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Design and Evaluation of Power Trading Loss Management by Using Battery for Interconnected Microgrids

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List of publications

A. Journal Papers

1. T. Suzuki, Y. Shomura, and M. Murata, “Effective electric power utilization between microgrids by optimized battery location and transmission management,” *IPSJ Journal,* vol. 62, no. 1, pp. 12-25, Jan. 2021. (in Japanese)

2. T. Suzuki and M. Murata, “Effective utilization for color-managed electric power by optimized battery location and transmission management,” *IPSJ Journal,* vol. 63, no. 1, pp. 1-17, to appear Jan. 2022. (in Japanese)

B. Refereed Conference Paper

1. T. Suzuki and M. Murata, “Power loss reduction for power trading between interconnected microgrids using batteries,” *Proceedings of 2021 9th International Conference on Smart Grid and Clean Energy Technologies* (*ICSGCE*), pp. 1-8, Oct. 2021.

Preface

Lately, the increase of renewable energy utilization such as solar power has been promoted to reduce greenhouse gases. However, such electric power is unstable due to the weather condition, etc. Therefore, the stabilization of the electric power supply by using a battery, etc. has been promoted. For example, in a local area, a microgrid that controls total power generation, energy storage, and power consumption has been attracting attention. In the microgrid, generated power is consumed inside area as much as possible.

For a local area that uses a single microgrid, it is not always possible to obtain the required power due to insufficient power generation or failure of power generation equipment. In such a case, the required power can be obtained from another microgrid by communicating between multiple microgrids. In consideration of this situation, interconnected microgrids, which trade electric power between multiple microgrids, are considered promising.

Although the interconnected microgrids are useful, there are several issues that are related to a power trade balance, security, resilience, and a cost of power generation, etc. In this thesis, we focus on the challenges of effective power usability. Specifically, reducing power loss is mainly discussed. The power loss is caused by transmission among microgrids and charge-discharge to a battery. Therefore, procedures to reduce the power loss are discussed when the power is traded between power supply and demand microgrids.

On the other hand, electric power generated by non-renewable energy is also used since the power by renewable energy is unstable. The rate of the power by renewable energy is likely to be set at various values depending on the situation of power generation and consumption. Therefore, procedures to reduce the power loss are needed when the rate of renewable energy is specified by a demand side, etc.

In this thesis, in a situation where power generation and demand patterns are different, we propose a high-efficiency electric power-use method that enables power trading by using the battery function as a first step. Specifically, we propose a scheme that can reduce power transmission loss between microgrids by minimizing loads that are defined by the multiplication of “volume of power transmission” and “transmission distance” as an objective function of a linear programming model. The proposed method is evaluated for a topology where 49 microgrids are connected to lattice-like (7x7). It is verified that the proposed method is improved by up to 20% compared to the k-means based method at our evaluation conditions. In the k-means based method, each battery location is decided to be a center of each cluster that is calculated according to the designated number of microgrids to be deployed the battery function.

At the second step, a scheme to reduce the power loss by transmission and charge-discharge is proposed by assuming the different quality of batteries. Specifically, the power loss of power trading among microgrids is reduced by minimizing an objective function of a mathematical programming problem that is defined by a total power loss due to the transmission, charging, and discharging of power. In our evaluation, the optimized number of batteries, location of each battery, and transmission paths and power are determined. As a result, compared with the route-based method considering transmission distance only, the proposed method results in an average of 26.7% improvements in terms of power loss reduction by transmission and charge-discharge.

At the third step, a scheme to reduce the power loss by transmission and charge-discharge is proposed for a long term. Specifically, the power loss is reduced by iterating minimization of an objective function of mathematical programming problem for one day that is defined by a total power loss considering battery efficiency degradation. The proposed method is evaluated for 1000 days. When the charge-discharge efficiency deterioration by the charging and discharging is advanced, it is confirmed that “power loss amount generated on each day” and “accumulation of power loss amount” are reversed during the evaluation period among the combinations of battery capacity and the number of deployments of it. As a result, it is clarified that the use setting of the battery function based on the long-term evaluation is necessary.

In addition, a scheme to reduce the power loss by transmission and charge-discharge is proposed under the condition that the rate of renewable energy is specified by a demand side. In the proposed method, the target rate of power consumption by renewable energy can be also managed by the color management of power which distinguishes power generation by renewable and non-renewable energy. The power loss of power trading among microgrids is reduced by minimizing an objective function of a mathematical programming problem that is defined by a total power loss by distinguishing power generation by renewable and non-renewable energy. The proposed scheme is evaluated by a simulation. As a result, we confirm that it is possible to optimally deploy the battery function to minimize the amount of power loss, to determine optimal power transmission paths, and to consume power as specified degree of renewable energy. Compared with the route-based method, the proposed method is improved by 20% or more under our evaluation conditions.

In this thesis, the schemes to reduce the power loss by transmission and charge-discharge are discussed in detail for the interconnected microgrids under the conditions where power generation and demand patterns are different. Through the evaluations, it is verified that our proposed methods are effective to reduce the power loss. We hope that our discussion can contribute even a little to the reduction of power loss for the interconnected microgrids.

Acknowledgments

This thesis could not have been accomplished without the assistance of many people, and I would like to acknowledge all of them.

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Contents

Chapter 1

Introduction

1.1. Background

The Sustainable Development Goals (SDGs) adopted at the United Nations Summit in September 2015 [1], [2] have established 17 development goals for various issues around the world as shown in Fig. 1.1. For example, there are many targets, such as "Ensure access to affordable, reliable, sustainable and modern energy". Even now, many people still do not have access to electricity. Therefore, with regard to the affordable and clean energy goal, providing electricity for anyone in the world is actively promoted.

THE 17 GOALS			
1	NO POVERTY	2	ZERO HUNGER
3	GOOD HEALTH AND WELL-BEING	4	QUALITY EDUCATION
5	GENDER EQUALITY	6	CLEAN WATER AND SANITATION
7	AFFORDABLE AND CLEAN ENERGY	8	DECENT WORK AND ECONOMIC GROWTH
9	INDUSTRY, INNOVATION AND INFRASTRUCTURE	10	REDUCED INEQUALITIES
11	SASTAINABLE CITIES AND COMMUNITIES	12	RESPONSIBLE CONSUMPTION AND PRODUCTION
13	CLIMATE ACTION	14	LIFE BELOW WATER
15	LIFE ON LAND	16	PEACE, JUSTICE AND STRONG INSTITUTIONS
17	PARTNERSHIPS FOR THE GOALS		

Figure 1.1 Sustainable development goals.

In addition, the Government of Japan is trying to build a new human-centric society with highly integrated cyber space and physical space by envisaging “Society 5.0” [3]. For example, the physical space is monitored by sensors, and the analysis is performed in the cyber space, and the control which enables a comfortable life for people is executed. As one of the values produced in such a control, stable and continuous energy supply by a variety of energies is being investigated.

With regard to the climate change, net zero emission to reduce greenhouse gases is being promoted as a global direction. Many countries have expressed their aim to achieve net zero emission of greenhouse gases [4]. To reduce the emission, utilization of renewable energy (Hereinafter referred to as RE), such as solar and wind power has been attracting attention. As an investment in power sector in the world, the investment of the renewable power relation is large [5]. With regard to environmental value, certificates of power generation by RE, such as ”Guarantee of Origin (GO)”, “Renewable Energy Certificate (REC)”, and “International Renewable Energy Certificate (I-REC)” are traded in the world [6]. By using these certificates, it is possible to indicate the amount of the utilization of electric power generated by RE. As an activity for increasing utilization of RE, there is RE100 [7]. RE100 is the global corporate renewable energy initiative and established in 2014. In January 2022, more than 340 members have been affiliated. They are aiming for 100% renewable electricity related to their business.

However, there are various issues in power generation and power supply related to RE as shown in Table I. As a first issue, there is a facility cost related to performing power generation by RE. For example, there are solar and wind power equipment costs. In addition, there is a cost of installation of RE power generation equipment. If the equipment and installation costs are high, it is conceivable that the introduction of equipment does not advance easily.

Second, there is an issue of power generation and consumption stability. For example, the amount of generated power by RE is not stable and varies depending on the weather. In addition, there is a problem that the power network becomes unstable when the difference between the supply and demand of power is large, and a power outage occurs if it is serious. As one of measures for power balance, the supply and demand adjustment market [8] was established in Japan in 2021. Thus, the power to correspond to the power generation instability by RE, it has become possible to procure from a wide area through the market.

Third, there is an issue related to the power transmission stability. In a conventional power network, electric power is basically generated in large power plants and the power is generally transmitted in one direction. However, when the power generation by RE increases, the power is generated in distributed regions. As a result, the power is transmitted in both directions. The conventional power network is generally constructed for one way power transmission. Therefore, the power network is considered to be necessary to correspond to the two-way power transmission. In addition, there is an issue on resilience of power transmission network. When power is generated in a distributed region, the control of transmission will be complicated. Therefore, a prompt recovery from a network failure is considered to be more difficult. There is also a power loss issue. When the distance between power generation and consumption is long, the power loss increases.

