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Electric Vehicle Charge-Discharge Management for Utilization of Photovoltaic by Coordination between Home and Grid Energy Management Systems

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***Abstract*—This study proposes an electric vehicle (EV) charge-discharge management framework for the effective utilization of photovoltaic (PV) output through coordination based on information exchange between home energy management system (HEMS) and grid energy management system (GEMS). In our proposed framework, the HEMS determines an EV charge-discharge plan for reducing the residential operation cost and PV curtailment without disturbing EV usage for driving, on the basis of voltage constraint information in the grid provided by the GEMS and forecasted power profiles. Then, the HEMS controls the EV charge-discharge according to the determined plan and real-time monitored data, which is utilized for mitigating the negative effect caused by forecast errors of power profiles. The proposed framework was evaluated on the basis of the Japanese distribution system (DS) simulation model. The simulation results show the effectiveness of our proposed framework from the viewpoint of reduction of the residential operation cost and PV curtailment.**

***Index Terms*— Charge-discharge management, distribution system, electric vehicle, home energy management system, photovoltaic system, voltage control.**

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NOMENCLATURE

Symbols

B	Battery storage capacity of EV.
c	Conversion/weighted coefficients.
$\boldsymbol{\gamma}$	Parameter set of LDC method.
$\overline{D}(\cdot)$, $\underline{D}(\cdot)$	Cumulative differences between target and reference voltage.
δ	Threshold for tap control in OLTC.
$e(\cdot)$	Function for calculation of electricity.
ε	Dead band for LDC method.
$\boldsymbol{i}$	Complex vector of secondary current of OLTC.
j	Node index in MV distribution system.
$\mathcal{J}$	Node index set in MV distribution system.
l	Line length.
$\mathcal{L}$	Set of appropriate parameter candidates of l.
m	Index of house with HEMS.
$\mathcal{M}$	Index set of houses with HEMSs.
n	Index of house without HEMS.
$\mathcal{N}$	Index set of houses without HEMSs.
O^{c}, O^{d}	Rated EV output of charging and discharging.
s	Tap position of OLTC.
$\overline{s}$, $\underline{s}$	Upper and lower limits of tap position of OLTC.
S	SoC of EV.
t	Index of time.
u	Index of time interval.
v	Scalar value of voltage.
$\overline{v}$, $\underline{v}$	Upper and lower limits of appropriate voltage.
$\dot{\boldsymbol{v}}$	Complex vector of secondary voltage of OLTC.
$\mathcal{V}$	Set of appropriate parameter candidates of v^{tar}.
$\boldsymbol{x}$	Vector of power profile.
$\boldsymbol{y}$	Vector of EV state.
$\dot{\boldsymbol{z}}$	Complex vector of unit line impedance between OLTC and reference point.

Subscripts and superscripts

$.\mathrm{c}$	For calculation of PV curtailment.
$.\mathrm{d}$	For calculation of electricity consumption of scheduled EV drive.

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$._{\mathrm{G}}$	For calculation of GEMS.
$._{\mathrm{H}}$	For calculation of HEMS.
$._{j}$	At node j.
$._{m}$	At house m (with HEMS).
$._{n}$	At house n (without HEMS).
$._{\mathrm{o}}$	For calculation of EV output.
$._{\mathrm{p}}$	For calculation of purchased electricity.
$._{\mathrm{PV}}$	For calculation of residential PV output.
$._{q}$	Of query.
$._{\mathrm{r}}$	For calculation of residential electricity consumption.
$._{\mathrm{ref}}$	At reference point.
$._{\mathrm{rev}}$	For calculation of reverse power flow.
$._{sc}$	Of scheduled driving.
$._{\mathrm{SoC}}$	For calculation of SoC.
$._{t}$	At the time t.
$._{\mathrm{tar}}$	Of target.
$._{u}$	At the time interval u.
$._{\mathrm{u1}}, ._{\mathrm{u2}}$	For calculation of unit.
$._{\mathrm{ur}}$	Of urgent driving.
$._{\mathrm{V2H}}$	For calculation of connection sate to EV charger in house.
$.^{*}$	Realized; $\boldsymbol{x}^{*}$ indicates actual sequence.

I. Introduction

Reduction of CO_2 emissions to prevent global warming is a worldwide challenge. Electricity will account for almost a quarter of the final energy consumption by 2040 [1]; the power sector is needed to lead the way toward a decarbonized energy system. In Japan, in addition to CO_2 emissions, primary energy self-sufficiency is a large issue. Energy self-sufficiency has stayed at only 6% after the Great East Japan earthquake and the Fukushima Daiichi accident in 2011. In order to break down this emergency, the government is aiming to increase it to approximately 25% by 2030 [2]. On the other hand, the amount of CO_2 emissions was 201 million only in the household sector in 2013, and the aim is to reduce this volume by 39.3% by 2030 [3]. To overcome these energy issues, the government is developing newly constructed houses with zero average emissions for deployment by 2030, so-called net-zero energy houses (ZEHs), which have an annual net energy consumption of zero or less, is receiving considerable attention [4]. To achieve ZEHs, utilization of residential photovoltaic (PV) systems is essential; besides, the energy storage systems should be deployed in households to flexibly utilize electricity from the PV systems. Additionally, home energy management system (HEMS) is expected to become an important component in realizing ZEH in Japan, and could be introduced in all (approximately 50 million) households by 2030 [2].

Electric vehicles (EVs) can be used for energy storage to effectively utilize PV, while it is originally used for driving. Connecting EVs to the power grid with renewable energy sources (RESs) will lead to various cost advantages [5] in terms of energy management, but the power flow tends to be complicated; the power flow derived from EVs has large and temporally unexpected variation compared with conventional flows. Therefore, in the energy management of EVs, the impact of EV charge-discharge on the grid must be addressed, along with the effective utilization of RESs. There are many previous studies on EV charge-discharge management [6]–[24]. These works can be classified by the connection system to the grid, i.e., vehicle-to-grid (V2G), which is the connection system through public charging stations, and vehicle-to-home (V2H), which is the connection system through houses. Table I shows the classification of previous studies in terms of the connection system, consideration of EV charge-discharge impact on the grid, and penetration of the RESs.

Many previous studies [6]–[16] focus on V2G, particularly on EV charging management schemes in parking lots. The coordination scheme of autonomous EV parking has been proposed for utilizing the EV batteries to support various V2G services [6]. The minimization of electricity cost and maximization of profit for the aggregators in parking lots has also been considered [7]–[12]. In these reports, the allocation of EV parking lots and impact of EV charging on the grid is evaluated in terms of voltage violation, total system loss, and peak system load. However, the RESs are not penetrated in the grid; therefore, the effective utilization of the RESs supported by EV management is not discussed. The authors of [13]–[16] proposed an EV charging scheme managed by the aggregator. The aggregators should manage EV charging to maximize their profit and mitigate the impact on the grid. In these cases, RESs, such as PV and wind power generation, are effectively utilized for EV charging, and the cost is reduced without increasing the negative impact on the grid.

On the other hand, for a V2H system, discharge management, in addition to the charge management, has been considered in terms of home energy management, based on human activity and the electricity rate. Several studies have focused on HEMSs integrated with EVs [17]–[24]. The HEMSs proposed in [17] maintain residential convenience by managing several home appliances, including the EV, while the consideration of the impact on the grid and the RESs penetration are not included. The authors of [18]–[21] proposed energy management schemes that use EVs to minimize the residential operation cost of home energy management. In these schemes, each EV charging plan is optimized for satisfying individual objectives, and the aggregator coordinates the plans to minimize the impact of EV charging on the grid. However, the potential for RES utilization has not been evaluated. HEMSs with PV and EV are discussed in [22]–[24]. These schemes manage the EV charge-discharge to minimize the residential operation cost by selling the surplus PV output. However, the researches mainly

TABLE I
Previous Studies on EV Charge-Discharge Management

Reference	EV connection system (V2G or V2H)	Consideration of EV charge-discharge impact on grid	Penetration of RESs
[6]–[12]	V2G	w/	w/o
[13]–[16]	V2G	w/	w/
[17]	V2H	w/o	w/o
[18]–[21]	V2H	w/	w/o
[22]–[24]	V2H	w/o	w/

focus on the optimization in the houses, and the impact on the grid has not been assessed; therefore, the profit reduction expected to be caused by PV curtailment under the voltage constraint has not been considered.

