Group Bidding for Guaranteed Quality of Energy in V2G Smart Grid Networks

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***Abstract*—With the aid of advanced Information and Communication Technologies (ICT), Vehicle-to-Grid (V2G) networks will play an important role in supporting and enhancing the distributed electricity supply in the next generation power grid–smart grid. In order to ensure stability of the power grid and satisfy the Quality of Energy (QoE) requirements of Electric Vehicles (EVs), this paper proposes a two-level group bidding mechanism for the electric energy trade between the grid and EVs. Communication networks are used to support the exchange of relevant information between the grid and EVs. EVs act as mobile energy storage and compete to be one of the members in the electricity feedback group organized by aggregators. We aim at minimizing the cost of given electricity demand of the grid and maximizing the profit of those auction winner EVs. A quantity based feedback electricity unit pricing scheme is proposed to incentivize the participation of EVs in V2G networks. Moreover, Vickrey-Clarke-Groves (VCG) auction-based algorithms are designed to implement our proposed mechanisms. Simulation results indicate that our mechanism is able to reduce the cost of the grid while offer EVs significant incentives to participate in the V2G power market.**

***Index Terms*—Vehicle-to-Grid (V2G) networks, auction, group-selling, truthful bidding strategy.**

I. Introduction

Vehicle-to-Grid (V2G) networks will be a kind of large interconnected infrastructures which enable bi-directional transmission of both electricity and information between the power grid and Electric Vehicles (EVs). To respond to imminent electricity demands in smart grid, V2G networks will play an important role in decreasing the need for producing and loading the grid with more newly generated electricity [1]. Surplus electricity stored in the batteries of EVs is allowed to be fed back into the grid in V2G networks. For the realization and performance of V2G networks, communication networks are one of the key components as the information including dynamic pricing of electricity, varying frequency regulation signals of the grid, and real-time State of Charge (SoC) of EVs should be delivered reliably and timely. Vehicle Ad hoc NETworks (VANETs), cognitive radio networks [2] and LTE networks can be applied to provide the communication platforms for V2G networks.

In addition, a market mechanism between EVs and the grid is used to trade surplus electricity of EVs since the grid and the EVs have contradictory objective functions. On one hand, the grid aims at minimizing the electricity cost when the grid buys from EVs. The cost should not be higher than the amount when the grid produces the same amount of electricity by power generators themselves in a peak load condition. On the other hand, in order to motivate EVs to participate in V2G networks, each EV is willing to sell its electricity only when the price is higher than its charging cost. The unit price of the feedback electricity from each EV may be different because each EV has variable Quality of Energy (QoE) requirements. QoE is a new Quality of Service (QoS) metric in V2G networks, that is, the degree of satisfaction of an EV to be charged or discharged, and it is directly related to the SoC of each EV.

There are many studies on resident load management and energy resource allocation in the smart grid with integration of renewable energy resources or microgrids. However, only few focuses on the energy resource allocation problem and QoE provision in V2G systems. In [3], distributed EV aggregations are coordinated with varying wind power and daily load. The work in [4] proposes a distributed demand response control strategy to dispatch the heating ventilation and air-conditioning loads with the integration of intermittent renewable power supply. In [5], the authors develop an energy resource allocation method in smart grids with renewable energy resources with short messaging services and direct access to individual load. [6] proposes energy resource allocation strategies of home energy consumers through particle swam optimization or heuristic methods. In [7], the authors utilize battery storage system and price management scheme to minimize the cost of a consumer equipped with a photo voltaic power or battery connected to the microgrid.

Game theory is often applied to model and analyze the resource allocation problem in the smart grid. In [8], the authors study residential power scheduling through a Stackelberg game in which the energy management controller is the leader and the service providers are the followers. A real-time pricing scheme is proposed to save the expense of consumers and to avoid peaks for the grid. The work in [9] investigates the benefits of distributed energy resources management for a smart community consisting of a large number of residential units and a shared facility controller, through a non-cooperative Stackelberg game model. In [10], the energy resource allocation problem is addressed in a network scenario with multiple utility companies and consumers. A Stackelberg game is applied to maximize the revenue of each utility company and the payoff of each user. In [11], the interaction between utility companies and residential users is modeled as a two-level game, where the competition among utility companies is a non-cooperative game and the interaction among residential users is an evolutionary game.

