Stable Matching Based Cooperative V2V Charging Mechanism for Electric Vehicles

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***Abstract*—In this paper, we investigate the flexible and efficient charging mechanism for electric vehicles (EVs). We first provide a developed V2V charging concept, termed as cooperative V2V charging, which enables active cooperation through charging and discharging operations between EVs as energy consumers and EVs as energy providers and is beneficial to both sides. Then, based on the defined utilities of EVs as energy consumers and EVs as energy providers, we propose a novel stable matching based cooperative V2V charging mechanism by taking each EV's individual rationality into consideration. Furthermore, we provide two efficient stable V2V matching algorithms, resulting in optimal V2V matching solutions in terms of the utilities of EVs as energy consumers and the utilities of EVs as energy providers, respectively. Simulation results verify the efficiency of our proposed stable matching based cooperative V2V charging mechanism in improving the utilities of both EVs as energy consumers and EVs as energy providers as well as reducing the energy consumption of the EVs compared with the traditional EV charging protocol.**

I. Introduction

With ever increasing concerns on environmental issues and clean energy, electric vehicles (EVs) have attracted more and more attention from governments, industries, and costumers. EVs are regarded as one of the most effective strategies to reduce the oil dependence and gas emission, and to increase the efficiency of energy conversion [1]. When integrated with the power grid based on charging and/or discharging operations, EVs become energy storage units, and can not only serve as a transportation tool but also act as controllable loads and distributed sources for the power grid [2].

On the one hand, the fast development of EVs brings a significant new load on the current power system. Without efficient control strategies, the EV charging process may overload the power grid at peak hours, especially in residential communities. On the other hand, EVs can benefit the power grid as a flexible load through smart charging/discharging scheduling to reduce the peak load and shape the load profile. Therefore, in the literature, with the concept of demand side management (DSM), many works [3]–[7] have focused on the charging/discharging scheduling and energy management protocols to control and optimize the charging process for EVs integrated with the power grid.

Although various optimization methods as well as game theory models have been employed to design different EV charging and energy management protocols in existing work, most current researches are still limited to the interactions and power transfer between EVs and the power grid. Most recently, some works [5]–[7] have proposed to investigate vehicle-to-vehicle charging strategies, which can offer more flexible charging plans for gridable EVs in order to offload the EV charging loads from the electric power systems. However, designing an effective and efficient online vehicle-to-vehicle charging strategy remains an open issue.

In this paper, we investigate the flexible and efficient charging mechanism for EVs by incorporating V2V charging into EV charging/discharging behaviors. We first provide a developed V2V charging concept from a cooperative perspective, termed as cooperative V2V charging, which describes direct EV-to-EV power transfer through active cooperation between EVs as energy consumers and EVs as energy providers. In order to evaluate the charging/discharging behaviors via cooperative V2V charging, we define the utilities of the EVs, based on which we find that cooperative V2V charging would be beneficial to both EVs as energy consumers and EVs as energy providers. Then, by taking the individual rationality of each EV into consideration, we propose a novel stable matching based cooperative V2V charging mechanism, and further provide two efficient stable V2V matching algorithms, that is, EV-consumer-oriented V2V matching algorithm and EV-provider-oriented V2V matching algorithm, leading to optimal V2V matching solutions in terms of the utilities of EVs as energy consumers and the utilities of EVs as energy providers, respectively. Simulation results verify the efficiency of our proposed stable matching based cooperative V2V charging mechanism in improving the utilities of both EVs as energy consumers and EVs as energy providers. Moreover, the simulation results also indicate that the energy consumption of the EVs can be reduced effectively with the proposed cooperative V2V charging mechanism compared with the traditional EV charging protocol.

The remainder of this paper is organized as follows. In Section II, the system model is described. In Section III, stable matching based cooperative V2V charging mechanism is proposed with two efficient stable V2V matching algorithms. Simulations are provided in Section IV and the conclusions are given in Section V.

II. System Model

In this paper, we consider a typical EV-integrated vehicular network, mainly comprising the EVs, the charging stations, the power/communication infrastructures, and a data control center. Each EV is equipped with an bidirectional charger and thus can perform both charging and discharging behaviors. The moving EVs in the investigated system can be divided

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into three categories: 1) EVs that demand power act as energy consumers, denoted by EV_i^C, $i = 1, 2, \ldots, N$; 2) EVs that have extra power act as energy providers, denoted by EV_j^P, $j = 1, 2, \ldots, K$; 3) EVs that are not interested to participate in any current energy trading. For presentation convenience, we denote $\mathcal{N} \triangleq \{1, 2, \ldots, N\}$ and $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$. The data control center is connected to all the distributed power and information infrastructures and can collect the real-time information about the nearby charging stations, parking lots, and the EVs via Internet of Things (IoT) and vehicular communications [8], [9].

