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P2P energy sharing EMS with EVs for resilience on an event-triggered control scheme

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Abstract: In recent years, the risk of power outages caused by natural disasters has become a new issue for the power system. As a countermeasure, a mutual aid resilience energy management method using the distributed energy resources of consumers to exchange power for mutual benefit is expected. However, if power distribution lines are damaged during a disaster, there is the vulnerability that the power exchange method cannot be used. Therefore, in this study, we assume power exchange between consumers using Electric vehicles (EVs), rather than distribution lines, as the power exchange method. First, we formulate an optimization problem that expresses power exchange through EV charging and discharging with a mixed integer optimization problem and evaluate a power exchange plan that optimizes the resilience performance of each consumer. Next, consumers are modeled as a multi-agent system and realize power exchange through EV charging and discharging based on Peer-to-Peer (P2P) negotiations in the manner of an event-triggered control method when any consumer's resilience performance decreases. The two proposed methods are compared with numerical simulations and thus are quantitatively evaluated, confirming the improvement of resilience performance.

Keywords: Resilience, Energy Management, Energy exchange, Electric Vehicle, Peer-to-Peer, Event-triggered Control.

1. INTRODUCTION

Power outages caused by natural disasters such as typhoons and earthquakes, which have been increasing in recent years in Japan, increase the risk of serious damage in urban functions. To establish a countermeasure, discussions on utilizing distributed energy resources (DERs) on the demand side are underway [1], [2]. Previous research has considered resilience from the perspective of power systems [3] and from the perspective of using DERs on the demand side [4-8].

In our previous research, we also considered an energy management system (EMS) that realizes power exchange by sharing distribution lines among multiple consumers in a limited area and enhances resilience through mutual aid energy management in the event of a disaster [9-14]. However, this approach assumed that the distribution lines for power exchange would be available even in the event of a disaster. Nevertheless, in real natural disasters, such as earthquakes and typhoons, distribution lines are sometimes damaged, and in many cases, become unusable due to broken lines caused by fallen trees and utility poles. Therefore, the purpose of this study was to propose and evaluate a new mutual aid resilience EMS method that does not rely on distribution lines in the event of a disaster.

Electric vehicles (EV) provide an alternative means of power exchange. Each consumer can estimate the consumer's resilience level within the prediction horizon based on its own DERs, such as a photovoltaic generator (PV), battery energy storage system (BESS), and fuel cell (FC), as well as its load forecast. If a poor resilience condition is detected and the consumer has a larger power deficiency than other consumers, the consumer can use an EV to travel to a neighboring consumer to borrow power. Such actions would not occur periodically but would occur only when conditions based on a certain resilience index are met. Therefore, we focus on an EMS strategy based on an event-triggered control scheme [15,16]. In addition, unlike n to n transactions using power exchange via distribution lines, power exchange using the EV is negotiated and traded 1 to 1 with the other consumer, so it can be considered as Peer-to-Peer (P2P) trading. The purpose of this study was to build an evaluation model for a problem setting with such characteristics and evaluate the resilience performance of the EMS from various angles through simulations.

In the following, Section 2 explains the problem setting related to resilience. In Section 3, we derive a globally optimal solution by rigorously formulating the problem of power exchange by EVs. In Section 4, a multi-agent simulation model of EV power exchange using P2P negotiation-based event-triggered control is proposed. In Section 5, numerical simulations are conducted and comparative evaluations of the two approaches are discussed. Finally, Section 6 provides a summary and presents future challenges.

2. EVALUATION MODEL AND METRIC

In this study, multiple consumers are represented as a consumer group using a multi-agent model. In Section 5 assumed 512 consumers as a realistic size of multi-agent model on a single feeder scale in a power distribution system. The DER configuration of each consumer is shown in Fig. 1.

Each consumer has a load, PV, BESS, and FC, and can suppress load (Lsup) or suppress PV (PVsup) depending on the energy balance condition. Each consumer also has an EV and can share energy with neighboring consumers within a certain range by charging and discharging the EV. There is also a communication network for mutual conversation and negotiation. A conceptual diagram of

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† Yutaka Iino is the presenter of this paper.