To minimize the residential operation cost, the EV should be charged when the PV is not generating and discharged when it is generating for covering the residential electricity consumption and selling as much surplus PV output as possible under the Feed-in Tariff (FIT) Program. However, in this case, PV curtailment in order to mitigate the overvoltage caused by the reverse power flow from the surplus PV output will become the main issue; the expected profit from selling the surplus PV output cannot be earned. Therefore, for effective utilization of PV output in V2H scenarios, an EV charge-discharge management framework for reducing PV curtailment by the voltage constraint in the grid is required.

Although, the authors have studied the EV charge-discharge framework based on information exchange between HEMS and grid energy management system (GEMS) for reduction of the residential operation cost and the amount of PV curtailment, the influence caused by the uncertainty of the forecasted power profiles utilized for the charge-discharge planning has not been considered. This paper is an extension of our previous work [25], and we propose the coordinated EV charge-discharge management under the condition with uncertainty of PV forecasting. In the proposed method, the coordination is also based on information exchange between the HEMS and GEMS. The HEMS determines an EV charge-discharge plan for minimizing the residential operation cost, without disturbing EV usage for driving, on the basis of the voltage constraint information in the distribution system (DS) obtained from the GEMS. The planning is also based on the forecasted profiles of PV output. When the EV charge-discharge control is carried out according to the determined plan based on forecasted profiles with significant deviation from the actual values, the charge-discharge amount will be larger or smaller than the ideal amount so as to reduce the residential operation cost and PV curtailment. In order to mitigate the negative impact of forecasting error, i.e., the opportunity loss of selling surplus PV and unnecessary electricity purchase, our proposed method adopts a following control scheme, which monitors the residential electricity consumption and PV curtailment and controls charge-discharge amount following to these values, after the planning. We carried out numerical simulations using a DS model and evaluated the effectiveness of our proposed EV charge-discharge framework from the viewpoint of the residential operation cost and the amount of PV curtailment.

The paper is organized as follows. In Section II, our proposed framework based on the coordination of the HEMS and the GEMS is briefly described. Then, the simulation results of our proposed EV operation scheme are presented in Section III. Finally, Section IV concludes this paper.

II. Framework of EV Charge-Discharge Management by HEMS Coordinated with GEMS

In this paper, we consider two energy management systems (EMSs), i.e., HEMS, which is composed of a roof-top PV, an EV, and a HEMS controller, and GEMS, which is composed of an on-load tap changer (OLTC) and a GEMS controller. Each EMS controller has automated control of its components, i.e., the EMS controllers can change the parameters of components at pre-set times. In general, these two EMSs is independently operated to meet their own requirements. Minimizing the residential operation cost while securing the EV usage for driving is an important requirement for the HEMS. To minimize the residential operation cost, the HEMS controller will charge the EV when the PV is not generating and discharge it to cover the residential electricity consumption when the PV is generating, selling as much surplus PV output as possible. However, such operations increase the reverse power flow which causes overvoltage in the DS, so that the PV inverter tend to curtail the PV output and expected power sales profit could not be obtained; the residential operation cost will increase. Meanwhile, maintaining the power quality in the power grid is a task for the GEMS. In the DS, the OLTC is widely deployed to maintain the voltage within the acceptable range. Note that increase of available PV output leads to cost reduction for the GEMS because the power source with high fuel cost will be replaced by PV. Therefore, the reduction of PV curtailment is a common profit for the GEMS and HEMS, and there is potential to expand the mutual profit by coordinating the two EMSs.

In this section, we explain our proposed coordinated framework of the EV charge-discharge management for reduction of residential operation cost and PV curtailment by effectively charging the expected PV curtailment to the EV. Our proposed framework, shown in Fig. 1, works according to a similar timeline proposed in [26], though it is especially focused on the EV operation. It starts with forecasting residential power profiles, which is composed of residential electricity consumption and PV output for the forthcoming period from 6:00 to 6:00 on the next day. Then, in the operational plan phase, the coordination between the HEMS and GEMS is conducted by the information exchange. The HEMS determines an EV charge-discharge plan for minimizing the residential operation cost on the basis of the forecasted PV output and expected PV curtailment due to the voltage constraint informed from the GEMS. The planned charge-discharge amount would be larger or smaller than the ideal amount for achieving the objectives when the forecasted PV output includes significant error. Hence, in the control phase, the EV charge-discharge is controlled to follow the real-time monitored data in addition to the determined plan (hereinafter called "following control"). The following control intends to mitigate the deficiency and excess of charge-discharge amount caused by the difference between the forecasted and actual profiles so as to avoid unnecessary electricity purchase and opportunity loss of surplus PV selling. The rest of this section explains the detailed procedures after the HEMS finishes forecasting the day-ahead power profiles.

A. *Provisional Planning of EV Charge-Discharge in HEMS*

In the first step of the operational plan phase, each HEMS controller determines a day-ahead EV charge-discharge plan to

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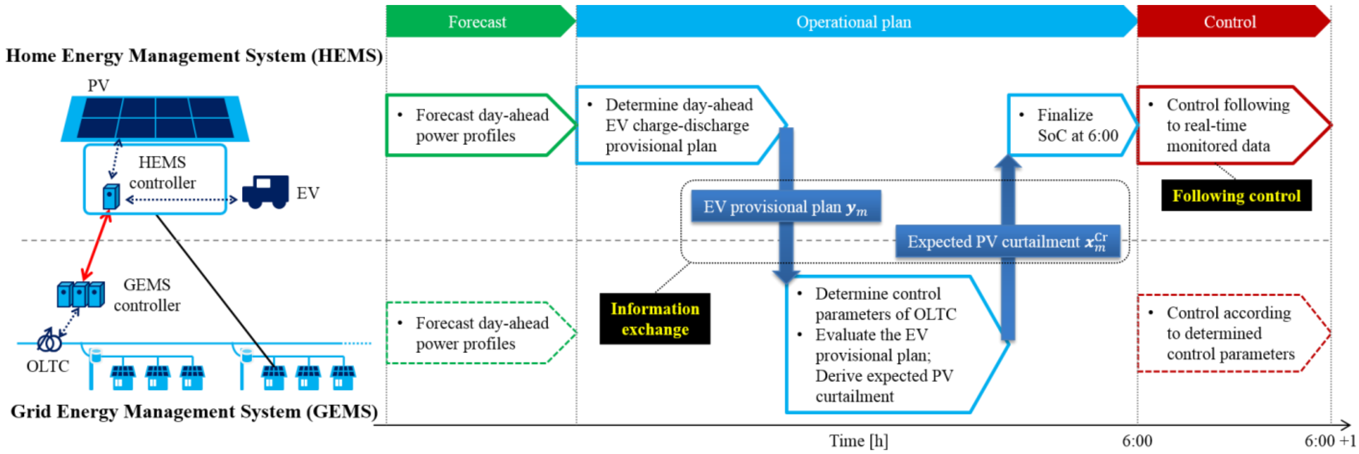

Fig. 1. Schematic image of the coordinated EV charge-discharge management framework. The coordination is based on information exchange between the HEMS and GEMS. The EV charge-discharge plan is determined through information exchange to minimize the residential operation cost and PV curtailment considering the voltage constrain in the DS. Then, following control is conducted, which controls the EV charge discharge amount following to the real-time monitored data to reduce the deficiency and excess of the charge-discharge amount caused by the forecasting error.

minimize the expected daily residential operation cost in the household without considering the voltage constraint. To achieve this purpose, the EV should be charged when the electricity rate is relatively low and should be discharged when the electricity rate is high or when the PV transmits as much surplus generation as possible. However, the SoC of the EV must be kept more than required for a scheduled and an urgent drive not to disturb EV usage for driving. Let t be the time in a day and $m \in \mathcal{M}$ be the index of house with HEMS where $\mathcal{M}$ be the index set of the houses the HEMSs. We also let $\boldsymbol{x}^{\mathrm{PV}} = (x_t^{\mathrm{PV}}; t \in \{1, \dots, T\})$ and $\boldsymbol{x}^{\mathrm{r}} = (x_t^{\mathrm{r}}; t \in \{1, \dots, T\})$ be sequences of the forecasted daily PV output and residential electricity consumption; $\boldsymbol{x}^{\mathrm{d}} = (x_t^{\mathrm{d}}; t \in \{1, \dots, T\})$ be a sequence of the electricity consumption for scheduled EV drive; $\boldsymbol{y}_{m,t} = \left(y_{m,t}^{\mathrm{o}}, y_{m,t}^{\mathrm{SoC}}, y_{m,t}^{\mathrm{V2H}}\right)$ be the set of EV states in a house m at time t where $y_{m,t}^{\mathrm{o}}$ be the EV output to the house, $y_{m,t}^{\mathrm{SoC}}$ be the SoC, and $y_{m,t}^{\mathrm{V2H}} \in \{0,1\}$ be the connection state to the EV charger in the house; and $\boldsymbol{y}_m = \{\boldsymbol{y}_{m,1}, \dots, \boldsymbol{y}_{m,T}\}$ be the daily EV charge-discharge provisional plan. Since, in general, the actual day-ahead PV output and residential electricity consumption are not accessible, we determine the appropriate EV operation by solving the following minimization problem using the forecasted profiles and scheduled electricity consumption for the EV drive $\boldsymbol{x}_m^{\mathrm{H}} = \{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{x}_m^{\mathrm{d}}\}$.

