Electric Vehicle Charging Management Using Auction Mechanism for Reducing PV Curtailment in Distribution Systems

Hiroshi Kikusato, Member, IEEE, Yu Fujimoto, Member, IEEE, Shin-ichi Hanada, Daiya Isogawa, Shinya Yoshizawa, Member, IEEE, Hiroshi Ohashi, and Yasuhiro Hayashi, Member, IEEE

Abstract—This paper proposes an electric vehicle (EV) charging management scheme for effective utilization of photovoltaic (PV) power based on an auction mechanism. The proposed scheme coordinates an amount of self-consumption of PV output by shifting the charging period of customers’ EVs, and it reduces PV curtailment caused by voltage rise in low-voltage distribution systems (LVDSs). The auction mechanism is introduced in order to assure both the equity of benefit in each customer and the autonomy that enables customers to voluntarily participate in the EV charging management scheme. The authors perform numerical simulations based on a Japanese distribution system model and evaluate the effectiveness of the proposed scheme. The results show that our proposed scheme reduces the residential operation cost and the PV curtailment in LVDSs without an enhanced communication network even taking into consideration the effects of forecasting errors of electricity demand and PV output, and unexpected disconnection condition of several EVs.

Index Terms—Auction mechanism, electric vehicle charging management, game theory, low-voltage distribution system, overvoltage, photovoltaic curtailment.

I. INTRODUCTION

The reduction of the photovoltaic (PV) curtailment is an important issue to achieve the maximum utilization of the penetrated PV power. It can be an alternative to power sources with high fuel cost in the supply side and can also reduce the residential operation cost, regarding domestic purchased and sold electricity, in demand side. The PV curtailment is carried out primarily for two purposes: one is to maintain the power supply-demand balance [1] when PV output exceeds electricity consumption with minimum thermal power generation in the power system, and the other is to avoid overvoltage from the prescribed voltage upper limit in the distribution system (DS) with intensive PV penetration [2]. The former is addressed to coordinate the supply-demand balance among whole grid scale, while the latter can be prevented by mitigating voltage rise in the DS. In particular, the voltage rise caused by PV penetration has been regarded as a significant problem, so that various energy management schemes have been proposed for mitigation [3]–[17]. Approaches that play an important role for mitigation of the voltage rise in the DS are roughly classified into the following two: supply side management and demand side management.

From the viewpoint of supply side, the simplest solution may be grid reinforcement though it costs much higher than other schemes in general [3], [4]. Other possible approaches are voltage control schemes using the medium-voltage (MV) and low-voltage (LV) on-load tap changers (OLTCs) [5]–[8], and battery energy storage system (BESS) [9]. A main advantage of these approaches is that the supply side can operate the devices in the most convenient way to achieve its objectives; however, additional investment is required in the supply side.

Another effective approach for mitigation of voltage rise and reduction of PV curtailment is based on utilization of the demand side controllable loads, such as the heat pump water heater (HPWH) [10], residential BESS [11], [12], and electric vehicle (EV) [13]–[17]. These operation schemes are expected to reduce PV curtailment by shifting their operation time so as to increase the self-consumption of the PV output in peak periods. In particular, the prohibition of selling gasoline and diesel cars proposed in several countries will promote future EV penetration, so that they have a large potential as the controllable load. Literature [18] has estimated that more than 90% of EVs are parked somewhere and 50% at houses in a daytime, so that the owners will utilize their EVs for load shifting (hereafter called “charging shift”) when it is connected to the house if there is reasonable motivation.

The EV utilization schemes [13]–[17] can be classified into distributed and centralized schemes; key issues for designing a motivative EV utilization scheme are considered as follows:
Issue 1: Determination of appropriate amount of charging shift.
The residential operation cost can be reduced by shifting the appropriate amount of demand so that the PV curtailment is reduced. However, an inappropriate amount of charging shift would increase the residential operation cost; excessive amount of charging shift consumes the PV output that could be sold.

Issue 2: Assurance of autonomy. The customers should voluntarily decide to participate in the charging shift by comparing the benefit of the charging shift and that of mobility for themselves.

Issue 3: Assurance of equity. The benefit should be coordinated depending on the contribution of each customer; customers who carry out the charging shift should receive a larger benefit than those who do not.

