2	55
13	3	5	0.3	0.6	60
14	4	5	0.1	0.8	58
15	2	3	0.7	0.2	55
16	4	5	0.1	0.8	58
17	2	3	0.7	0.2	55
18	4	5	0.1	0.8	58
19	2	3	0.7	0.2	55
20	3	5	0.3	0.6	60
21	4	5	0.1	0.8	58
22	4	5	0.1	0.8	58
23	4	5	0.1	0.8	58
24	3	5	0.3	0.6	60
25	2	3	0.7	0.2	55

From Fig. 5, we can see that it is not necessary that the higher generation price implies the higher real-time selling price, taking the first time slot as an example. The two main reasons behind such a phenomenon are the intelligence of selfish EVs and the discharging of cooperative EVs. It is demonstrated in Fig. 5 that even though the generation price is the highest (55.69) at the first time slot, the real-time selling price is the lowest (24). The charge station does not buy any power from the generation plant. Instead, it schedules the cooperative EVs to discharge, as shown in Fig. 7. Moreover,

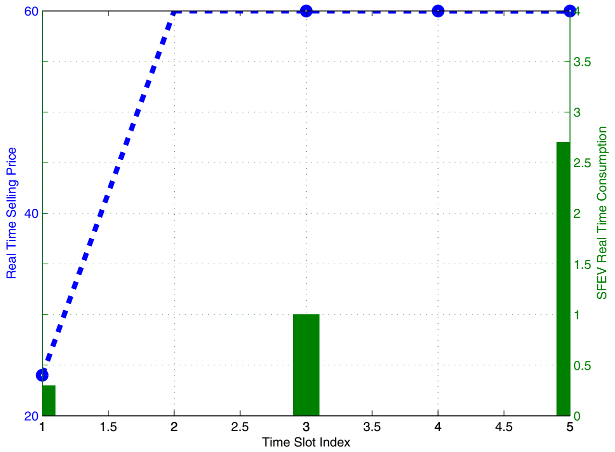

Fig. 3. optimal real-time pricing and the corresponding optimal total consumption of selfish EVs

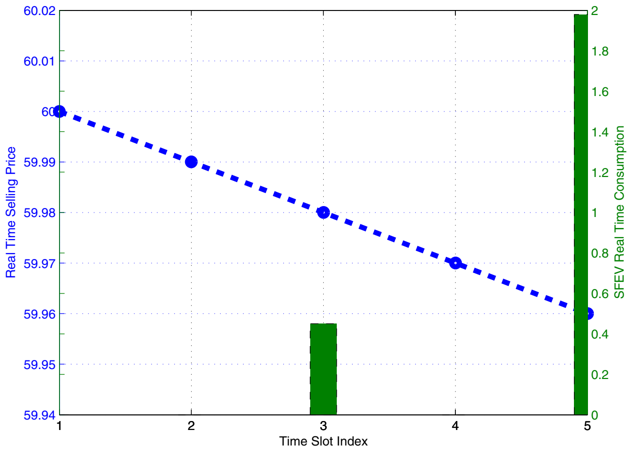

Fig. 4. maximal real-time pricing and the corresponding optimal total consumption of selfish EVs

only one selfish EV could be charged at the first time slot as can be seen from Table I. Thus the charge station set the real-time selling price low enough to persuade the selfish EV to be charged when cooperative EVs would discharge.

From Fig. 3 we can see that setting real-time selling price to $p_{max} = 60$ all the time is not the optimal choice to maximize the profit of the charge station. To validate this conclusion, we set the real-time selling price around 60 for 5 hours and optimize the charging scheme of cooperative EVs. The results are shown in Fig. 4. We can see that the charging amount of all 15 selfish EVs over 5 hours are $0, 0, 0.45, 0, 1.98$, respectively. Compared with the results in Fig. 3, we can see that the optimal total consumption of selfish EVs decreases significantly at all time slots due to the non-optimal real-time selling price. In such a case, even though the selling price is higher, the profit of charge station still decreases from 183.8062 to 100.3814.

B. Availability of Cooperative EV

The increasing availability of cooperative EVs would enlarge the maximal profit of the charge station when other conditions keep unchanged. The availability can be represented as stay length, charging/discharging speed, number of EVs, etc.. Such a phenomenon is because cooperative EVs, which are under the direct control of the charge station, can be used to enlarge the profit of the charge station. Without loss of generality, this paper takes the stay length of cooperative EVs as an example.

Specifically, we adjust the stay length of the first 5 cooperative EVs to 5 while keeping the other parameters unchanged. That is 5 out of 10 cooperative EVs would arrive at charge station at the first time slot and leave at the last time slot. With such a setting, the number of available cooperative EVs at the charge station increases from $3, 6, 8, 7, 2$ to $6, 8, 9, 9, 6$, while the optimal charging amount of cooperative EVs changes from $0, 0.3, 2.2, 0.7, 0.6$ to $-0.3, 0, 2.3, 01.8$, as shown in Fig. 6 and Fig. 7. In such a case, the profit of the charge station increases from 183.8062 to 217.9916, which verifies our conclusion that the profit of the charge station increases as the availability of cooperative EVs increases.

