DEVELPMENT OF A GRID INDEPENDENT ENERGY SYSTEM USING ENERGY SUPPLY AND DEMAND PREDICTION (Part 3) Designing Model Predictive Control by Energy Simulation

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ABSTRACT

In this research, we aim to develop an energy self-sufficient building by applying model predictive control (MPC). In this paper, the details of the objective functions (OF) for the MPC, at the Takasago Innovation Centre are explained. One OF aims to prevent reverse power flow, and the other aims to minimize the peak of received power, during the predicted period. Then, the validity and effect of the MPC is shown through energy simulations. As a result, both OFs worked as planned, and the annual peak of received power was reduced 55.3% , compared to the case of conventional sequence control.

1. INTRODUCTION

This study aims to build an energy management system (EMS) which can achieve an energy self-sufficient building by renewable energy. In this context, model predictive control (MPC) is employed to optimally control the system against various objective functions (OFs) and constraints, based on the predicted results of energy demand and power generation. Therefore, the objective of this study is to propose a design method of prediction models, as well as OFs and constraints of the MPC, through verification on an actual building (TIC: Takasago Thermal Engineering Innovation Center).

In the first report [1], system overview of TIC (Fig. 1), and the fact that reverse power flow is restricted was introduced, as well as operational issues. It was stated that given the energy balance of TIC, stored electricity will reach maximum, and excessed energy will lose its way and reverse power flow will occur in some periods. It was also stated that charged energy of the battery (SOE: State of Energy [kWh]) will run out on some periods, resulting in the excessing of received power over the target value of 10kW. In the second report [2], methodology and case study results of the solar radiation prediction, which is required for the hourly PV output prediction were presented.

In this report, two MPCs were formulated as measures to address the operational issues presented in the first report [1], and the results of the verification of the MPCs through energy simulation are described. The first MPC aims to control the maximum SOE of the battery energy storage system (BESS) and prevent reverse power flow. The second MPC aims to reduce the peak of received power, based on the assumption that the basic electricity bill is determined according to the maximum received power in the previous 12 months [3]. In the next report [4] (Part 4), the improved methodology and case study results in predicting solar radiation are described.

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2. BATTERY ENERGY STORAGE SYSTEM (BESS)

2.1 Model overview and calculation formula

As shown in Fig. 1, the three components of the BESS are: (1) storage battery, (2) PCS (Power Conditioning Subsystem), (3) auxiliary equipment (temperature control function, power supply for controls, etc.).

In addition, the following assumptions were made.

1) Energy losses of BESS occur only at the PCS and the proportion of power going in and out (η_{PCS}: PCS coefficient) of PCS is constant.

2) Power consumption of auxiliaries (P_{AUX})is constant.

3) Power going in and out of the storage battery is equal to the change in SOE (State of energy).

Equations based on these conditions are shown in Eq (1) ~ (3).

$$P_{Battery} \geq 0 \text{ (Discharge)}$$

$$P_{Sytem} = \eta_{PCS} P_{Battery} - P_{AUX} \qquad \cdot\cdot\cdot (1)$$

$$P_{Battery} < 0 \text{ (Charge)}$$

$$P_{Sytem} = \frac{1}{\eta_{PCS}} P_{Battery} - P_{AUX} \qquad \cdot\cdot\cdot (2)$$

$$E_{Battery,t+1} = E_{Battery,t} - \int_t^{t+1} P_{Battery}\, dt \qquad \cdot\cdot\cdot (3)$$

(P_{Sytem}: System output [kW], $P_{Battery}$: Battery output [kW], P_{AUX}: Auxiliary Power [kW], $E_{Battery,t}$: SOE at step(t) [kWh] and η_{PCS}: PCS coefficient [-])

As the only measured data of TICs BESS are the system output and SOE, auxiliary power and PCS coefficient were estimated from these measured values. Specifically, auxiliary power and PCS coefficient that minimize the residual difference between the measured difference of SOE between each time step, and the estimated difference of each time step from Eq. (1) ~ (3), were calculated. Summary of used data and estimated values are shown in Table 1.