However, the scheme that simultaneously addresses these three issues has not been discussed well. In the distributed scheme [13], [14], each customer could not know the other’s statuses. In this case, Issue 2 can be addressed because the EV utilization depends on the customers’ intention. However, for example, Issue 1 is difficult to be resolved because the voltage rise causing the PV curtailment affected by mutual behaviors of the customers connected to the same DS. Meanwhile, in the centralized scheme [15], [16], Issues 1 and 2 may be simultaneously alleviated under an enhanced communication network, such as real-time communication in all customers. Whereas, with regard to Issue 3, it has not been well-studied; the previous literatures have mainly focused on Issues 1 and 2. For example, in [12] and [14], the customers obtain the profit according to the contract signed in advance though its specific procedure has not been described. The EV charge-discharge scheme proposed in our previous study [17] mainly focused on Issue 1 for reduction of the PV curtailment and residential operation cost; however, it does not address Issue 3. If the profit to be enjoyed does not depend on the individual EV owner’s participation in the charging shift, the owners would lose their motivation for the EV charging shift.

In this paper, we propose an EV charging management scheme, which simultaneously addresses the three issues noted above, based on an auction mechanism in terms of game theory for reducing PV curtailment originating from the voltage constraint and residential operation cost in the low-voltage distribution system (LVDS). To the best of our knowledge, the issues caused by voltage constraint in the DS have not been discussed well from the viewpoint of the auction mechanism though many methodologies applying game theories to the demand side EV management for cost reduction and/or supply-demand balancing have been proposed [19]–[21]. In order to simultaneously resolve the three issues without an enhanced real-time communication network, the proposed scheme determines the appropriate amount of charging shift on the basis of the day-ahead power forecasting. Meanwhile, the introduction of auction mechanism assures the autonomy and equity. Although utilization of the forecasting scheme and consideration of customer’s autonomy bring a kind of uncertainty in the expected effect, the proposed scheme is designed to be robust to the effects of forecasting errors and unexpected disconnection condition of several EVs. The effectiveness of the proposed scheme and the robustness to these kinds of uncertainties are evaluated by the numerical simulation using a DS model in terms of the PV curtailment and the residential operation cost.

The remainder of this paper is organized as follows. In Section II, the formulation and the issues of the EV charging shift for reducing PV curtailment and residential operation cost are described. We introduce the proposed EV charging scheme based on the auction mechanism in Section III. Section IV describes the expected bidders’ behavior in the auction mechanism. The simulation results of the proposed charging shift scheme are shown in Section V. Section VI concludes this paper.

II. EV CHARGING SHIFT FOR REDUCING PV CURTAILMENT

In our scheme, an EV is assumed to be charged by considering the residential operation cost and customer’s convenience. To minimize the residential operation cost in a house with a rooftop PV and an EV under the present Feed-in Tariff (FIT) Program, the electricity consumption should be reduced when the PV is generating so as to sell surplus PV output to the grid as much as possible. However, considering the grid voltage constraint, the significant reverse power flow caused by surplus PV output leads to voltage rise and PV curtailment resulting in the reduction of expected profit. In this situation, although the supply side utility is required to reinforce the grid to mitigate voltage rise so as to prevent the output curtailment of the PVs installed in the target area, demand side customers residing within the target area also potentially contribute to reduce the PV curtailment by shifting the charging period of EVs so as to increase the self-consumption of PV output. The reduction of PV curtailment will reduce the residential operational cost of the customers because some purchased electricity is replaced by the curtailed PV output; therefore, the implementation of effective charging shift in the demand side provides benefits to both the supply and demand sides. In this section, we formulate the problem setting of the EV charging shift scheme and discuss issues of the charging shift for reducing PV curtailment and residential operation cost.

A. Formulation of EV Charging Shift

Suppose some houses with rooftop PVs and EVs are connected to an LVDS where PV curtailment frequently occurs. We introduce a charging shift scheme to reduce PV curtailment and residential operation cost in the target LVDS. Let \( t \in \{1, \ldots, T\} \) be the time in a day where \( T \) is the total time, and \( n \in \mathcal{N} \) be an index of a customer in the LVDS where \( \mathcal{N} \) is the index set of the customers. We also let \( p = (p_{n, t}; n \in \mathcal{N}, t \in \{1, \ldots, T\}) \) be a sequence of the consequent (after curtailed) PV output in the target houses and \( p^* \) be the original (before curtailed) one; then, a sequence of the PV curtailment \( x \) in the target houses is given by

\[
x = p^* - p.
\] (1)

Let \( y = (y_{n, t}; n \in \mathcal{N}, t \in \{1, \ldots, T\}) \) and \( z = (z_{n}^{\text{org}}, z_{n}^{\text{net}}; n \in \mathcal{N}) \) be electricity consumptions...
of uncontrollable load and EV in houses where \( z_{n}^{\text{org}} = (z_{n,t}^{\text{org}}, t \in \{1, \ldots, T\} ) \) and \( z_{n}^{\text{sft}} = (z_{n,t}^{\text{sft}}, t \in \{1, \ldots, T\} ) \) indicate the sequences of EV charging electricity consumption determined without considering PV curtailment and that shifted for reducing PV curtailment, respectively. We also let \( W \subset N \) be the subset of customers who carry out the charging shift (hereinafter called “shifters”). In the case of \( W = \emptyset \), the sequence of EV charging in all customers becomes \( z_{n} = z_{n}^{\text{org}} \) for all \( n \) and the total residential operation cost of customers in the LVDS is given by

