Pilot Study on Residential Measures against Unpredictable Outages with Batteries and Photovoltaics Considering Necessary Loads

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***Abstract*—Sudden natural disasters such as earthquakes sometimes cause a sudden blackout in the power grid, and households suffer unpredictable outages. This paper aims to determine residential measures against unpredictable outages using batteries and photovoltaics (PVs). This paper focuses on the effect of the SoC margin that the battery keeps its state-of-charge (SoC) high in the normal state, and the operation of the battery is simulated by an optimization problem considering the predictability of outages. This paper also introduces three resilience indices to quantify the duration, the maximum power, and the weighted energy of a supply shortage. As a result, the SoC margin reduces a supply shortage of important demand during an outage, and a 40% SoC margin reduces the outage cost by half in a 24-hour unpredictable outage. The SoC margin also improves the worst 5% value of resilience indices, especially in the weighted energy of a supply shortage, by half with a 40% SoC margin. However, the yearly electricity cost increases by 16% with a 40% SoC margin, so the SoC margin has an economic tradeoff.**

***Index Terms*—Battery, Photovoltaics, Resilience indices, SoC margin, Unpredictable outage**

I. Introduction

Power grids suffered from severe disasters, and large blackouts caused people anxiety. In Japan, typhoons, heavy rains, and earthquakes yearly damage the transmission and distribution systems. In particular, direct earthquakes suddenly damage many transmission, distribution, and substation facilities. As a result, these disasters sometimes cause extensive and lengthy blackouts. Thus, the resilience of the grid becomes important to keep the function normal during extreme situations such as disasters. The measure to improve resilience attracts the attention in the power system.

Grid owners and operators take measures against disasters to prevent, mitigate, and recover the damage to the grid. In prevention, the hardening equipment plan reduces the risk of damage, considering the future demand and climate trends [1], [2]. In mitigation, grid operators minimize the load shedding by separating the damaged nodes [3], [4]. In recovery, the optimal dispatch of mobile generators and repair crews reduces the total load shedding [5]. However, the grid operators cannot prevent all blackouts. Some households will suffer from outages until the grid restoration. Thus, the demand-side self-protective measures mitigate inconvenience during outages and improve the overall resilience of the power system.

Residential systems that supply electricity during outages contain power generation resources and backup energy storage. Photovoltaics (PVs) are potent as a generation resource due to their low environmental burden. The PV-battery system improves self-sufficiency and shaves the peak of residential demand [6]. The PV-battery-diesel system is demonstrated in India [7], but the duration of considered outages is short (up to 3 hours). Cooperation among households improves resilience [8], but outages are considered predictable. [9] analyzes the self-sufficient duration during outages but does not focus on the operation in the normal state. The PV-battery system can be a cost-effective solution to frequent outages in developing countries [10]. [11] proposes the model predictive control-based operation method with battery degradation in developing countries, but outages are considered periodical and predictable. The PV-battery sizing problem is considered in [12], [13] using stochastic optimization. The sizing problem [12], [13] considers the risk of outages but does not propose a proactive operation. [14] simulates the PV output during past hurricanes in the US. [15] compares the resilience of the PV-battery system among household types, regions, and outage causes. [16] proposes the method to calculate residential reliability without simulations. However, the cause of outages does not include earthquakes. In Japan, several large earthquakes suddenly caused an extensive and lengthy blackout in the grid. The operation of the PV-battery system should consider unpredictable outages.

Sudden earthquakes sometimes cause lengthy and unpredictable outages in households. The measures in the grid reduce the damage from disasters, but self-protective measures in households can also mitigate damage. Although previous research simulates the PV-battery systems [7], [8], [10]–[13], [15], unpredictable outages and measures are yet to be analyzed. This paper aims to mitigate the damage caused by unpredictable outages by the PV-battery system in households. The optimization problem, considering unpredictable outages, decides the operation of the battery to minimize the supply

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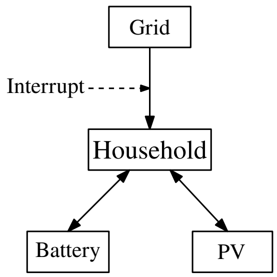

Fig. 1. Household model.

shortage with the importance of demand. This paper also analyzes how effective keeping the state-of-charge (SoC) of the battery high in the normal state is from both normal and outage perspectives. In addition, this paper introduces three indices to quantify residential resiliency and describes the outage mitigation.

