Maximizing Profit of Battery Swap Station: A Dynamic Matching Game Approach

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Abstract

Battery swapping station (BSS) is a place where electric vehicles (EVs) can swap their depleted battery for full-charged battery in short time. Most of studies focus on charging scheduling in order to maximize BSSs' ability of providing battery exchange services. However, price of battery exchange services in these works does not take the increasing energy demand of EVs into account. Meanwhile, being hurry situation EVs naturally spare no expense to compete and get battery exchange service if their budget is strong. Providing battery exchange service with fixed utilizes thus has a negative effect on profit of BSSs. Unlike other works, we consider scenario that EVs have to compete together by negotiating price with BSS in order to swap their depleted battery. Our proposed mechanism brings economic benefit to BSSs, especially when they are insufficient of full-charged batteries. A mathematical model is formulated as dynamic many-to-one matching. We perform simulation to demonstrate the efficient of the proposed algorithm.

Key word: Dynamic Price, Electric vehicle, Battery exchange, Battery swapping station, Matching game.

1. Introduction

Battery swapping station (BSS) is where electric vehicles (EVs) can swap their depleted battery for full-charged battery. The swapping time only takes within ten of seconds to several minutes [1] while charging at charging station takes long charging time [1, 2, 3]. Therefore, reducing the charging time is the most advantages of using BSS model. Due to this benefit, EVs being in hurry situation such as in emergence cases, low batteries are the most suitable users to use battery exchange service.

Most of studies on BSS focus on charging scheduling at BSS to minimize the cost of BSS while satisfying demand of battery swapping [1, 4]. In these works, energy price is determined without care about rising demand for energy. BSSs thus cannot harvest budget of EVs. Especially, when being extremely hurry, these EVs easily agreed to pay at high price to complete with others for getting service. A dynamic price mechanism therefore needs to investigate for battery exchange at BSS.

In this work, we design a battery exchange at BSSs based on matching game. We then compare the dynamic matching-based battery exchange mechanism to fixed price-based matching mechanism.

The remainder of this paper is organized as follows. The full sketch of system model is demonstrated in Section 2. In section 3 we show our problem formulation based on matching game. Simulation results are shown in section 4. Section 5 summarizes the paper.

2. System model

In this study, we present the system model of battery exchange at BSSs. As shown in Fig.1, the proposed system model is comprised set of BSSs and set of EVs requiring battery exchange services. In such networks, depleted EVs are as demanders while BSSs

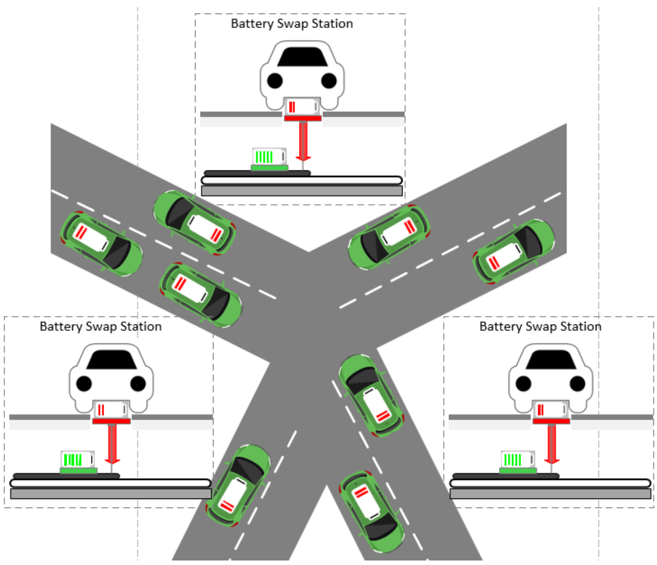

Figure 1: System model illustration

are as suppliers. These EVs are in hurry situation, they thus want to exchange their current depleted batteries (DB) for full battery (FB) being at BSSs. The EV can establish a relationship by matching with BSSs to exchange battery. The battery exchange is processed as a supplier-demander battery exchange by meeting at BSS. The suppliers, and demanders are denoted by $S = \{1, 2, ..., m\}$ and $D = \{1, 2, ..., n\}$, respectively.