\[
C(z) = \sum_{n \in N} C_{n}^{\text{org}} (z(W)) = \sum_{n \in N} \sum_{t=1}^{T} \left( c_{t}^{g} [y_{n,t} + z_{n,t}^{\text{org}} - p_{n,t} (z(W))] + c_{t}^{PV} [p_{n,t} (z(W)) - y_{n,t} - z_{n,t}^{\text{org}}]\right), \tag{2}
\]

where

\[
[a]_{+} = \begin{cases} a & \text{if } a \geq 0 \\ 0 & \text{otherwise}, \end{cases} \tag{3}
\]

\( C_{n}^{\text{org}} \) is the residential operation cost of non-shifter \( n \notin W \), who does not carry out the charging shift, and \( c_{t}^{g} \) and \( c_{t}^{PV} \) are the cost conversion coefficients of the purchased and sold electricity at time \( t \), respectively. On the other hand, when customers carry out the charging shift \( W \neq \emptyset \), the electricity consumption of EV charging of shifters \( n \in W \) is converted from \( z_{n}^{\text{org}} \) to \( z_{n}^{\text{sft}} \), so that the total residential operation cost in the LVDS is given by

\[
C(z(W)) = \sum_{n \in W} C_{n}^{\text{sft}} (z(W)) + \sum_{n \notin W} C_{n}^{\text{org}} (z(W)), \tag{4}
\]

where \( C_{n}^{\text{sft}} \) indicates the residential operation cost of shifters \( n \in W \) given by

\[
C_{n}^{\text{sft}} (z(W)) = \sum_{t=1}^{T} \left( c_{t}^{g} [y_{n,t} + z_{n,t}^{\text{sft}} - p_{n,t} (z(W))] + c_{t}^{PV} [p_{n,t} (z(W)) - y_{n,t} - z_{n,t}^{\text{sft}}]\right). \tag{5}
\]

As shown in (2)–(5), the effectiveness of charging shift depends on how to determine the subset of shifters \( W \) and the shifted EV charging profiles \( z_{n}^{\text{sft}} \). The charging shift scheme can be classified into two types from a perspective of how to determine them: distributed and centralized approaches. Both types of charging shift might be executed according to the preset schedules given via in-home controllers. In the distributed charging shift approach, each customer autonomously manages individual charging shift; \( W \) and \( z_{n}^{\text{sft}} \) are determined as a result of the customers’ decisions. On the other hand, in the centralized charging approach, an aggregator manages the charging shift in the target area; \( W \) and \( z_{n}^{\text{sft}} \) are determined by the aggregator and customers carry out the EV charging shift according to the aggregator’s decision. In the next subsection, issues of the EV charging shift in each approach are discussed.

### B. Issues in EV Charging Shift

As denoted in Section I, there are three issues in introducing the EV charging shift for reducing the PV curtailment and residential operation cost. The first issue is determination of an appropriate amount of charging shift based on \( W \) and \( z_{n}^{\text{sft}} \). An inappropriate amount of charging shift would result in an inappropriate amount of self-consumption of PV output; the residential operation cost would increase when the PV output that could be sold is self-consumed, or the PV output that would be curtailed is not self-consumed. In the distributed approach, it is difficult for each customer to appropriately determine when and how much EV charging should be shifted to reduce the PV curtailment and residential operation cost because the voltage varies with the electricity consumption of all houses connected to the same LVDS. The PV curtailment in a house increases when the loads in the other houses are light, and decreases when they are heavy. Therefore, customers cannot accurately estimate their expected PV curtailment unless they acquire the behavior of the other customers. On the other hand, in the centralized charging shift approach, an aggregator can manage when and how much charging shift should be carried out considering an appropriate balance between amounts of charging shift and the expected PV curtailment in all houses connected to the same LVDS.

The second issue is assurance of autonomy: a philosophy such that the customers should voluntarily decide to participate in the charging shift based on a comparison between an EV utilization benefit by the charging shift contribution and that by transportation for themselves, because the EV is preliminary utilized for transportation. In the distributed charging shift approach, autonomy is difficult to be secured because it is difficult for the aggregator to compare the individual values of EV utilization. Let \( W' \subset N \) be the set of shifters determined by the aggregator; \( W' \) is determined for satisfying the objectives indicated by the aggregator, even though the target customers \( n \in W' \) will not contribute to the charging shift when the benefit of EV transportation is higher for the customer than the value of cost reduction by the charging shift. In order to assure the autonomy and not to neglect the convenience of customers, the centralized approach should include the mechanism that the customers voluntarily participate in the charging shift evaluating the values of EV utilization.