II. Simulation and Resilience Evaluation Method

A. Household Model

Fig. 1 shows the household model. The household is supplied electricity from the grid. However, it is suddenly interrupted by blackouts in the grid, which causes an outage. The household has a battery and a PV and uses the generation of the PV. The PV supplies electricity in both normal and outage states. The battery can charge and discharge electricity from the grid and PV. The battery also charges excess electricity from the PV during the outage.

B. Optimization and Outage Model

The optimization problem simulates the operation of the battery. The objective is to minimize the sum of electricity and outage costs, as shown in Equation (1).

$$\text{min. } TC = \sum_t (C_{\text{elec},t} \times E_{\text{grid},t} + C_{\text{short}} \times E_{\text{short},t} + C'_{\text{short}} \times E'_{\text{short},t}). \quad (1)$$

E_{grid} denotes the energy from the grid. E_{short} and E'_{short} denote the supply shortage of important demand and unimportant demand, respectively. C_{elec} denotes the electricity price. C_{short} and C'_{short} denote the outage unit costs, which correspond to the important and unimportant demand, respectively. t denotes the number of time slots, and the resolution is 5 minutes.

The optimization problem describes the outage in the constraints on the balance of supply and demand and the maximum power from the grid. Equations (2) and (3) show the balance of supply and demand, and the maximum power from the grid, respectively.

$$E_{\text{grid},t} + E_{\text{BTd},t} + E_{\text{PV},t} + E_{\text{short},t} + E'_{\text{short},t} = E_{\text{dem},t} + E_{\text{BTc},t}. \quad (2)$$

$$E_{\text{grid},t} \leq (1 - BIN_{\text{outage},t}) \times E^{\text{max}}_{\text{grid}}. \quad (3)$$

$E_{\text{PV}}, E_{\text{dem}}, E_{\text{BTc}}$, and E_{BTd} denote the energy of the PV, electricity demand, and battery's charge and discharge, respectively. BIN_{outage} denotes the outage state. During the outage ($BIN_{\text{outage}} = 1$), the energy from the grid becomes zero. The battery and the PV can supply electricity during the outage. The supply shortage (E_{short} and E'_{short}) happens when the demand exceeds the supply.

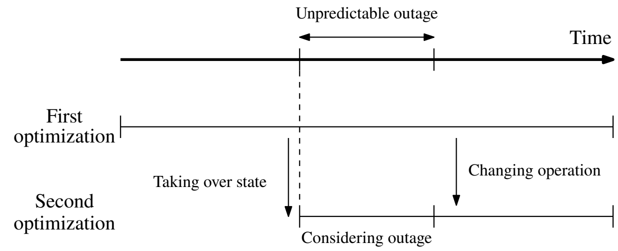

Fig. 2. Optimization sequence with an unpredictable outage.

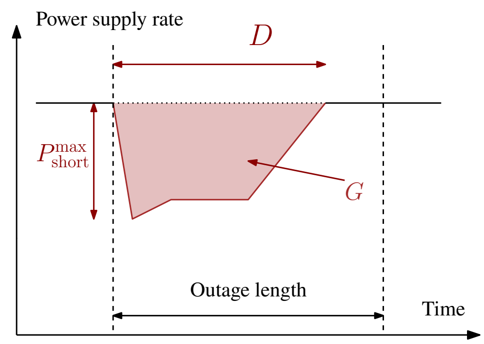

Fig. 3. Relation between proposed resilience indices and resilience curve.