Table I Issues in Increasing Use of RE

#	Category	Issue
1	Facility cost	1) Solar and wind power equipment costs 2) Cost of installation of RE power generation facilities
2	Power generation and consumption stability	3) Unstable power generation by RE 4) Balance between power supply and demand
3	Power transmission stability	5) Two-way power transmission 6) Resilience of power transmission network 7) Power loss due to power transmission and distribution

Under such circumstances, the use of RE is being promoted carefully as part of a response for sustained society. The amount of electric power generated by solar, etc. has fluctuated due to weather conditions and time. For example, the amount of power generation increases and decreases when the weather is good and bad, respectively. Therefore, measures to stabilize the electric power supply are needed, for example, using batteries.

A microgrid [9], etc. has been studied as a system to effectively utilize the generated power by monitoring using sensors. The microgrid that controls total power generation, energy storage, and power consumption has been attracting attention in a local area. As the generated power in a microgrid is consumed as much as possible, it is possible to reduce the loss of power by transmission. In Japan, a microgrid is studied for improving resilience in the case of natural disaster [10]. This type of microgrid is connected to a major power grid during the peacetime. When the major power grid is affected, the microgrid is then separated and required to operate independently.

However, for a local area that uses a single microgrid, it is not always possible to obtain the required power due to insufficient power generation or failure of power generation equipment. In such a case, the required power can be obtained from another microgrid by communicating between multiple microgrids. In consideration of this situation, interconnected microgrids [11]–[14], which trade electric power between multiple microgrids, are considered promising.

There are several issues to develop the interconnected microgrids. For example, the system needs to be controlled to meet the simultaneous same amount of power between power supply and demand. If there is a large difference between power supply and demand, electric power supply will become unstable. In addition, when the system is centralized, the system will not run as a whole if the management function is damaged. Therefore, when a plurality of microgrids cooperate, it is considered that it is necessary to adopt the system management of the autonomous distributed type. In this area, management schemes of the distributed type have been studied [15]–[18]. In addition, the control of power supply and demand needs to be executed securely. To address this issue, secure management schemes have been studied. For example, methods using Software-Defined Networking (SDN), blockchain, and reputation, etc. have been studied [19]–[21]. Another issue is that the system needs to be rapidly recovered by detecting a failure. Therefore, resilient management schemes have been studied [22]–[25]. The various studies above show the benefits and robust operation of the power trading between microgrids.

Besides, as a management of power trading, there is a power loss issue. For example, electricity transmission and distribution losses are estimated about 4 % or more [26], [27]. When electric power that is generated by RE such as sunlight is used at different time by using charging and discharging, power loss by charge-discharge is further increased. Concerning about energy storage deployment, much research has been conducted to reduce system costs and to stabilize power networks [28]–[32]. Specifically, to constitute a plurality of microgrids in a small power network such as a distribution network, it is discussed battery position and capacity. The power network of interest, there are many studies that target the distribution network having a radial topology.

However, microgrid networks configured in a narrow area are likely to be affected as a whole by the weather. When performing stable power trading between microgrids, microgrid networks for a wide area where they are connected to each other is considered promising. Therefore, targeting wide area connected microgrids connecting the distribution networks is also needed. In order to effectively use the electric power produced by RE, power loss by trading between microgrids should be reduced as much as possible. We focus on the power loss reduction for the power trading between wide area connected microgrids. Specifically, a proper battery deployment and power transmission between microgrids are studied. The battery deployment in the case of considering the deterioration of the charge and discharge efficiency for long-term operations is also discussed. Besides, we will discuss reducing the power loss in consideration of rate of the electric power produced by RE in the case of distinguishing power generated by RE and non-RE.

1.2. Issue of Effective Power Trading and Objective

In this thesis, we focus on the interconnected microgrids and discuss effective electric power trading between multiple microgrids. In order to make effective power trading between microgrids, there are several issues related to power loss.

The first issue is power loss when the electric power is transmitted between microgrids. The power loss increases based on transmission distance, at least. As the power transmission distance between microgrids becomes longer, the power loss is increased. Therefore, the power transmission distance should be shortened as much as possible.

The second one is the power loss by a battery when electric power is charged and discharged. The power loss is increased when the power is charged and discharged in an inefficient battery. Therefore, when charging and discharging the power, it is necessary to use the efficient battery as much as possible.

The third one is consideration of battery deterioration and a long-term evaluation. When the battery is used for a long time, the deterioration of the charge-discharge efficiency is manifested. Therefore, it is necessary to consider the degradation of the battery performance when evaluating power loss due to transmission and charge-discharge over a long period of time.

The fourth one is to make it possible to control the utilization rate of the electric power produced by RE while reducing the power loss related to the transmission and charge-discharge. Electric power is generated by a variety of power sources. There is power generation by RE, and power generation which is not so. The cost of power generation varies from generation sources and regional environment to various other factors. Moreover, the electric power generation by RE such as sunlight is unstable. The rate of the electric power generated by RE is assumed to be various. Therefore, the system needs to be controllable the rate of the trade power generated by RE to meet the specified RE rate.

Our purpose is to provide a control policy to develop an effective power trade in view of the above issues. Specifically, we will provide a control policy to reduce the power loss due to transmission and charge-discharge. In addition, the management policy to meet specified RE utilization rate will be also provided.

1.3. Outline of Thesis

In this thesis, there are six chapters.

In Chapter 1, we describe research background and purpose. Specifically, it refers to the need for increasing power usage by RE and a promising system to do so. We will also discuss the issues we are focusing on in order to achieve this system.

In Chapter 2, we focus on the power loss for the power transmission and propose a power loss reduction method for that. Specifically, we propose interconnected microgrids that can reduce power transmission loss between microgrids by minimizing loads that are defined by the multiplication of "volume of power transmission" and "transmission distance" as an objective function of a linear programming model. The optimized locations and sizes of batteries are discussed by using the proposed model. The content of this chapter is based on our paper [33].

In Chapter 3, we focus on the power loss for both power transmission and charge-discharge and propose a power loss reduction method for that. Specifically, the power loss of power trading among microgrids is reduced by minimizing an objective function of a mathematical programming problem that is defined by a total power loss due to the transmission, charging, and discharging of power. The proposed method is evaluated by a simulation. The content of this chapter is based on our paper [34].

In Chapter 4, we focus on the power loss due to both the power transmission and charge-discharge for a long term and propose a power loss reduction method for that. In order to reduce the power loss for a long term, an objective function that is a nonlinear is defined. In addition, to evaluate the power loss by using the objective function, we propose a scheme for calculating approximate values for the objective function. The content of this chapter is based on our submitted paper [54].

In Chapter 5, we focus on a control of utilization rate of the electric power produced by RE and propose a power loss reduction method for that. Specifically, we propose a high-efficiency power utilization method that minimizes power loss by transmission, charging, and discharging between microgrids by solving a mathematical programming problem. In the proposed method, the target rate of power consumption by RE can be also managed by a color management of power which distinguishes power generation by RE and non-RE. Optimal battery locations, power transmission, and charge-discharge are discussed through a simulation. The content of this chapter is based on our paper [35].

In Chapter 6, we conclude by summarizing our proposals and evaluation results. We also describe future works.

Chapter 2

Effective Electric Power Utilization between Microgrids by Optimized Battery Location and Transmission Management

2.1. Introduction

In this chapter, we focus on the interconnected microgrids and propose a high-efficiency power utilization method that reduces the transmission loss for power trading. In the proposed method, power transmission loss is reduced by minimizing loads that are defined by the multiplication of "volume of power transmission" and "transmission distance" as an objective function of a linear programming model. The optimal position and capacity of each battery function to be deployed are discussed.

In this thesis, a power network capable of transmission control is assumed. We discuss the position control and transmission path control of the battery function to reduce power loss associated with the power transmission among power-supply, transmission, and power-demand business operators. Power-supply operators manage microgrids capable of powering other microgrids as power balances in each microgrid. Power-demand operators manage microgrids that require power from other microgrids. A business operator who performs a power transmission between the power-supply operator and power-demand operators is called a power transmission operator.

In the above-mentioned roles, it is assumed that multiple battery functions are deployed in the power network connecting between power-supply and power-demand microgrids.

In the case where the power generation and power consumption are different, the management to charge excessively generated power temporarily and discharge when the generated power is lack is discussed. In particular, in order to reduce the power loss associated with transmission and to realize efficient power utilization, we solve the optimal position and transmission path of the battery function by minimizing the multiplication of "volume of power transmission" and "transmission distance".

