Model Predictive Control for Imbalance Compensation of Solar Power Generation in Local Area Energy Management System

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***Abstract*—The local area energy management system plays an important role in constituting the virtual power plant, which includes photovoltaics and batteries installed in multiple households. The aim of this paper is to develop a control method to compensate for the imbalance between the planned and actual values of a retailer's sales and procurement plan by charging and discharging the batteries. The rule-based model predictive control is designed as a centralized battery management to match the planned and actual values of the total power flow using the real-time time-series forecast models of power generation and power demand. The numerical validation based on the emulated dataset of the multiple households with photovoltaics and batteries demonstrates that the developed approach reduces the imbalance. The developed approach reduces the economic risk of the imbalance price for the retailer that operates the local area energy management system as a virtual power plant.**

***Index Terms*—Model Predictive Control, Imbalance Compensation, Solar Power Generation, Energy Management System, Virtual Power Plant**

I. INTRODUCTION

For the transition to a carbon-neutral society by 2050 in Japan, the regional power companies that manage the sales and procurement as retailers are developing for decarbonization and local energy self-sufficiency. The regional power companies have the business potential to operate a local area Energy Management System (EMS) for multiple households with PhotoVoltaics (PV) and batteries as a Virtual Power Plant (VPP). Compared to microgrids, VPP is designed to be connected to the grid and provides electricity as a controlled renewable energy resource. Regional power companies with small-scale businesses often face financial risks due to the imbalance that is the gap between the planned and actual power flow. Therefore, it is necessary to develop an imbalance compensation method that considers both the retailer's operation and the EMS communication constraints. Several studies have been conducted on VPP such as demand response [1]–[4], resource coordination [5], battery capacity optimization [6], and forecast error and imbalance compensation [7]–[9].

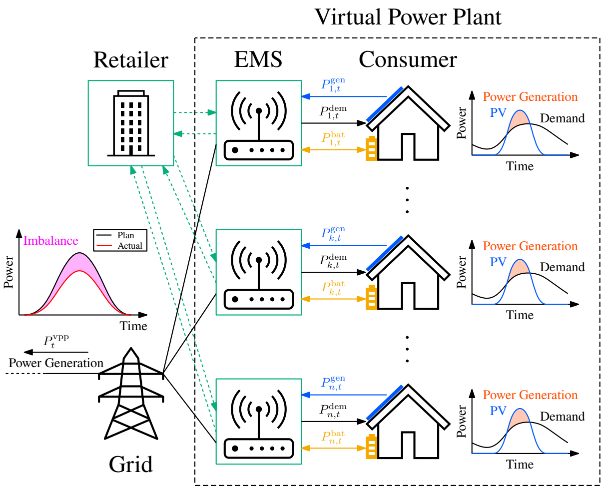

Fig. 1. Overview of the local area EMS as a VPP. Multiple households with PV and batteries are managed to compensate for the imbalance between the retailer's planned and actual values of sales and procurement in the local area.

Although there have been several studies on VPP, the real-time imbalance compensation using the local area EMS considering the operation and communication constraints to reduce the economic risk of the regional power company has not been developed. The aim of this paper is to develop a Model Predictive Control (MPC) method for imbalance compensation. The contributions of this paper are

C1) developing the centralized battery management method using rule-based MPC for imbalance compensation, and
C2) considering the retailer's planning operation constraints and the EMS communication constraints.

II. PROBLEM FORMULATION

A. Local area energy management system

Fig. 1 shows the overview of the local area EMS as a virtual power plant with multiple households with PV and batteries. The retailer can measure the power generation $P^{\text{gen}}_{k,t}$,