III. Stable Matching Based Cooperative V2V Charging Mechanism

A. Cooperative V2V Charging

In this paper, we propose a developed concept based on the V2V operation of V2X concept [5], termed as cooperative V2V charging, which describes the power flow connection among different EVs in a cooperative charging/discharging manner. Cooperative V2V charging is beneficial to both EVs as energy consumers and EVs as energy providers, leading to a win-win energy trading situation. Based on cooperative V2V charging, the charging/discharging behaviors of EVs can be performed in a more flexible and smarter manner.

Currently, a feasible way to realize V2V power transfer among different EVs is through the V2V framework described in [5], where an aggregator is employed for coordinated control of grouping EVs for charging and discharging. The aggregator behaves as a control device that collects all the information about the EVs and the grid status and then executes the V2V power transfer. Since these aggregators do not need to pull in power from the power grid to operate the V2V power transfer, they would be much cheaper and more easily deployed than the charging stations. For instance, such aggregators can be widely deployed in various communities or public parking lots.

B. EV Utility Definition

In order to achieve smart and efficient cooperative V2V charging, first, we need to define the utilities of the EVs as energy consumers/providers to evaluate their charging/discharging behaviors. The utilities are designed based on the EVs' cost/profits through potential energy trading and the corresponding energy and time cost for driving to the selected trading spot.

1) EV as an Energy Consumer: The utility of EV_i^C, $i \in \mathcal{N}$ as an energy consumer is defined as

$$U_i^C\left(\mathrm{EV}_j^P\right) = -p_t a_i^C - \mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{EV}_j^P\right) \tag{1}$$

where p_t is the unit power trading price, a_i^C represents the requested power amount, and EV_j^P is the potential paired energy provider for EV_i^C. In general, the electricity buying price p_b set by the power grid for the EVs to trade their surplus power is often considerably lower than the electricity selling price p_s for the EVs to get charged [10].

As a preference baseline, we also define the utility of EV_i^C when getting charged at the charging stations as

$$U_i^C\left(\mathrm{CS}\right) = -p_s a_i^C - \mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{CS}\right) \tag{2}$$

where CS denotes the nearest charging station for EV_i^C and p_s is the electricity selling price set by the power grid, that is, the power trading price between the charging station and the EVs as energy consumers.

Note that $\mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{EV}_j^P\right)$ and $\mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{CS}\right)$ denote the energy cost for EV_i^C to drive to the selected parking lot to achieve power transfer with EV_j^P and to drive to the nearest charging station to get charged, respectively, which can be given as

$$\mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{EV}_j^P\right) = p_t \times \beta_i^C \times \mathrm{Dis}\left(\mathrm{EV}_i^C, \mathrm{PL}\right) \tag{3}$$

and

$$\mathrm{Cost}\left(\mathrm{EV}_i^C, \mathrm{CS}\right) = p_s \times \beta_i^C \times \mathrm{Dis}\left(\mathrm{EV}_i^C, \mathrm{CS}\right) \tag{4}$$

where β_i^C is the moving energy cost per km for EV_i^C, $\mathrm{Dis}\left(x, y\right)$ represents the driving distance between x and y, and PL denotes the selected parking lot for EV_i^C to achieve power transfer with EV_j^P. Note that here the energy cost for EV_i^C to get charged at the charging station is valued by the electricity selling price p_s of the power grid.

2) EV as an Energy Provider: The utility of EV_j^P, $j \in \mathcal{K}$ as an energy provider is defined as

$$\begin{aligned} &U_j^P\left(\mathrm{EV}_i^C\right) \\ =\ &\left(p_t - p_0\right) a_i^C - \mathrm{Cost}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right) - \mathrm{Time}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right) - \Phi \end{aligned} \tag{5}$$

where p_t and p_0 are the current trading price and the original cost price per unit power, respectively, and Φ is the amortized cost to value the battery loss per each V2V power transfer. $\mathrm{Cost}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right)$ and $\mathrm{Time}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right)$ denote the energy cost and the time cost for EV_j^P to drive to the selected parking lot to achieve power transfer with EV_i^C, respectively, which can be given as