This chapter is organized as follows. In Sec. 2.2, issues for interconnected microgrids and the policy to solve them are discussed. In Sec. 2.3, the new method to reduce power transmission loss by allocating battery functions properly is proposed. Section 2.4 presents the evaluation results of the proposed method. In Sec. 2.5, we discuss the results. In Sec. 2.6, related works are described. We conclude with a summary in Sec. 2.7.

2.2. Issue of Effective Use of Electric Power and Measure Policy

2.2.1. Overview of Microgrid

Figure 2.1 shows an example of a microgrid, which is composed of a power switch, multiple photovoltaic equipment, power consumption equipment, and batteries. Microgrids are interconnected with others via the power switch. If the amount of power generated in a microgrid is greater than that consumed inside, power can be supplied to other microgrids that lack power.

Figure 2.2 shows the changes in the amount of photovoltaic power generation as an example. The horizontal axis shows the time over a three-day period, and the vertical axis shows the amount of power generated in kWh. In this example, the increases in power generation are repeated due to the sunlight from good weather conditions. The amount of power generated per day is 100 kWh.

Figure 2.3 shows an example of the changes in electric power consumption in the microgrid. The horizontal axis shows the time over a three-day period, and the vertical axis shows the amount of power consumed in kWh. This example shows a consumption pattern in which power consumption increases slightly before going to work and substantially after coming back to home. The amount of power consumed per day is 100 kWh. The power consumption in the time zone which does not generate electricity is supported by the power supply from batteries.

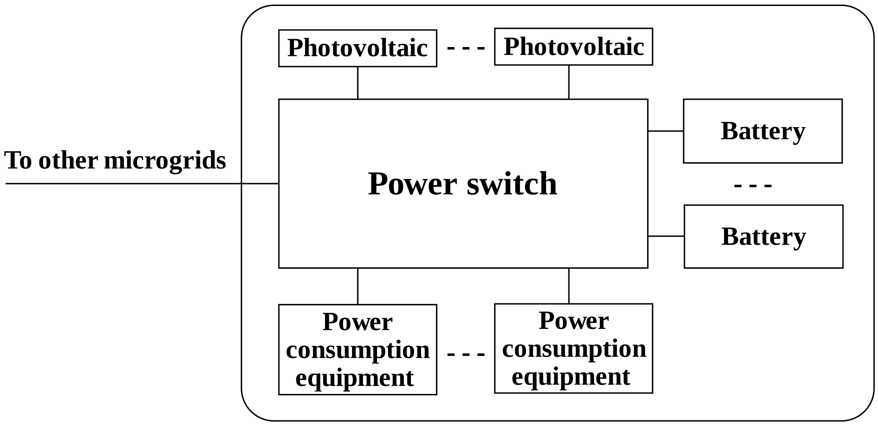

Figure 2.1 Example of a microgrid.

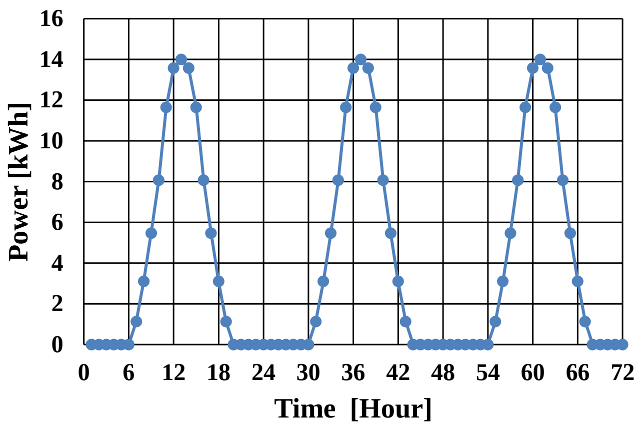

Figure 2.2 Predicted power supply cycle in a microgrid.

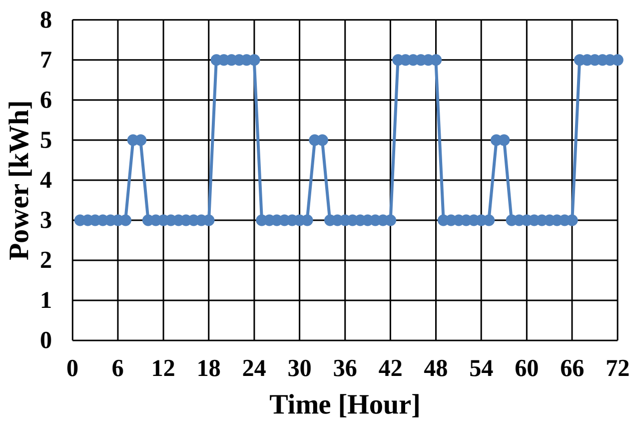

Figure 2.3 Predicted power demand cycle in a microgrid.

2.2.2. Issue for Effective Use of Electric Power

The green line (Battery) in Fig. 2.4 shows the charge-discharge amount required when the power generated is temporarily charged and discharged at required times. The blue and red lines (Supply, Demand) represent the amount of power generation and consumption, respectively.

As shown in Fig. 2.2, it is not possible to generate electric power when there is insufficient sunlight, and it cannot correspond to the power demand shown in Fig. 2.3. Therefore, it is necessary to charge to an initial value; this amount is 21.77 kWh as shown in Fig. 2.4.

When there is no charge-discharge function, excessively generated power that is not consumed for each time is discarded. To effectively use the electric power generated during the day, it is necessary to charge the power during that time and discharge it to cope with a large amount of power demand from the evening onward. In such a situation, the capacity to temporarily charge the unconsumed power is required, which is shown as 62.64 kWh in Fig. 2.4.

In the case where the power supply and demand amounts do not match at each point in time, it is necessary to use batteries to shift the power needed.

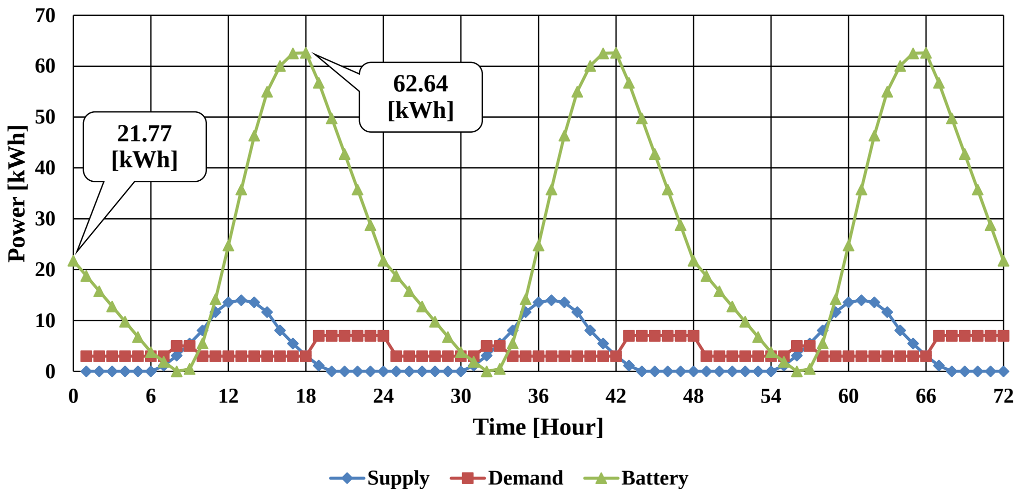

Figure 2.4 Power relation among supply, demand, and batteries.

2.2.3. Overview of Interconnected Microgrids and Challenge

An example of interconnected microgrids is shown in Fig. 2.5. Each square with a number corresponds to a microgrid shown in Fig. 2.1. The interconnected microgrids are composed of 49 microgrids and they are connected in lattice form (7x7). In Fig. 2.5, microgrids (2, 5, 9, 13, 21, 24, 32, 35, 38, 43) that have “S” character represent those in which the power is excessive in the power balance and supplying power to other microgrids is possible. In addition, the amount shown in Fig. 2.2 is used as an example to simulate the power generation pattern caused by sunlight. Microgrids (3, 7, 11, 17, 23, 27, 33, 37, 44, 46) that have “D” character represent those in which the power is insufficient in the power balance, and demand power from other microgrids. In addition, the amount shown in Fig. 2.3 is used as an example to simulate the power demand pattern.

In actual microgrids, the difference between the amount of power generated and that consumed is the amount that can be supplied or demanded. Here, as an example of simulating the different states in different microgrids, the power generation and consumption shown in Figs. 2.2 and 2.3, respectively, are used. In Fig. 2.5, other microgrids with no character represent those in which there is no shortage of power balance, and the power relay is possible.

For each microgrid constituting the interconnected microgrids, if the power supply and demand amounts in each time do not match, a battery function is required to charge the surplus power generated temporarily, corresponding to power demands at different time. However, if the battery function is not deployed in the appropriate position, power loss by transmission can increase. This is because the power is temporarily charged in the battery that exists along the path, which is not the shortest, between the power supply and demand microgrids. Therefore, it is necessary to reduce the power loss by using an appropriate battery function in the power trading between interconnected microgrids.