For all demanders $d \in D$ and suppliers $s \in S$, we introduce a binary variable $x_{d,s}$ that indicates whether d is assigned to exchange battery with s or not.

$$x_{d,s} = \begin{cases} 1 \text{ if } d \text{ is exchanged battery with s,} \\ 0 \text{ otherwise.} \end{cases} \quad (1)$$

Since state of charge (SoC) is a value that determines the current battery capacity as a percentage of maximum capacity, each demander submits their desired SoC to BSS. Each demander looks over the suppliers that can minimize their expense of energy sharing. The expense energy sharing includes two types of payments (1) energy payment that is money paid for buying amount energy measuring by subtracting the remaining amount from the amount of exchanged DB. (2) Moving cost that is money expensed as demanders drive to meet and get energy suppliers at BSSs.

Energy payment: Let us the remaining amount is ω_d^r and the amount of full battery is ω_d^{full}. Then, the energy payment of demander d for buying energy from supply s, p_d^e, is determined by multiplying selling energy price (per 1 energy unit), ρ_s and buying energy amount expressed as follows,

$$p_{d,s}^e = \rho_s * (\omega_d^{full} - \omega_d^r) \quad (2)$$

Moving cost: Demanders EVs need to visit the BSS to exchange battery when having low SoC. Then $m_{d,s}^o$, and $m_{d,s}^t$ are denoted as driving distance from current position of d to BSS s, and from BSS s to the destination of d, respectively. In addition, E_{travel} is the energy consumption per unit driving distance for each demander. The moving cost then is presented as follows,

$$p_{d,s}^m = p_s * (\mathrm{E}_{travel} * (m_{d,s}^o + m_{d,s}^t)) \quad (3)$$

3. Dynamic matching-based battery exchange mechanism at BSS

In this section, we model the two-sides battery exchange matching problem as a two-sides many-to-one matching game. A matching game is defined by two separate sets of players. Each set of players evaluate one of another side using well-defined preference relations [5]. The concept of preferences is used to model the common and conflicting interest. The preference profiles built by the demanders and the suppliers are denoted P_d, and P_s, respectively. Let the tuple, $(D, S, \succ_D, \succ_S)$ is our many-to-one matching design. Here, $\succ_D \overset{\Delta}{=} \{\succ_d\}_{d \in D}$ and $\succ_S \overset{\Delta}{=} \{\succ_s\}_{s \in S}$ represent the set of the preference relations of demanders and suppliers, respectively [6].

Definition 1 A matching μ is defined on the set $D \cup S$, which satisfies for all $d \in D$ and $s \in S$:

1) $|\mu(d)| \le 1$ and $\mu(d) \in S \cup \varnothing$.
2) $|\mu(s)| \le q_s$ and $\mu(s) \in D \cup \varnothing$.
3) $s \in \mu(d)$ if only if $\mu(d) = s$.

Demanders' Preferences: Each demander seeks BSS that can minimize its battery exchange cost including the energy payment and the moving cost. Therefore, d ranks BSSs s in descending order based on the following ranking function:

$$R_d(s) = \left\{ \sum_{d \in D} \left[\alpha p_{d,s}^e + (1-\alpha) p_{d,s}^m \right] x_{d,s} \right. \quad (4)$$

BSSs' Preferences: For BSSs, they only care about energy payment that is as their profit getting from battery exchange process. Hence, each BSS s descendingly ranks the demander d according to the following ranking function:

$$R_d(s) = \left\{ \sum_{s \in S} p_{d,s}^e x_{d,s} \right. \quad (5)$$

As mentioned earlier, the battery exchange problem is formulated as many-to-one matching problem. Unlike other works, the selling price is fixed, the selling price in our work is dynamic and can be different between suppliers. At the initial time, suppliers broadcast their initial selling price. The initial selling price of CS s is noted as $\rho_s^{(0)}$. Each BSS locally determines its initial selling price by itself. For example, it can pick energy market price as the initial selling price. Then, whenever the number of demanders going to be got charge at its place excesses quota of BSS denoted σ_s, BSS will increase its selling price by δ presented as in (3). EVs then update their BSS preference list according to new