$$\boldsymbol{y}_m = \underset{\boldsymbol{y}_m}{\operatorname{argmin}} \sum_{t=1}^{T} \Big(c_t^{\mathrm{p}} e_{m,t}^{\mathrm{p}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^H, \boldsymbol{y}_{m,t-1}, \dots, \boldsymbol{y}_{m,0}\right) - c_t^{\mathrm{PV}} e_{m,t}^{\mathrm{rev}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^H, \boldsymbol{y}_{m,t-1}, \dots, \boldsymbol{y}_{m,0}\right)\Big), \quad (1)$$

subject to

$$-O^{\mathrm{c}} \le y_{m,t}^{\mathrm{o}} \le O^{\mathrm{d}},$$
$$y_{m,t}^{\mathrm{o}} = 0 \ \text{if} \ y_{m,t}^{\mathrm{V2H}} = 0,$$
$$\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right) \le y_{m,t}^{\mathrm{SoC}} \le \overline{S},$$

where

$$\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right) = \begin{cases} \underline{S}^{\mathrm{ur}}, & \text{if} \ \sum_{t=t+1}^{T} x_{m,t}^{\mathrm{d}} = 0, \\ \underline{S}^{\mathrm{ur}} + \underline{S}^{\mathrm{sc}}, & \text{otherwise}. \end{cases}$$

Here, c_t^{p} and c_t^{PV} are the cost conversion coefficients of the power purchase and selling, respectively; $\boldsymbol{y}_0$ is the initial state; $e_{m,t}^{\mathrm{p}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^{\mathrm{H}}, \boldsymbol{y}_{m,t-1}, \dots, \boldsymbol{y}_{m,0}\right)$ and $e_{m,t}^{\mathrm{rev}}\left(\boldsymbol{y}_{m,t} | \boldsymbol{x}^{\mathrm{H}}, \boldsymbol{y}_{m,t-1}, \dots, \boldsymbol{y}_{m,0}\right)$ are the purchased electricity and the reverse power flow from PV, respectively, as a function of $\boldsymbol{y}_{m,t}$ under the previous parameters subset $\{\boldsymbol{y}_{m,t-1}, \dots, \boldsymbol{y}_{m,0}\}$ and the power profiles $\boldsymbol{x}^{\mathrm{H}}$; O^{c} and O^{d} are the rated EV output of charging and discharging, respectively; $\overline{S}$ is the upper limit of the SoC; $\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)$ is the lower limit of the SoC as a function of $x_{m,t}^{\mathrm{d}}$; and $\underline{S}^{\mathrm{ur}}$ and $\underline{S}^{\mathrm{sc}}$ are the minimum SoC required for the urgent and scheduled driving, respectively, where the latter one is derived by the time length and electricity consumption for the scheduled driving. Then, the determined EV provisional plans in the all houses with HEMSs $\boldsymbol{y} = (\boldsymbol{y}_m; m \in \mathcal{M})$ are sent to the GEMS.

B. Determination of OLTC Control Parameters in GEMS

In the GEMS, the voltage control phase is divided into U time intervals. The voltage control parameter set $\boldsymbol{\gamma}_u; u \in \{1, \dots, U\}$ is updated in each time interval to appropriately perform the voltage control according to the voltage variation in the time intervals. Let $n \in \mathcal{N}$ be the index of house without HEMS where $\mathcal{N}$ be the index set of the houses without HEMSs. The appropriate voltage control parameter set of the OLTC are determined using the forecasted power profiles and the EV provisional plan $\boldsymbol{x}^{\mathrm{G}} = \{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{y}_m; m \in \mathcal{M}\} \cup \{\boldsymbol{x}_n^{\mathrm{PV}}, \boldsymbol{x}_n^{\mathrm{r}}; \in \mathcal{N}\}$ and the EV provisional plans sent from the HEMSs $\boldsymbol{y}$ are evaluated under the voltage constraint. Our grid management is carried out by the GEMS composed of a GEMS controller and an OLTC. The tap ratio of the OLTC is regulated using the line drop compensator (LDC) method [27] so as to maintain the voltage in the DS. In this method, the OLTC monitors its secondary current and voltage to dynamically control the tap position. Let $\boldsymbol{i}_t$ and $\dot{\boldsymbol{v}}_t$ be the secondary current and voltage of

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the OLTC, respectively. The OLTC estimates a voltage v_t^{ref} at a voltage reference point on the secondary side of the OLTC:

$$v_t^{\mathrm{ref}}(l) = |\dot{\boldsymbol{v}}_t - l_u \dot{\boldsymbol{z}} \boldsymbol{i}_t|, \quad (2)$$

where l_u is the line length between the OLTC and the voltage reference point at time interval u and $\dot{\boldsymbol{z}}$ is the unit line impedance. Then, the OLTC regulates the tap position s_t when the cumulative differences between the target voltage v_u^{tar} and v_t^{ref} with the dead band ε,

$$\overline{D}_t(\boldsymbol{\gamma}_u) = \max\{0, \overline{D}_{t-1} + v_t^{\mathrm{ref}}(l_u) - v_u^{\mathrm{tar}} - \varepsilon\}, \quad (3)$$

$$\underline{D}_t(\boldsymbol{\gamma}_u) = \max\{0, \underline{D}_{t-1} + v_u^{\mathrm{tar}} - \varepsilon - v_t^{\mathrm{ref}}(l_u)\}, \quad (4)$$

exceed the threshold δ as follows,

$$s_t = \begin{cases} s_{t-1} - 1, & \text{if } \overline{D}_t(\boldsymbol{\gamma}_u) > \delta \text{ and } s_t \neq \underline{s}, \\ s_{t-1} + 1, & \text{if } \underline{D}_t(\boldsymbol{\gamma}_u) > \delta \text{ and } s_t \neq \overline{s}, \\ s_{t-1}, & \text{otherwise}, \end{cases} \quad (5)$$

where $\boldsymbol{\gamma}_u = \{l_u, v_u^{\mathrm{tar}}\}$ is a parameter set of the LDC method at the time interval u, $\underline{s}$ and $\overline{s}$ are the lower and upper tap position, respectively. The cumulative differences $\overline{D}_t(\boldsymbol{\gamma}_u)$ and $\underline{D}_t(\boldsymbol{\gamma}_u)$ become zero when the tap position is changed.