The purpose in this chapter is to propose a method to reduce transmission power loss for the trading of power between interconnected microgrids by the optimal deployment of the battery function, charge-discharge control, and transmission path. Specifically, it is intended to reduce power transmission loss for the power transmission operator by allocating batteries with proper capacity appropriately in the microgrids in Fig. 2.5 that do not supply and demand power.

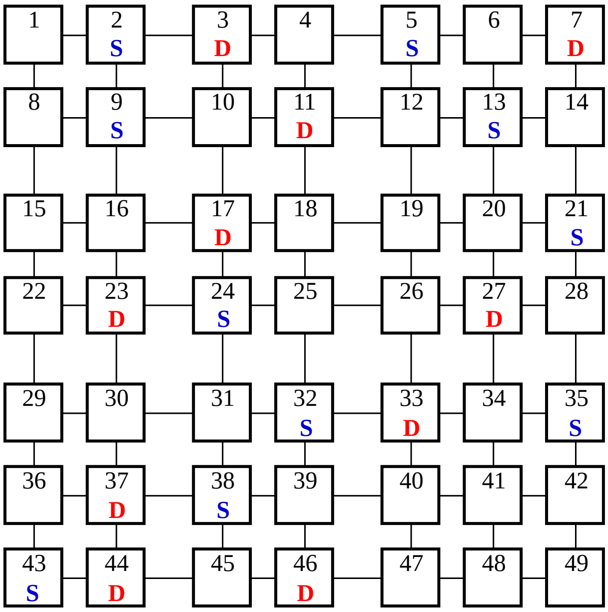

Figure 2.5 Example of interconnected microgrids.

2.2.4. Optimal Transmission Path and Battery Function Deployment Policy

In this thesis, transmission power loss is assumed to be proportional to the amount of power transmitted and the transmission distance by considering information of reference [36]. Therefore, as an objective function for evaluations, we specify a transmission load that is defined by the multiplication of the "volume of power transmission (kWh)" and "transmission distance (km)" between microgrids.

As a proposed method, optimal transmission paths and transmitted power for each path are decided by minimizing the power transmission load in the case where all generated power by power supply microgrids is stored in the batteries or consumed by power demand microgrids. In addition, based on the specified number of deployments and the capacity limit of the battery function, we search to minimize the transmission load for the total amount of power transmitted during the evaluation period and determine the optimal locations of battery functions.

2.3. Proposal of a Method to Reduce Power Transmission Loss

This section presents a method to reduce the power transmission loss by using a linear programming model. We define symbols to describe defined conditions and decision valuables to minimize the transmission loss. In order to find a minimum power transmission loss, an objective function is defined and solved by using the symbols and decision valuables.

2.3.1. List of Symbols for Evaluation Model

As shown in Fig. 2.5, we focus on the interconnected microgrids. The purpose is to minimize the power loss due to transmission by appropriately allocating batteries in the microgrids for relay. To solve this problem, we set three decision variables. The first one is a variable whether to deploy a battery function in a microgrid for relaying. The second one is a variable that controls the amount of electric power in a battery function. The third one is a variable that controls the amount of power transmitted between the microgrids. An objective function to solve the problem is formulated by using these decision variables.

In the formulation, it is necessary to identify the microgrid for the supply and demand of electric power. It is necessary to identify the time and microgrid to deploy battery functions to charge excessively generated power and to discharge power when it is lack. Since the transmission capacity is finite and the power loss by transmission depends on the amount of power to be transmitted and the transmission distance, it is necessary to specify the power transmission capacity and transmission distance between microgrids. In the process to transmit power generated by a microgrid and to evaluate the power transmission loss, it is necessary to define the amount of power for generation and consumption in the microgrid. The battery functions are used to temporarily charge surplus electric power and to discharge when it is necessary. Since the capacity of the battery function is finite, the capacity as the upper limit must be defined. In addition, it is necessary to specify the total number of microgrids to deploy the battery function. Furthermore, it is necessary to specify the total amount of charge as the initial value for supplying the power consumed before power generation, and the minimum required total charge capacity to charge the excessively generated power. It becomes possible to deal with more specific problems by making the above settings. The solution to solve the issue is described in detail later in the following sections.

Table II shows a list of symbols specified for calculating the solution. i indicates the microgrid number when there are N microgrids. When the time range to be evaluated is divided into T slots, t indicates the slot number. $C(i,j)$ shows the distance between the adjacent microgrid i and j in the configuration where multiple microgrids are connected to each other. $L(i,j)$ shows the upper limit of the amount of power that can be transmitted between adjacent microgrids i and j. $P(i,t)$ shows the amount of power supplied by microgrid i at time t. $D(i,t)$ shows the amount of power consumed by microgrid i at time t. $W(i)$ shows the capacity of the charge-discharge function deployed in microgrid i. M represents the total number of microgrids with battery functions. V represents the total amount of charge as the initial value for supplying the power consumed before power generation for all microgrids. U represents the minimum required total charge capacity to charge the surplus power generated during the evaluation period.

Table II List of Symbols

Symbol	Definition
i	Number of microgrid ($i = 1,\cdots,N$)
t	Number of time slot ($t = 0,\cdots,T$)
$C(i,j)$	Distance between adjacent microgrid i and j (km)
$L(i,j)$	Limit of transmission amount between adjacent microgrid i and j (kWh)
$P(i,t)$	Amount of power supplied from microgrid i in time slot t (kWh)
$D(i,t)$	Amount of power consumed by microgrid i in time slot t (kWh)
$W(i)$	Battery capacity in microgrid i (kWh)
M	Number of microgrids with distributed battery functions, $0<M<N$
V	Initial value of the total amount of power in the distributed batteries (kWh) (Refer to (2-6))
U	Necessary capacity of the distributed batteries (kWh) (Refer to (2-7))

2.3.2. List of Decision Variables for Evaluation Model

Our purpose is to determine the optimal placement of the battery function to reduce the power loss by transmission. Therefore, it is necessary to have a variable whether to allocate the battery function for each microgrid. Since the electric power loss by transmission is dependent on the amount of power transmitted, a variable is needed to optimize the amount of power transmitted between microgrids for each time. A variable is needed to optimize charge or discharge electric power for each time. By setting variables to determine the optimal battery position, transmission amount, and charged electric power, it is possible to calculate optimal solution and to evaluate the power loss by transmission.

The decision variables listed in Table III are determined by the optimization problem described as follows. $Q(i,j,t)$ determines the amount of power transmitted from adjacent microgrid i to j at time t. $B(i,t)$ determines the amount of power remaining in the battery function of microgrid i at time t. The value of $\delta(i)$ is determined to be 1 or 0 if the battery function is deployed or not, respectively, in microgrid i. All these valuables are decided by the following optimization problem. i of $B(i,t)$ and $\delta(i)$ indicates the number of the microgrid for the relay that does not supply and demand power.

Table III List of Decision Variables

Variable	Definition
$Q(i,j,t)$	Amount of power transmitted from adjacent microgrid i to j in time slot t (kWh)
$B(i,t)$	Amount of power remaining in the battery of microgrid i in time slot t (kWh)
$\delta(i)$	Deployment/No deployment of battery in microgrid i (1/0)

2.3.3. Objective Function and Constraints

The proposed system aims to minimize transmission load defined by the multiplication of the volume of power transmission and transmission distance, and the minimization can be done by evaluating an objective function as the linear programming problem. Power loss due to transmission depends on transmission amount and transmission distance. Therefore, it is necessary to evaluate the transmission load due to power trading between all microgrids.

The objective function is shown as follows. $C(i,j)$ shows the distance between the adjacent microgrid i and j. $Q(i,j,t)$ shows the amount of power transmitted from microgrid i to j at time t.

$$Minimize \sum_{t=1}^{T} \sum_{i=1, i \neq j}^{N} C(i,j) Q(i,j,t) \qquad (2-1)$$

The constraints are described as follows.