The optimization problem includes the constraints on the SoC margin. The SoC margin limits the minimum SoC in the normal state as it is higher than the actual minimum SoC. The gap between the actual minimum and the minimum in the normal state is called the SoC margin. The battery has the actual minimum and maximum SoCs (10 % and 90 %) to avoid over-discharging and over-charging. The battery is prohibited from violating this minimum SoC even during the outage. The minimum SoC in the normal state can be larger than the actual minimum SoC to measure unpredictable outages. This paper externally defines the SoC margin as constant over time.

This paper proposes multiple optimizations to describe the change of the operation after an unpredictable outage. The scheme of multiple optimizations is shown in Fig. 2. At first, the household decides on the operation without being aware of the outage. The first optimization assumes that any outage does not occur ($BIN_{\text{outage},t} = 0$ for all t) to reflect the awareness of unpredictable outages. Immediately after the outage occurs, the household adjusts the operation to endure the outage. The second optimization decides again the operation after the outage occurs, including the outage state.

C. Resilience Indices

The resilience indices can evaluate the improvement of residential resilience by the measures against outages. Resilience curves [3] and resilience triangles [17] are widely used to describe the system's state affected by a large disturbance.

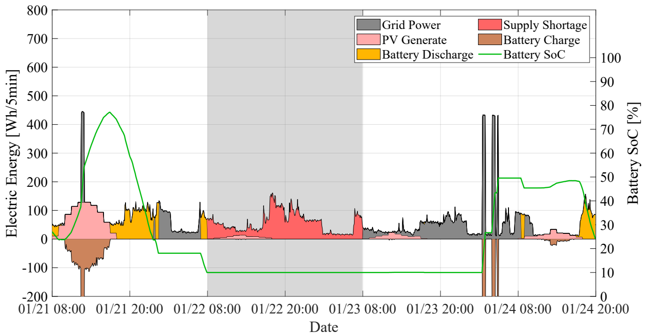

Fig. 4. Power supply around a 24-hour unpredictable outage without an SoC margin.

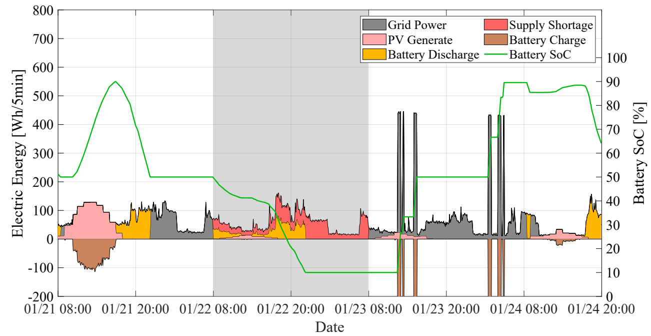

Fig. 5. Power supply around a 24-hour unpredictable outage with a $40\,\%$ SoC margin.

They show the transition of functionality around the disturbance. The concept of resilience includes a time dimension [18], so defining one index to describe resilience is difficult. For example, Panteli et al. [3] propose four indices. They describe the speed and amount of dropping functionality, the degraded state's duration, and the restoration speed. Chatterji et al. [13] also propose the indices for residential resilience. They include the average, maximum, and duration of load sheddings, aggregating the different outage scenarios.

This paper introduces resilience indices that describe the mitigation of outages in a household. Households can prepare and mitigate outages but cannot remove the cause of outages. Thus, the indices mainly focus on how long and large the supply can be kept during the outage. This paper proposes three indices as below.

- D, which denotes the cumulative duration of supply shortages.
- $P_{\mathrm{short}}^{\mathrm{max}}$, which denotes the maximum power of supply shortages.
- G, which denotes the ratio of the total supply shortage with the measure to the one without the measure.

These indices correspond to the duration and amount of degradation and the area of the resilience curve, as shown in Fig. 3. When they get smaller, the residential system gets more resilient. Only G includes the importance of demand. For calculating G, the weight for important demand is five, and the weight for unimportant demand is one. This ratio equals the proportion of outage unit costs (Section III-A). The proposed indices are similar to the ones in [13], but our indices are defined in each outage scenario.