The OLTC automatically controls the voltage if the control parameter set $\boldsymbol{\gamma}_u$ is implemented. In our framework, the GEMS controller determines the appropriate control parameters $\boldsymbol{\gamma}_u^q$ for the each time interval u so as to minimize the amount of voltage violation from the appropriate range. Let $v_t^j(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}})$ be the voltage at the medium-voltage (MV) node $j \in \mathcal{J}$ under the given parameter set $\boldsymbol{\gamma}_u^q$ where $\mathcal{J}$ is the index set of MV nodes in the DS, $\overline{v}^j$ and $\underline{v}^j$ be the upper and lower limits of the appropriate voltage at the node j, respectively, c_1 and c_2 be the weight coefficients, the appropriate parameters $\boldsymbol{\gamma}_u^q$ can be obtained by solving the following minimization problem using the forecasted power profiles and the EV provisional plan $\boldsymbol{x}^G = \{\boldsymbol{x}_m^{\mathrm{PV}}, \boldsymbol{x}_m^{\mathrm{r}}, \boldsymbol{y}_m; m \in \mathcal{M}\} \cup \{\boldsymbol{x}_n^{\mathrm{PV}}, \boldsymbol{x}_n^{\mathrm{r}}; \in \mathcal{N}\}$.

$$\boldsymbol{\gamma}_u^q = \underset{\boldsymbol{\gamma}_u^q}{\mathrm{argmin}} \left\{ \sum_{j\in\mathcal{J}} \sum_{t=1}^{\mathrm{T}_u} h_1\left(v_t^j(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}}); \overline{v}^j, \underline{v}^j\right) + c_1 \sum_{t=1}^{\mathrm{T}_u} |s_{t-1} - s_t| + c_2 \sum_{j\in\mathcal{J}} \sum_{t=1}^{\mathrm{T}_u} h_2\left(v_t^j(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}}); \overline{v}^j, \underline{v}^j\right) \right\}, \quad (6)$$

where

$$h_1\left(v_t^j; \overline{v}^j, \underline{v}^j\right) = \begin{cases} v_t^j - \overline{v}^j, & \text{if } v_t^j > \overline{v}^j, \\ \underline{v}^j - v_t^j, & \text{if } v_t^j < \underline{v}^j, \\ 0, & \text{if } \underline{v}^j \le v_t^j \le \overline{v}^j, \end{cases}$$

$$h_2\left(v_t^j; \overline{v}^j, \underline{v}^j\right) = v_t^j - \frac{\overline{v}^j + \underline{v}^j}{2}.$$

The above objective function can be evaluated by conducting the power flow calculation for each parameter set $\boldsymbol{\gamma}_u = \{l_u \in \mathcal{L}, v_u^{\mathrm{tar}} \in \mathcal{V}\}$ where $\mathcal{L}$ and $\mathcal{V}$ are the candidate sets. The GEMS evaluates the amount of expected PV curtailment in all houses with the HEMSs operated on the basis of each provisional plan, i.e.,

$$\boldsymbol{x}_m^{\mathrm{c}} = \boldsymbol{x}_m^{\mathrm{c}}(\boldsymbol{\gamma}_u^q|\boldsymbol{x}^{\mathrm{G}});\ m \in \mathcal{M}, \quad (7)$$

and sends the derived PV curtailment $\boldsymbol{x}_m^{\mathrm{c}}$ to each HEMS.

C. *Following Control of EV Charge-Discharge in HEMS*

Finally, each HEMS controller determines the SoC at the beginning of the control phase $y_{m,0}^{\mathrm{SoC}}$ and conducts the following control, which controls the EV charge-discharge output $y_{m,t}^{*\mathrm{o}}$ monitoring the real-time data of the residential electricity consumption and PV curtailment. The SoC $y_{m,0}^{\mathrm{SoC}}$ is adjusted to ensure the adequate free capacity for charging the curtailed PV during the daytime and the charged capacity for the scheduled EV drive as follows:

$$y_{m,0}^{\mathrm{SoC}} = \frac{1}{2}\left\{\left(1 - \frac{\sum_{t=1}^{T} x_{m,t}^{\mathrm{c}}}{B}\right) + \frac{\sum_{t=1}^{T}\left(x_{m,t}^{\mathrm{r}} + x_{m,t}^{\mathrm{d}}\right)}{B}\right\}, \quad (8)$$

where B is the battery storage capacity of the EV. Let, $\boldsymbol{x}^{*\mathrm{r}} = (x_t^{*\mathrm{r}}; t \in \{1, \dots, T\})$, $\boldsymbol{x}^{*\mathrm{c}} = (x_t^{*\mathrm{c}}; t \in \{1, \dots, T\})$, and $\boldsymbol{y}^{*\mathrm{SoC}} = (y_t^{*\mathrm{SoC}}; t \in \{1, \dots, T\})$ be the realized profiles of the electricity consumption, curtailed PV output, and SoC. In the control phase, the EV battery controls the charge-discharge amount monitoring the actual value of the residential electricity consumption $x_t^{*\mathrm{r}}$ and the PV curtailment $x_t^{*\mathrm{c}}$ as follows,

if $y_{m,t}^{*\mathrm{c}} = 0$,

$$y_{m,t}^{*\mathrm{o}} = \begin{cases} x_{m,t}^{*\mathrm{r}}, & \text{if } \left(y_{m,t-1}^{*\mathrm{SoC}} - c^{\mathrm{u1}} x_{m,t}^{*\mathrm{r}}\right) \ge \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right), \\ 0, & \text{if } y_{m,t-1}^{*\mathrm{SoC}} = \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right), \\ c^{\mathrm{u2}}\left(y_{m,t-1}^{*\mathrm{SoC}} - \underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)\right), & \text{otherwise}, \end{cases} \quad (9)$$

if $x_{m,t}^{*\mathrm{c}} \neq 0$,

$$y_{m,t}^{*\mathrm{o}} = \begin{cases} -x_{m,t}^{*\mathrm{c}}, & \text{if } \left(y_{m,t-1}^{*\mathrm{SoC}} + c^{\mathrm{u1}} x_{m,t}^{*\mathrm{c}}\right) \le \overline{S}, \\ 0, & \text{if } y_{m,t-1}^{*\mathrm{SoC}} = \overline{S}, \\ c^{\mathrm{u2}}\left(y_{m,t-1}^{*\mathrm{SoC}} - \overline{S}\right), & \text{otherwise}, \end{cases}$$

$$y_{m,t}^{*\mathrm{SoC}} = y_{m,t-1}^{*\mathrm{SoC}} - y_{m,t}^{*\mathrm{o}}, \quad (10)$$

where c^{u1} and c^{u2} are the coefficients for converting the unit of value from Watt to SoC [%] and SoC [%] to Watt. The EV usage for driving could not be disturbed when the constraint of the lower limit of SoC $\underline{S}_{m,t}\left(x_{m,t}^{\mathrm{d}}\right)$ is satisfied. Let $\boldsymbol{x}^{*\mathrm{PV}} = (x_t^{*\mathrm{PV}}; t \in \{1, \dots, T\})$ be a sequence of the actual PV output. As a result, the actual value of the purchased electricity $e_{m,t}^{*\mathrm{p}}$ and the reverse power flow $e_{m,t}^{*\mathrm{rev}}$ becomes

$$e_{m,t}^{*\mathrm{rev}} = \max\{0, \left(x_{m,t}^{*\mathrm{PV}} - x_{m,t}^{*\mathrm{c}} - x_{m,t}^{*\mathrm{r}} + y_{m,t}^{*\mathrm{o}}\right)\}, \quad (11)$$

$$e_{m,t}^{*\mathrm{p}} = x_{m,t}^{*\mathrm{r}} - y_{m,t}^{*\mathrm{o}} - \left(x_{m,t}^{*\mathrm{PV}} + x_{m,t}^{*\mathrm{c}}\right). \quad (12)$$

III. NUMERICAL SIMULATION

To verify the effectiveness of our proposed EV charge-discharge framework from the viewpoint of the residential operation cost and total amount of PV curtailment, we perform numerical simulation based on the 30-day (June 2007) real-world PV output and residential electricity consumption profiles with a time step of 10 [s] and using a DS model [28]. This model simulates the actual Japanese DS including both MV (6.6 [kV]) and low-voltage (LV, 100/200 [V]) systems (Fig. 2). The model has an OLTC at the distribution substation and includes 435 residential customers installing residential PV systems. Sixty-five houses at the