The third issue is assurance of equity: another philosophy such that the customers’ benefit obtained by the charging shift should be coordinated depending on contribution of the customers, i.e., the shifters should receive a larger benefit than the non-shifters. The charging shift carried out by certain customers will reduce PV curtailment not only in their own house but also in other local houses connected in the same LVDS because the increase of self-consumption of PV output by the charging shift reduces the voltage, which is the implicit constraint of PV curtailment, in the entire LVDS. The reduction of voltage depends on the number and location of shifters. Therefore, the consequent PV output \( p_{n,t} (z(W)) \) changes depending on set of shifters \( W \).
Equation (5) suggests that the residential operation cost of shifters changes depending on the increase of consequent PV output $p_{n,t}$, i.e., reduction of PV curtailment, caused by customer’s own and others’ charging shift. On the other hand, (2) shows that the residential operation cost of non-shifters changes depending on the increase of consequent PV output $p_{n,t}$ caused by the decrease of voltage due to the others’ charging shift. This relationship implies that the total benefit produced by the charging shift carried out by a subset of customers is expressed as the total reduction of PV curtailment in all the customers. However, from the viewpoint of the shifters, the benefit seems only the cost reduction resulting from reducing PV curtailment in shifter’s own house; the benefit is lower than the appropriate value of the charging shift, so that non-shifters could obtain the benefit even though they do not contribute to the charging shift (see Fig. 1). This inequity on the benefit would discourage customers to participate in the charging shift. Thus, the value for non-shifters should be appropriately evaluated and returned to shifters. In the distributed charging shift approach, the mechanism for solving the inequity is not included. Meanwhile, the centralized charging shift approach have a potential to equitably share the benefit between the customers mediated by the aggregator.

Therefore, the admissible charging shift scheme requires to solve above three issues, i.e., determination of appropriate amount of charging shift, assurance of autonomy, and assurance of equity. In the next section, we propose an EV charging shift scheme based on an auction mechanism, which is a hybrid approach of the distributed and centralized ones, to tackle these three issues. In the proposed scheme, a part of determination of $\mathcal{W}$ is performed in distributed manner and determination of $z_n^{\text{shift}}$ is performed in centralized manner.

III. EV CHARGING SHIFT BASED ON AUCTION MECHANISM

We focus on the second-price sealed-bid auction mechanism [22] in the EV charging shift scheme to determine the shifters so as to assure the autonomy and equity in the charging shift as well as an appropriate amount of charging shift. This auction mechanism is known that it is reasonable for the bidders to submit their bids according to the truthful bids for the target value. In the auction mechanism, customers voluntarily determine the bids without knowing the other’s bids and compete to obtain the rights to carry out the charging shift. Customers can determine the bids that will not win the auction when they do not want to carry out the charging shift, so that the autonomy is assured. Moreover, the winners of the auction carry out the charging shift and obtain the incentive that is sum of collected fee from the other bidders to compensate for the difference between the appropriate total value of charging shift and the benefit resulting from reducing their own PV curtailment, thereby the equity is assured. The detailed procedure of the auction mechanism is explained below. The auction is assumed to be held in the previous day of charging shift. The charging shift is scheduled to be autonomously carried out in the period suggested by the aggregator.

A. Determination of Participants and Number of Winners

The aggregator decides to hold the auction for EV charging shift in the next day on the basis of the estimated result of day-ahead PV curtailment, i.e.,

$$\hat{x} = \hat{p}^* - \hat{p},$$

because the actual day-ahead sequences in (1) are not available; here, we will use the symbol $\cdot^*$ to denote forecasted values. We assume that the aggregator owns information of the target LVDS and estimate the day-ahead PV curtailment $\hat{x}$ on the basis of the numerical simulation that can grasp the voltage in the whole LVDS. The auction for charging shift is held when: 1) PV curtailment would occur in the next day in multiple customers; this gives the following inequality,

$$\sum_{n \in \mathcal{N}} \delta (\hat{x}_n) \geq 2,$$

where

$$\delta (\hat{x}_n) = \begin{cases} 1 & \text{if } \sum_{t=1}^T \hat{x}_{n,t} > 0 \\ 0 & \text{otherwise} \end{cases},$$

and 2) the expected residential operation cost in the target LVDS would be reduced by carrying out the charging shift, i.e.,

$$C (z (\mathcal{W} = \emptyset) | \hat{x}) < C (z (\mathcal{W} = \emptyset) | \hat{x}).$$