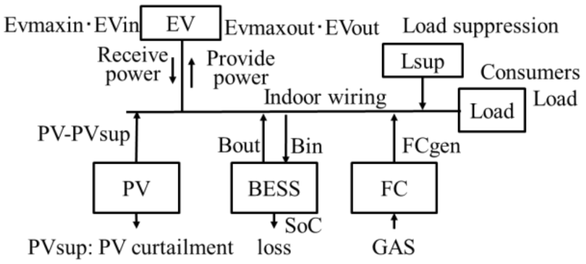


Fig.1 Configuration of DERs at a consumer.

the configuration is shown in Fig. 2. In this case energy sharing neighboring consumers j of consumer i is $\mathcal{N}(i) = \{i-2, i-1, i+1, i+2\}$.

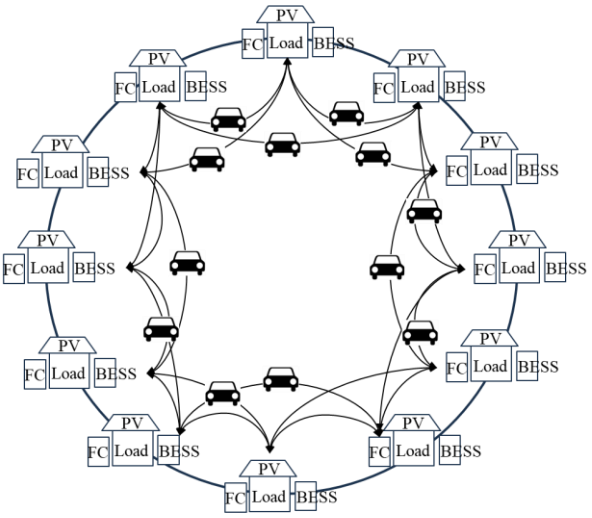


Fig.2 Configuration of Enegy sharing group of consumers.

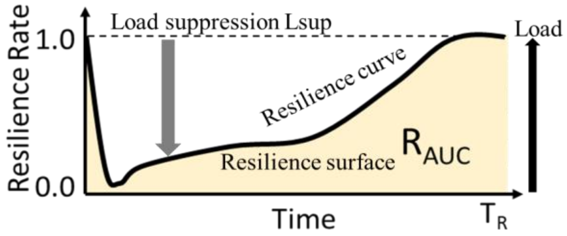


Fig.3 Definition of Resilience curve and area R_{AUC}.

Next, the resilience performance index for each consumer is defined as follows. For the i-th consumer's power demand $Load_i(t)$, the degree of resilience is defined as the ratio of the actual power supplied as a result of load suppression $Load_i\ (t) - L^i_{sup}(t)$.

$$R^i_{rate}(t) = \frac{Load_i\ (t) - L^i_{sup}(t)}{Load_i\ (t)} \tag{1}$$

The resilience ratio $R_{rate}(t)$ is a function of time determined from the supply and demand balance conditions for each customer during the disaster period and can take the shape shown in Fig. 3. Here, the area under the curve in the figure is defined as the resilience area under the curve: $R^i_{AUC} = \frac{1}{T}\int_{t=0}^{T} R^i_{rate}(t)dt$, where,

$$0 \leq R^i_{AUC} \leq 1 \tag{2}$$

When the R_{AUC} is closer to 1, the required power demand is closer to being met. This index is used in the evaluation of each proposed method in the subsequent Section 5. In the following discussion, the time variable t is treated as a discrete time with a 30-minute period.

3. FORMULATION OF ENERGY SHARING PLANNING OPTIMIZATION METHOD

Here, we consider mutual aid by power interchange through EV charging and discharging among a group of consumers i = 1,…, N. A day is divided into 48 × 30-minute intervals (t = 1,…,48), and one power interchange is assumed to involve charging at another consumer at time t, traveling at time t + 1, and discharging within one's own facility at time t + 2. The execution and suspension of power interchange is expressed as the integer variables *EVin*(t) = {0,1} and *EVout*(t) = {0,1}. Their optimization is formulated below as a mixed integer linear programming (MILP) problem.