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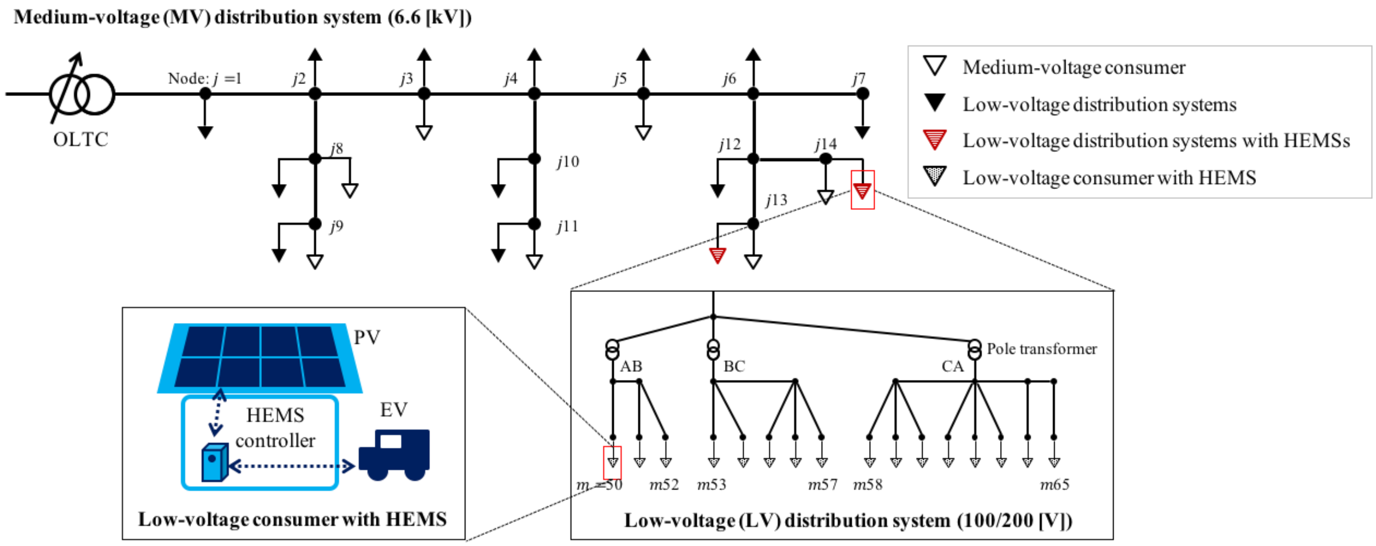

Fig. 2. Simulation model.

terminal areas of the feeder also install the HEMSs and EVs. The forecasted profile of the PV output used for operational planning is derived by the so-called just-in-time modeling scheme [29]. Table II shows the simulation setup including some dominant parameters. Table III shows the electricity rate for calculating the residential operation cost that is based on an actual time-of-use (TOU) menu provided by Chubu Electric Power CO., Inc. We assume that EVs are used for picking up and shopping according to the driving schedule shown in Table IV, and the SoC decreases during the driving time.

In this simulation, we assess the effectiveness of the coordinated framework of EV charge-discharge focusing on the following five frameworks (detailed explanations not given in the proposed framework are described in the appendix):

- Framework 1 (F1), which adopts a provisional daily EV charge-discharge plan directly determined by the HEMS without the information exchange and controls EV charge-discharge according to the plan.
- Framework 2 (F2, ideal situation), which can determine an ideal daily EV charge-discharge plan by the information exchange on the basis of realized power profiles, and controls EV charge-discharge according to the ideal plan.
- Framework 3 (F3), which determines a daily EV charge-discharge plan by the HEMS coordinated with the GEMS (i.e. information exchange), and controls EV charge-discharge according to the plan.
- Framework 4 (F4), which controls EV charge-discharge following real-time monitored data (i.e. following control). The SoC at the beginning of control phase $y_{m,0}^{\mathrm{SoC}}$ assumes a pre-set value; this is determined without any information exchange between the HEMS and GEMS.
- Framework 5 (F5, proposed framework), which controls the EV charge-discharge following to the real-time monitored data (i.e. following control). The SoC at the beginning of the control phase $y_{m,0}^{\mathrm{SoC}}$ is

TABLE II
SIMULATION SETUP

DS model	Load capacity	2113 [kVA]
	Acceptable voltage range at node 1	6621.4 - 6878.6 [V]
	Acceptable voltage range at node 2 - 14	6474.3 - 6725.7 [V]
OLTC parameters	Tap position	{1, 2, ..., 21}
	Tap width	60 [V]
	Dead band	1 [%]
	Candidates for l_u	{0.1, 1.1, ..., 6.1} [km]
	Candidates for v_u^{REF}	{95, 95.5, ..., 107}×6600/105 [V]
Spec of PV inverters	Curtailment starting voltage	107 [V]
	Curtailment ending voltage	106.5 [V]
	Speed of curtailment	0.02 [kW/s]
Spec of EV	Rated power output of charging	3 [kW]
	Rated power output of discharging	3 [kW]
	Rated storage capacity	24 [kWh]
	Minimum SoC for urgent driving	30 [%]
	Electricity consumption for driving	4 [kWh/h]

TABLE III
ELECTRICITY RATE

Electricity rate	TOU pricing	0:00- 7:00	9.33 [JPY/kWh]
		7:00- 9:00	21.23 [JPY/kWh]
		9:00-17:00	31.43 [JPY/kWh]
		17:00-24:00	21.23 [JPY/kWh]
	Feed-in-Tariff		31.00 [JPY/kWh]

TABLE IV
DRIVING SCHEDULE

Pick up	Driving time	7:00-7:10, 7:20-7:30, 18:30-18:40, 18:50-19:00
	Parking time	7:10-7:20, 18:40-18:50
Shopping	Driving time	13:30-13:40, 14:20-14:30
	Parking time	13:40-14:20
Parking at house		Otherwise

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determined by the information exchange between the HEMS and the GEMS.

Fig. 3 shows the simulation results, i.e., the daily averages of the PV curtailment per household in the HEMS installed area (Fig. 3(a)) and the daily average of the realized residential operation cost per household in the HEMS installed area (Fig. 3(b)). Comparing the results of the EV charge-discharge operation in the ideal condition (F2) with that planned by only HEMS (F1), the PV curtailment is reduced by 73% and the profit is 4.1 times larger. This result suggests that the coordination between the HEMSs and GEMS based on the information exchange can remarkably reduce the PV curtailment that is caused by the EV operation without considering the voltage constraint.

Fig. 4 shows an example of the EV charge-discharge management results by each framework, i.e., the realized PV output, expected PV output, EV output, purchased electricity, and SoC. In the ideal condition (F2), the PV curtailment is reduced by shifting the EV operation discharge to charge during the daytime, and the residential operation cost is also reduced because the purchased electricity during the night is replaced by the charged PV output. The results show that the scheduled control on the basis of the coordinated plan (F3) drastically reduces the PV curtailment by charging the forecasted PV curtailment comparing with the charge-discharge operation conducted only by the HEMS (F1). The profit slightly increased, and the residential operation cost slightly decreased; however, the reduction amount is not as large as that of the PV curtailment. The results imply that the charged amount becomes smaller because the amount of the PV curtailment estimated by the GEMS is smaller due to the forecast error of the PV output, thus the purchased electricity from the grid increased at night. On the other hand, the PV curtailment is reduced by 72% and the profit improves 3.04 times from F1 by implementing the following control (F4). This implies that the following control of EV charge-discharge mitigates the decline of performance caused by the forecast uncertainty. The PV curtailment and residential operation cost are further reduced by determining the appropriate SoC at the beginning of the control phase (6:00) on the basis of the information exchange between the HEMS and GEMS in addition to the following control (F5). Comparing EV operation results shown in Figs. 4(d) and 4(e), the proposed framework F5 could charge a larger amount of PV output than F4 during the daytime because SoC at 6:00 in F5 is set to an appropriate value on the basis of exchanged information between the HEMS and GEMS. The value is set to lower than that of F4 to avoid the deficiency of free capacity for charging the expected PV curtailment during the daytime (at 12:30-13:30). As a result, our proposed framework (F5) achieves the 3.56 times increase of the profit and 74% reduction of the PV curtailment compared to F1. These results are also in close agreement to those of the ideal condition (F2). The effect of the following control in addition to the information exchange can be seen by comparing the results of F3 and F5. The effect of the forecast errors in the power profiles is mitigated by the implementation of the following control. Additionally, we assume that a pre-set SoC value at the beginning of the control phase $y_{m,0}^{\mathrm{SoC}}$ is used when any communication error affects the information exchange. Therefore, the impact of communication errors on the information exchange can be seen by comparing the simulation results of F4 (with communication error) and F5 (without communication error).