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Algorithm 1: Dynamic matching-based Battery Exchange at BSS

Input: $P_{d,s}^e$, $P_{d,s}^m$, $\rho^{(0)}$, σ_s, b_d, $\forall d, s$

Output: A matching μ

1. Calculate the preference lists of EVs and BSSs using Eq. (4) and Eq. (5).
2. Determine temporary matching $\mu^{(0)} = \{(d,s \mid (d,s)$ prefer to each other$\}$
3. **Repeat**
4. t= t + 1
5. if number of matched EVs in $\mu^{(t-1)}$ at $s > \sigma_s$: s updated $\rho^{(t)}$ using Eq. (6)
6. if $\rho^{(t)} < b_d$: d and s updated their preference list using Eq. (4) and Eq. (5).
7. Using Gale-Shapley based many-to-one algorithm illustrated in [7] to seeking $\mu^{(t)}$.
8. **Until** $\mu^{(t)} = \mu^{(t-1)}$

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selling price. whenever the selling prices ρ_s excess EV's maximum buying price b_d, these EVs will keep the same previous matching results. The negotiation process will stop either matching result has no more change or matching process reaches given number of iterations.

$$\rho_s^{(t+1)} = \rho_s^{(t)} + \delta \quad (6)$$

Therefore, we static matching based on the deferred-acceptance algorithm [6] is not suitable to our propose. We propose dynamic matching-based battery exchange that captures the fluctuation of the battery exchange price following the rule as we mention above.

Our goal is to find a stable matching, which is key concept as optimal result by using matching game. To seek a stable matching.

A stable matching is verified through the concept of blocking pair defined as follows:

Definition 2 A matching μ is stable, if only if no pair of $\{(d,s) \mid d \in D, s \in S\}$ blocks the matching. That is, $\nexists(d,s)$, s.t $d \succ_s \mu(s)$, $s \succ_d \mu(d)$.

Our proposed battery exchange algorithm is presented in Algorithm 1. The result of this algorithm, μ, is a stable matching.

4. Simulation Results

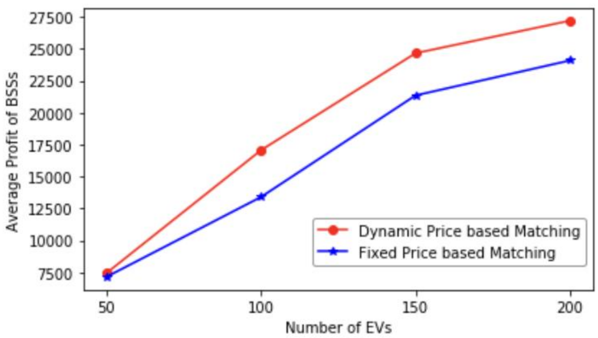

Fig. 2: Average total profit of BSSs with different number of EVs

For our simulations, we consider a system with 4 BSSs, and different number of vehicles distributed over city with 1000m x 1000m size. The remaining SoC of each EV are randomly set in range [10%, 35%] [54] α is set to 0.5. E_{travel} = 0.07456kWh/km [8].

Full Battery Capacity is set to 24 kWh [53]. b_d and ρ_s^0 are uniformly set to [13,15] and [6.7,12.4], respectively.

We evaluate the average total profit of BSSs under different algorithms. Since dynamic price-based matching battery exchange will wisely adjusts energy price as need of batteries increase. The results are shown in Fig. 2 that dynamic price-based matching scheme provides more benefit than fixed price-based scheme.

5. Conclusion

In this paper, we investigate battery exchange problem to improve EVs' range anxiety and BSSs' benefit. A mathematical model is formulated as dynamic many-to-one matching game. Simulation results show that our proposal guarantees better benefit than that of fixed price-based matching approach.

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