$$\mathrm{Cost}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right) = p_t \times \beta_j^P \times \mathrm{Dis}\left(\mathrm{EV}_j^P, \mathrm{PL}\right) \tag{6}$$

and

$$\mathrm{Time}\left(\mathrm{EV}_j^P, \mathrm{EV}_i^C\right) = \theta_j^P \left(\frac{\mathrm{Dis}\left(\mathrm{EV}_j^P, \mathrm{PL}\right)}{v_j^P} + \tau a_i^C\right) \tag{7}$$

where β_j^P is the energy cost per km for EV_j^P, θ_j^P is a quantized factor to value the time cost of EV_j^P for energy trading, v_j^P is the velocity of EV_j^P, and τ denotes the V2V power transfer speed per unit power amount. Here we assume that the current surplus power amount of EV_j^P for energy trading denoted by a_j^P satisfies $a_j^P \geq a_i^C$.

Since the electricity buying price p_b set by the power grid for EVs as energy providers to trade their surplus power is lower than the power trading price p_t via cooperative V2V charging, EVs as energy providers would prefer to trade with EVs as energy consumers instead of the power grid, if a positive utility can be achieved.

C. Scheduling Protocol for Cooperative V2V Charging

Based on the defined utilities, EVs as energy consumers and EVs as energy providers have the incentive to participate in the energy trading with each other through cooperative V2V charging, leading to potential improvements of their own utilities. In this section, we propose a centralized scheduling protocol for cooperative V2V charging. In the proposed scheduling protocol, the data control center acts as the central controller for EV charging scheduling decision-making. During the procedure, the data control center collects and updates the real-time information via IoT and mobile Internet periodically. The collected information at the data control center mainly includes the real-time location and moving information from EVs, the location information of the nearby charging stations, smart houses, and parking lots, the charging requests and demanded power amounts from EVs as energy consumers, the available trading power amounts from EVs as energy providers, and the real-time unit electricity price from the charging stations. Based on the collected information, the data control center performs a V2V matching algorithm to obtain an efficient and effective V2V matching and help the EVs make smart charging/discharging decisions.

Note that during the V2V matching process, the data control center will automatically choose a best available parking lot for each potential paired EV based on the stored parking lots information. After the V2V matching process, for each matched EV as energy consumer, the achievable utility through the cooperative V2V charging will be checked whether to be larger than the utility when getting charged at a nearby charging station. If not, the corresponding matched EV pair will be marked as unmatched and put into the energy trading buffer again. Similarly, for each matched EV as energy provider, if the achievable utility through the cooperative V2V charging is not a positive value, the corresponding matched EV pair will also be marked as unmatched and put into the energy trading buffer again. If an EV as an energy consumer fails to be matched for more than m times, the data control center will feedback a failure-matched notice, which means it is a better option for the EV to get charged at the nearby charging stations. If a cooperative V2V charging deal is finally reached, the two involved EVs will perform the power transfer at a nearby parking lot selected by the data control center.

In practical applications, each involved EV has its own preference for energy trading. Ignoring the EVs' individual rationality may lead to unstable and deviated behaviors in the energy trading market. Therefore, in the following, we employ the stable matching concept and provide two stable V2V matching algorithms by taking each involved EV's individual rationality into consideration.

D. Stable V2V Matching Algorithm

In this section, by taking the individual rationality of each EV into consideration, we propose two efficient stable V2V matching algorithms, that is, EV-consumer-oriented V2V matching algorithm and EV-provider-oriented V2V matching algorithm, leading to optimal V2V matching solutions in terms of the utilities of EVs as energy consumers and the utilities of EVs as energy providers, respectively.

1) Stable Matching Concept: First, we introduce some basic concepts of the stable matching. As illustrated in Fig. 1, in our investigated V2V matching problem, EVs as energy consumers and EVs as energy providers can be regarded as men and women in the one-to-one marriage model, respectively. Each involved EV on one side (either energy consumer set or energy provider set) has a complete and transitive preference

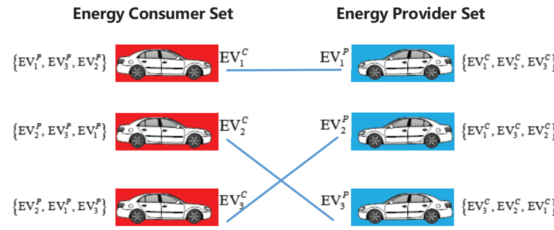

Fig. 1. A simple example of the V2V matching with individual rationality. The shown matching is a stable matching.

over the EVs on the other side, and can be represented by a rank order list including all the acceptable EVs on the other side. Note that if an EV (e.g., EV_i^C) prefers to remain single (i.e., unmatched) than being matched to another EV (e.g., EV_j^P), then EV_j^P is said to be unacceptable to EV_i^C. We denote the preferences of EV_i^C and EV_j^P by $\mathcal{L}_i^C$ and $\mathcal{L}_j^P$, respectively, $i \in \mathcal{N}$, $j \in \mathcal{K}$.