Nomenclature

EVin(t): Power provision from EV discharge for energy sharing: integer variable {0,1}.
EVout(t): Power consumption for EV charge (Ibid.)
IB(t): An integer variable {0,1} as simultaneous charging and discharging prohibition flag.
Lsup(t): Load suppression amount [kWh/30min].
PVsup(t): PV generation suppression [Ibid.].
Bin(t): BESS charging power amount [Ibid.].
Bout(t): BESS discharging power amount [Ibid.]
SoC(t): State of charge in BESS [%]
FCgen(t): Fuel cell generation power amount [kWh/30min]
Csup: Incentive price for demand suppression [yen/kWh]
Cin: Unit cost for receiving energy via EV sharing [yen/kWh]
Cout: Unit incentive price for providing energy via EV sharing [yen/kWh]
Cfc: Unit cost of fuel cell power generation [yen/kWh]
Load(t): Consumer's demand [kWh/30min]
PV(t): Potential power generation of Photovoltaic generation system (PV) [kWh/30min]
Bmax: Upper limit of BESS charge/discharge [Ibid.]
SoCmax: Capacity of BESS [kWh]
FCmax: Capacity of fuel cell generation [kWh/30min]
$\eta in, \eta out$: Efficiency of BESS charge/discharge[%]
EVmaxin, EVmaxout: Unit energy for sharing with EV per one charge/discharge action [kWh].
EV_{max} : maximum EV utilization for energy sharing per a day for each consumer.
N: Total number of consumers
i: index number of each consumer ($0 \leq i \leq N$)

Formulation

$$Cost\ \ function: \qquad J = \sum_{i=1}^{N} f_i^T x^i \rightarrow min \tag{3}$$

$$f_i = [Cin, Cout, 0, Csup, 0, 0, 0, 0, Cfc]^T$$
$$x^i = [EVin, EVout, IB, Lsup, PVsup, Bin, Bout, SoC, FCgen]$$

$$x = [x^1, x^2, \cdots, x^N]^T$$

Constraint conditions: for each consumer *i=1,…,N*

Power balance condition:

$$\begin{aligned} &EVmaxin \cdot EVin(t) - EVmaxout \cdot EVout(t) \\ &+ Lsup(t) - PVsup(t) \\ &- Bin(t) + Bout(t) + FCgen(t) \\ &= Load(t) - PV(t) \end{aligned} \qquad (4)$$

BESS SoC conditions:

$$0 \le SoC(t) \cdot SoCmax = SoC(t-1) \cdot SoCmax + Bin(t) \cdot \eta in - \frac{Bout(t)}{\eta out} \le SoCmax \qquad (5)$$

Upper and lower limit conditions:

$$0 \le Lsup(t) \le Load(t) \qquad (6a)$$

$$0 \le PVsup(t) \le PV(t) \qquad (6b)$$

$$0 \le Bin(t) \le Bmax \cdot IB(t) \qquad (6c)$$

$$0 \le Bout(t) \le Bmax \cdot \left(1 - IB(t)\right) \qquad (6d)$$

$$0 \le SoC(t) \le 100[\%] \qquad (6e)$$

$$0 \le FCgen(t) \le FCmax \qquad (6f)$$

Area EV sharing power balance condition:

$$\sum_{i=1}^{N} Ein^i(t+2) = \sum_{i=1}^{N} Eout^i(t) \qquad (7)$$

Area power balance condition:

$$0 \le Ein^i(t+2) \le \sum_{j \in \mathcal{N}(i)} Eout^j(t) \qquad (8)$$

Max EV utilization times:

$$\sum_{t=1}^{48} EVin^i(t) \le EV_{max} \qquad (9)$$

Eq. (6c) & (6d) means simultaneous charge and discharge of BESS is prohibited. Eq. (7) means Total charge into EVs and total discharge from EVs for energy sharing should be balanced in each time. Eq. (8) means only neighboring consumers $\mathcal{N}(i)$ can provide energy to consumer i. Eq. (9) means a consumer can use EV for energy sharing only EVmax times per a day.

4. MULTI-AGENT MODEL WITH P2P NEGOTIATION AND EVENT-TRIGGERED SCHEME

In the previous section, a central solution was presented for a resilience optimization EMS using EVs. However, this method has the disadvantage that it requires all information from individual consumers to be collected in the central server, and that it requires solving a large-scale MILP optimization problem, resulting in huge communication costs and computer resource costs. Therefore, in this section, the algorithm is reconstructed using a distributed coordinated control system scheme. Its features are as follows:

- Each consumer agent can learn the average resilience performance of the entire region through a consensus algorithm by communicating only with neighboring agents and can monitor the relative deviation value of its own resilience performance.
- A sparse EV usage plan is realized through event-triggered control [15,16], in which an agent negotiates with neighboring agents for power sharing when its own resilience performance declines.
- When an event occurs, the best partner is selected through negotiations with neighboring agents, and EVs are activated via P2P to share power.