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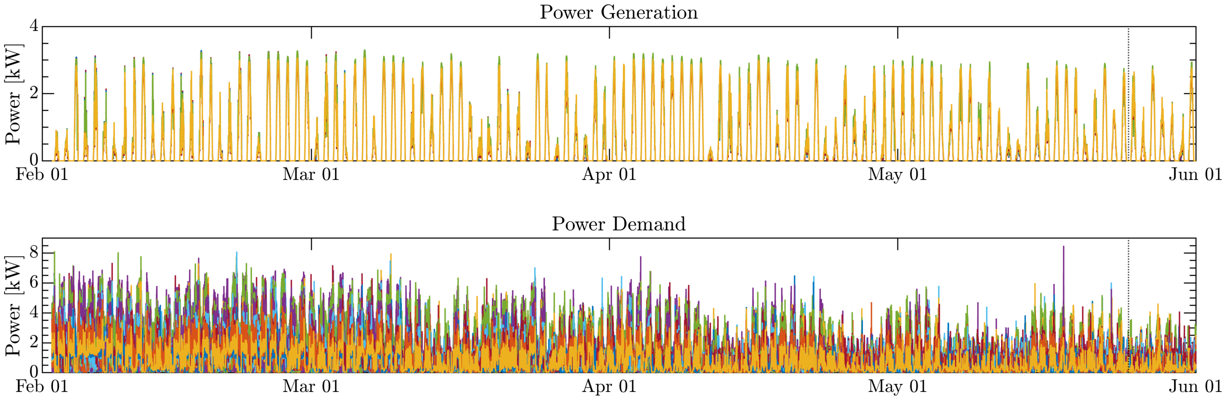

Fig. 2. Emulated dataset of power generation and power demand for 80 households with PV without battery in Japan from February 2nd to May 31st in 2022 [4], [10]. The first 112 days are used as training data for the forecast model and the last 7 days are used as validation data for imbalance compensation.

TABLE I
PARAMETERS OF LOCAL AREA ENERGY MANAGEMENT SYSTEM.

Symbol	Description	Value
Δt	Time step of control and communication	$10\,\mathrm{min}$
$P^{\mathrm{gen}}_{\mathrm{max}}$	PV maximum output	$5\,\mathrm{kW}$
$P^{\mathrm{bat}}_{\mathrm{max}}$	Battery maximum output	$3\,\mathrm{kW}$
Q^{bat}	Battery capacity	$11\,\mathrm{kWh}$
$S^{\mathrm{bat}}_{\mathrm{min}}$	Battery minimum State Of Charge (SOC)	$10\,\%$
$S^{\mathrm{bat}}_{\mathrm{max}}$	Battery maximum State Of Charge (SOC)	$90\,\%$
η	Battery charge and discharge efficiency	$94\,\%$

the power demand $P^{\mathrm{dem}}_{k,t}$, the discharge power $P^{\mathrm{bat}}_{k,t}$, and the battery State Of Charge (SOC) $S^{\mathrm{bat}}_{k,t}$ of kth household at time t every $10\,\mathrm{min}$. The specification of the EMS is shown in TABLE I.

The batteries are managed to compensate for the imbalance between the planned and actual power flow for the retailer's sales and procurement plan to work as a VPP connected to the grid. The emulated dataset of power generation and power demand for 80 households with PV without battery in Japan from February 2nd to May 31st in 2022 [4], [10] is used in this paper as shown in Fig. 2. The first 112 days are used as training data for the forecast model and the last 7 days are used as validation data for imbalance compensation. The conventional decentralized battery management without EMS communication is to maximize the self-consumption of each household, in which the battery charges surplus power and discharges to cover power shortages independently. In Japan, the imbalance price is determined by the marginal price of the balancing market after supply and demand adjustment. Therefore the imbalance because of the insufficient day-ahead forecast accuracy becomes the economic risk of the retailer who manages the virtual power plant in the local area.

B. Problem description

This paper develops the battery management method for imbalance compensation considering the following requirements:

R1) The Imbalance between the planned and actual power flow should be compensated by battery management.

R2) Constraints of the retailer's planning operation and the EMS communication should be considered.

TABLE II
COEFFICIENT OF DETERMINATION OF FORECAST RESULTS IN POWER GENERATION AND POWER DEMAND FROM MAY 25TH TO 31ST IN 2022.

