Proposal for Fast Directional Energy Interchange Used in MCMC-Based Autonomous Decentralized Mechanism toward Resilient Microgrid

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***Abstract*—Microgrid is well known as key technology to improve renewable energy's ease of use. Some previous works focused on a microgrid that is divided into autonomous electricity subsystems (AESs) for its reliability and scalability. We have proposed the MCMC-based autonomous decentralized mechanism (ADM) to perform energy interchange between AESs so as to be supply energy appropriately for different energy demands among AESs. In this paper, toward resilient of microgrids, we design a method to realize directional energy interchange in our ADM on the basis of the convection diffusion. We investigate the effectiveness of the proposed method through simulation experiment considering energy shortage and emergency situations. We clarify that the proposed method can fast supply energy from external power grid to a microgrid under energy shortage situation, and can fast gather distributed energy to a specific AES (e.g., safe shelter) under emergency situation.**

I. Introduction

Renewable energy resources (e.g., sunlight) are hopeful alternatives of conventional fuels (e.g., fossil fuel). The renewable energy generation is well known as low carbon emission, but its output is usually small scale and unstable. Hence, renewable energy generators have difficulty supplying the generated energy appropriately for instantaneous energy demand. In order to alleviate the disadvantage of renewable energy, the electricity systems should equip batteries to absorb fluctuations of energy supply and demand. Moreover, since there is the difference among energy demand of electric loads distributed in the electricity systems, surplus energy in a battery should be transmitted to an electric load with high demand. Hence, it is important challenge for renewable energy to develop an effective method to realize such energy transmission.

Microgrid [1]–[3] is an electricity system to transfer energy among batteries, micro-scale generators (e.g., photovoltaic array and wind turbines), and electronic loads. It would be a key technology to provide energy transmission for improving renewable energy's ease of use.

Some previous works [4]–[6] focused on a microgrid that is divided into autonomous electricity subsystems (AESs) for its reliability and scalability. For instance, AES corresponds to electricity system in a home and a community. AESs are interconnected like a mesh network to be able to perform energy interchanges among them, see Fig. 1 (a). In [5], the authors designed the internet-like mechanism of the multi-hop energy interchange to transfer energy between an AES pair in a mesh network by using an energy routing. In [6], we designed an autonomous decentralized mechanism (ADM) of energy interchange between AESs on the basis of Markov chain Monte Carlo (MCMC). Each AES autonomously determines the amount of an energy interchange for adjacent AESs in a mesh network by using MCMC-based expression. We ensured that the MCMC-based expression achieves the energy supply appropriately for energy demand in all over the mesh network. The MCMC-based ADM is such a lightweight solution of the energy interchange, but is not efficiently support diverse situations (e.g., abnormal weather and disaster).

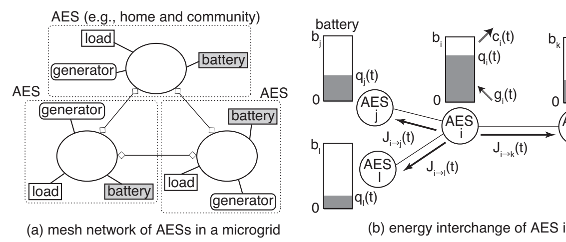

Fig. 1: System model

In the world, people take a growing awareness for abnormal weather and disaster, so a mechanism in microgrids should have high resiliency for diverse situations. If the weather is abnormal, generators using renewable energy may not supply energy to be able to satisfy energy demand in a microgrid. For such energy shortage situation, energy should be supplied from an external power grid. However, connectable AESs to the external power grid are limited by geographical condition. Hence, it is necessary to fast supply energy in a direction away from the connectable AESs, see Fig. 2 (a). When disaster (e.g., earthquake) occurs, people evacuate to a safe shelter, and energy should be supplied preferentially there. For such emergency situation, energy in a microgrid should be fast gathered at the safe shelter. Therefore, it is necessary to fast supply energy in the direction to a high priority AES from other AESs, see Fig. 2 (b). Considering diverse situations, a mechanism in microgrids should support directional energy interchange so as to realize such energy supply.