Based on these characteristics, each agent only needs to communicate and negotiate with neighboring agents, and share power with EVs, resulting in simple logic that is easy to implement. In addition, the framework of a distributed coordinated control system is expected to have the advantage of being robust against partial communication outages and partial road closures during disasters.

The proposed algorithm is shown below.

Resilience EMS method:

The consumer agent i calculates its own resilience performance R_{AUC}^i based on its own demand and PV generation forecast, and battery charge/discharge plan. The following consensus algorithm is used to obtain the average value and standard deviation of the resilience performance of the region, and to find its own resilience performance deviation value σ_{RAUC}^i.

$$xi(0) = R_{AUC}^i \qquad (10a)$$

$$x_i\ (t+1) = x_i\ (t) + \varepsilon \textstyle\sum_{j \epsilon \mathcal{N}_i}(x_j\ (t) - x_i\ (t)) \qquad (10b)$$

$$x_i^2(t+1) = x_i^2(t) + \varepsilon \textstyle\sum_{j \epsilon \mathcal{N}_i}(x_j^2(t) - x_i^2(t)) \qquad (10c)$$

$$\varepsilon \le \left(\max_i |\mathcal{N}_i|\right)^{-1} \qquad (10d)$$

$$t \to \infty: \quad \mu = x(\infty), \ \sigma^2 = \left(x^2(\infty) - \mu^2\right) \qquad (10e)$$

Self-resilience performance index:

$$\sigma_{RAUC}^i = \frac{R_{AUC}^i - \mu}{\sigma} \qquad (11)$$

Where μ is average and σ is standard deviation of resilience performance R_{AUC}^i. Event-triggered control determines EV operation as follows:

$$IF\ \sigma_{RAUC}^i \le \sigma_{min} \text{ then start EV control} \qquad (12)$$

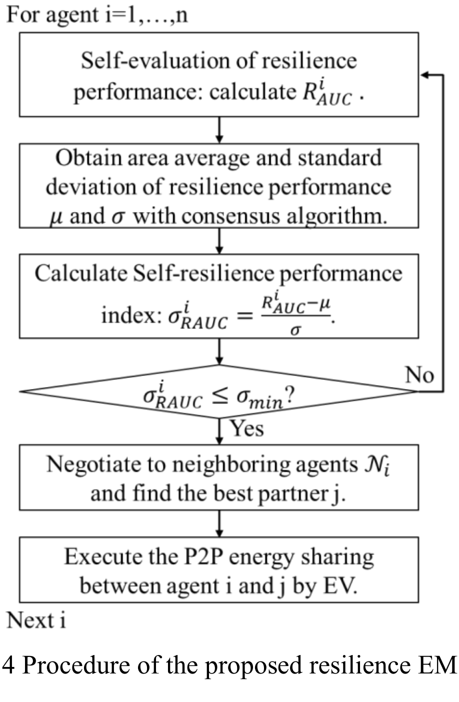


Fig.4 Procedure of the proposed resilience EMS.

The negotiation between consumer agent i and its neighboring agents is as follows:

Find agent j: s.t. $\{j|\sigma^{j}_{RAUC} \geq \sigma^{k}_{RAUC}, j, k \in \mathcal{N}_i\}$,then do the P2P energy sharing between agent i and j by EV charge at agent j on time t, move back on time t+1 and discharge at agent i on time t+2.

Fig.4 shows the procedures of the proposed resilience EMS method based on distributed coordinated control.

5. NUMERICAL SIMULATION

5.1 Conditions for simulation

Here, the proposed method described in Sections 3 and 4 is evaluated with numerical simulations. The simulation conditions are summarized in Table 1.

Table 1. simulation conditions.