1) Power balance condition: At all times, the amount of power flowing into and

generated in a microgrid must be equal to the sum of the amount of power flowing out, the amount of power consumed, and the amount of power discharged. In time *t*, the amount of power supply and demand in microgrid *i* is equal to the sum of the power quantities *Q*(*k,i,t*) and (-1)**Q*(*i,k,t*), and (*B*(*i,t-1*)-*B*(*i,t*)). *Q*(*k,i,t*) represents the amount of power flowing from adjacent microgrid *k*. *Q*(*i,k,t*) represents the amount of power flowing into microgrid *k*. *B*(*i,t*-1)-*B*(*i,t*) indicates the amount of charge change in the battery. The supply amount from the microgrid supplying power is equal to (-1)**P*(*i,t*). The amount of power consumed by the microgrid that requires power is equal to *D*(*i,t*). In addition, the power balance is zero in microgrids for the relay that does not supply nor demand power.

$$\sum_{k} Q(k,i,t) - \sum_{k} Q(i,k,t) + B(i,t-1) - B(i,t)$$
$$= D(i,t) - P(i,t) \qquad (2-2)$$

2) Transmission quantity condition: In time *t*, the amount of power *Q*(*i,j,t*) that is transmitted from adjacent microgrid *i* to *j* is less than or equal to the maximum value *L*(*i,j*) that can be transmitted.

$$0 \leqq Q(i,j,t) \leqq L(i,j) \qquad (2-3)$$

3) Battery function number condition: It is necessary to deploy optimal battery functions in the range of the number of deployments set as a plan for them. The number of microgrids for the relay to deploy the battery function is less than or equal to the specified number *M*.

$$\sum_{i=1}^{N} \delta(i) \leqq M \qquad (2-4)$$

4) Charge and discharge quantity condition: Only in microgrids which have been equipped with the battery function, it is possible to charge power within the battery capacity. In time *t*, the amount of power *B*(*i,t*) charged to microgrid *i* with the battery

function is less than or equal to the specified capacitance $W(i)\ \delta(i)$.

$$0 \leqq B(i,t) \leqq W(i)\delta(i) \qquad (2-5)$$

5) Initial value of charge amount condition: In order to supply the power required in the time zone that has not started the power generation, it is necessary to keep the minimum necessary power in advance. The sum of the charge amount $B(i,0)$ is equal to the specified initial power amount value V to supply the power required before power generation.

$$\sum_{i=1}^{N} B(i,0) \ = V \qquad (2-6)$$

6) Capacity condition for battery function: In order to accumulate the surplus power generated at a certain time without discarding it, it is necessary to deploy a total battery capacity of more than the minimum necessary. The total capacity of the battery functions to be deployed is at least the minimum charge-discharge capacity U required to temporarily charge and hold surplus power generated during the period of evaluation.

$$\sum_{i=1}^{N} W(i)\delta(i) \ \geqq U \qquad (2-7)$$

2.3.4. Proposal of Optimal Deployment Method for Battery Function

In this thesis, electric power is supplied from a microgrid where it is surplus, and the power is consumed in a microgrid where it is insufficient. When power generation and consumption do not match at each time, the surplus power is temporarily charged in the battery function and discharged power is used in the microgrid where the power is insufficient. We focus on this case and minimize the power loss due to power transmission. For this purpose, it is necessary to deploy the battery function in the optimal location. If the battery is not appropriately deployed, the transmission distance increases. As a result, the power loss due to transmission increases.

A battery deployment and power transmission method that minimizes transmission load is proposed. Specifically, three decision variables are introduced. The first one is indicating whether to deploy a battery function for a microgrid. The second one is used to control when and how much charge or discharge the power. The third one is used to define the amount of power transmitted between the microgrids. Using these decision variables, we propose a method to determine the optimal battery locations within the specified number of units to minimize the transmission load as an evaluation function.

Figure 2.6 shows an example of a small interconnected microgrids to explain an overview of the solution search in the proposed method. As a simple example, in t=1, it is assumed that the power generation of 100 kWh by microgrid 1 (MG-1) and consumption of 75 kWh by microgrid 2 (MG-2) are carried out. In addition, in t=2, it is assumed that the power generation of 50 kWh by microgrid 1 (MG-1) and consumption of 75 kWh by microgrid 2 (MG-2) are carried out. It is also assumed that the distance between MG-1 and MG-3 and between MG-3 and MG-2 are 10 km, between MG-1 and MG-4 and between MG-4 and MG-2 are 50 km. Each transmission capacity between microgrids is set to be 100 kWh.

In this condition, 100 kWh is generated in t=1, but only 75 kWh of power is consumed. Therefore, it is necessary to temporarily charge 25 kWh to the battery in order not to dispose of 25 kWh. In t=2, power generation of 50 kWh and consumption of 75 kWh are assumed, therefore power of 25 kWh is insufficient. It is possible to correspond to the power consumption of 75 kWh by discharging and using the 25 kWh that is charged in the battery function at t=1.

In the case of this charge-discharge control, it is possible to correspond by equipped with the battery function in the MG-3 or MG-4 in the transmission network. In this management, there are many patterns to supply power from MG-1 to MG-2. As examples, two patterns are evaluated.

In the first pattern, in t=1, 100 kWh is transmitted from MG-1 to MG-3 and 25 kWh is charged in the MG-3. In addition, 75 kWh is transmitted from MG-3 to MG-2 and it is consumed in MG-2. In t=2, 50 kWh is transmitted from MG-1 to MG-3 and 25 kWh is discharged in MG-3. Then the total of 75 kWh is transmitted from MG-3 to MG-2 and it is consumed in MG-2. In the second pattern, the battery function is deployed to MG-4 rather than MG-3 and excess power is temporarily charged at t=1. In t=2, lacking power is compensated by discharging the power that is charged at t=1.

For the two patterns described above, the objective function specified in previous section is used to determine whether to deploy the battery function in either MG-3 or MG-4. In addition, when the optimal battery location is determined, it is evaluated whether the constraints prescribed by previous section are satisfied. As described above, we search for the optimal battery locations within the constraint conditions to minimize the objective function with decision variables to decide whether to deploy battery function in each microgrid and how much power should be transmitted between microgrids.

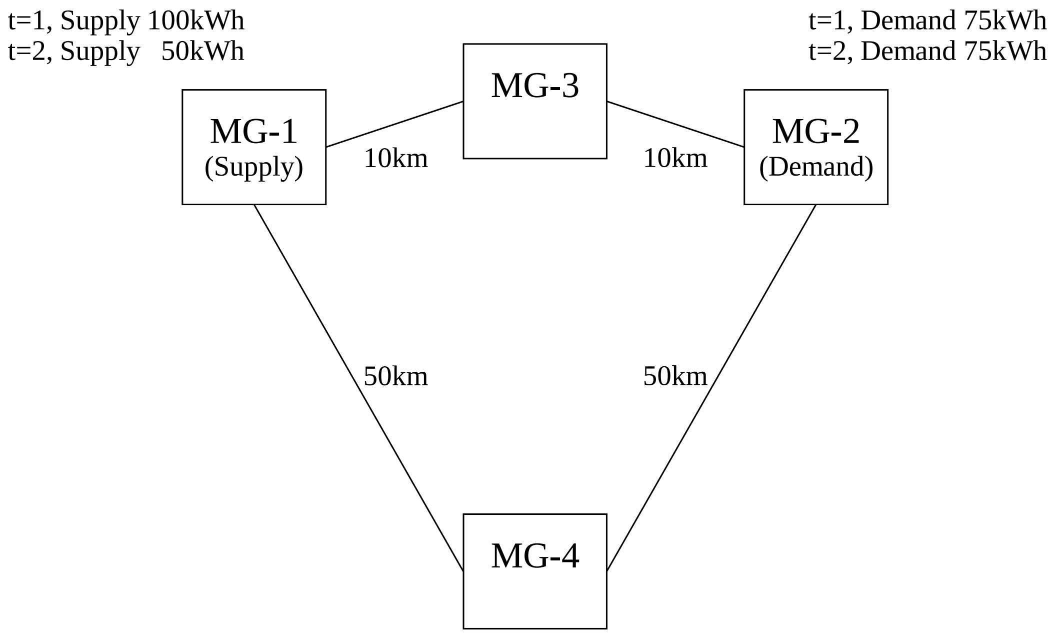

Figure 2.6 Example of small interconnected microgrids.

2.4. Evaluation and Results

2.4.1. Overview of Evaluation

In the first evaluation, we clarify the relationship between the power transmission load and a total battery capacity in order to minimize the transmission power loss. The total battery capacity is set by changing both each battery capacity and number of microgrids that equip with battery function. In order to reduce the transmit power loss, it is necessary to minimize the transmission load defined by the multiplication of transmission amount and distance. Therefore, in this evaluation, we change the number of battery functions M and the battery capacity $W(i)$ to be deployed to the interconnected microgrids as a parameter, compare the minimum value of the transmission load in each case, and evaluate the number of microgrids where the battery function should be deployed and the capacity of the battery function to be equipped.

Second, in the case that the capacity of a total battery function to be deployed is fixed, we clarify the relationship between the power transmission load and the combination of the number of battery functions and battery capacity. In particular, we compare which pattern is suitable to reduce the transmission load. There are mainly two patterns. In the first pattern, a large number of batteries with small capacity are deployed. In the second pattern, a small number of batteries with large capacity are deployed. Therefore, the multiplication of each battery capacity $W(i)$ and the number of microgrid with battery M is fixed, and the transmission load is evaluated by changing the combination $W(i)$ and M.

Third, we show the effectiveness of the proposed method by comparing it with other methods. The candidates to be compared include the related research [37]–[46]. In particularly, the research [42], [43] from the deployment relevance of the charge-discharge function is conceivable. However, it is difficult to compare between the research [42], [43] and our method since the purpose and constraints are different. Therefore, the method to deploy the battery function by using the k-means method is compared.