In this paper, toward resilient of microgrids, we propose a method to realize the directional energy interchange, which enables the MCMC-based ADM to fast transfer energy in an

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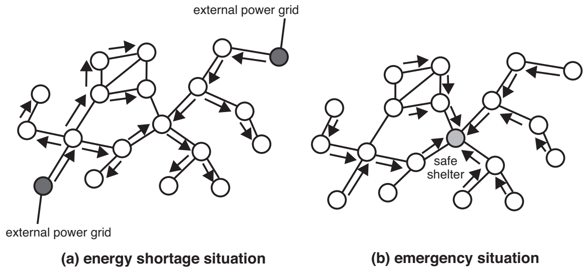


Fig. 2: Directional energy interchange

appropriate direction. We first design the directional energy interchange based on the convection diffusion equation, and investigate the effectiveness of the proposed method through simulation experiment considering energy shortage and emergency situations. We clarify that the proposed method can fast supply energy from external power grid to a microgrid under energy shortage situation, and fast gather distributed energy to a specific AES (e.g., safe shelter) under emergency situation.

This paper is organized as follows: Section IV explains the system model. Section III describes the MCMC-based ADM for energy interchange. Section IV shows the method for fast directional energy supply. Experimental results are described in Section V. Section VI concludes this paper.

II. System Model

To discuss fundamental properties of the proposed method, we use a simple electricity system model, which is also used in [6]. This model assumes that any energy transformation loss in AESs can be ignored. Thank to this assumption, we can focus on the behavior of energy interchange in mesh networks because all equipments with a similar function (e.g., generation) in an AES are merged to a single equipment. Hence, the evolution of remaining battery amount $q_i(t)$ in AES i is simply given by

$$q_i(t+\Delta T_J) - q_i(t) = \int_t^{t+\Delta T_J} \big(g_i(t) - c_i(t)\big)\mathrm{d}t + \Delta T_J \sum_{j\in a_i} \big(J_{j\to i}(t) - J_{i\to j}(t)\big), \quad (1)$$

where $g_i(t)$ and $c_i(t)$ are the generated and consumed energies in AES i at time t, respectively. Note that $c_i(t)$ represents instantaneous energy demand of AES i. Let G be the mesh network of AESs in a microgrid. a_i is the set of adjacent AESs of AES i in mesh network G. ΔJ is the time interval of energy interchange, and $J_{i\to j}(t)$ is the amount of energy interchange from AES i to an adjacent AES $j \in a_i$ during $[t, t+\Delta T_J)$. Figure 1 (b) shows the energy interchange of AES i in the system model. In the figure, we denote battery capacity of AES i by b_i.

In general, each AES has different battery capacity and energy demand than other AESs. To represent percentage achievement of energy supply appropriately for energy demand in an AES, we introduce sufficiency level $\hat{q}_i(t)$ of AES i by

$$\hat{q}_i(t) := \frac{q_i(t) - \theta_i}{b_i}, \quad (2)$$

where θ_i is the target remaining battery amount of AES i. If $q_i(t) \geq \theta_i$, the energy demand of AES i is satisfied. AES i can know whether its adjacent AES $j \in a_i$ needs more energy by the observation of $\hat{q}_j(t)$. If $\hat{q}_i(t) = \hat{q}_j(t)$ for all AES pairs (i, j)'s, the energy supply would be achieved appropriately for the energy demand of nodes at time t. The MCMC-based ADM performs energy interchanges to equalize sufficiency levels of all AESs.

III. MCMC-Based Autonomous Decentralized Mechanism of Energy Interchange

A. Autonomous Decision of Energy Interchange

To equalize sufficiency levels of all AES, each AES calculates energy interchange amount $J_{i\to j}(t)$ by

$$J_{i\to j}(t) = b_i\, k_{\text{diff}}\, f_{i\to j}(\hat{q}_i(t), \hat{q}_j(t))\, \hat{q}_i(t), \quad (3)$$

where k_{diff} is a positive constant that determines equalizing speed of sufficiency levels. $f_{i\to j}(\hat{q}_i(t), \hat{q}_j(t))$ is given by

$$f_{i\to j}(\hat{q}_i(t), \hat{q}_j(t)) = 1 - k_{\text{MC}} |\hat{q}_j(t) - \hat{q}_i(t)| (\hat{q}_j(t) - \hat{q}_i(t))^+, \quad (4)$$

where k_{MC} is a positive parameter and $[x]^+ = \max(0, x)$. In [6], we derived Eq. (3) on the basis of MCMC [7]. As k_{diff} or k_{MC} increases, sufficiency levels are equalized faster.