This paper focuses on solving the energy resource allocation problem in V2G systems using auction theory. Since a single EV can only provide limited electric energy resources, the proposed mechanism should offer enough incentive to encourage large number of EVs to participate in the V2G system. Inspired by Groupon for spectrum auction [12], we propose a quantity based feedback electricity unit pricing scheme. Moreover, as the power grid is the only buyer and the EVs are the multiple sellers, reverse auction matches this scenario. Therefore, we propose a group-selling based incentivized bidding mechanism, operated in a distributed manner with low complexity and guaranteed truthfulness. We attempt to reduce the cost for balancing the supply and the demand of the grid, while seeking more profit to stimulate more EVs to participate in the V2G system. In this paper, we have the following major contributions.

- The group-selling mechanism is introduced into V2G systems. The energy resource allocation problem in a V2G scenario is formulated as a two-level auction model, i.e., the first level auction between EVs and aggregators followed by the second level auction between aggregators and the electric grid.
- We propose the Group-Selling Formation (GSF) algorithm and the Group Determination (GD) algorithm to realize an auction based energy resource allocation scheme in V2G system.
- We demonstrate the efficiency of the proposed approach. Our mechanism is theoretically proved to truthfulness guaranteed.

The rest of this paper is organized as follows. In Section II, we propose the system model, followed by the quantity based feedback electricity unit pricing scheme as well as the cost function of the grid. Section III presents the group bidding mechanism in detail. Then, we analyze the truthfulness of the proposed mechanism. Simulation results presented in Section IV verify that our mechanism is able to reduce the cost of the grid for supplying its deficit power and obtain more profit for the EVs participating in the V2G system. Finally, Section V concludes this paper.

II. System Model

As shown in Fig. 1, our proposed group bidding mechanism is implemented by a two-level reverse auction based approach. Each EV first submits its sealed bid to an aggregator which organizes an electricity feedback group. To satisfy QoE requirement of an EV, the aggregator should be located in its reachable range. The remaining electricity in the EV should be sufficient to reach the aggregator in addition to the electricity fed back to the grid. After receiving bids from numerous EVs, the aggregator forms a sealed group bid to the grid. A sealed group bid includes the amount of electricity that the electricity feedback group can offer, and the unit price of feedback electricity provided the group. Hence, with this group bidding mechanism, auction processes will be conducted twice to complete energy resource allocation in the V2G system. Aggregators as group organizers decide the winner EVs in their groups, and on the other hand, the grid determines the winner aggregators. Winner EVs belonging to the groups of winner aggregators finally get the opportunities to feed their surplus electricity back into the grid. The auction process usually contains the allocation stage and the payment stage. The payment to each auction winner is calculated in the second stage.

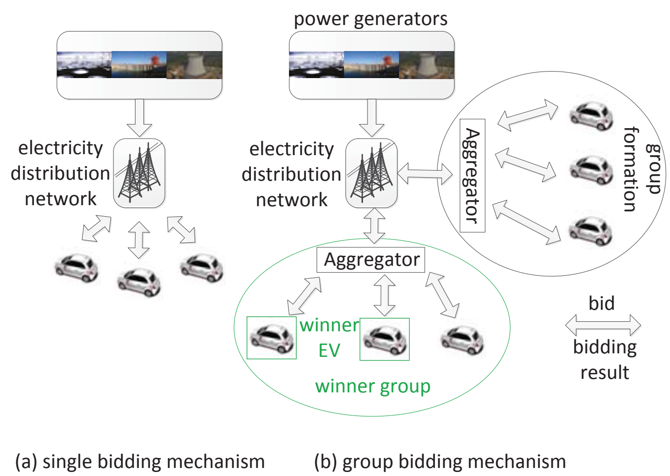

Fig. 1: The proposed group bidding mechanism in V2G networks

Let $\mathbf{W}$ denote the set of final winner EVs, $\mathbf{N} = \{1, 2, ..., N\}$ denote the set of all EVs, and $\mathbf{A} = \{1, 2, ..., A\}$ denote the set of aggregators. We consider that the whole operation time in one day is divided into N_t time slots. The length of each time slot can be set as required. At the beginning of each time slot, according to the supply and demand relationship of the last time slot as well as the prediction for this slot, the grid decides the amount of electricity that should be bought from EVs if the supply of the grid is less than the demand. D denotes the quantity of deficit power of the grid, i.e. the difference between the demand and the supply from the power generators in the grid.