Items	Conditions
Number of consumers:	512
Evaluation period:	One day (a sunny day in May)
Consumers load data:	NEDO Ohta city open data[17,18]
PV generation data:	Calculated from solar radiation
PV capacity:	4.4 [kW] [18]
EV Power capacity:	*EVmaxin*=3.0[kWh/30min] *EVmaxout*=4.0[kWh/30min]
BESS PCS capacity:	*Bmax*=4.4 [kW] [18] (= PV capacity)
BESS capacity:	*SOCmax*=5.5 [kWh] [18]
BESS efficiency:	$\eta in=\eta out$=0.95
Fuel cell capacity:	*FCmax*=0.7 [kW]
Cost Parameters:	*Cin*=50 [yen/an EV discharge], *Cout*=-20 [yen/an EV charge], *Csup*=100 [yen/kWh], *Cfc*=33.2 [yen/kWh]

5.2 Simulation results

The following was assumed as a simulation case:

Case1: $|\mathcal{N}_i| = 0$
Case2: $|\mathcal{N}_i| = 2$
Case3: $|\mathcal{N}_i| = 4$
Case4: $|\mathcal{N}_i| = 8$
Case5: $|\mathcal{N}_i| = 16$
Case6: $|\mathcal{N}_i| = 32$

This means that the number of neighboring consumers who cooperate with each other in energy sharing gradually increases from Case 1 to Case 6. The event-triggered control method (ETC) defined in section 4 is compared to the central solution (CS) defined in section 3 for each case. Demand and PV generation in the evaluation day are shown in Fig.5.

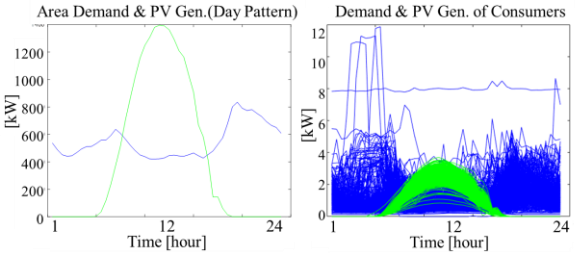
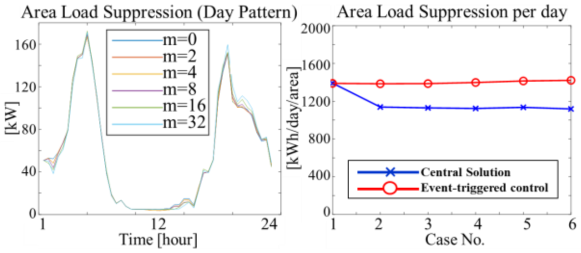
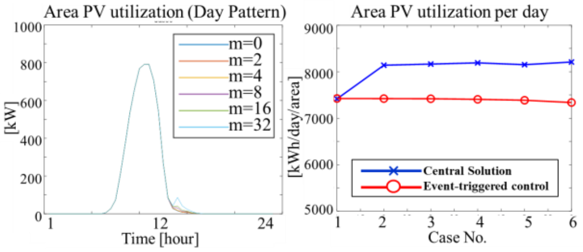


Fig.5 Demand and PV generation in day pattern.

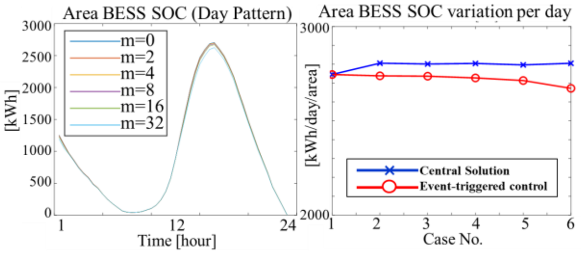
The following graphs in Fig.6 are results of a day pattern (left graph) and comparison between case 1-6 and each method: CS & ETC (right graph).