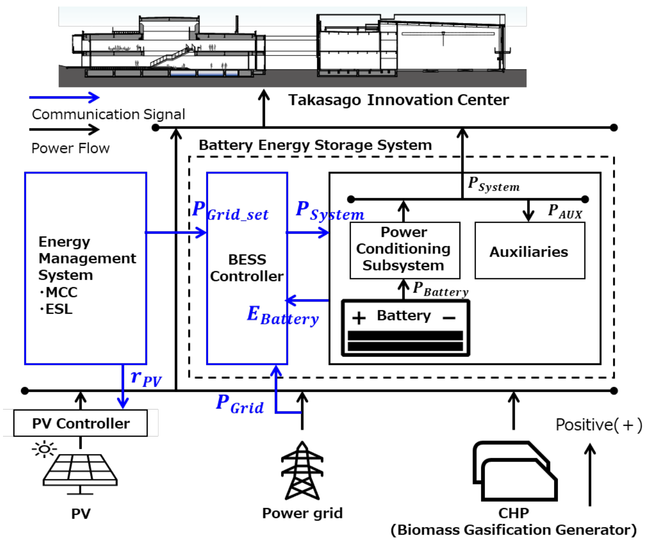

Fig. 1 TIC System Overview

Table 1 Data and Results of Parameter Estimation

Used Data	Time Step	1 hour
	Period	May 2021～December 2021
Estimated Values	P_{AUX}	3.49 kWh
	η_{PCS}	0.95

2.2 Time series SOE estimation

Transition of SOE over a one-week period was calculated from Eq. (1) ~ (3), which were compared with measured values. Initial value of SOE was set to the measured value at 2022/1/12/00:00, from which the transition of SOE was calculated by iterating the calculation of Fig. (3). The storage battery output ($P_{Battery}$) at each time step was calculated from Eq (1) and (2), as well as the measured system outputs (P_{System}). The results showed that mean absolute percentage error was 2.99%, and that the calculation model described above is sufficient for predicting the transition of SOE.

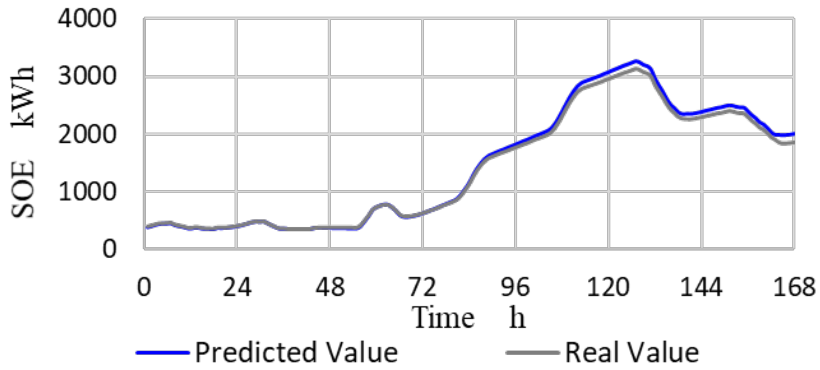

Fig. 2 SOE Prediction Result

2.3 Constant Power Receiving Control (CPC)

The existing BESS controller determines the system output value which brings the received power closest to a specific value (RPV: Receiving Power Value), within the boundaries of the system output determined by the current SOE and rated value. On the other hand, as a safety measure against control errors due to CPC response delays etc., RPV is basically set to10 kW (RPT: Receiving Power Target) [1].

3. FORMULATION OF MPC

MPC requires the formulation of an OF within a given prediction period, as well as optimizing the problem at each time step, with the control inputs as variables [2]. This chapter describes the formulation of the following optimization problem: maximum energy capacity control (MCC) which aims to prevent reverse power flow, energy supply levelling control (ESL) which aims to cut the peak of received power.

3.1 Maximum Energy Capacity Control (MCC)

Control overview is shown in Fig. 3, and the OF and constraints are shown in Eq. (4). The OF is defined as the residual square between the predicted maximum SOE, and the predetermined maximum SOE threshold (MST) within the prediction period. Therefore, the PV output rate at each time step that minimizes the OF is the output of MCC.