The cost function $C_{grid}(S)$ is defined as the sum of the expenses of buying electricity and the extra monetary cost for balancing the different amount of electricity between the demands of the grid and the total electricity trading volume S, that is

$$C_{grid}(S) = g(|D - S|) + \sum_{i \in \mathbf{W}} \bar{p_i}\bar{q_i} \tag{1}$$

where $g(.)$ is the cost function of the grid, $\bar{p_i}$ denotes the negotiated prices between the grid and each winner EV and $\bar{q_i}$ represents the trading volume between the grid and each winner EV. It is assumed that $g(.)$ follows the generation cost curve [13] shown in Fig. 2, since the electricity amount difference between D and S is considered to be generated by power generators themselves when $S < D$. When $S > D$, the cost function needed to balance D and S should also be an increasing function of $|D-S|$.

Based on the generation cost curve, the quantity based feedback electricity unit pricing scheme should be carefully designed. The electric grid aims at minimizing the cost function, thus, a large number of EVs should be encouraged to participate in the V2G system, as surplus electricity provided by one single EV is far lower than the amount that the grid needs. However, EVs expect to get the payment from discharge above their charging costs. The payment from the grid should cover the cost due to the degradation of EVs' batteries when feeding back the electricity. The pricing mechanism should ensure that EVs can make profit.

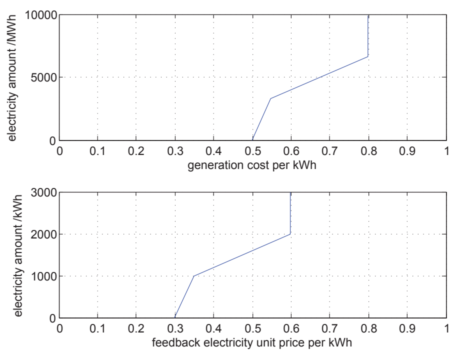

Fig. 2: Quantity based feedback and new generation electricity unit prices

Motivated by this, we design a quantity based feedback electricity unit pricing scheme for the power grid, as shown in Fig. 1. The bidding price of the bidder is a function of the quantity of electricity that the bidder can supply. The feedback electricity unit price paid by the grid should be lower than the unit price of the generation cost of the grid, but higher than the unit price of the charging cost of EVs. We consider the feedback electricity unit price as a piecewise linear function of the quantity of electricity, denoted by $g_p(.)$.

III. Group Bidding Mechanism

In this section, we propose an incentive auction based group bidding mechanism for V2G systems to minimize the cost of the grid and maximize the profit of EVs meanwhile satisfying the QoE requirements of both the grid and EVs.

In the group bidding mechanism, in order to obtain high feedback electricity unit prices, V2G EVs first join feedback electricity groups. The bidding price that each EV bids is related to its expectation of the amount of electricity that the group it joins could offer to the grid. With the quantity based feedback electricity unit price scheme, the proposed group-selling approach is processed through two-level auction phases. In the first level auction, each EV sends one sealed bid to one aggregator which is within its reachable range. Aggregator j decides the set of winner EVs $\mathbf{W_j^f}$. Based on these winning bids, the aggregators calculate the group bids and submit these bids to the grid. In this second level auction, aggregators become sellers and the grid is the buyer. All winner aggregators in the second level auction, $\mathbf{W_a}$, is notified by the grid, and aggregator j $(j \in \mathbf{W_a})$ is paid unit price $\bar{p_j^g}$. Then, the winner aggregators publish bidding results to the winner EVs in their groups, and finally those EVs are paid the unit price $\bar{p_{ij}}$. The utility of EV i is defined as

$$U_i = \begin{cases} \bar{p_{ij}} - p_{ij} & if \ i \in \mathbf{W_j^f} \\ 0 & otherwise \end{cases} \tag{2}$$

The utility of aggregator j is defined as

$$U_j^a = \begin{cases} \bar{p_j^g} - \bar{p_{ij}} & if \ j \in \mathbf{W_j^a} \\ 0 & otherwise \end{cases} \tag{3}$$

A. Electricity Feedback Group Formation

Aggregators as group organizers calculate the amounts and the unit prices of feedback electricity for their own groups. These results are the crucial elements of the two-tuple bids submitted to the grid in the second level auction.