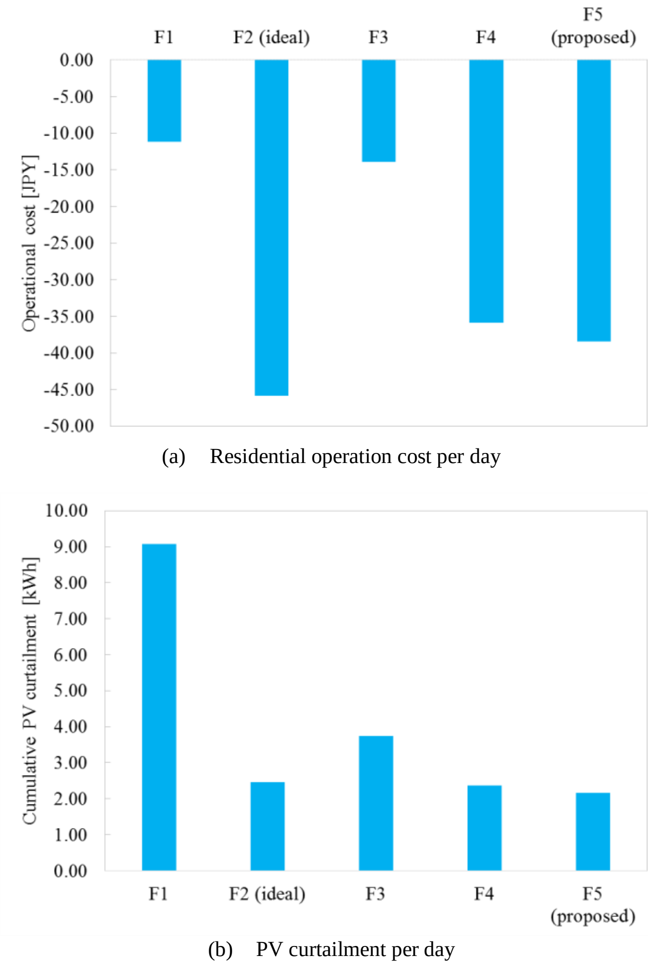

Fig. 3. Simulation results.

IV. Discussion and Conclusion

In this paper, we proposed a coordinated EV charge-discharge management framework. The coordination is based on the information exchange between the HEMS and GEMS. The proposed framework determines a daily EV charge-discharge plan on the basis of the exchanged information and day-ahead forecasted power profiles to ensure the adequate free capacity for charging the curtailed PV during the daytime and the charged capacity for the scheduled EV drive. We also proposed a following control scheme. The scheme controls the EV charge-discharge amount following to the real-time monitored data for mitigation of the deficiency and excess of charge-discharge amount caused by the forecast errors. The effectiveness of the proposed framework was evaluated using a DS simulation model from the viewpoint of the residential operation cost and the amount of PV curtailment.

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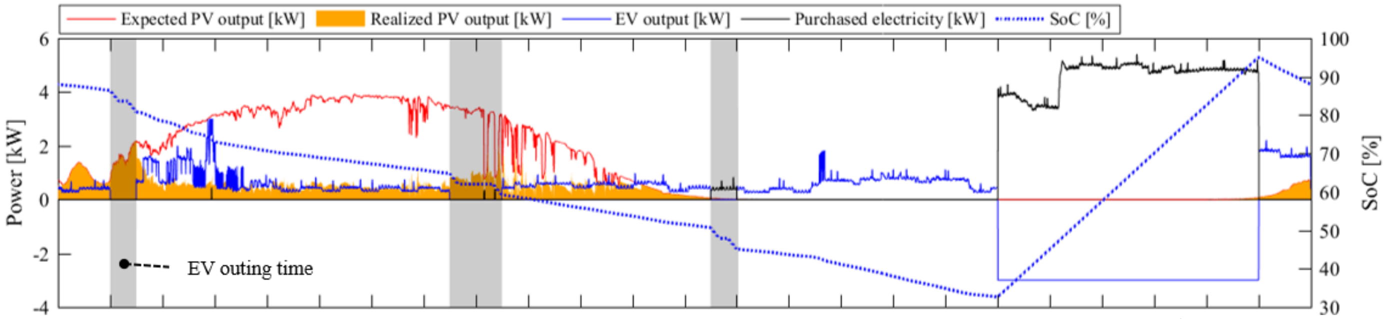
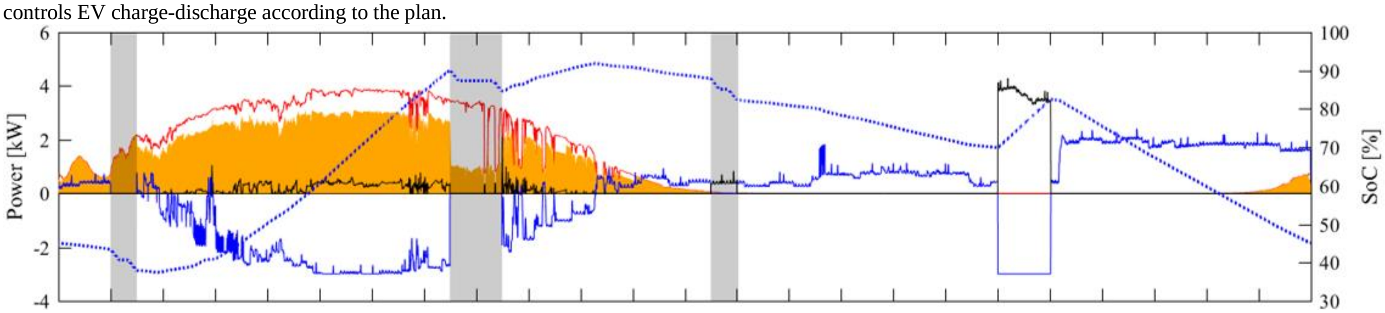
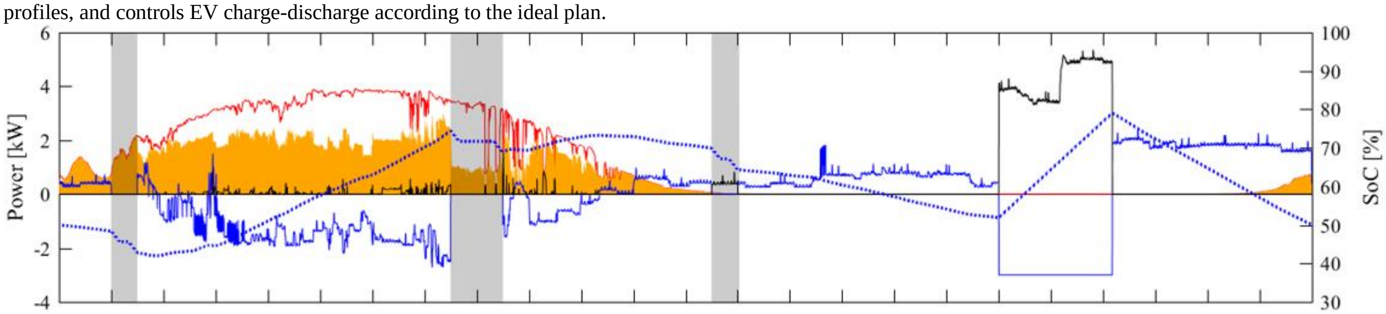


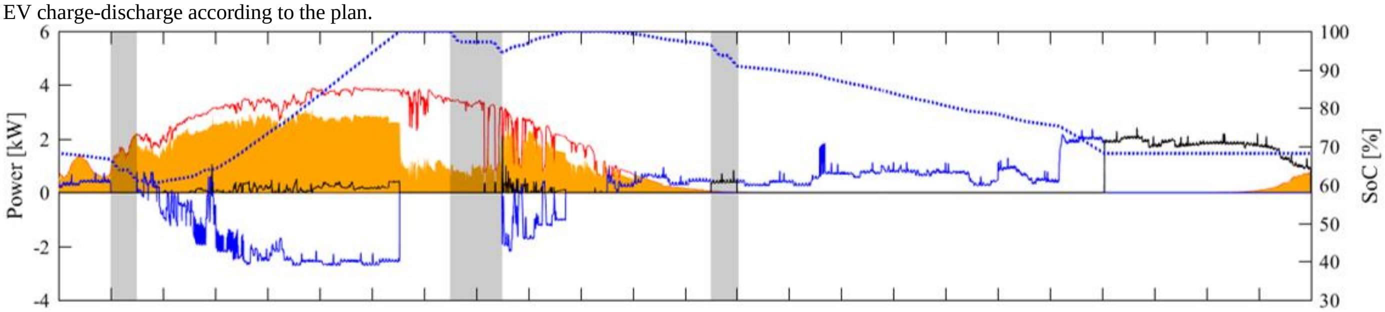
(a) Framework 1 (F1), which adopts a provisional daily EV charge-discharge plan directly determined by the HEMS without the information exchange and controls EV charge-discharge according to the plan.