III. Case Study

A. Situation and Battery Operation

Based on the household's actual data, this paper simulates the proposed measure against an unpredictable outage. The demand are based on the actual demand for a detached house in the Kansai region in Japan. This paper focuses on the winter because the PV generates less power. The power and capacity of the battery are $3\,\mathrm{kW}/13.5\,\mathrm{kWh}$. The capacity of the PV is $3\,\mathrm{kW}$ at peak. The electricity price is connected to the Japanese wholesale market price in 2023. In Section III-A, the unpredictable outage occurs during the day with little generation of the PV. The outage duration is 24 hours, based on the $50\,\%$ recovery time after the blackout due to the Hokkaido Eastern Iburi earthquake in Japan 2018.

The operation of the battery depends on the important demand during outages. There are surveys on the type of important demand [15], [19]. Refrigerators, cell phone chargers, and televisions have higher needs during the outage by a large earthquake [19]. In the outage simulation, [9] considers that the important demand is half the demand during the outage. This paper assumes that the important demand during the outage is half the demand the household would use without the outage. The outage unit cost, or the value of lost load, is estimated by surveys. The unit cost depends on the regions and outage situations, but the representative value is around $100\,\mathrm{JPY/kWh}$ to $1000\,\mathrm{JPY/kWh}$ [20]–[22]. This paper assumes that the outage unit costs are $500\,\mathrm{JPY/kWh}$ for the important demand [23] and $100\,\mathrm{JPY/kWh}$ for the unimportant demand.

First, we compare costs and resilience indices with different SoC margins. The total costs and outage costs with different SoC margins are shown in Table I. The resilience indices with different SoC margins are shown in Table II. From $0\,\%$ to $40\,\%$, the SoC margin reduces the outage cost by around 1200 JPY per $20\,\%$ point increase in the SoC margin. The decrease in the outage cost also reduces the total cost. However, the total cost at an $80\,\%$ SoC margin is higher than at a $40\,\%$ SoC margin. With a very high margin, the electricity cost increases more than the decrease in the outage cost. The SoC margin improves the indices, especially G, which describes the weighted energy of the supply shortage. Compared to no SoC margin, a $40\,\%$ SoC margin does not reduce D but reduces $P_{\mathrm{short}}^{\mathrm{max}}$ by $33\,\%$ and G at half.

Next, we show the operation around the outage. The power supply around the unpredictable outage without the SoC margin and with a $40\,\%$ SoC margin is shown in Figs. 4 and 5, respectively. For comparison, the power supply around a 24-hour predictable outage is shown in Fig. A1 (see Appendix). When the outage is predictable, the battery refrains from

TABLE I
TOTAL AND OUTAGE COSTS WHEN A 24-HOUR UNPREDICTABLE OUTAGE OCCURS AT 08:00 IN THE SUNLESS DAY.

SoC margin	Total cost [JPY]	Outage cost [JPY]
0 %	12570	4550
20 %	11450	3330
40 %	10470	2120
80 %	10610	610

TABLE II
RESILIENCE INDICES WHEN A 24-HOUR UNPREDICTABLE OUTAGE OCCURS AT 08:00 IN THE SUNLESS DAY.

SoC margin	D [min]	$P_{\text{short}}^{\max}$ [kW]	G [%]
0 %	1440	1.93	90.8
20 %	1440	1.82	66.5
40 %	1440	1.29	42.3
80 %	920	0.97	12.1

discharging before the outage. In contrast, when the outage is unpredictable, the battery does not charge before the outage because the operation before the outage is defined without being aware of it. Thus, there is little SoC in the case without the SoC margin (Fig. 4). There is a large supply shortage for important demand without the SoC margin because of little energy from the battery and the PV. In contrast, the battery has some energy before the outage with a $40\,\%$ SoC margin (Fig. 5). Thus, the battery can supply electricity to important demand until around 22:00. In conclusion, unpredictable outages are an important factor in the operation of the battery. In particular, setting the SoC margin can mitigate the damage of such unpredictable outages.