In the investigated V2V matching problem, each EV cares most about its own utility through cooperative V2V charging. Therefore, based on the utilities of EVs as energy consumers and EVs as energy providers, we define the prefer relation for EV_i^C and EV_j^P (denoted by $\succ_{\mathrm{EV}_i^C}$ and $\succ_{\mathrm{EV}_j^P}$) in Definition 1 and Definition 2, respectively.

Definition 1: For EV_i^C, it prefers EV_j^P to $\mathrm{EV}_{j'}^P$, i.e., $\mathrm{EV}_j^P \succ_{\mathrm{EV}_i^C} \mathrm{EV}_{j'}^P$, if $U_i^C\left(\mathrm{EV}_j^P\right) > U_i^C\left(\mathrm{EV}_{j'}^P\right)$, $i \in \mathcal{N}$, $j, j' \in \mathcal{K}$, $j \neq j'$.

Definition 2: For EV_j^P, it prefers EV_i^C to $\mathrm{EV}_{i'}^C$, i.e., $\mathrm{EV}_i^C \succ_{\mathrm{EV}_j^P} \mathrm{EV}_{i'}^C$, if $U_j^P\left(\mathrm{EV}_i^C\right) > U_j^P\left(\mathrm{EV}_{i'}^C\right)$, $j \in \mathcal{K}$, $i, i' \in \mathcal{N}$, $i \neq i'$.

In order to judge whether a matching is a stable one, we need to introduce the following definitions first.

Definition 3: A matching $\mathcal{M}$ is *individual rational* to all the EVs, if and only if there does not exist an involved EV that prefers being unmatched to being matched within $\mathcal{M}$.

Definition 4: A matching $\mathcal{M}$ is *blocked* by a pair of EVs if they prefer each other than the paired EVs through the matching $\mathcal{M}$. Such a pair is called a *blocking set* in general.

Note that if there is a blocking set in the matching, the EVs involved will have an incentive to break up and form new marriages. Therefore, the matching is considered to be unstable.

Definition 5: A matching $\mathcal{M}$ is *stable* if and only if $\mathcal{M}$ is individual rational and is not blocked by any pair of EVs.

2) EV-Consumer-Oriented and EV-Provider-Oriented V2V Matching Algorithms: The Gale-Shapley algorithm [11] has been proposed as an efficient method to find a stable one-to-one matching between men and women in the stable marriage problem. Similarly, in our investigated problem, EVs as energy consumers and EVs as energy providers can be regarded as men and women, respectively. Then, referring to the Gale-Shapley algorithm, we design the EV-consumer-oriented and EV-provider-oriented V2V matching algorithms in order to obtain the stable matching between EVs as energy consumers and EVs as energy providers. The detailed procedure of the EV-consumer-oriented V2V matching algorithm is given in Algorithm 1.

The proposed EV-consumer-oriented V2V matching algorithm can be easily transformed into an EV-provider-oriented one by swapping the roles of EVs as energy consumers and

EVs as energy providers, that is, EVs as energy providers make proposals to EVs as energy consumers and EVs as energy consumers decide to hold or reject the received proposals.

According to the polarization of stable matchings introduced in [11], we have that the EV-consumer-oriented algorithm can yield an EV-consumer-optimal stable matching, in which each EV as energy consumer has the best matched partner that it can have in any stable matching, whereas the EV-provider-oriented algorithm leads to an EV-provider-optimal output.