R^2	Total power generation	Total power demand
Day-ahead forecast	0.771	0.527
Real-time forecast	0.997	0.955

III. PLAN OF POWER GENERATION AND POWER DEMAND

A. Day-ahead forecast of power generation

The day-ahead forecast value of the total power generation is given by the weather forecast data based on the Meso-Scale Model Grid Point Value (MSM GPV) [11]. The scaled solar radiation data is used as the forecast value of the total power generation. The scaling factor is given by the fitting of the total power generation for the first 112 days of the dataset.

B. Day-ahead forecast of power demand

The day-ahead forecast value of the total power demand is given by the time-series forecast model based on the Seasonal AutoRegressive Integrated Moving Average (SARIMA) model [12]. In the dataset, the total power demand of the first 112 days is used as training data for the SARIMA model.

C. Retailer's sales and procurement plan

Because of the retailer's planning operation constraints, the day-ahead forecast is conducted at $6\,\mathrm{AM}$ for the $24\,\mathrm{hours}$ of the next day as shown in Fig. 3. The retailer's sales and procurement plan is designed by using the day-ahead forecast value of the total power generation and the total power demand. It is assumed that the battery in each household is expected to charge and discharge following the balance of the power generation and the power demand to maximize self-consumption. From this assumption, the retailer's sales and procurement plan $\tilde{P}^{\mathrm{vpp}}_t$ is designed the same as the total power flow using the total battery model that charges surplus power

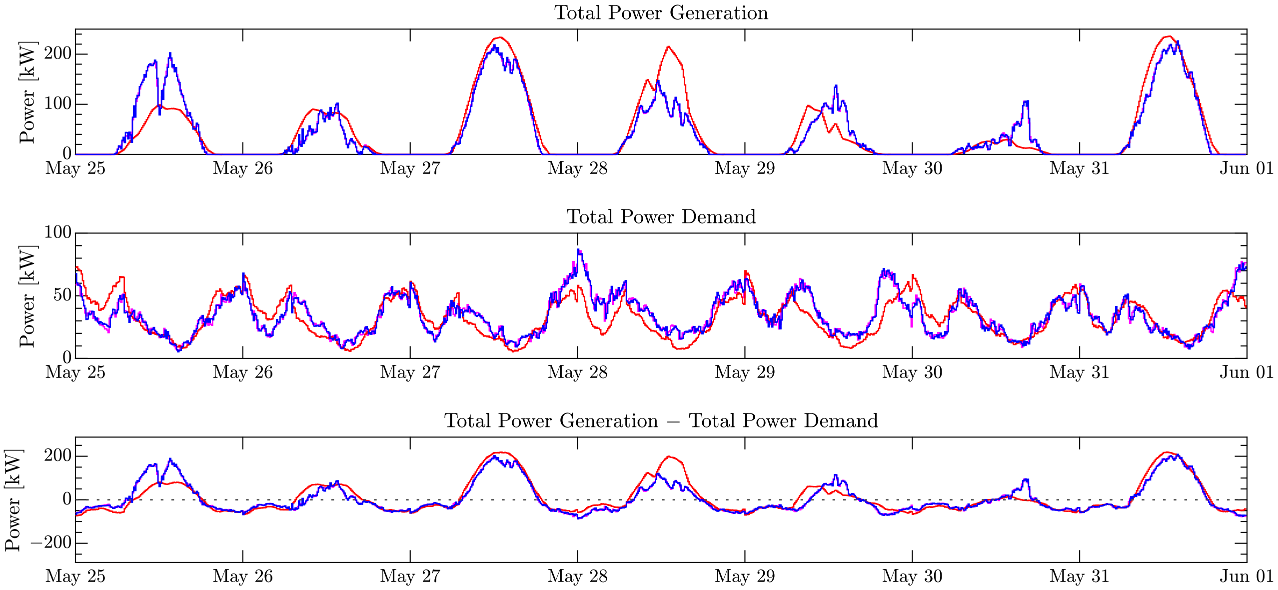

Fig. 3. Forecast of total power generation and total power demand: actual value in magenta lines (—), day-ahead forecast value for the plan in red lines (—), and real-time forecast value for MPC in blue lines (—), respectively. The magenta and blue lines are almost overlapped with high forecast accuracy.