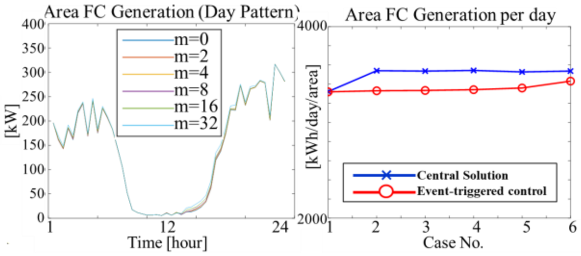
(a) Load suppression



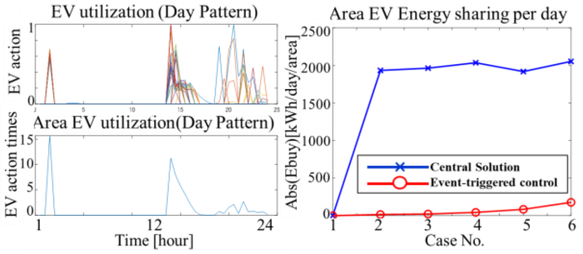
(b) PV curtailment



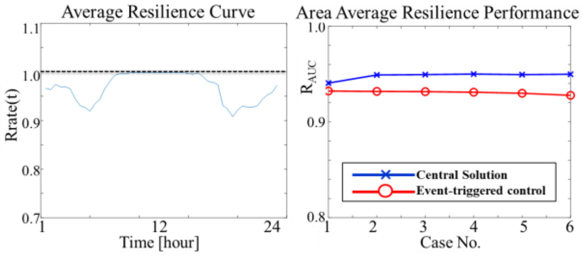
(c) BESS SOC pattern and variation



(d) Fuel Cell generation



(e) EV energy sharing



(f) Resilience performances

Fig. 6 Results of each DER behaviors.

Finally, the equality of resilience performance of each consumer was evaluated by Gini coefficient [14,19,20] as an evaluation index. The closer the coefficient is to 0, the more equal it is. The results are shown in Fig. 7.

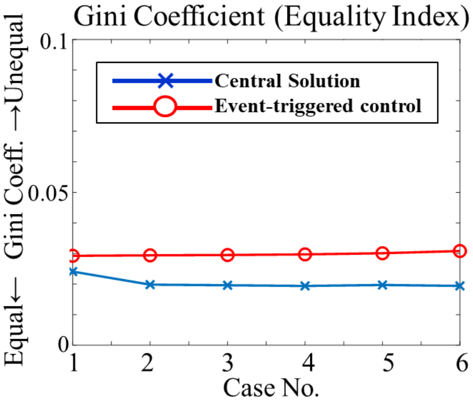


Fig.7 Equality of resilience performance of each consumer

In Fig.6 (a), load suppression for each consumer occurs more frequently in the morning and evening. There is not much difference between the cases. The amount of suppression is slightly less in ETC than in CS.

Fig.6 (b) shows PV utilization with curtailment during the day. CS reduces PV curtailment more than ETC, making more effective use of PV power.

In Fig.6 (c), the SOC change pattern of the BESS does not so differ between the cases. CS utilizes slightly more BESS capacity than ETC. In ETC, the use of BESS decreases as well as the number of neighboring consumers. This means that BESSs are being replaced by EVs.

In Fig.6 (d), the operation pattern of the FC does not so differ between the cases. CS generates slightly more FC power than ETC. In ETC, the amount of FC power generation increases as well as the number of neighboring consumers. This means that FCs are contributing to other consumers through EVs.

Fig.6 (e) shows the frequency and amount of energy sharing using EVs. Compared to CS, ETC keeps the occurrence of events to a minimum, realizing sparse EV utilization. However, the amount of energy sharing is considerably limited compared to CS.

Fig.6 (f) shows the resilience curve and resilience index R_{AUC} as the average resilience performance of all consumers. The index R_{AUC} is kept above 0.9 throughout the day, that means more than 90% of the required power is always supplied. The difference between CS and ETC is not so large.

Finally, in Fig.7, the result of evaluating the equality of resilience performance between consumers shows that ETC sacrifices equality slightly compared to CS.

5.3 Considerations

The essential role of the proposed method is to level the imbalance in resilience performance between consumers by energy sharing using EVs. If the power distribution system is available, ideal leveling is possible by continuous energy sharing and a distributed coordinated control scheme. However, the means using EVs are discrete, and the ETC mechanism is introduced to aim for a sparse operation plan considering travel time and driving effort. As a result, the opportunities for energy sharing are restricted, and there is a certain limit to the improvement of resilience performance. Furthermore, in comparison with CS, the results of this simulation show that although the difference in average resilience performance is small. On the other hand, ETC is not enough in terms of equality between individual consumers, and this will be an issue of future research.

6. CONCLUSION

This paper proposed an energy management optimization method for power interchange between consumers using EVs to improve the resilience performance of consumer groups during power outages. First, as the central solution, an optimization problem was formulated to determine the consumer pairs and timing of power interchange through EV charging and discharging. Next, the consumer groups were modeled as multi-agents, and an algorithm for a P2P negotiation process using an event-triggered control method was proposed. The two methods were compared using numerical simulation, and the latter multi-agent P2P method with its event-triggered manner provided results that were close in a sense to the global optimal solution of the former, demonstrating its effectiveness as an EMS method that can be realized with a simple mechanism in practical operations.

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