Then, the aggregator suggests a set of relevant participants $\mathcal{P} = \{ n | \delta (\hat{x}_n) = 0 \}$, preferable number of winners, i.e., shifters, $|\mathcal{W}'|$, and request of the charging shift $z_n^{\text{shift}}$. Note that the number of shifters for minimizing PV curtailment and that for minimizing the residential operation cost would be different. Since the charging shift in the demand side is not achieved without contribution of customers, the aggregator should consider increasing the benefit to the customers even though a major objective of the charging shift is to reduce PV curtailment. Here, the preferable number of winners $|\mathcal{W}'|$ is derived by a set of winners $\mathcal{W}'$ that is determined for minimizing the total residential operation cost in the LVDS under the forecasted PV curtailment $\hat{x}$,

$$\mathcal{W}' = \arg\min_{\mathcal{W} \subset \mathcal{P}} C (z (\mathcal{W}) | \hat{x}).$$
Equation (10) can be solved through the power flow calculation by evaluating the total residential operation cost described in (4) in terms of all combinations of $W$ in $P$. Note that computational cost required for searching minimizer $W'$ increases exponentially according to the number of participants $|P|$; therefore, the computational cost for exact minimization of (10) becomes significantly high when $|P|$ is large. We introduce the following greedy algorithm for searching such a set of winners $W'$.

Note that, since the set of winners $W'$ and participants $P$ determined by the aggregator are derived on the basis of the forecasted values $\hat{x}$, it is not always equal to the optimal set of winners $W^*$ and participants $P^*$ derived on the basis of the consequent values $x$ given by

$$W^* = \text{argmin}_{W \in P} C(z(W)|x),$$

and

$$P^* = \{n | \delta(x_n)\} 0\}$$

**B. Determination of Winners Based on Bidding**

Assume that a bidder $n \in P$, who is determined by the aggregator as a participant, submits his/her bid $b_n$, which is not known by the other bidders. The aggregator determines $|W'|$ winners from the lowest bidders. Let $b[|W'|]$ be the $|W'|$th lowest bid. Then, the final winners are shown as $W^* = \{n | b_n \leq b[|W'|]\}$ and the losers are shown as $\{n | b_n \geq b[|W'|+1]\} = P \backslash W^*$. The aggregator collects the fee $b_{|W'|+1}$ from all the losers and distributes the incentive cost,

$$\frac{|P| - |W'|}{|W'|} b_{|W'|+1},$$

to the winners $n \in W^*$. Hence, the expected residential operation cost of each customer after carrying out the charging shift based on the auction mechanism is given as

$$C_n(z(W'_b)) = \begin{cases} 
C_n^{\text{fit}}(z(W'_b)) - \frac{(|P| - |W'|)b_{|W'|+1}}{|W'|} & (n \in W^*) \\
C_n^{\text{reg}}(z(W'_b)) + b_{|W'|+1} & (n \notin W^*)
\end{cases}, \quad (11)$$

where $W'_b = W^*(\{b_n\})$. In this scheme, the collected fee $b_{|P|+1}$ never exceeds any bid of the losers. The bidders will submit their bids by considering the amount of incentive when they win and the benefit of their individual PV curtailment reduction when they lose; the bidders will set their bids high when they want to utilize the EVs for transportation and not to contribute to the charging shift. Besides, the aggregator does not need to prepare the additional incentive because the sum of the incentive cost and the collected fees is zero. The benefit of the charging shift is produced from the total reduction of the PV curtailment, i.e., the total reduction of the purchased electricity of all customers in the target LVDS. Moreover, the required communication in the proposed scheme is significantly low; therefore, the proposed scheme can be operated without an enhanced communication infrastructure.

**IV. EXPECTED BEHAVIOR OF BIDDERS**

Economic rationality is an important factor for the bidders to determine the bids. Although some economical decision policies have been discussed for determination of such bids, here, we assume the minimax strategy for bidders’ decision making, which minimizes the possible loss for a worst-case scenario. Fig. 2 depicts the schematic image of customer’s bid determination based on the minimax strategy. Applying the minimax strategy to our auction mechanism, the individual bid is determined to minimize the possible total cost, which is the sum of the residential operation cost and the incentive or the collected fee, for a worst-case winner set that makes the total cost the highest as following:

$$b_n^* = \text{argmin}_{b_n} \left( \max_{W \in \mathcal{P}} \left( \max_{W \notin W^*} \left\{ \frac{C_n^{\text{fit}}(z(W)) - (|P| - |W'|) b_{n}}{|W'|} \right\} \right. \right) + o_n \right), \quad (12)$$

where $o_n$ indicates the opportunity cost of the charging shift, which is the conceptual value that the bidder loses by selecting the charging shift instead of the EV utilization for transportation. Note that required computational cost for evaluation of all winner sets $W \subset \mathcal{P}$ is proportional to $|P| C_W$; again, the computational cost for exact determination of bids and winners becomes significantly high when $|P|$ is large. In our simulation given in the next section, the plausible bids derived from the economic rationality are assumed to be determined according to the following greedy algorithm.
Algorithm 2: Derivation of Expected Bids \( \{b_n^*\} \) Based on Minimax Policy.