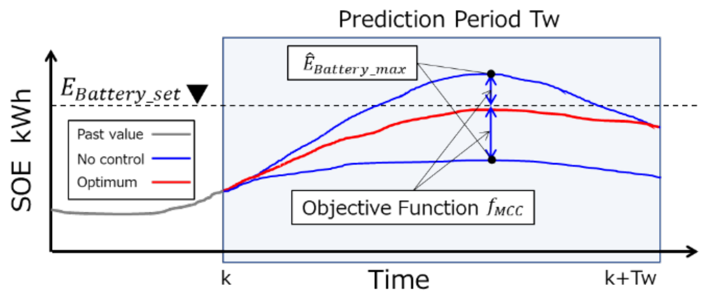

Fig. 3 Maximum Capacity Control (MCC)

$$\min.f_{MCC} = \left(\hat{E}_{Battery\_max} - E_{Battery\_Set}\right)^2 \qquad \cdots (4)$$
$$s.t.\hat{P}_{Load} = \hat{r}_{PV}\hat{P}_{PV\_MAX} + \hat{P}_{CHP} + \hat{P}_{System} + \hat{P}_{Grid}$$
$$\hat{P}_{Battery}, \hat{P}_{Grid} = f_{CPC}{}_{(P_{Grid\_Target})}$$
$$0 \leq \hat{r}_{PV} \leq 1$$

($\hat{E}_{Battery\_max}$: Predicted maximum SOE, $E_{Battery\_set}$: MST, $\hat{P}_{Load}$: Predicted load, $\hat{r}_{PV}$: PV output rate, $\hat{P}_{PV\_MAX}$: Predicted maximum PV output, $\hat{P}_{CHP}$: Predicted CHP output, $\hat{P}_{System}$: Predicted BESS output, $\hat{P}_{Grid}$: Predicted received power and f_{CPC}: Function of CPC)

If the maximum SOE in the prediction period is to exceed the MST, PV output it is suppressed by multiplying the PV output rate, which is considered to avoid full charge and can prevent reverse power flow.

3.2 Energy Supply Leveling Control (ESL)

Control overview is shown in Fig. 4, and the OF and constraints are shown in Eq. (5). The objective of ESL is to find the PRV (which is the control set value of CPC) that will result to the lowest peak of received power during the prediction period. Thus, the residual square between the RPT and the peak of received power is defined as the OF.

$$\min f_{ESL} = \left(\hat{P}_{Grid\_max} - P_{Grid\_target}\right)^2 \qquad \cdots (5)$$
$$s.t.\hat{P}_{Load,t} = \hat{r}_{PV,t}\hat{P}_{PV_{MAX},t} + \hat{P}_{CHP,t} + \hat{P}_{Battery,t} + \hat{P}_{Grid,t}$$
$$\hat{P}_{Battery}, \hat{P}_{Grid} = f_{CPC}{}_{(P_{Grid\_set})}$$

($\hat{P}_{Grid\_max}$: Predicted maximum received power , P_{Grid_Target}: RPT)

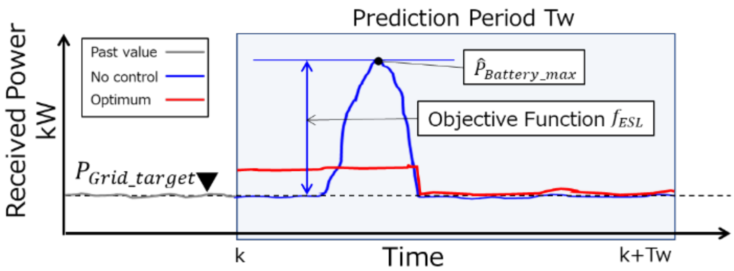

Fig. 4 Energy Supply Leveling (ESL)

3.3 MPC Flow

The Flow of MPC is shown in Fig. 5. First, the PV output rate during the prediction period is calculated by MCC, based on the given prediction results as well as the current SOE. Next, the PRV is calculated by ESL based on the given PV output rate. Finally, the control values (PV output rate, RPV) are input to each controller respectively.

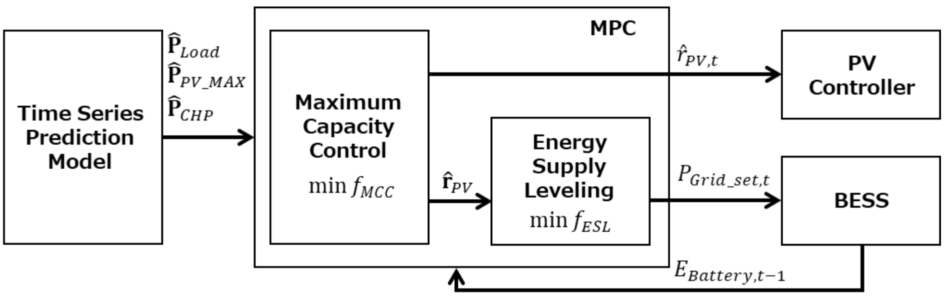

Fig. 5 Flow diagram of MPC

3. MPC Verification

This chapter presents verification results under hypothetical conditions for the two MPCs presented in Eq. (4) and (5). It is assumed that both power consumption and generation can be predicted with 100% accuracy. The effectiveness and validity of the MPCs are demonstrated through simulations. Also, the assumed prediction period is changed and the effects on the occurrence of reverse power flow and the peak of received power are shown. The Powell method from the Python library SciPy [5] was used to solve the MPCs.