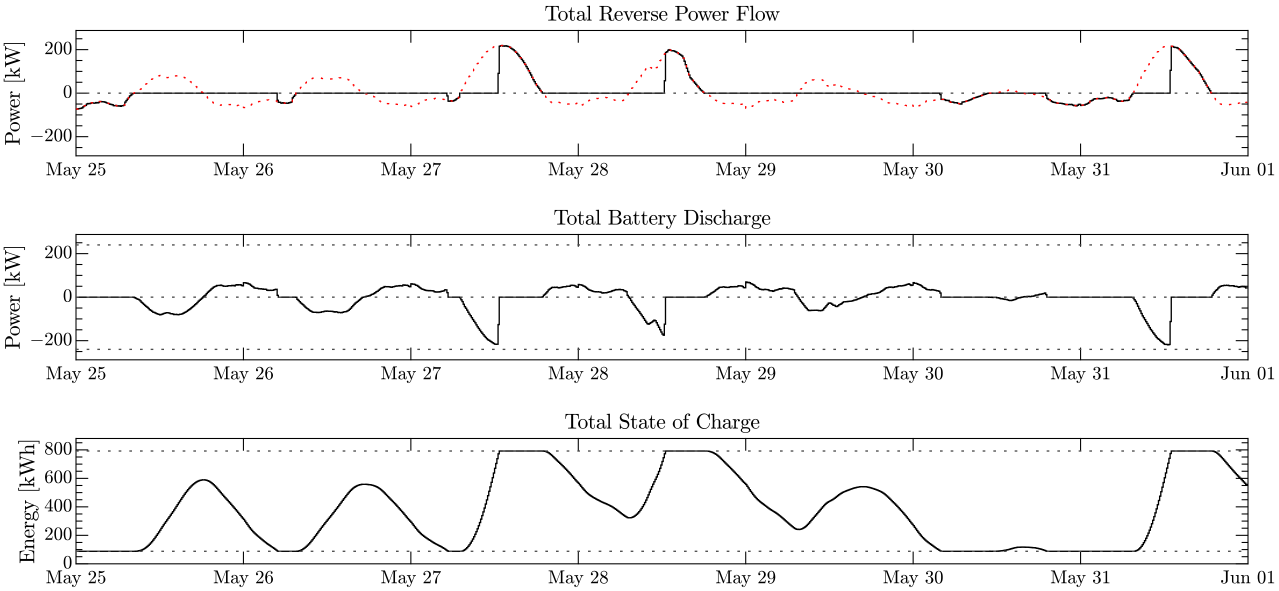

Fig. 4. Plan of power generation and power demand: day-ahead forecast value of total reverse power flow without battery charge and discharge in a red dotted line (- - - -), and planned value with battery charge and discharge in black lines (—), respectively.

and discharges to cover power shortages as shown in Fig. 4. Since the day-ahead forecast accuracy is not enough as shown in Fig. 3 and TABLE II, the imbalance between the planned and actual power flow is inevitable.

IV. CENTRALIZED BATTERY MANAGEMENT USING RULE-BASED MODEL PREDICTIVE CONTROL

A. Real-time forecast of power generation and power demand

Because of the EMS communication constraints, the actual data up to $10\,\mathrm{min}$ ago can be used. In the developed rule-based model predictive control, the SARIMA model forecasts the total power generation $\hat{P}_t^{\mathrm{gen}}$ and the total power demand $\hat{P}_t^{\mathrm{dem}}$ in real-time. In the dataset, the first 112 days are used as training data for the SARIMA model of the total power generation and the total power demand. The real-time forecast enables higher forecast accuracy compared to that of the day-ahead forecast as shown in Fig. 3 and TABLE II.