If $k_{\text{MC}} = 0$, $J_{i\to j}(t)$ is simply calculated by $b_i\, k_{\text{diff}}\, \hat{q}_i(t)$. In this case, the dynamics of $\hat{q}_i(t)$ is given by the well-known diffusion equation. The dynamics using Eq. (3) if $k_{\text{MC}} > 0$ corresponds to a non-linear diffusion equation with the same equilibrium state where all values are equalized. In [6], we showed that the MCMC-based ADM can fast equalize sufficiency levels thank to the non-linear effect.

IV. Method for Fast Directional Energy Interchange Based on Convection Diffusion

The dynamics of sufficiency levels in the MCMC-based ADM corresponds to a non-directional diffusion phenomenon shown in the left of Fig. 3. The MCMC-based ADM would not support the diverse situations (e.g., abnormal and emergency situations) requiring the directional energy supply shown in Fig. 2. Hence, we design a method that enables the MCMC-based ADM to support directional energy interchange.

The convection diffusion equation explains directional diffusion phenomenon observed in physics model. Compared with the diffusion phenomenon, the convection diffusion phenomenon has an additional effect to fast diffuse for a specific direction, see the right of Fig. 3. The discrete convection diffusion equation of $\hat{q}(t)$ on mesh network G is given by

$$\hat{q}_i(t+\Delta T_J) = \hat{q}_i(t) + k_{\text{diff}} \Delta T_J \sum_{j\in a_i} [\hat{q}_j(t) - \hat{q}_i(t)] - k_{\text{conv}} \Delta T_J \sum_{j\in v_i(t)} [\hat{q}_j(t) - \hat{q}_i(t)], \quad (5)$$

where k_{conv} is convection diffusion coefficient, and $v_i(t)$ is the set of adjacency AESs for which AES i should perform directional energy interchange ($v_i(t) \subseteq a_i$).

Since the second term of the right side in Eq. (5) represents diffusion phenomenon, it describes the dynamics of $\hat{q}_i(t)$ by

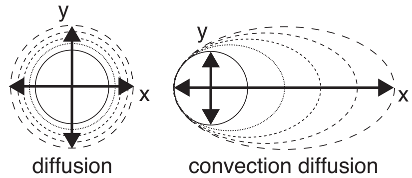


Fig. 3: Diffusion vs. convection diffusion for x-axis direction

using Eq. (3), in essentials.[1] Hence, to perform the directional energy interchange, we should replace the expression of $J_{i\to j}(t)$ by

$$J_{i\to j}(t) := J_{i\to j}(t) - b_i\, k_{\mathrm{conv}} \sum_{j\in v_i(t)} \left[\hat{q}_j(t) - \hat{q}_i(t)\right]. \qquad (6)$$

Note that the first term of the right side in Eq. (6) is calculated by Eq. (3).

$v_i(t)$ is set to be able to perform energy interchange in appropriate directions. Considering energy supply appropriately for energy demand, each AES should perform energy interchange in the direction for adjacency AESs with small sufficiency levels. Namely, $v_i(t)$ is set by

$$v_i(t) = \{j \mid \hat{q}_j(t) < \hat{q}_i(t),\ j \in a_i\}. \qquad (7)$$

The setting of v_i by Eq. (7) is simple, but the proposed method with the setting supports diverse situations (e.g., energy shortage and emergency situations) discussed in Section I. When supplying energy from external power grid under energy shortage situations, sufficiency levels of the connected AESs are always 0, and their sufficiency levels are larger than those of other AESs. When gathering energy to a high priority AES h from other AESs under emergency situations, we set energy demand θ_h to high value, and the sufficiency level of AES h becomes smaller than those of other AESs. Hence, by using Eq. (7), each AES can perform energy interchange in the appropriate direction under such situations.