3.1 Operation check

For each MPC, simulations were carried out with hypothetical values for the following time series of each hour: power consumption, maximum PV output, CHP output.

(1) MCC

The preconditions are shown in Table 2, and PV output and SOE are shown in Fig. 6 and 7. Hypothetical conditions were set up where surplus power was continuously generated and the SOE exceeded the MST when no controls were applied. It was set so that surplus power continues to be generated even when the PV is shut down, due to the base operation of CHP which is a feature of TIC. The results showed that MCC was able to keep the SOE below the MST regardless of the prediction period. But when the prediction period was 80h, the exceedance was predicted earlier, resulting in an earlier start of PV suppression.

(2) ESL

The preconditions are shown in Table 3, and the SOE and received power are shown in Fig. 8 and 9. Hypothetical conditions were set up where SOE would go down to 0%, and the received power increases from the target value of 10 kW to 120 kW. The simulation results showed that the ESL was able to calculate the optimum RPV regardless of the prediction period. When the prediction period was 80h, the peak of received power was lower because ESL responded earlier.

Table 2 Preconditions for RPP test

Time Step	1 h
Period	60 h
Max. Charged Energy Set Value	2,500 kWh
Initial Charged Energy	0 kWh
Prediction Period	20 h, 80h

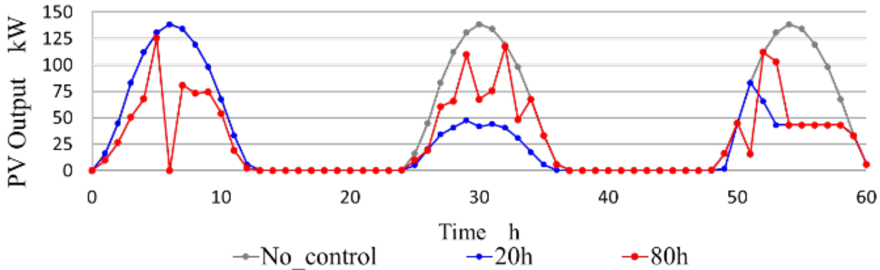

Fig.6 Results of PV Output

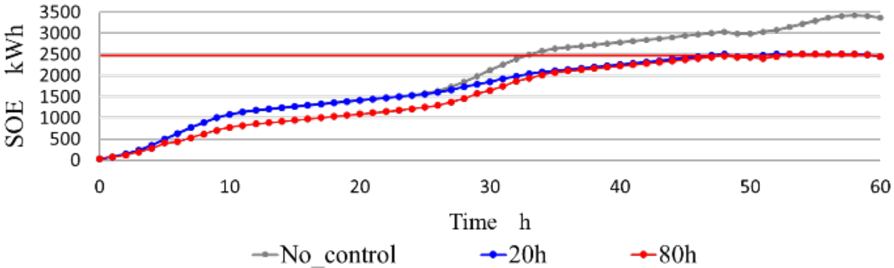

Fig.7 Results of SOE

Table 3 Preconditions for PCC test

Time Step	1 h
Period	60 h
Target of Power from Grid	10 kW
Initial Charged Energy	2,500 kWh
Prediction Period	20 h, 80h