Let $\mathbf{N_j}$ denote the set of EVs which send their bids to aggregator j, and N_j represent the number of bids. N_j also represents the number of EVs which participate in the electricity feedback group of aggregator j. Each EV bidder sends its two-tuple sealed bid $B_i = (p_{ij}(Q_{ij}), q_{ij}^{max}), i \in \mathbf{N_j}, j \in \mathbf{A}$ to an aggregator located in its reachable range, where $\mathbf{A}$ denotes the set of aggregators as feedback electricity group organizers. Let Q_{ij} denote the amount of electricity that aggregator j's group could offer predicted by EV i. The unit price p_{ij} asked by EV i can be determined under the quantity based feedback electricity unit price scheme. For example, if EV i predicts the group of aggregator j could offer 2000 kWh electricity, the unit price that EV i asks aggregator j for its electricity will be 0.5983 per kWh according to Fig. 1. $\mathbf{W_j^f}$ denotes the set of winner EVs in the first level auction organized by aggregator j. Algorithm 1 presents the details of the feedback electricity group formation process.

Algorithm 1 GSF: Group-Selling Formation algorithm

Initialization:

$B_i = (p_{ij}(Q_{ij}), q_{ij}^{max})$; j; η_j; N_j; $\mathbf{W_j^f} = \varnothing$

Iteration:

```
Q_s ⇐ Sort(q_ij^max, "non − increasing");
q_j^c = Q_s(⌈ η_j ∗ N_j ⌉);
Q_ss ⇐ Sort(Q_ij, "non − decreasing");
for k = ⌈ η_j ∗ N_j ⌉ − 1 to 1 do
    if Q_kj ≤ (⌈ η_j ∗ N_j ⌉ − k) ∗ q_j^c then
        W_j^f = [1 : k];
        q_j^g = sizeof(W_j^f) ∗ q_j^c;
        p_j^g = g_p(Q_(k+1)j);
        break;
    end if
end for
```

Output:

q_j^g, p_j^g

Algorithm 1 presents the details of the feedback electricity group formation process. The GSF algorithm is proposed to obtain group-selling electricity amount and group-selling unit prices. The idea of the proposed GSF algorithm is that first remove those V2G EVs which ask for higher prices beyond certain limit, and of which the quantity of electricity they can supply is less than the clear quantity of electricity q_j^c, then, aggregator forms an electricity feedback group with as much electricity as possible. η_j is a parameter used by each aggregator j to decide the clear quantity of electricity. Different aggregators could have either the same or different η_j. EVs are first sorted by the quantity of electricity that they can provide in non-increasing order. EVs that are only able to sell less than q_j^c are removed. Then, going through the remaining EVs, EVs with too high unit price for their feedback electricity lose the auction. The GSF algorithm is executed independently by each aggregator. The tuple (p_j^g, q_j^g) forms the bid B_j^a of aggregator j ($j \in \mathbf{A}$), which will be sent to the grid to compete for the second level auction. Auction results of the first level are not published by aggregators immediately, because EV i ($i \in \mathbf{W_j^f}$), is not the final winner in the two-level auction, and p_j^g is not the final unit price. If aggregator j wins the second level auction, those winner EVs belonging to the winner groups are able to feed back electricity to the grid.

In the GSF algorithm, the two sortings have the complexity with $\mathscr{O}(N_j log N_j)$ [12] and the loop takes at most $\mathscr{O}(\lceil \eta_j * N_j \rceil - 1)$ time. Therefore, the time complexity of the GSF algorithm is $\mathscr{O}(N_j log N_j)$.