V. Evaluation

A. Setting

We investigate the performance of the proposed method through simulation experiment considering energy shortage and emergency situations. We use a static simulation model for easily understanding fundamental properties of the proposed method. We assume (a) generated energy $g_i(t)$ of AES i is always equal to consumed energy $c_i(t)$ of AES i, and (b) target remaining battery amount θ_i of AES i does not vary with time. As the future work, we will confirm the effectiveness of the proposed method by using a dynamic simulation model.

During simulation, each AES transmits own energy according to the MCMC-based ADM without the proposed method (hereafter referred to as *previous mechanism*) or with the proposed method (hereafter referred to as *proposed mechanism*).

We use the N_k-th nearest neighbor network as mesh network G. The N_k-th nearest neighbor network is generated

[1] Strictly speaking, the dynamics of $\hat{q}_i(t)$ should be described by a nonlinear equation, but we omit rigorous explanation due to space limitation.

TABLE I
Parameter configuration

mesh network	G	N_k-nearest neighbor network
number of nearest AESs	N_k	4
number of AESs	N	100
battery capacity of a AES	b_i	100
target remaining battery amount of a AES	θ_i	50
diffusion coefficient	k_{diff}	0.0001
control parameter of MCMC	k_{MC}	1000
convection diffusion coefficient	k_{conv}	0.001
interval of recalculating $J_{i\to j}$	ΔT_J	1

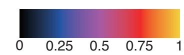


Fig. 4: Color map to visualize results shown in Fig. 5

by the following procedures. Initially, each AES is randomly placed on the two dimensional plane. Then, each AES selects N_k nearest AESs as its adjacent AESs. Note that an AES has adjacent AESs greater than or equal to N_k. N_k-th nearest neighbor network is a network with considering geographical dispersion of AESs and wiring cost between AESs.

We use the parameter configuration shown in Tab. I as a default parameter configuration.

B. Result for Energy Shortage Situation

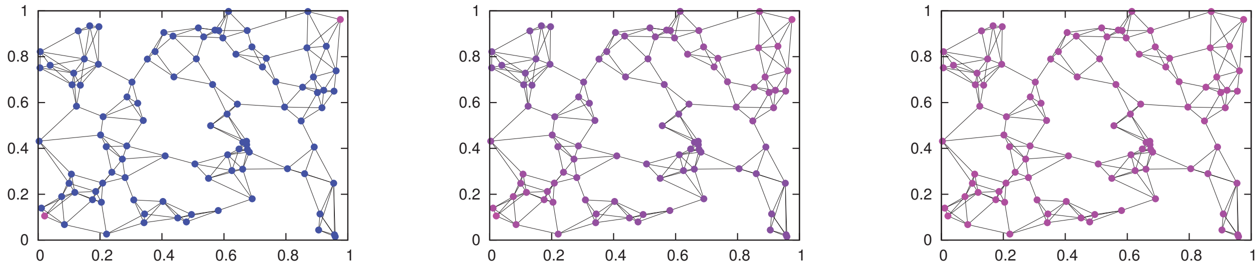
We assume that the most upper right and the most lower left AESs in a N_k-th nearest neighbor network are connected to the external power grid. $\hat{q}_x(t)$ of AESs x connected to the external power grid are always 0. For convenience, we show the results when setting the initial sufficiency levels $\hat{q}_i(0)$ of other AESs to -0.2. We also obtained the same conclusion for the results with other setting (e.g., randomly setting of $\hat{q}_i(0)$).

First, we visually confirm the effectiveness of the proposed method. Figure 5 shows AES sufficiency levels at $t = 0$, 300, and 600 on mesh network G when using the MCMC-based ADM with the proposed method. In this figure, we use the color map shown in Fig. 4 to visualize sufficiency levels of AESs. According to this figure, the MCMC-based ADM with the proposed method realizes the energy supply from the external power grid.