Algorithm 1: EV-Consumer-Oriented V2V Matching Algorithm

Input: Given the constructed bipartite graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$.
Step 1: Set up the preference lists of vertices V_i^C and V_j^P denoted by $\mathcal{L}_i^C$ and $\mathcal{L}_j^P$, respectively.
Step 2: Initialize $\mathcal{U}$ including all the unmatched EVs as energy consumers, i.e., $\mathcal{U} = \left\{V_i^C \mid i \in \mathcal{N}\right\}$.
Step 3: Initialize $\mathcal{H}_j = \Phi$ as the current hold of V_j^P, $j \in \mathcal{K}$.
Repeat
Step 4: V_i^C proposes to the vertex that locates first in its preference list $\mathcal{L}_i^C$, $\forall V_i^C \in \mathcal{U}$.
Step 5: **for** $j = 1, 2, \cdots, K$ **do**
  if V_j^P *receives a more preferred proposal from* $V_{i'}^C$ *than the current hold* **then**
    $V_{i'}^C$ is removed from $\mathcal{U}$ and the current hold $\mathcal{H}_j$ is added into $\mathcal{U}$;
    V_j^P updates $\mathcal{H}_j = V_{i'}^C$.
  end
  else
    V_j^P rejects the received proposals and continues the current hold.
  end
end
Step 6: **for** $i = 1, 2, \cdots, N$ **do**
  if V_i^C *is rejected in this round* **then**
    Update the preference list $\mathcal{L}_i^C$ by deleting the first element in $\mathcal{L}_i^C$.
  end
end
Until $\mathcal{U}$ is empty or each vertex in $\mathcal{U}$ has an empty preference list.
Step 7: **for** $j = 1, 2, \cdots, K$ **do**
  if $\mathcal{H}_j \neq \Phi$ **then**
    Add V_j^P and $\mathcal{H}_j$ as a matched pair into $\mathcal{M}$.
  end
end
Output $\mathcal{M}$.

IV. Simulations and Discussions

To evaluate the efficiency of the proposed stable matching based cooperative V2V charging mechanism for the EVs in the investigated system, we conduct the following simulations. As a performance comparison baseline, we employ the traditional EV charging protocol, in which the EVs as energy consumers choose to get charged at the nearest charging station. The utilities of EVs as energy consumers when getting charged at the selected charging station are given in (2).

TABLE I
Simulation Parameters

Parameters	Value
EV's Velocity	Within 20 $\sim$ 60 km/h
Unit Power Trading Price p_t	15 c/kWh
Electricity Selling Price p_s	18 c/kWh
Initial Cost Price p_0	5 c/kWh
The Time Cost Value Factor θ_j^P	0.1 c/min
The Amortized Battery Cost Φ	15 c
The Moving Energy Cost for EV$_i^C$ β_i^C	Within 0.2 $\sim$ 0.5 kWh/km
The Moving Energy Cost for EV$_j^P$ β_j^P	Within 0.2 $\sim$ 0.5 kWh/km
The Required Power Amount a_i^C	Within 20 $\sim$ 40 kWh
Number of EVs as Energy Consumers N	10
Number of EVs as Energy Providers K	[10, 15, 20, 25, 30, 35, 40]

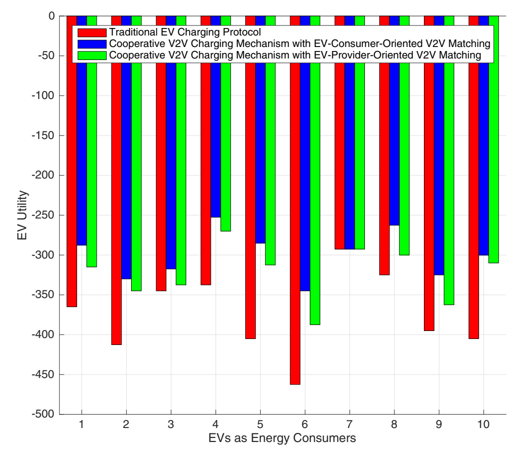

Fig. 2. Utility performance comparison for EVs as energy consumers ($N = K = 10$).

A. Simulation Parameters

In the simulations, we consider a 20 km $\times$ 20 km urban network with 50 EVs driving in it. The EVs are initialized at random locations with a random driving direction and we assume that in a specific energy trading task period, the EVs follow uniform rectilinear motion. There are two charging stations located at $(10\,\text{km}, 5\,\text{km})$ and $(10\,\text{km}, 15\,\text{km})$, respectively, and 25 available parking lots located uniformly in the simulated scenario. We randomly select N EVs as energy consumers that demand power for further driving towards their individual destinations and K EVs as energy providers that have surplus power for energy trading. The detailed simulation parameters are listed in Table I.