B. Multiple Scenarios of Outages

Since the damage of an outage depends on its occurrence timing, the effectiveness of outage measures should be discussed based on multiple outage scenarios. In each scenario, a 24-hour unpredictable outage occurs during the optimization time (14 days). The timing of outage occurrence in the first scenario is 6 hours later than the start of optimization to simulate the normal operation before the outage. The occurrence timing in each scenario is different at 30 minutes. The occurrence timing in the last scenario is 30 hours before the end of optimization to avoid the violation of constraints. The number of the scenarios is 601 (= (24×14−36)×(60/30)+1). The scenarios includes severe and mild ones because each scenario differs in demand and PV output during the outage and the SoC at the outage occurrence.

Fig. 6 shows the sorted distribution of G with different SoC margins. The sorted distributions of D and $P_{\text{short}}^{\max}$ are shown in Figs. A2 and A3 (see Appendix). Table III shows the worst $5\,\%$ value of proposed indices. Supply shortage happens in most scenarios, even with the SoC margin. However, the SoC margin decreases the index G, showing resilience improvement. At the worst $5\,\%$ values, the index G decreases much with the SoC margin. The battery with the SoC margin supplies the important demand with priority. Thus, G decreases a lot because it is calculated by the supply shortage weighted by

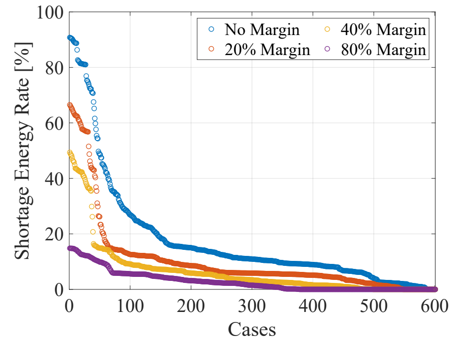

Fig. 6. Ratio of the total supply shortage (G) in descending order in the multiple outage scenarios.

the demand importance. In contrast, the worst $5\,\%$ values of D and $P_{\text{short}}^{\max}$ do not decrease so much because there are supply shortages of unimportant demand and scenarios that the battery's SoC is short.

C. Cost Reduction in Normal State

The battery can reduce electricity costs by charging and discharging at electricity prices. However, the SoC margin restricts the discharge in the normal state. Thus, higher margins increase the costs in the normal state. The yearly optimization without outages simulates the normal operation of the battery with the PV. We compare the costs in the normal state among different SoC margins. The objective function and constraints are the same as in Section II, but the resolution is 30 minutes to reduce the computational burden.

The yearly costs with different SoC margins are shown in Table IV. The cost does not include the outage and initial costs of the battery and PV. The battery cannot charge and discharge at an $80\,\%$ SoC margin, so the cost at an $80\,\%$ SoC margin equals the cost without the battery. This cost is higher than when the battery can charge and discharge. The SoC margin increases the cost. A $40\,\%$ SoC margin increases the cost by $16\,\%$ (18300 JPY) compared to the case without a margin. In addition, the cost increase accelerates with an increase in the margin. The accelerating increase in the cost is because the battery loses the opportunity to reduce the cost, such as discharge at high electricity prices, with a high SoC margin. In contrast, with a small SoC margin, the battery actively charges and discharges when there are fluctuations in electricity prices. The battery's energy discharged is $2.58\,\mathrm{MWh}$ without an SoC margin. However, it decreases to $1.73\,\mathrm{MWh}$ ($33\,\%$ decrease) with a $40\,\%$ SoC margin and zero with an $80\,\%$ SoC margin. In conclusion, the SoC margin mitigates the risk of unpredictable outages but increases the cost in the normal state.

IV. CONCLUSION

This paper simulates the operation of the battery to reduce the residential supply shortage through the optimization problem considering unpredictable outages. The battery only sometimes has enough energy before unpredictable outages, but the SoC margin reduces the supply shortage of important

TABLE III
WORST 5 % OF RESILIENCE INDICES IN THE MULTIPLE OUTAGE SCENARIOS.