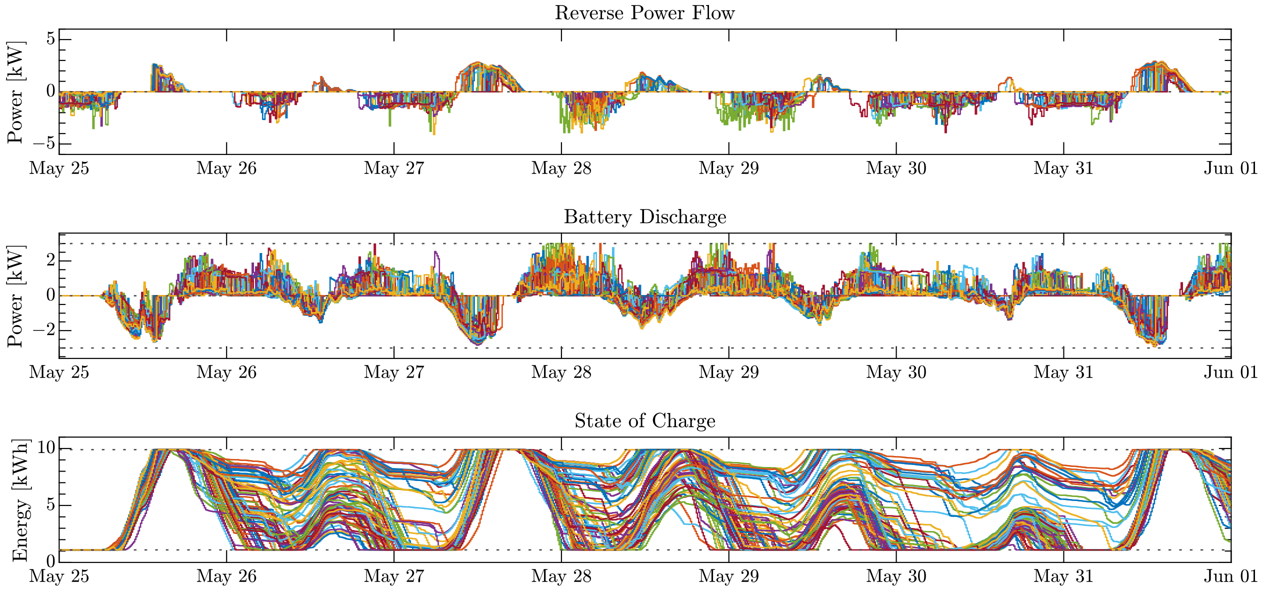

Fig. 5. Decentralized battery management to maximize self-consumption for 80 households with PV and battery. Each household independently charges and discharges the battery according to the balance of each power generation and power demand.