B. Auction Between the Aggregators and the Grid

Bid $B_j^a = (p_j^g, q_j^g)$ is submitted by aggregator j to the grid. The allocation stage of the second level auction can be formulated as an integer linear problem (ILP). The decision variables in the ILP are binary variables $x_j, j \in \mathbf{A}$, and $x_j = 1$ if the group organized by aggregator j wins the second level auction, 0 otherwise. The objective of the optimal problem in the allocation stage of the second level auction is to minimize the cost for the grid. The optimization problem is formulated as an ILP as follows.

$$min\ C_{grid}(\sum_{j=1}^{A} x_j q_j^g) \tag{4}$$

$$s.t.\ x_j \in \{0, 1\}, \forall j \in \mathbf{A} \tag{5}$$

$$x_j = 0, \forall j \notin \mathbf{W_a}; x_j = 1, \forall j \in \mathbf{W_a} \tag{6}$$

The objective function (4) minimizes the cost to balance the difference between demand and supply of the grid. Constraints (5) and (6) ensure the integrality of the binary decision variables, where $\mathbf{W_a}$ is the set of aggregators that are the second level auction winners.

However, the time complexity to find the optimal solution of the above problem is high if the classic Vickrey-Clarke-Groves (VCG) auction mechanism is used [16]. We propose the Group Determination (GD) algorithm to determine the winner groups in the second level auction. This algorithm retains the property of truthfulness of the VCG auction mechanism.

Algorithm 2 GD: Group Determination algorithm

Initialization:

D; $B_j^a = (p_j^g, q_j^g)$; $j \in \mathbf{A}$; $\mathbf{W_a} = \varnothing$

Iteration:

$L_g \Leftarrow Sort(\frac{p_j^g}{q_j^g}, "non-decreasing");$
for all $j \in L_g$ **do**
  if $D > 0$ **then**
    $D = D - q_j^g$;
    $\mathbf{W_a} = \mathbf{W_a} \bigcup \{j\}$;
  end if
end for

Output:

$\mathbf{W_a}, max(p_j^g, j \in \mathbf{W_a})$

In the GD algorithm, aggregators are first sorted in non-decreasing order by $\frac{p_j^g}{q_j^g}$. Then, the grid goes through the aggregators in the sorted list. For each aggregator, the grid examines whether the total electricity demand has been satisfied. The loop ends when the electricity demand is satisfied. If not, the aggregator in this round becomes an auction winner and the electricity demand is updated. The unit price paid to all winner aggregators is the maximum unit price that aggregators belonging to $\mathbf{W_a}$ request. For the GD algorithm, the time complexity is $\mathscr{O}(A)$, where $A \ll N$.

In the final stage, the electric grid now publishes the aggregator winners, and the EV winners after the two-level auction can also be notified. At this time EV winner i ($i \in \mathbf{W_j^f}, j \in \mathbf{W_a}$) begin to feed q_j^c units of electricity through aggregator j towards the grid. Aggregators charges the grid the unit price $\bar{p_j^g}$ and each aggregator pays to its winner EVs the unit price $\bar{p_{ij}}$.

C. Truthfulness of Group Bidding Mechanism

Truthfulness is essential in bidding mechanism as it requires all buyers or sellers to report the true values in their bidding information. In this section, we will prove that the truthfulness of the proposed mechanism is guaranteed.

Theorem 1: The group bidding mechanism is truthful in both the first level auction and the second level auction.

Proof: Realization of the group bidding mechanism consists of the GSF algorithm and the GD algorithm. Hence, the truthfulness proof of the group bidding mechanism will be accomplished in two parts, i.e., one proof for the truthfulness of the GSF algorithm, and another for the truthfulness of the GD algorithm. ■

Lemma 1: The first level auction is truthful for all EVs.

Proof: We show that in all cases EVs cannot improve their utilities by bidding untruthfully.

Case 1: EV i wins when both bidding truthfully and untruthfully. No matter whether EV i bids truthfully or untruthfully, it will get the same payment as an auction winner.

Case 2: EV i fails when both bidding truthfully and untruthfully. The utility of EV i is always zero, and there is no incentive to bid untruthfully.