B. EV Utility Comparison

In Fig. 2, we simulate the utilities of EVs as energy consumers with the traditional EV charging protocol and the proposed cooperative V2V charging mechanism with both stable V2V matching algorithms. From Fig. 2, we can clearly find that with our proposed stable matching based cooperative V2V charging mechanism, the utilities of EVs as energy consumers are improved significantly, leading to smarter and more effective charging behaviors. It can be also found that EV$_7^C$ has the same utility value with our proposed cooperative V2V charging mechanism and the traditional EV charging protocol. This implies that for EV$_7^C$, cooperative V2V charging with other EVs as energy providers in the network cannot lead

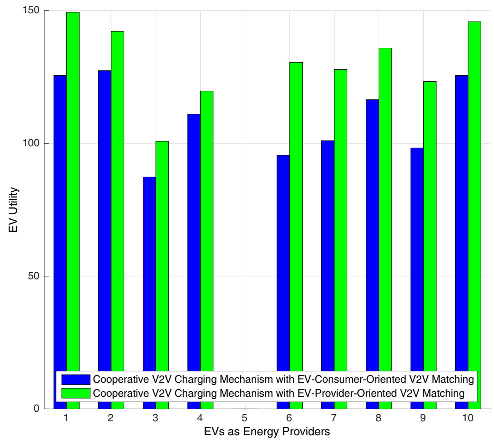

Fig. 3. Utility performance comparison for EVs as energy providers ($N = K = 10$).

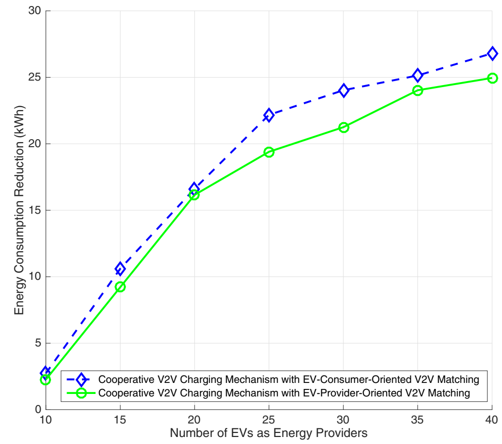

Fig. 4. Energy consumption reduction through the proposed stable matching based cooperative V2V charging mechanism.

to a better utility than to get charged at the charging station. Therefore, it finally chooses to get charged at the nearest charging station based on the feedback decisions from the data control center.

In Fig. 3, we simulate the utilities of EVs as energy providers with the proposed cooperative V2V charging mechanism with different stable V2V matching algorithms. From Fig. 3, we can see most EVs as energy providers can achieve a positive utility value, which makes the EVs that have extra power have an incentive to participate in the cooperative V2V charging process as energy providers. It can be found that EV_5^P has zero utility value, which means EV_5^P does not find an effective partner for energy trading (i.e., unmatched) with our proposed stable matching based cooperative V2V charging mechanism. There are two reasons resulting in this situation. First, EV_5^P cannot achieve a positive utility based on the V2V matching solutions and thus it prefers to be unmatched. Second, the matched partner of EV_5^P cannot achieve a better utility through cooperative V2V charging than to get charged at the charging station (e.g., EV_7^C in Fig. 2), and thus the matched partner leaves the matched relation, making EV_5^P also become unmatched.

C. Energy Consumption Reduction

In Fig. 4, we simulate the energy consumption reduction of all the involved EVs through the proposed stable matching based cooperative V2V charging mechanism compared with the traditional EV charging protocol. Here the energy consumption reduction is calculated as the network energy cost (i.e., the sum of energy cost of EVs as energy consumers and EVs as energy providers that finally participate in energy trading) difference between our proposed cooperative V2V charging mechanism and the traditional EV charging protocol. From Fig. 4, we can clearly find that the energy consumption of the involved EVs can be reduced effectively through our proposed stable matching based cooperative V2V charging mechanism. This leads to a more flexible and smarter energy management for the EV system.

V. Conclusions

In this paper, we investigated the flexible and efficient charging mechanism for EVs based on the active cooperation between EVs as energy consumers and EVs as energy providers. We first introduced the cooperative V2V charging concept. Then, we proposed a stable matching based cooperative V2V charging mechanism with different stable V2V matching algorithms, which can help the EVs achieve flexible and smart charging/discharging behaviors. Simulation results verified the efficiency of our proposed cooperative V2V charging mechanism in improving the EV utilities as well as reducing the network energy consumption.

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