The k-means method provides a clustering method for classifying a given set of data into a specified number of groups by unsupervised learning. By utilizing this method, it is possible to divide into clusters according to the number of battery functions planned to be deployed, for all microgrids that supply power or demand. For example, if 10 microgrids supply power and 10 microgrids demand, the total 20 microgrids will be targeted. Here, when the charge-discharge function is planned to be deployed in five places, the microgrids of 20 places are divided into five clusters. At first, a center of each cluster is calculated. Then, a microgrid is selected if it is used for power relay and is the shortest distance from one of the centers. The selected microgrids can be deployed the battery function. By deploying the battery function in this way, it is possible to reduce the transmission distance in the cluster when the power is trading between microgrids by using the battery function.

On the other hand, the proposed method can accurately evaluate the amount of power and path length transmitted and received between microgrids and optimize them. Therefore, we compare the proposed method with the k-means based method and evaluate the effectiveness of our method.

2.4.2. Evaluation Model

Table IV shows a list of the set values for the defined symbols. To decide a topology for the interconnected microgrids, we consider research [42], [43] that used 21 regions and 34 nodes and the number of prefectures in Japan. As a result, we use the configuration shown in Fig. 2.5 as the interconnected microgrids for the evaluation. Specifically, the number of microgrids N to be deployed is 49. The microgrids for power supply and demand are set to 10 locations, respectively. For the time slots to be evaluated, the cycle of charge amount shown in Fig. 2.4 is considered. Specifically, the charge amount is evaluated until t=56, which is the third period where the charge amount is 0.

The distance $C(i,j)$ between the microgrids is set 10 km or 50 km as shown in Fig. 2.7. The upper limit of the transmission amount $L(i,j)$ is set to 1,000 kWh as there is sufficient power transmission capacity in this evaluation. The amount of power generated shown in Fig. 2.2 is used as $P(i,t)$ for every power-supply microgrids. The amount of power consumed shown in Fig. 2.3 is used as $D(i,t)$ for every power-demand microgrids. Although the forecast values should be used as the supply and demand values, in this evaluation, the values shown in Figs. 2.2 and 2.3 are used for convenience as predicted values.

Capacity $W(i)$ of each battery to be deployed in the microgrid is set between 100 and 250 kWh in order to evaluate the transmission load by changing the total capacity (Evaluation 1). The number of deployments M is set in the range of five to ten places. When the transmission load is evaluated at a constant of the total battery capacity (Evaluations 2 and 3), the capacity of each battery $W(i)$ to be deployed in the microgrid is set by considering the minimum required battery capacity U (626.4 kWh, described in the next section). Specifically, a combination of battery capacity $W(i)$ and the number of microgrids with battery functions (M) is set as 31.32*20, 41.76*15, 62.64*10, 125.28*5, and 313.2*2.

The amount of power (V), for which the battery function is initially charged, is set to 217.7 kWh that is ten times of the value in Fig. 2.4 since there are 10 microgrids that demand power. The total amount for the minimum required batteries is set to 626.4 kWh, in consideration of the graph in Fig. 2.4 and the power trading between ten supply and ten demand microgrids.

Table IV Value of Symbols

Symbol	Value
i	1,⋯, 49
t	1,⋯, 56
$C(i,j)$	Distance between adjacent microgrids i and j as shown in Fig. 2.7 (10km/50km)
$L(i,j)$	1,000 (kWh)
$P(i,t)$	Powe supply cycle shown in Fig. 2.2 (i=2, 5, 9, 13, 21, 24, 32, 35, 38, 43)
$D(i,t)$	Power demand cycle shown in Fig. 2.3 (i=3, 7, 11, 17, 23, 27, 33, 37, 44, 46)
$W(i)$	Evaluation 1: 100-250 (kWh)
	Evaluation 2 and 3: 31.32, 41.76, 62.64, 125.28, 313.2 (kWh)
M	Evaluation 1: 5-10
	Evaluation 2 and 3: 20, 15, 10, 5, 2
V	217.7 (kWh)
U	626.4 (kWh)

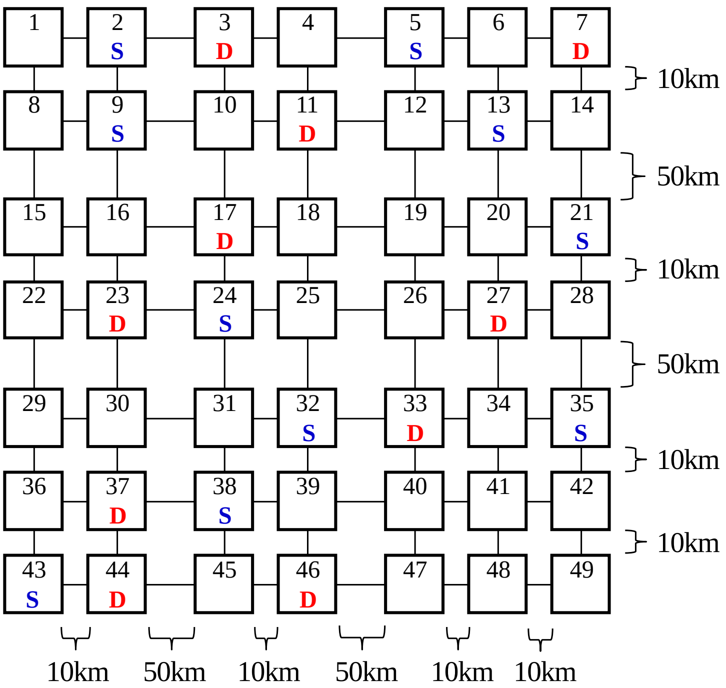

Figure 2.7 Distance between adjacent microgrids.

2.4.3. Evaluation Results

2.4.3.1. Transmission load evaluation by changing battery capacity and number of batteries in microgrids

Figure 2.8 shows the results of the evaluation of transmission load by changing the battery capacity and number of microgrids that equip with the battery function. The proposed method is evaluated by setting between 100 kWh and 250 kWh, using the same upper limit capacity for multiple battery functions in the interconnected microgrids. In addition, the number of microgrids that equip battery function is set between five and ten locations. In regions where the calculation result is not drawn in the figure, the calculation of the optimum value is impossible areas. For example, in the case of deploying 100 kWh battery into five microgrids, it is not possible to accumulate the total amount of power to be generated. Therefore, optimized transmission load is not calculated and not drawn. As the evaluation result, it can be seen that the transmission load is very high when the number of microgrids that deploy the battery function is small. Moreover, it is understood that the transmission load does not decrease even if an individual charge-discharge capacity is larger than the necessity. In this evaluation, there are 10 microgrids for supply and demand power respectively. When the number of microgrids that equip with the battery function is between eight and ten, the transmission load is reduced. The calculation time for optimization is about 10 minutes.

In this evaluation, the optimal value is calculated by changing the number of deployments and capacity of the battery function, and it is possible to find the optimal number of battery functions and the capacity of each battery function in order to reduce the transmission load. As a first point of view, when individual capacities of the installed battery functions are the same, we can find an optimal number of microgrids with the battery function to minimize the power transmission load. As a second point of view, when the number of microgrids with the battery function is the same, we can find an optimal battery capacity to minimize the power transmission load. Under the conditions in this evaluation, when the battery function of the capacity of 100 kWh is deployed in 10 microgrids, the transmission load is minimum.

As an example of the deployment of the battery function, it is shown in Fig. 2.9 the optimal arrangement when the battery function of 100 kWh is deployed in ten microgrids, and the evaluation result of the amount of battery power required as the initial value. In addition, the change of charged power in each battery function is shown in Fig. 2.10.

In Fig. 2.9, as shown by the microgrid which is displayed in the square in the thick red frame, the battery function is deployed in ten microgrids (4, 10, 14, 16, 18, 20, 34, 36, 39, 45) as set as conditions. In addition, in the total amount of battery power stored as the initial value, the 217.7 kWh set as a condition (the cumulative value of the red frame values) is deployed. In addition, when t=1, the red arrow in Fig. 2.9 shows the transmission path and amount power from the microgrid with the battery function to the microgrid that requires power. By this, it is confirmed that power is supplied by the microgrid with the battery function at the time when power generation is not performed by the power supply side microgrid.

From Fig. 2.10, it is confirmed that the operation to charge excess power and to discharge stored power when the power generation is insufficient. In the time t=8, 32, and 56, the amount of stored power of zero is repeated in the battery function, and periodic charge and discharge operations without excess power are confirmed. In addition, in this evaluation, it is set to 100 kWh as the upper limit of the battery capacity, but it is clarified that the capacity of about 70 kWh is enough when deploying to ten microgrids.

As another example of the deployment of the battery function, it is shown in Fig. 2.11 the optimal arrangement when the battery function of 200 kWh is deployed in five microgrids, and the evaluation result of the amount of battery power required as the initial value. In addition, the change of charged power in each battery function is shown in Fig. 2.12.