Case 3: EV i wins when bidding truthfully and fails when bidding untruthfully. According to the utility function of EVs, a winner EV's utility is non-negative and a loser EV's utility is zero.

Case 4: EV i fails when bidding truthfully and wins when bidding untruthfully. By the GSF algorithm, if EV i fails when bidding truthfully, it fails either because $q_{ij}^{max} < q_j^c$ or because $Q_{ij} > (\lceil \eta_j * N_j \rceil - i) * q_j^c$. If $q_{ij}^{max} < q_j^c$, assume EV i wants to win by bidding untruthfully. It then has to submit $q_{ij}^{max} \geq q_j^c$. Suppose EV i wins by submitting $q_{ij}^{max} \geq q_j^c$. However, its utility remains zero because it cannot afford that winner EVs are appointed to feedback q_j^c kWh electricity. If $Q_{ij} > (\lceil \eta_j * N_j \rceil - i) * q_j^c$, and EV i wants to win by bidding untruthfully, it has to submit $Q_{ij} \leq (\lceil \eta_j * N_j \rceil - i) * q_j^c$. By the GSF algorithm, $g(Q_{ij}) > g(Q_{(i+1)j})$ and the winner EVs will be paid a price of $g(Q_{(i+1)}j)$. The untruthful Q_{ij} is smaller than the truthful Q_{ij}, hence the payment of untruthful bidding will be less.

Consequently, the analysis of all the cases above proves that all EVs will choose to send the truthful two-tuple bids $(p_{ij}(Q_{ij}), q_{ij}^{max})$. ■

Lemma 2: The second level auction is truthful for aggregators.

Proof: We first elaborate that a two-dimensional reverse auction is truthful if it is qualified with the characters of exactness, monotonicity, participation and critical defined in [16].

Exactness and participation are satisfied in the GD algorithm and the utility definition of aggregators. In the GD algorithm, aggregators are sorted by $\frac{p_j^g}{q_j^g}$ in non-decreasing order, and there exists an critical value $(\frac{p_j^g}{q_j^g})_c$. Hence the GD algorithm satisfies both Monotonicity and Criticality. ■

IV. Performance Evaluation

Matlab based simulation experiments are conducted to evaluate the performance of our auction based group-selling approach for energy resource allocation in V2G systems. We will evaluate if our group bidding mechanism can reduce the cost of the grid. It is expected show that the group bidding mechanism can seek more profit for the EVs in a V2G system compared to the single bidding mechanism in which EVs send bids directly to the grid without electricity feedback groups. TABLE I shows the parameters used in our simulation experiments..

We consider 3.3494 million EVs participating in the simulation scenario according to the data report of Fujian Province, China [15]. The number of aggregators A is 16497, which is the number of the results by searching "gasoline station in Fujian Province" on the Google map. Support that vehicles will be substituted by EVs and charging stations or aggregators for EVs are ubiquitous in the future as gasoline stations now. It is assumed that the number of EVs feeding back their electricity through each aggregator is Gaussian distributed with the mean value 203 ($\approx 3349400/16497$) and the variance 4. The maximum amount of electricity each EV could offer is a random value which is uniformly distributed over $[7.857\ 33.162]$ kWh, where the upper bound and lower bound are set to be 50% of the maximum and minimum battery capacities of EVs [14]. The unit prices asked by EVs is $g_p(Q_{ij})$. η is set as 0.9 for all aggregators.

TABLE I: Simulation parameters

number of EVs	3.3494 million
number of aggregators	16497
distribution of EVs at each aggregator	$N(203, 4)$
distribution of q_{ij}^{max}	$U[7.857\ 33.162]$
$\eta_j, j \in \mathbf{A}$	0.9

Fig. 3 shows the convergence of the GD algorithm under the change of the grid's cost. It is observed that the cost of the grid converges before the algorithm terminates. Moreover, when the demand for electricity becomes lower, the convergence speed of the GD algorithm is faster.