Then, we investigate the speed of the proposed method. Figure 6 shows time series for statistics (i.e., average and minimum) of AES sufficiency levels when using the MCMC-based ADM without and with the proposed method. According to Fig. 6, the proposed method can fast supply energy from the external power grid. Figure 7 (a) shows the average of times taken to supply energy until $\hat{q}_i(t) = \pm 5\%$ for all AESs. According to this result, the improvement of the proposed method increases as the initial sufficiency level decreases. Hence, the proposed method has high effectiveness for severe energy shortage situation.

C. Result for Emergency Situation

Disaster occurs suddenly, and stops equalizing sufficiency levels of AESs halfway. Hence, when disaster occurs, each



(a) $t = 0$ (b) $t = 300$ (c) $t = 600$

Fig. 5: AES sufficiency levels $\hat{q}_i(t)$ on mesh network G when using the MCMC-based ADM with the proposed method

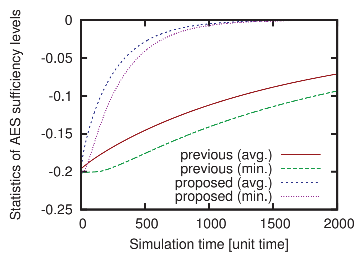
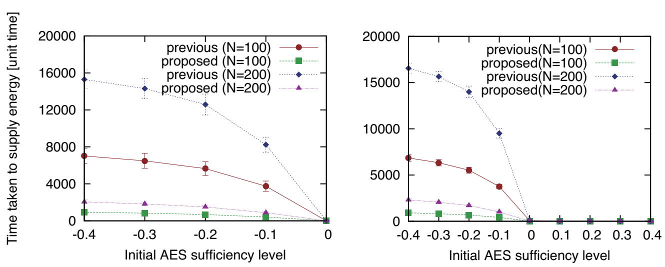


Fig. 6: Time series for statistics of AES sufficiency levels



(a) energy shortage situation (b) emergency situation

Fig. 7: Time taken to supply energy

AES has a different sufficiency level reflecting its energy generation and consumption. In microgrids, there are several factors affecting the variability among sufficiency levels of AESs. In this paper, we represent the variability only by the variance of initial sufficiency levels $\hat{q}_i(0)$'s. Namely, at the start of simulation, initial sufficiency level $g_i(0)$ of AES i is given by normal distribution $\mathrm{N}(\mu_q^{\mathrm{st}}, \sigma_q^{\mathrm{st}})$ where $\sigma_q^{\mathrm{st}} = 0.3\,\mu_q^{\mathrm{st}}$.

We give high target remaining battery amount (i.e., $\theta_h = 90$) to a randomly selected AES h as the high priority AES that means a safe shelter under emergency situation. The speed of the directional energy supply may be affected by the location of AES h. We investigate the effect of the location on the effectiveness of the proposed method. Figures 7 (b) shows the average of times taken to supply energy for different initial sufficiency levels, μ_q^{st}, respectively. According to Fig. 7 (b), the proposed mechanism can very fast gather the distributed energy to the high priority AES. Therefore, we can conclude that the proposed method has the effectiveness under emergency situations.

VI. Conclusion and Future Work

In this paper, toward resilient of microgrids, we proposed a method to realize the directional energy interchange, which enables the MCMC-based ADM to fast transfer energy in an appropriate direction. We first designed the directional energy interchange based on the convection diffusion equation, and investigated the effectiveness of the proposed method through simulation experiment considering energy shortage and emergency situations. We clarified that the proposed method can perform fast directional energy interchange under these situations, so conclude that the MCMC-based ADM would support diverse situations.

To realize the proposed method in a practical electricity system, we should further investigate the performance of the proposed method. The dividing of a microgrid into AESs improves the reliability and scalability of microgrids, but generates energy loss by energy interchange among AESs. In this paper, we ignored such energy loss in the evaluation. We should clarify the effect of the energy loss on the effectiveness of the proposed method. Moreover, we should investigate the performance with considering realistic characteristics (e.g., fluctuations in energy generation/consumption and transmission capacity).

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