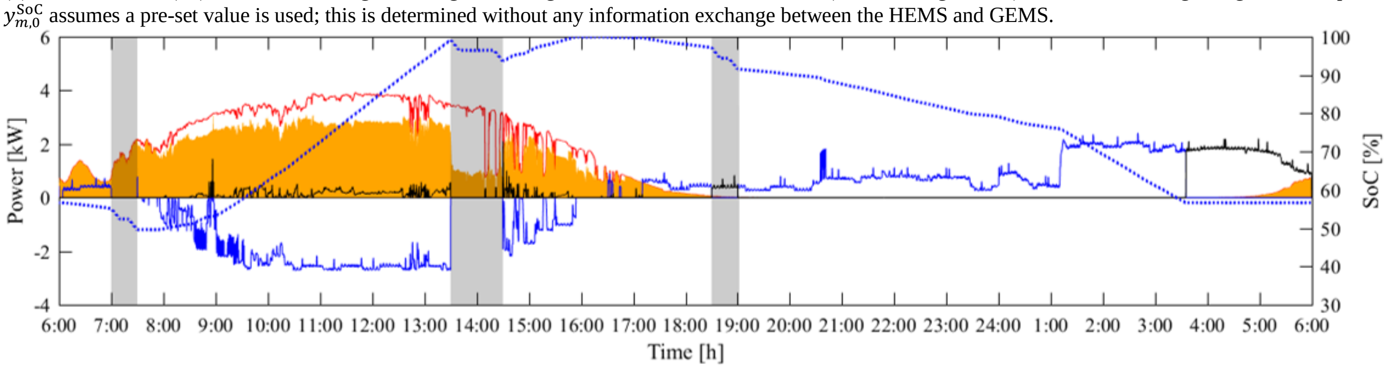
(b) Framework 2 (F2, ideal situation), which can determine an ideal daily EV charge-discharge plan by the information exchange on the basis of realized power profiles, and controls EV charge-discharge according to the ideal plan.



(c) Framework 3 (F3), which determines a daily EV charge-discharge plan by the HEMS coordinated with the GEMS (i.e. information exchange), and controls EV charge-discharge according to the plan.



(d) Framework 4 (F4), controls EV charge-discharge following to the real-time monitored data (i.e. following control). The SoC at the beginning of control phase $y_{m,0}^{\mathrm{SoC}}$ assumes a pre-set value is used; this is determined without any information exchange between the HEMS and GEMS.



(e) Framework 5 (F5, proposed framework), which controls EV charge-discharge following to the real-time monitored data (i.e. following control). The SoC at the beginning the control phase $y_{m,0}^{\mathrm{SoC}}$ is determined by the information exchange between the HEMS and GEMS.

Fig. 4. Comparison of daily EV charge-discharge management results. All frameworks could ensure the SoC over $\underline{S}_{m,t}(x_{m,t}^{\mathrm{d}})$% for urgent and scheduled driving in all day long. All horizontal axes are same as (e).

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The simulation results implied that the proposed framework achieves to reduce the residential operation cost and the PV curtailment by the information exchange and the following control.

In order to implement our proposed framework practically, the battery degradation impact must be included. Although we did not assess the impact of battery degradation on the residential operation cost in this paper, our framework can take the impact into consideration by adding the function of the cost of battery degradation to the objective function of HEMS planning shown in (1). According to the literature [30], the battery degradation is assessed by focusing on temperature-related degradation, SoC-related degradation, and depth of discharge (DOD) degradation. Comparing the degradation impact of our proposed framework (Framework 5) and Framework 1 in Figs. 4(a) and 4(e), the degradation impact of the proposed framework does not seem to be worse than Framework 1, while the utilized SoC range, i.e., maximum daily SoC minus the minimum, are 50.4% and 62.5%, respectively. This result suggests that the proposed framework does not require a large SoC range; therefore, the decline of the energy management performance by the reduction of available SoC range due to the battery degradation is smaller than that of Framework 1. The charge-discharge framework should probably be updated according to the degree of battery degradation; therefore, we will assess this topic as a future work.

We have implemented the proposed framework under the assumption that the EVs are connected only to the owners' houses. However, the EV could be connected to the grid in the various locations such as the destinations and others' houses. Investigation of the effects of our proposed framework considering the movement of the EV in the expanded large-scale DS model is remained on a future work. With regard to the EV driving schedule, we assumed that the EV owner added the driving schedule to the HEMS. It is more convenient for the owner if the HEMS automatically forecasts the driving schedule. With regard to the EV driving schedule, we assumed that the EV owner added the driving schedule to the HEMS. It is more convenient for the owner if the HEMS automatically forecasts the driving schedule. The HEMS should conduct the operation considering the effect on the forecast error in the future work. In the GEMS, we focused on an OLTC, but the proposed coordination framework could be similarly implemented in the HEMS and GEMS using other voltage regulators such as capacitor banks and step voltage regulators. The application of our coordination framework with a GEMS composed of other voltage regulators will be the topic of future research.

APPENDIX

The planning of the EV charge-discharge frameworks (F1–F4) that were compared with the proposed framework (F5) in Section III can be explained as follows.

In F1, F2, and F3, each HEMS determines a daily EV charge-discharge operation $y^{\mathrm{o}}_{m,t}$ to minimize the residential operation cost and control the EV according to the determined plan. The frameworks perform EV charge-discharge planning in different conditions. F1 determines the plan without considering the voltage constraint in the grid. F2 and F3 determine the plan under consideration of the voltage constraint based on the expected PV curtailment. In F2, the realized PV curtailment $\boldsymbol{x}^{*\mathrm{c}}_{m}$ is used as the expected PV to evaluate the results under ideal conditions, which means the forecast power profiles include no error. In F3, the estimated PV curtailment $\boldsymbol{x}^{\mathrm{c}}_{m}$ is used to evaluate the results under realistic conditions, which means the forecast power profiles include the forecast error. The flowchart of the planning profiles for F1–F3 is shown in Fig. 5. First, we estimate the daily charging amount y^{ttl}, which is the estimated electricity consumption in a day:

Framework 1

$$y^{\mathrm{ttl}} = \sum_{t=1}^{T}\left(x^{\mathrm{r}}_{m,t} + x^{\mathrm{d}}_{m,t}\right), \tag{13}$$

Framework 2

$$y^{\mathrm{ttl}} = \sum_{t=1}^{T}\left(x^{\mathrm{r}}_{m,t} + x^{\mathrm{d}}_{m,t} - x^{*\mathrm{c}}_{m,t}\right), \tag{14}$$

Framework 3

$$y^{\mathrm{ttl}} = \sum_{t=1}^{T}\left(x^{\mathrm{r}}_{m,t} + x^{\mathrm{d}}_{m,t} - x^{\mathrm{c}}_{m,t}\right). \tag{15}$$

Then, we separate each day into two time zones: T^{ld}, which runs from sunset to sunrise, and T^{pv}, which runs from sunrise to sunset. The time zone T^{ld} is further separated according to the TOU pricing into $T^{\mathrm{ld}}_1, T^{\mathrm{ld}}_2, \ldots, T^{\mathrm{ld}}_p$, where TOU pricing in each time zone is $T^{\mathrm{ld}}_1 < T^{\mathrm{ld}}_2 < \cdots < T^{\mathrm{ld}}_p$. The EV operation $y^{\mathrm{o}}_{m,t}$ for charging is determined from the time zone whose TOU pricing is lowest until the daily charging amount y^{ttl} is satisfied. That is, if $\sum_t y^{\mathrm{o}}_{m,t} < y^{\mathrm{ttl}}$,

$$y^{\mathrm{o}}_{m,t} = O^{\mathrm{C}}, \tag{16}$$

otherwise,

$$y^{\mathrm{o}}_{m,t} = 0. \tag{17}$$

In time zone T^{pv}, the EV operation is determined in accordance with each framework. That is,

Framework 1

$$y^{\mathrm{o}}_{m,t} = -x^{\mathrm{r}}_{m,t}, \tag{18}$$

Framework 2

$$y^{\mathrm{o}}_{m,t} = -x^{\mathrm{r}}_{m,t} + x^{*\mathrm{c}}_{m,t}, \tag{19}$$

Framework 3

$$y^{\mathrm{o}}_{m,t} = -x^{\mathrm{r}}_{m,t} + x^{\mathrm{c}}_{m,t}. \tag{20}$$

F1 discharges the EV to cover all electricity consumption in the house. F2 and F3 discharge the amount of electricity consumption minus the expected PC curtailment.