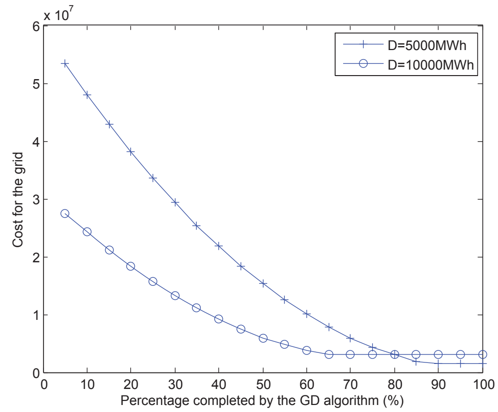

Fig. 3: Convergence of the GD algorithm

Fig. 4 shows that our proposed group bidding mechanism is effective in shaping the electric load curve for the grid. Under the group bidding mechanism for energy resource allocation in V2G system, the trading volume between the grid and EVs is close to the amount that the grid demands as much as possible. It is obvious that peak load and load variation of the grid can be reduced remarkably by our proposed mechanism.

Fig.5 shows that the cost for the grid when applying the group bidding mechanism is always lower than **Generating by Power Generators**. Another observation is that the cost gap between these two ways becomes larger when the grid demands more electricity.

Fig. 6 compares the unit prices that each EV auction winner will receive by applying the single bidding mechanism

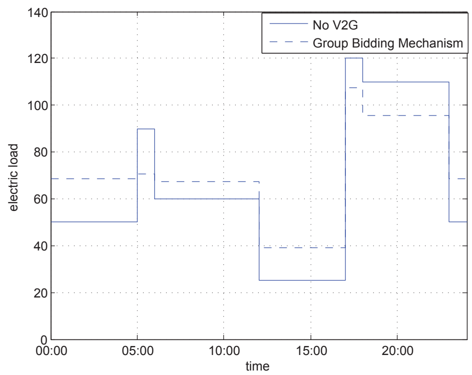

Fig. 4: Electric load curve under different schemes

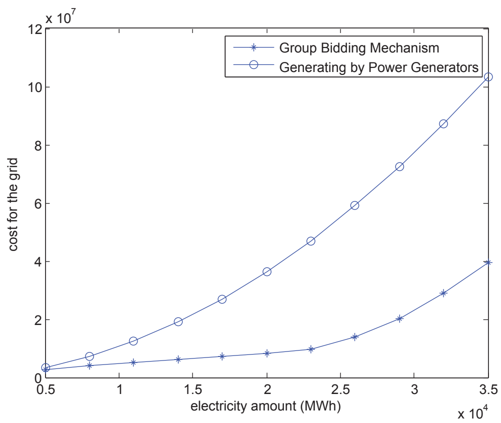

Fig. 5: Cost for the grid under different schemes

and the group bidding mechanism. With the single bidding mechanism, the price is always around 0.3 per kWh, which may not be able to motivate the EVs to participate in the V2G system. By applying the group bidding mechanism, the EV auction winners can gain much higher unit prices for their feedback electricity.

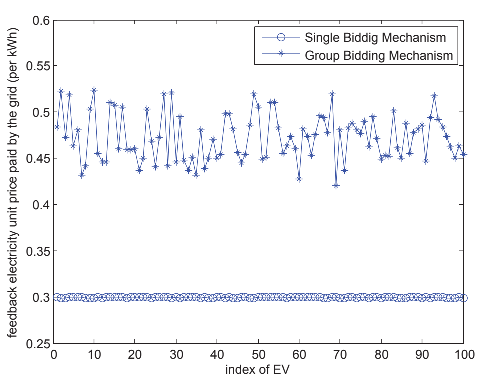

Fig. 6: Feedback electricity unit prices that EV winners charge the electric grid

V. Conclusion

In this paper, we have proposed a group bidding mechanism for energy management in smart V2G networks. A quantity based feedback electricity unit price scheme is designed for the electric grid with incentives for EVs to participate in the V2G trading system. Moreover, a group bidding mechanism is implemented as a two-level distributed reverse auction. Simulation results indicate that our approach can reduce the cost of the grid. The proposed scheme provides incentives to the EVs for feeding power back into the grid. Consequently, the auction based group-selling approach for energy resource allocation in V2G networks is a win-win approach for both EVs and the electric grid.

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