\[
P^{(0)} = \{n|\delta(\hat{x}_n) = 0\} \\
\text{FOR } i = 1 \text{ to } |\mathcal{W}| \\
b_n^* = \arg\min_{b_n} \left\{ \max_{m \in \mathcal{P}^{(i-1)} \setminus \{n\}} \left[ C_{\text{shift}}(z(\mathcal{W} = \{n\})) - (|\mathcal{P}^{(i-1)}| - 1)b_n + o_n \right] + C_{\text{org}}(z(\mathcal{W} = \{m\})) + b_n \right\} \\
n^{*}(i) = \arg\min_{n \in \mathcal{P}^{(i-1)}} b_n^* \\
\mathcal{P}^{(i)} = \mathcal{P}^{(i-1)} \setminus n^{*}(i) \\
\text{FOREND}
\]

In Algorithm 2, \( n^{*}(i) \) denotes the determined winner and \( n^* \in \{n^{*}(i)|i = 1, ..., |\mathcal{W}|\} \) is the set of winners. Note that \( \mathcal{W}^* \) may not equal to \( \mathcal{W} \) when the assumption of economic rationality and equality of opportunity cost are violated.

V. SIMULATION

Our proposed EV charging management scheme based on the auction mechanism is expected to effectively reduce the residential operation cost and PV curtailment while assuring the autonomy and equity. Since the proposed scheme utilizes the power forecast results and assures the customers’ autonomy, the uncertainties due to forecasting error and charging shift conducted by different customers from ideal ones would be concerned. To verify the effectiveness and the robustness of our scheme to these types of uncertainties, we conducted numerical simulation using a DS model [23] based on 30-day (June 2007) actual measurement of PV output and electricity consumption with a time step of 10 s. This model simulates an actual DS in Japan and comprises two distribution feeders (industrial area and residential area), which include MV (6.6 kV) and LV (100/200 V) systems (Fig. 3). The model has four MV OLTCs operated on the basis of the centralized voltage control method [5], and includes 35 MV customers, 91 LVDSs, and 812 LV customers. The residential PV systems are installed in 90% of the LV customers, the situation suggests the condition that the total PV curtailment in the DS is significantly large. The load shift based on the auction mechanism is implemented in the LVDS #10 which includes 14 LV customers with a PV and an EV. Table I shows the simulation setup, including some dominant parameters. Table II presents the electricity rate for calculating the residential operation cost, which is based on an actual time-of-use (TOU) menu provided by the Tokyo Electric Power Company Energy Partner, Inc.

In this simulation, we assessed the effectiveness and robustness of the charging shift based on the auction mechanism in the LVDS #10. We assumed that all LV customers charge their EVs 4 kWh (2 kW × 2 hours) in a day. The all winners of the auction charge their EVs at 11:00–13:00 when PV curtailment frequently occurs, while others charge their EVs at 2:00–4:00 when the purchasing price of the TOU menu is low. We used 10 s resolution EV charging load profiles for evaluation in simulation with a time step of 10 s. The simulation is carried out for the following seven cases (see also in Table III). Cases 1, 2 represent the distributed charging management for evaluating the effectiveness of the proposed scheme. Cases 3–7 are proposed schemes prepared for validating the robustness to the forecasting error of PV curtailment \( \hat{x} \) and the charging shift conducted by different customers from ideal ones. It would occur when any customer intentionally rises the bid to lose the auction when the customer wants to use the EV for transportation and the state of charge required to realize the charging shift could not be secured.

### Table I: Simulation Setup

| Distribution system model | Line length | Load capacity | Appropriate voltage range |
|---------------------------|------------|--------------|--------------------------|
| Feeder 1                  | 18.4 km    | Feeder 1     | 95–107 V                 |
| Feeder 2                  | 7.48 km    | Feeder 2     |                          |
|                           |            |              | 2113 kW                  |
| Spec of PV inverters      |            |              |                          |
| Curtailment starting voltage | 107 V  | Curtailment ending voltage | 106.5 V |
| Speed of curtailment      | 0.02 kW/s  |              |                          |

### Table II: Electricity Rate

| Purchasing price (TOU pricing) | Selling price (Feed-in tariff) |
|-------------------------------|-------------------------------|
| 7:00–23:00                    | 23:00–7:00                    |
| 32.14 JPY/kWh                 | 20.74 JPY/kWh                 |
|                               | 30.00 JPY/kWh                 |

### Table III: Simulation Cases

| Case | Auction mechanism | Consideration of uncertainties effects | EV charging period |
|------|-------------------|----------------------------------------|-------------------|
| 1    | w/o               | Forecast error of PV curtailment       | Random            |
| 2    | w/o               | Charging shift by not ideal customers  | 2:00–4:00         |
| 3    | w                 |                                        | Winners: 11:00–13:00, Others: 2:00–4:00 |
| 4    | w                 |                                        | 2:00–4:00         |
| 5    | w                 |                                        | 2:00–4:00         |
| 6    | w                 |                                        | 2:00–4:00         |
Fig. 4. Simulation result.