In Fig. 2.11, as shown by the microgrid which is displayed in the square in thick red frame, the battery function is deployed in five microgrids (6, 10, 18, 34, 45) as set as conditions. In addition, in the total amount of battery power stored as the initial value, the 217.7 kWh set as a condition (the cumulative value of the red frame values) is deployed. In addition, when t=1, the red arrow in Fig. 2.11 shows the transmission path and amount power from the microgrid with the battery function to the microgrid that requires power. By this, it is confirmed that power is supplied by the microgrid with the battery function at the time when power generation is not performed by the power supply side microgrid.

From Fig. 2.12, it is confirmed that the operation to charge excess power and to discharge stored power when the power generation is insufficient. In the time t=8, 32, and 56, the amount of stored power of zero is repeated in the battery function, and periodic charge and discharge operations without excess power are confirmed. In addition, in this evaluation, it is set to 200 kWh for five microgrids as the upper limit of the battery capacity, but it is clarified that the maximum capacity battery is about 190 kWh and the capacities for other battery functions are much less than that.

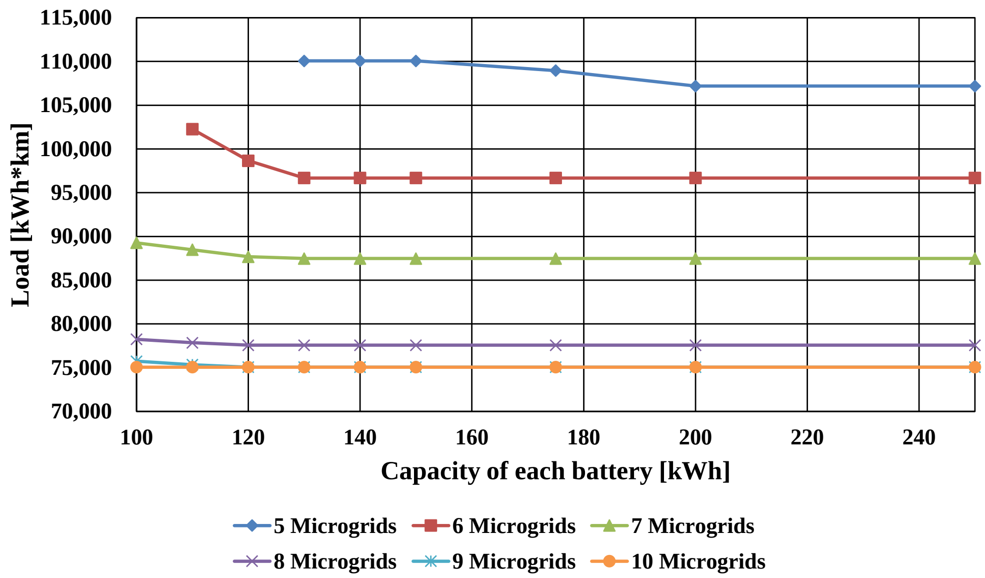

Figure 2.8 Transmission load evaluation by changing battery capacity and number of batteries in microgrids.

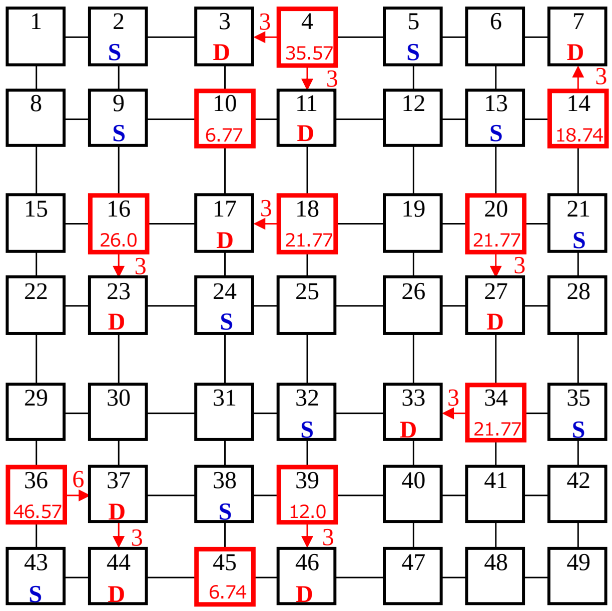

Figure 2.9 Optimized location and initially stored power for 10 batteries with 100kWh capacity.

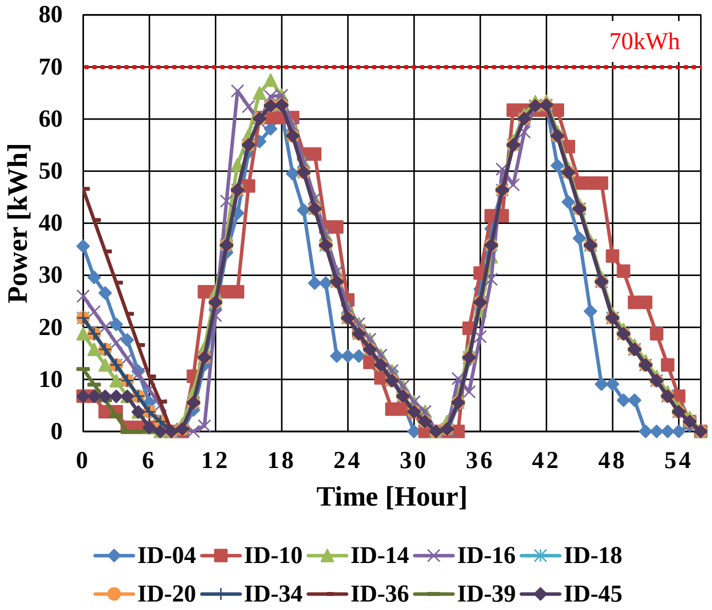

Figure 2.10 Remained power change for 10 batteries.

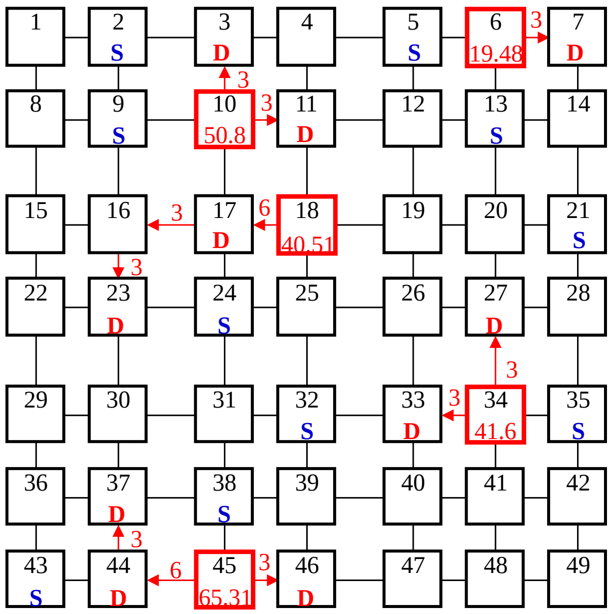

Figure 2.11 Optimized location and initially stored power for 5 batteries with 200kWh capacity.

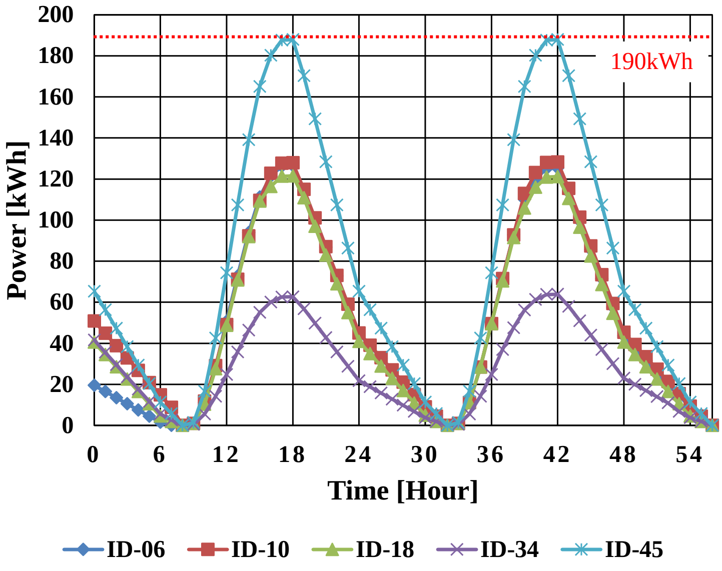

Figure 2.12 Remained power change for 5 batteries.