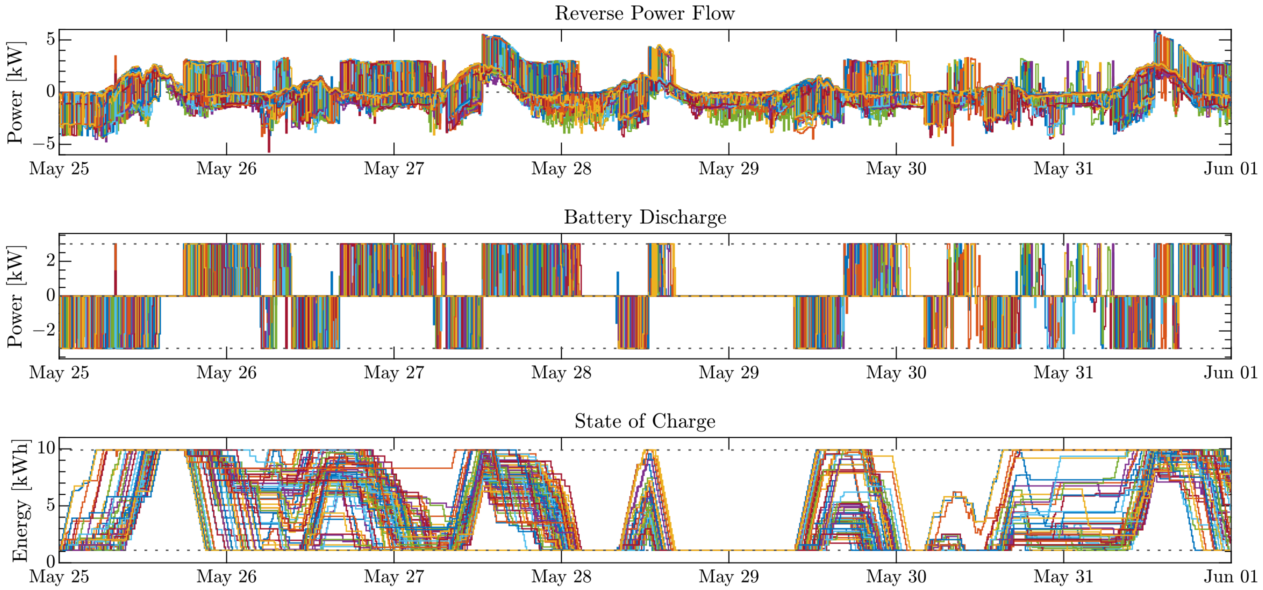

Fig. 6. Centralized battery management to minimize imbalance for 80 households with PV and battery. Charge and discharge commands are sent to each battery by the retailer every 10 min to minimize the imbalance between the planned and actual power flow.

B. Rule-based battery management to minimize imbalance

The developed centralized battery management is conducted by the rule-based MPC with the following procedures:

1) Step 1: The total power generation $\hat{P}_t^{\mathrm{gen}}$ and the total power demand $\hat{P}_t^{\mathrm{dem}}$ are forecasted in real-time by the SARIMA model using the actual data up to 10 min ago.

2) Step 2: The total discharge power P_t^{bat} is given by

$$P_t^{\mathrm{bat}} = \tilde{P}_t^{\mathrm{vpp}} - (\hat{P}_t^{\mathrm{gen}} - \hat{P}_t^{\mathrm{dem}}), \qquad (1)$$

where $\tilde{P}_t^{\mathrm{vpp}}$ is the planned total reverse power flow.

3) Step 3: If the total discharge power P_t^{bat} is a positive value, the maximum output discharge command $P_{k,t}^{\mathrm{bat}}$ is sent to the kth battery in order of the battery SOC from the highest to lowest. If the total discharge power P_t^{bat} is a negative value, the maximum output charge command $P_{k,t}^{\mathrm{bat}}$ is sent to the kth battery in order of the battery SOC from the lowest to highest. The commands are sent to multiple batteries until their total power matches the total discharge power as $P_t^{\mathrm{bat}} = \sum_k P_{k,t}^{\mathrm{bat}}$.