(Distributed charging schemes)

- **Case 1**: distributed charging management scheme; all customers charge their EVs at random arbitrary time.
- **Case 2**: distributed charging management scheme; all customers charge their EVs at 2:00–4:00 to reduce residential operation cost.

(Proposed charging schemes w/ and w/o considering effects of uncertainties)

- **Case 3**: customers carry out the charging shift based on the auction mechanism in the ideal condition; there is no forecasting error; the winners are the ideal winners, i.e., $\mathcal{P} = \mathcal{P}^o, \mathcal{W}^r = \mathcal{W}^o = \mathcal{W}'$.
- **Case 4**: customers carry out the charging shift based on the auction mechanism under the condition with the existence of the forecasting error. The aggregator estimates the forthcoming PV curtailment $\hat{x}$ on the basis of the forecast of PV output [24], [25] and electricity consumption [26]; note that forecasting error affects the number of participants $\mathcal{P}$ and winners $|\mathcal{W}'|$ suggested by the aggregator, so that $\mathcal{P}$ and $\mathcal{W}'$ would be different from the ideal ones $\mathcal{P}^o$ and $\mathcal{W}^o$, respectively. Namely, this case assumes that $\mathcal{W}^r = \mathcal{W}'$ holds, but $\mathcal{P} = \mathcal{P}^o$ and $\mathcal{W}' = \mathcal{W}^o$ may not.
- **Case 5**: customers who are not ideal from the system point of view carry out the charging shift based on the auction mechanism. The final winners $\mathcal{W}^r$ would be different from the ideal condition because some customers intentionally raise or lower the bid. Namely, this case assumes that $\mathcal{P} = \mathcal{P}^o$ and $\mathcal{W}' = \mathcal{W}^o$ hold, but $\mathcal{W}^r = \mathcal{W}^o$ may not.
- **Case 6**: customers carry out the charging shift based on the auction mechanism on the condition considering both uncertainties involved in Cases 4, 5. Namely, this case assumes that $\mathcal{P} = \mathcal{P}^o, \mathcal{W}^r = \mathcal{W}^o$, and $\mathcal{W}' = \mathcal{W}^o$ may not hold.

Fig. 4 shows the simulation results on the total amount of the residential operation cost (Fig. 4(a)) and PV curtailment (Fig. 4(b)) in the LVDS #10 for 30 days. The results of Cases 4–6 indicate the average values of 100 times simulations. The residential operation cost of Case 1 is 2.17 times higher than that of Case 2, although the amount of PV curtailment of Case 1 is smaller than that of Case 2. This result suggests that if the individual EVs are charged at a random arbitrary time, the residential operation cost can be large. If all EVs are charged at the same period (2:00–4:00) in which the TOU pricing is low, the residential operation cost is significantly reduced. This result also implies that customers should charge the EVs at night to reduce the residential operation cost when there is no aggregator to coordinate charging shift in the LVDS. However, the residential operation cost in Case 2 seems to be further reduced by effectively reducing PV curtailment. On the other hand, the introduction of our proposed charging shift based on the auction mechanism in the ideal condition (Case 3) achieves 20.1% reduction in the residential operational cost and 45.1% reduction in the amount of PV curtailment compared with Case 2. The figures also show that Cases 4–6 reduce the residential operational cost by 18.8%, 12.2%, and 6.2%, respectively, and PV curtailment by 45.1%, 28.4%, and 22.2%, respectively, compared with Case 2 (w/o the charging shift scheme), although the reduction ratio is smaller than in Case 3. These results suggest that the proposed charging shift scheme can effectively reduce the residential operation cost and the amount of PV curtailment, with robustness to the uncertainties in using the forecasting methods and assured autonomy. Note that the residential operation cost and the PV curtailment of Case 4 are lower than that of Case 5. This result suggests that the negative effect caused by the forecasting error of the PV curtailment is smaller than the other effect.