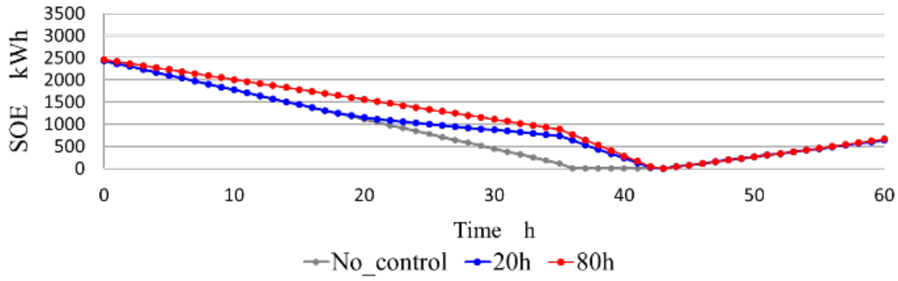

Fig.8 Results of SOE

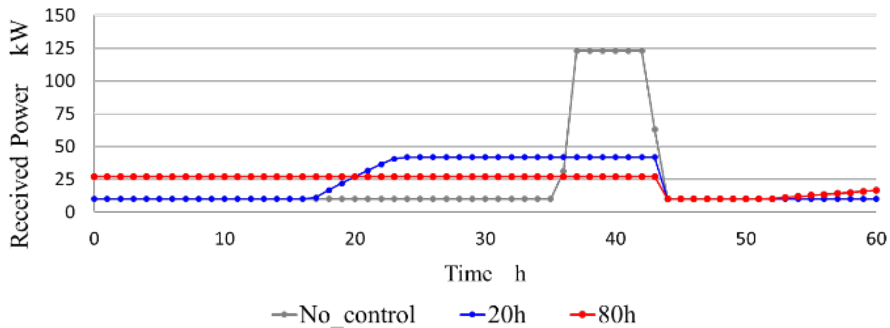

Fig.9 Results of Power from Grid

3.2 Annual Simulation

(1) Operation plan of CHPs

As described in the first report [1], if the CHPs annual operation is not set so that the balance between power consumption and generation is matched, surplus power will be constantly generated and SOE will reach maximum, leading to excessive PV suppression. Therefore, the CHP operation pattern was determined according to the following conditions.

1) Annual total of CHP generation, PV generation and received power (10 kW) equals the total of power consumption.
2) CHPs operate in base operation, simultaneously.
3) CHPs are shutdown on holidays longer than three days
4) CHPs are shut down on weekends once every 600 hours (maintenance cycle recommended by the manufacturer)

(2) Other Preconditions

Other preconditions are shown in Table 4.

(3) Simulation Results

The results of annual SOE and received power are shown in Fig.10 and 11. The results from the conventional sequence control [1] are plotted together for comparison. For example, in the case of sequence control, SOE reached maximum just after 6,000h resulting in reverse power flow, whereas MCC kept SOE below the threshold value and prevented it. On the other hand, ESL reduced the peal of received power of approximately 109 kWh (55.3%), compared to sequence control.

Table 4 Preconditions for Annual Simulation

Time Step		1 h
Period		August 2020 ~ July 2021 (8760h)
Input Data (N=8760)	Load	Measured Data [kW]
	Max. PV Output	Estimated from Measured Insolation [kW]
	CHP	Calculated from Operation Plan [kW]
Equipment Specifics	PV	200 kW (Max.)
	CHPs	Rated Output: 75 kW
		Power of Auxiliaries: 20kW
	Battery	SOE Capacity: 4,590 kWh
		Ouput Range: ±625 kW
Target of Power from Grid		10 kW
MPC	Max. SOE Threshold	4,131 kWh (90% of Max. Capacity)
	Initial SOE	0 kWh
	Prediction Period	100 h

(4) Effects of Prediction Period

Finally, effects on the annual occurrence of reverse power flow, as well as the peak of received power was verified when the prediction period was changed. The results showed a gradual decrease in the peak of received power as the prediction period increased (Fig. 12). This can be considered that the longer the prediction period, the earlier the received power could be increased, and so that the annual peak could be further decreased. As for reverse power flow, it was found that the annual occurrence could be prevented if the prediction period was longer than 50h (Fig. 13). This is considered that at least 50h is required to respond to the sudden increase in SOE, immediately after 6,000h. and start suppressing the PV output.