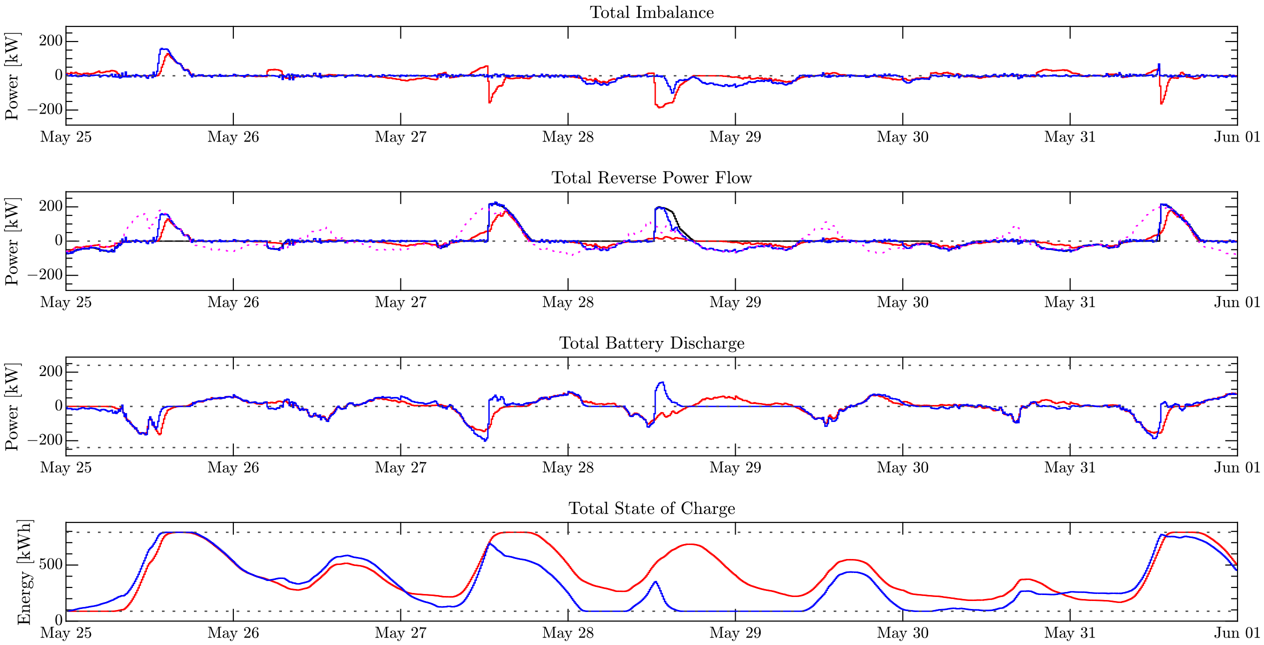

Fig. 7. Total imbalance compensation utilizing battery charge and discharge: decentralized battery management to maximize self-consumption in red lines (—), and centralized battery management to minimize imbalance in blue lines (—), respectively. In the total reverse power flow, the planned value is in a black line (—) and the actual value without battery charge and discharge is in a magenta dotted line (----), respectively.

V. VALIDATION FOR IMBALANCE COMPENSATION

A. Conditions

In the validation, the emulated dataset in Fig. 2 [4], [10] is used. The number of households with PV and battery is $n = 80$. The training data is 112 days from February 2nd to May 24th, and the validation data is 7 days from May 25th to 31st. The validation starts from the minimum SOC of the batteries. The imbalances between the planned and actual values of the total power flow are evaluated in the conventional decentralized and developed centralized battery management.

B. Results

Fig. 5 shows the conventional decentralized battery management to maximize the self-consumption of each household. Although the real-time data of power generation and power demand of each household is used without forecast, each household independently charges and discharges the battery according to each power flow, and the imbalance is not taken into account. Fig. 6 shows the developed centralized battery management to minimize the imbalance of total power flow. Charge or discharge commands are sent to multiple batteries by the retailer every $10\,\mathrm{min}$ until their total power matches the total charge or discharge power to compensate imbalance.

The total imbalances with the conventional decentralized and developed centralized battery managements are shown in Fig. 7. The cumulative absolute imbalances are shown in TABLE III, in which the imbalance P_t^{imb} is defined as

$$P_t^{\mathrm{imb}} = \sum_{k=1}^{n} (P_{k,t}^{\mathrm{gen}} - P_{k,t}^{\mathrm{dem}} + P_{k,t}^{\mathrm{bat}}) - \tilde{P}_t^{\mathrm{vpp}}. \qquad (2)$$

TABLE III
CUMULATIVE ABSOLUTE IMBALANCE FROM MAY 25TH TO 31ST IN 2022.

Approach	$\sum_t \lvert P_t^{\mathrm{imb}} \rvert$	Ratio
Decentralized battery management	$2.81\,\mathrm{MWh}$	$100\,\%$
Centralized battery management	$2.03\,\mathrm{MWh}$	$72\,\%$

The result shows that the developed approach reduces the imbalance risk about $28\,\%$ from the conventional approach.

VI. CONCLUSION

The local area EMS enables a virtual power plant by multiple households with PV and batteries. In this paper, a control method to compensate for the imbalance between the planned and actual values of a retailer's sales and procurement plan by charging and discharging the batteries is developed. The rule-based model predictive control is designed as a centralized battery management to match the planned and actual values of the total power flow using the real-time forecast of power generation and power demand by the SARIMA model. The validation result demonstrates that the imbalance is reduced by the developed centralized battery management compared to that of the conventional decentralized battery management. The developed approach reduces the economic risk of the imbalance price for the retailer that operates the local area EMS as a VPP.

Ongoing researches focus on balancing the trade-off between self-consumption by each household and imbalance compensation by the retailer and the economic risk analysis with the actual imbalance price every $30\,\mathrm{min}$ in Japan.

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