F4 adopts the following control under the HEMS without coordinating with the GEMS, and the EV operation is conducted according to (9), (10). In F4, there is no information exchange between the HEMS and GEMS, and the SoC at the beginning of the control phase $y^{\mathrm{SoC}}_{m,0}$, which was determined on the basis of the exchanged information in F5, is determined as the average of the optimal value $y^{*\mathrm{SoC}}_{m,0}$ over 30 days. This is assumed as the pre-set value and is used when any

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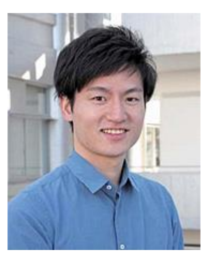
communication error occurs in the information exchange.
Framework 4

$$y_{m,0}^{\mathrm{SoC}} = \frac{1}{30}\sum_{d=1}^{30} y_{m,0}^{*\mathrm{SoC}}(d), \tag{21}$$

where d is the index of the simulation date.

REFERENCES

[1] *World Energy Outlook 2015*. International Energy Agency, 2015.
[2] "Related materials of Long-term energy outlook (in Japanese)," *Ministry of Economy, Trade and Industry/Agency for Natural Resources and Energy*, 2015. [Online]. Available: http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/011/pdf/011_07.pdf. [Accessed: 11-Feb-2017].
[3] "Submission of Japan's Intended Nationally Determined Contribution (INDC)," 2015. [Online]. Available: http://www4.unfccc.int/Submissions/INDC/Published Documents/Japan/1/20150717_Japan's INDC.pdf. [Accessed: 05-Sep-2017].
[4] "Definition of ZEH and future measures proposed by the ZEH Roadmap Examination Committee," *Energy Efficiency and Conservation Division/Agency for Natural Resources and Energy/Ministry, Trade and Industry*, 2015. [Online]. Available: http://www.enecho.meti.go.jp/category/saving_and_new/saving/zeh_report/pdf/report_160212_en.pdf. [Accessed: 31-Aug-2017].
[5] M. Duvall, "Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles," 2002.
[6] A. Y. S. Lam, J. J. Q. Yu, Yunhe Hou, and V. O. K. Li, "Coordinated autonomous vehicle parking for vehicle-to-grid services," in *2016 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2016, pp. 284–289.
[7] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle-to-grid energy and ancillary services," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 351–359, 2012.
[8] M. Shafie-khah, E. Heydarian-Forushani, G. Osório, F. S. Gil, J. Aghaei, M. Barani, J. S. Catalao, "Optimal Behavior of Electric Vehicle Parking Lots as Demand Response Aggregation Agents," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2654–2665, Nov. 2016.
[9] L. Yao, W. H. Lim, and T. S. Tsai, "A real-time charging scheme for demand response in electric vehicle parking station," *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 52–62, Jan. 2017.
[10] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011.
[11] A. Dubey and S. Santoso, "Electric vehicle charging on residential distribution systems: Impacts and mitigations," *IEEE Access*, vol. 3, pp. 1871–1893, 2015.
[12] M. H. Amini and A. Islam, "Allocation of electric vehicles' parking lots in distribution network," in *ISGT 2014*, 2014, pp. 1–5.
[13] M. Honarmand, A. Zakariazadeh, and S. Jadid, "Self-scheduling of electric vehicles in an intelligent parking lot using stochastic optimization," *J. Franklin Inst.*, vol. 352, no. 2, pp. 449–467, Feb. 2015.
[14] A. Y. Saber and G. K. Venayagamoorthy, "Plug-in vehicles and renewable energy sources for cost and emission reductions," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1229–1238, Apr. 2011.
[15] M. R. Mozafar, M. H. Moradi, and M. H. Amini, "A simultaneous approach for optimal allocation of renewable energy sources and electric vehicle charging stations in smart grids based on improved GA-PSO algorithm," *Sustain. Cities Soc.*, vol. 32, pp. 627–637, 2017.
[16] A. Mohamed, V. Salehi, T. Ma, and O. Mohammed, "Real-time energy management algorithm for plug-in hybrid electric vehicle charging parks involving sustainable energy," *IEEE Trans. Sustain. Energy*, vol. 5, no. 2, pp. 577–586, Apr. 2014.
[17] T. Shoji, W. Hirohashi, Y. Fujimoto, and Y. Hayashi, "Home energy management based on Bayesian network considering resident convenience," *2014 Int. Conf. Probabilistic Methods Appl. to Power Syst.*, pp. 1–6, 2014.
[18] M. Rastegar, M. Fotuhi-Firuzabad, and M. Moeini- Aghtaie, "Developing a two-level framework for residential energy management," *IEEE Trans. Smart Grid*, pp. 1–11, 2016.
[19] E. L. Karfopoulos and N. D. Hatziargyriou, "A multi-agent system for controlled charging of a large population of electric vehicles," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1196–1204, May 2013.
[20] Y. He, B. Venkatesh, and L. Guan, "Optimal scheduling for charging and discharging of electric vehicles," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1095–1105, 2012.
[21] C.-K. Wen, J.-C. Chen, J.-H. Teng, and P. Ting, "Decentralized plug-in electric vehicle charging selection algorithm in power systems," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1779–1789, Dec. 2012.
[22] O. Erdinc, N. G. Paterakis, T. D. P. Mendes, A. G. Bakirtzis, and J. P. S. Catalao, "Smart household operation considering bi-directional EV and ESS utilization by real-time pricing-based DR," *IEEE Trans. Smart Grid*, vol. 6, no. 3, pp. 1281–1291, May 2015.
[23] A. Ito, A. Kawashima, T. Suzuki, S. Inagaki, T. Yamaguchi, and Z. Zhou, "Model predictive charging control of in-vehicle batteries for home energy management based on vehicle state prediction," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 1, pp. 51–64, 2018.
[24] A. Kawashima, T. Yamaguchi, R. Sasaki, S. Inagaki, T. Suzuki, and A. Ito, "Apartment building energy management system in group optimization with electricity interchange using in-vehicle batteries," *SICE J. Control. Meas. Syst. Integr.*, vol. 8, no. 1, pp. 52–60, 2015.
[25] K. Mori, H. Kikusato, S. Yoshizawa, Y. Hayashi, Y. Hayashi, A. Kawashima, S. Inagaki, T. Suzuki, "Information exchange between HEMS and GEMS for effective EV charge/discharge planning," *Int. Conf. Electr. Eng.*, pp. 1–6, 2015.
[26] Y. Fujimoto, H. Kikusato, S. Yoshizawa, S. Kawano, A. Yoshida, S. Wakao, N. Murata, Y. Amano, S. Tanabe, Y. Hayashi, "Distributed energy management for comprehensive utilization of residential photovoltaic outputs," *IEEE Trans. Smart Grid*, pp. 1–13, 2016.
[27] C. Gao and M. A. Redfern, "Automatic compensation voltage control strategy for on-load tap changer transformers with distributed generations," in *2011 International Conference on Advanced Power System Automation and Protection*, 2011, pp. 737–741.
[28] Y. Hayashi, "Development of distributed cooperative EMS methodologies for multiple scenarios by using versatile demonstration platform, CREST," 2015. [Online]. Available: https://www.jst.go.jp/kisoken/crest/en/project/36/36_05.html. [Accessed: 14-Jan-2018].
[29] H. Homma, T. Yamazaki, S. Yoashizawa, H. Kikusato, S. Wakao, Y. Fujimoto, Y. Hayashi, "PV output prediction under various conditions of time and spatial resolutions by Just-in-Time modeling," *29th Eur. Photovolt. Sol. Energy Conf. Exhib.*, pp. 2904–2907, 2014.
[30] A. Hoke, A. Brissette, K. Smith, A. Pratt, and D. Maksimovic, "Accounting for Lithium-Ion Battery Degradation in Electric Vehicle Charging Optimization," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 2, no. 3, pp. 691–700, Sep. 2014.



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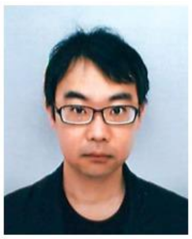

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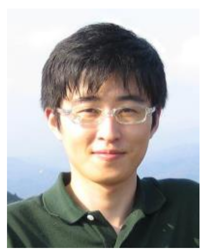

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