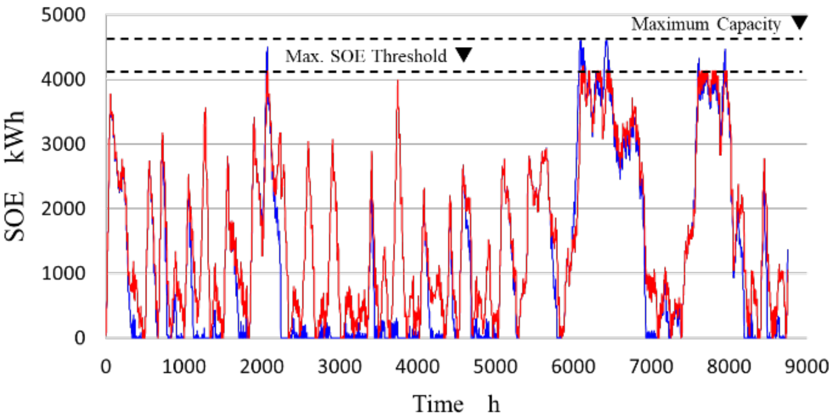

Fig.10 Annual Results of SOE

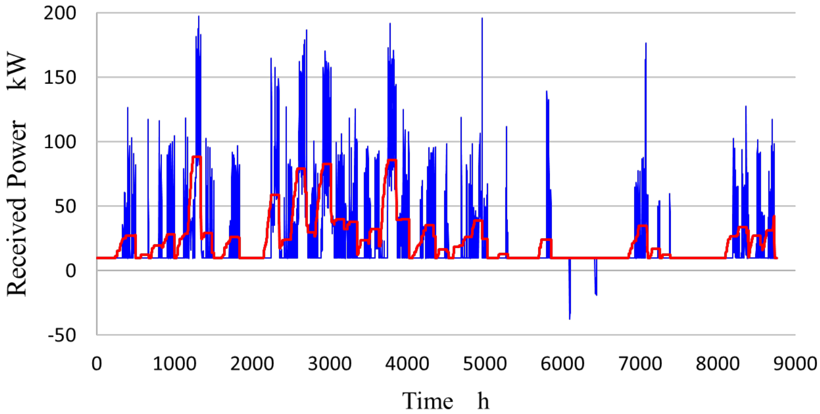

Fig.11 Annual Results of Received Power

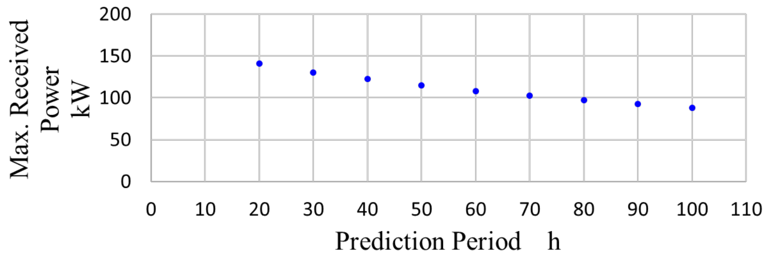

Fig.12 Maximum Received Power

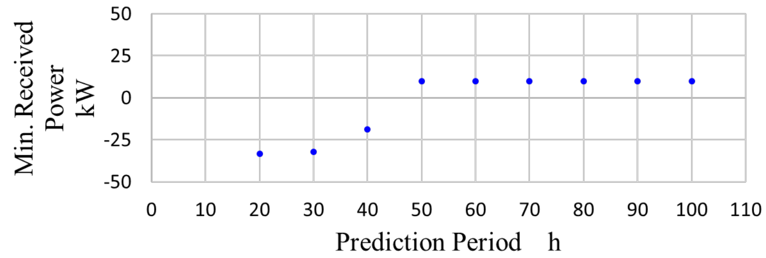

Fig.13 Minimum Received Power (-:Reverse Power Flow)

CONCLUSION

The BESS calculation model and two MPCs were formulated, and the results of their operation test and effectiveness were presented. The results showed that for the given preconditions, there exists an aptitude value length of prediction, in which reverse power flow can be prevented (approximately 40~50 h). Results also showed that MPC is effective in reducing the peak of received power by 55.3% when the prediction period is 100 h, compared to the conventional control method.
In this report, confliction of the 2 OFs from MCC and ESL where not considered. But when prediction period becomes longer, conflict is expected when MCC intends to reduce SOE as it reaches near maximum, but on the other hand, ESL intends to increase SOE and lower the future peak of received power. Furthermore, it was assumed that a 100% accurate prediction was obtained. Henceforth, study on conflicts between OFs (Requiring a multi-objective optimization) as well as effects of prediction error is necessary.

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要　約

本研究ではモデル予測制御（MPC）を適用することにより、建物内の自家発電で得た再生可能エネルギーで自給自足することを目指した「エネルギー自立型システム」の開発を目的としている。
本報では、高砂イノベーションセンターにおける MPC の目的関数について述べる。片方の目的関数は予測期間中の逆潮流の防止を目的とし、もう片方は同期間中の受電電力ピークを最小に抑えることを目的としている。またエネルギーシミュレーションにより MPC の有効性と効果を示した。その結果、どちらの目的関数も計画通りに動作し、従来のシーケンス制御の場合と比較して、年間受電電力のピークを 55.3% 低減できる効果が示された。