Fig. 5 shows the total residential operation cost (Fig. 5(a)) and the total amount of PV curtailment (Fig. 5(b)) in a day for
Cases 1–3 and 6 under various number of shifters (number of winners on the auction mechanism). In Case 3, the residential operation cost declines until the number of winners increases to four and then increases, although the amount of PV curtailment is monotonically reduced when the number of winners increases. It is notable that the residential operation cost of Cases 3 and 6 becomes higher than that of Case 2 when more than ten (Case 3) or eight (Case 6) customers carry out the charging shift. However, in the proposed scheme, the aggregator can determine the number of shifters to reduce the residential operation cost on the basis of the forecasted amount of day-ahead PV curtailment. Since the sensitivity of the operational cost to the optimal number of winners is low, there seems to have little impact of the estimation error of number of winners due to the PV forecast error in the proposed scheme.

Fig. 6 shows the total amount of PV curtailment in the LVDS with the charging shift and in the other LVDSs. The result indicates that the introduction of the proposed scheme reduces PV curtailment not only in the LVDS where the scheme is introduced but also in the other LVDSs. This can be interpreted as follows; the reduction of the reverse power flow by the charging shift in the LVDS slightly reduced the voltage in other LVDSs, so that the PV generation in the LVDSs were increased.

The simulation results suggest that our proposed scheme can reduce the residential operation cost and PV curtailment and is robust to the uncertainties without assuming an enhanced communication network, while assuring the autonomy and equity on the charging shift.

VI. CONCLUDING REMARKS

In this study, we proposed the EV charging management scheme based on the auction mechanism to reduce PV curtailment caused by voltage rise in the DS. The proposed scheme contributes:

- To reduce the PV curtailment and residential operation cost by determining the appropriate amount of EV charging shift,
- To assure the autonomy and equity in the charging shift by introduction of the auction mechanism, and
- To assure the robustness to the uncertainties caused by the forecasting error and EVs’ availability.

The proposed scheme reduces PV curtailment by increasing the self-consumption of PV output, and lowers the voltage by shifting the charging period of EVs, while assuring the autonomy of contributing to the charging shift and the equity of customers’ benefit. The introduction of the auction mechanism allowed EV owners to participate in the load shift of EV charging voluntarily by comparing the benefits of using EV for carrying out load shift and for transportation. In this scheme, customers who contribute to the charging shift can obtain not only the benefit from reducing PV curtailment in their own houses but also the benefit of the incentive of contributing to reduce PV curtailment in other houses. Besides, the proposed scheme can be implemented without an enhanced communication network. The effectiveness of the proposed scheme was evaluated using a DS simulation model and actual measurements of power profiles in terms of the residential operation cost and PV curtailment. The simulation results described that our proposed scheme is expected to achieve a reduction in the residential operation cost and PV curtailment, while achieving robustness to the uncertainty in the day-ahead PV curtailment forecast and voluntary participation that allows the unexpected disconnection condition of the EVs.

Our proposed scheme is sufficiently adaptive to any widely used EVs. The requirement for EVs is the capability for charging a specific amount in a specific time period. A possible manner to realize our scheme in a primitive way is that the EV owners manually connect their EVs to the chargers and set a specific charging amount in a specific time suggested in the system implementing the auction procedure. But, since there can be many possible manners to realize our scheme, further discussion will be necessary for the real-world implementation. Although this study utilizes the auction mechanism for the load shift of EV charging, the same mechanism could be applied in other frameworks that require autonomy of customers’ participation and the equity of the customers’ benefit, such as the active power control of PV and EV even with the dynamic response. The ideal communication system is assumed in the paper, so that their detailed frameworks should be discussed in the future work.

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Hiroshi Ohashi received the Ph.D. degree in economics from Northwestern University, Evanston, IL, USA, in 2000. He was an Assistant Professor from 2000 to 2003 with the Sauder School of Business, University of British Columbia, Vancouver, BC, Canada, and as an Associate Professor from 2003 to 2012 and a Full Professor since 2013 both with the Graduate School of Economics and the Graduate School of Public Policy, University of Tokyo. He has been the Vice-Dean of the Graduate School of Public Policy since 2018. His areas of research include industrial organization, particularly, energy policy.

Yasuhiro Hayashi (M’91) received the B.Eng., M.Eng., and D.Eng. degrees from Waseda University, Tokyo, Japan, in 1989, 1991, and 1994, respectively. In 1994, he became a Research Associate with Ibaraki University, Mito, Japan. In 2000, he became an Associate Professor with the Department of Electrical and Electronics Engineering, Fukui University, Fukui, Japan. He has been with Waseda University as a Professor of the Department of Electrical Engineering and Bioscience since 2009 and has been a Director of the Research Institute of Advanced Network Technology since 2010. He has been the Dean of the Advanced Collaborative Research Organization for Smart Society, Waseda University, since 2014. His current research interests include the optimization of distribution system operation and forecasting, operation, planning, and control concerned with renewable energy sources and demand response. He is a member of the Institute of Electrical Engineers of Japan and a regular member of CIGRE SCC6 (Distribution Systems and Dispersed Generation).