SoC margin	D [min]	$P_{\text{short}}^{\text{max}}$ [kW]	G [%]
0 %	1440	1.93	74.8
20 %	1440	1.69	56.8
40 %	1440	1.29	36.7
80 %	1032	0.97	12.1

TABLE IV
YEARLY TOTAL COSTS CALCULATED BY THE OPTIMIZATION WITHOUT ANY OUTAGE.

SoC margin	Total cost [JPY]	Difference [JPY]
0 %	115200	(base)
20 %	121300	+6100
40 %	133500	+18300
80 %	188500	+73300

demand. In addition, the SoC margin mitigates the damage of unpredictable outages, quantified by the outage cost. Compared to no SoC margin, the outage cost decreases by half (2400 JPY) in a 24-hour unpredictable outage with a 40 % SoC margin. However, a high SoC margin restricts discharge in the normal state and increases the yearly electricity cost by 16 % (18300 JPY) at a 40 % SoC margin. It shows a tradeoff between a measure against unpredictable outages to decrease discomfort and an operation to reduce the electricity cost.

This paper proposes resilience indices representing a supply shortage's duration, maximum power, and energy during an outage. The SoC margin, in particular, effectively reduces the index describing the energy of a supply shortage (G). It decreases by 50 % at a worst 5 % value with a 40 % SoC margin because the battery supplies electricity to important demand. These indices help evaluate the residential resilience, considering the importance of demand.

In this paper, the value of the SoC margin is constant in one optimization problem. However, it may unnecessarily restrict the operation of the battery to reduce electricity costs. The variable SoC margin, which is low in moderate situations and high in severe situations, may balance resilience and economic operation. The method to set optimal and variable SoC margins is our future work. In addition, the probability of large earthquakes is very small (twice within the past 25 years). It may be reasonable not to set the SoC margin from the view of stochastic optimization. A comprehensive analysis of the cost and mitigation is our future work.

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APPENDIX

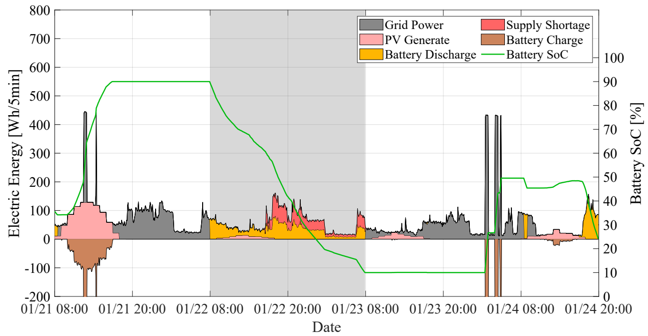

Fig. A1. Power supply around a 24-hour predictable outage without an SoC margin.

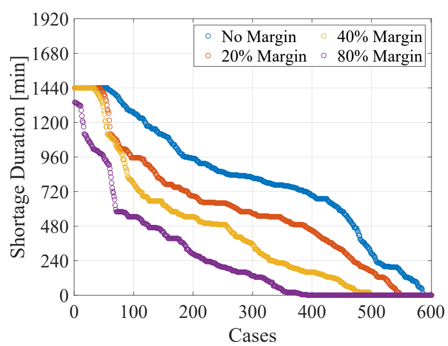

Fig. A2. Duration of the supply shortage (D) in descending order in the multiple outage scenarios.

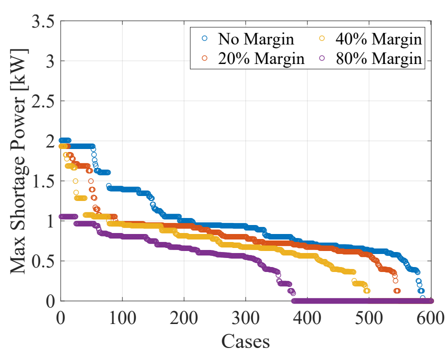

Fig. A3. Maximum power of the supply shortage ($P_{\mathrm{short}}^{\mathrm{max}}$) in descending order in the multiple outage scenarios.