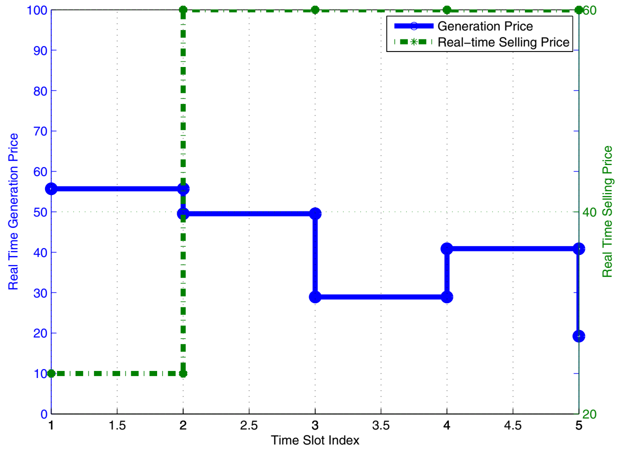

Fig. 5. generation price and the corresponding real-time selling price

The increasing stay length of cooperative EVs also enables more flexible ability of charging and discharging at each time slot. From Fig. 2, we can see that the generation price is the lowest at the last time slot. With the increasing stay length of cooperative EVs, more cooperative EVs can be charged at the last time slot as shown in Fig. 7. The total charging amount of 10 cooperative EVs at the last time slot has increased from 0.6 to 1.8. Moreover, the enlarged stay length enables the cooperative EVs to be discharged by 0.3 at the first time slot, where the generation price is the highest. In this way, the enlarged stay length increases the charge station's profit.

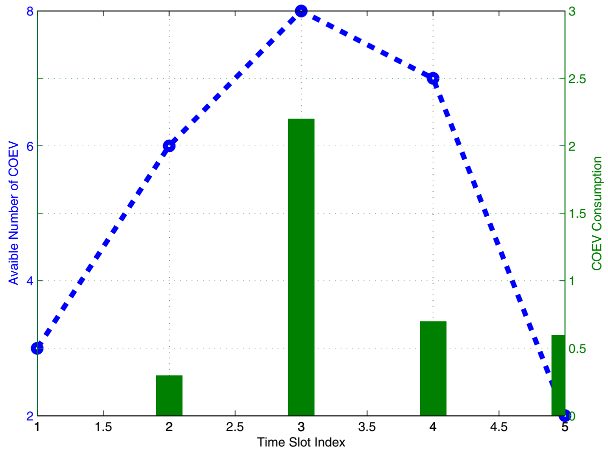

Fig. 6. number and optimal total consumption of cooperative EVs with original stay length

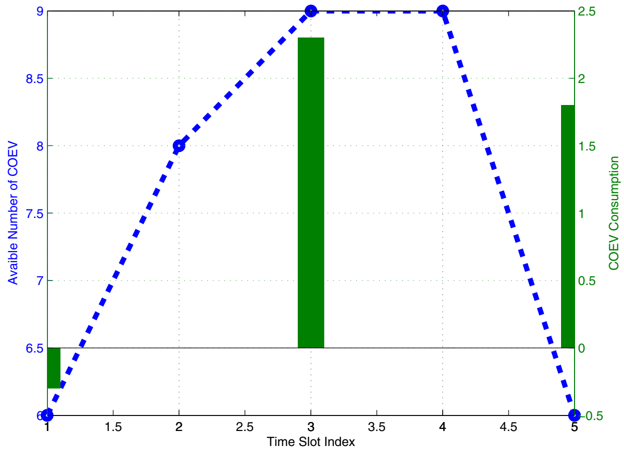

Fig. 7. number and optimal total consumption of cooperative EVs with enlarged stay length

VI. CONCLUSION AND FUTURE WORK

In this paper, we consider a V2G system where there is a profit-driven charge station and a set of EVs which can be either cooperative or selfish. By analyzing selfish EVs' utility function, the charge station can derive an optimal real-time selling pricing for selfish EVs and an optimal scheduling for cooperative EVs to maximize its own profit. Simulation results verify the optimality of the proposed scheme. Moreover, from the simulation results, we find that the availability of cooperative EVs is one key factor regarding the charge station's profit. To obtain higher profit, charge station should provide incentive such as low price to attract more cooperative EVs and enlarge their stay duration.

The major contribution of this paper is to treat all participants including both EVs and the charge station as rational players in the power market. Such a setting increases the penetration level of theoretical reasoning into practice. One important future work is to relax the fixed cooperative and selfish EV population to dynamic population where EV has the freedom to choose either as a cooperative EV or a selfish EV. Moreover, in this paper, we assume that there is only one charge station. To avoid monopoly, we will extend our work to the scenario with multiple charge stations where there exists another game among different charge stations.

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