2.4.3.2. Transmission load evaluation with a constant total battery capacity

Figure 2.13 shows the evaluation result of the transmission load for the combination of the battery capacity and the number of microgrids to deploy it. In this evaluation, a total battery capacity for the combination of each battery capacity and the number of microgrids is set as shown in Table IV. Specifically, a total battery capacity is set to 626.4 kWh as minimum required capacity. From the evaluation results, when the battery function is deployed to ten microgrids, the transmission load is minimized to 75,053 kWh*km. In addition, if the battery function is deployed in 20 or 15 microgrids, the transmission load is increased by 8% and 15%, respectively, compared with the case of ten microgrids. On the other hand, if the battery function is deployed in five or two microgrids, the transmission load is increased by 47% and 135%, respectively, compared with the case of ten microgrids.

In this evaluation, the total capacity of the battery functions to be deployed is set as a constant, and it is evaluated by changing a combination of the number of microgrids with battery function and each battery capacity. Therefore, when the total battery capacity is constant, it is possible to clarify the relation between the transmission load and the combination. In this evaluation, it is confirmed that when the 62.64 kWh battery is installed in ten microgrids, it would be the best result in the evaluation.

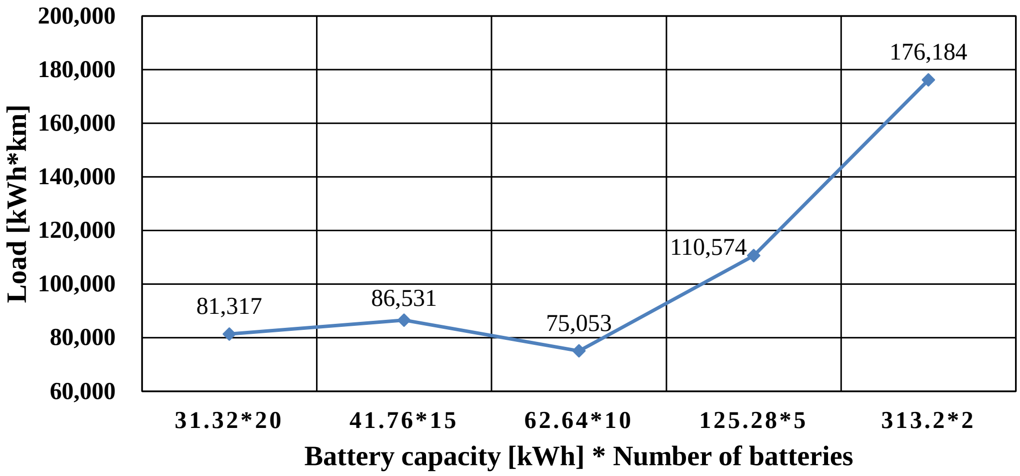

Figure 2.13 Transmission load evaluation with a constant battery capacity.

2.4.3.3. Transmission load comparison between proposed method and k-means based method

The comparison results for transmission load between the proposed method that deploys battery functions optimally and the k-means based method is shown in Fig. 2.14. In this evaluation, a total battery capacity is set to 626.4 kWh as minimum required capacity similarly to the evaluation in Fig. 2.13. In addition, the evaluation results shown as the "Proposed method" in the figure are identical to those of the evaluation in Fig. 2.13. From the results shown in Fig. 2.14, in the evaluation of the transmission load when the number of battery functions is small, the proposed method obtained a dominant result than the k-means based method. In particular, in the case of the proposed method with the minimum power transmission load in ten microgrids, the power transmission load is more effective than the k-means based method by 20%.

Power loss by transmission depends on the transmission amount and distance. Therefore, we compare the proposed method that focuses on both the transmission amount and distance with the k-means based method. As a result, in the case of deploying the charge-discharge function in ten microgrids, the proposed method is improved by 20% compared with the k-means based method. The effectiveness of the proposed method to reduce transmission loss by focusing on both the transmission amount and distances is confirmed.

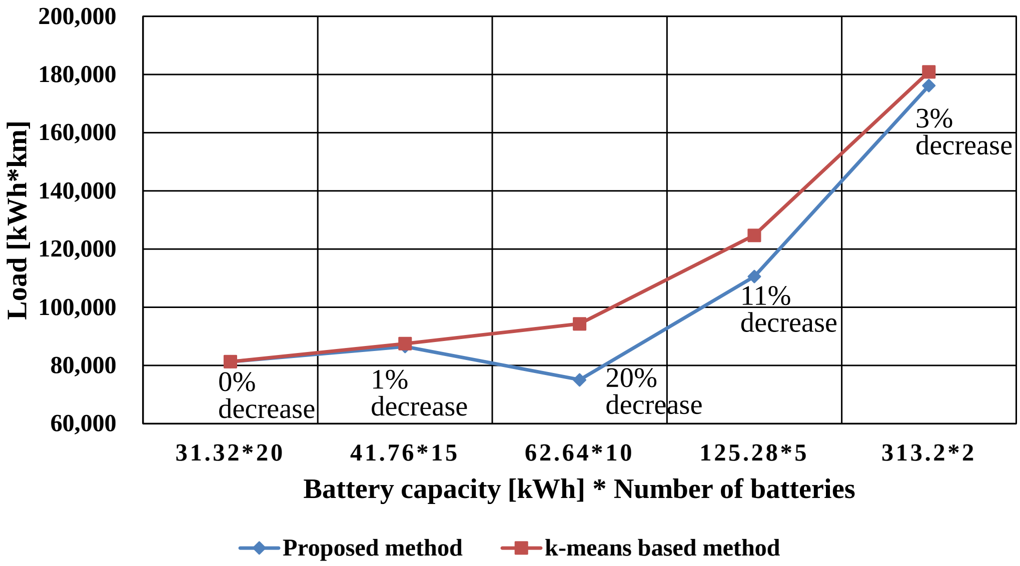

Figure 2.14 Transmission load comparison between proposed method and k-means based method.

2.5. Discussion of Evaluation Results

In the evaluations, the supply and demand amount of power are all the same in order to investigate the basic characteristics. However, in such a case, when the number of battery functions to be deployed is extremely small or deployed at a position not suitable, it is clarified that the power loss (transmission load) is increased. As a result, the design policy of the interconnected microgrids with the battery function is limited, but it is possible to show the effectiveness of this formulation. We consider that the proposed optimization solution can evaluate various cases, and that the evaluation for a more general case is also applicable, such as setting the supply and demand amount of each microgrid to a different value. As a specific limitation, the number of microgrids that perform the supply and demand of power is fixed to both 10. In the evaluation by setting above conditions, when the number of the battery functions is 10, it is the best result. The number of battery functions that can be deployed is a combination of the paths from the microgrid that supplies the power to the demand side, and it is likely to depend on how independent pathways exist for the route where the power transmission is actually needed.

For example, if the power from two microgrids is supplied to two microgrids, four routes are present as the transmission path. It is desirable to deploy a battery function for each route if the path is independent and each transmission path is required to transmit the power. In such a situation, the number of battery functions to be deployed must be equal to the number of independent routes.

On the other hand, if there is an intersection between the paths and there is no restriction on the battery capacity and the allowable amount of power transmission, it is not necessary to deploy the battery function to each route by deploying it at the intersection. The required capacity of the battery function is dependent on the pattern of the power supply and demand and the timing of the charge-discharge control. Therefore, it seems to be difficult to accurately estimate the optimal number of battery functions and the capacity of them.

The optimal number of deployments, locations, and capacity of the battery functions depend on the number of microgrids, topology, transmission power patterns, and capacity of power transmission. Therefore, it is necessary to calculate the optimal number, location, and capacity of the battery function for each condition. By using the proposed method, it is necessary to calculate each time, but by setting various conditions such as power supply, demand, and connection topology, it is confirmed that the optimal number and location of the battery function can be calculated. In actual management, it is necessary to calculate the optimal number and location of the battery function by using the statistical values of power supply and demand patterns, or by using the predicted values.

When estimating the stored initial battery power and capacity of the battery function, it is considered possible to use the accumulated value for the entire interconnected microgrids. Specifically, based on the supply and demand pattern of the power as shown in Fig. 2.4, it seems to be possible to estimate the amount of initially stored power in the batteries and the capacity of the whole batteries to charge the excess power generated. Therefore, as shown in Table IV, V (217.7 kWh) as the lower limit of the initially stored total battery power, and U (626.4 kWh) as the lower limit of the entire battery capacity is set, and the transmission load is evaluated.

On the other hand, the optimal amount of initially stored power and the optimal capacity of each battery function are not the same between batteries. Therefore, they are calculated based on the minimization of the transmission load. However, if the lower limit of the entire battery capacity is defined, it is necessary that the multiplication of the "capacity" and "number" of the battery functions are more than the lower limit. Therefore, U is considered to be available as an indicator to limit the range to be evaluated. If multiple battery functions are deployed in each microgrid that supply or demand power, it tends to lead to an increase in the transmission path. For this reason, the total number of battery functions is considered to be not necessary to deploy beyond the total number of microgrids for supply and demand.

For example, it is assumed that a microgrid that supplies or demands power equips with the battery function, and the capacity of it is enough to charge the power generated in excess from the transmission path. In this case, the power generated in excess is stored and it is possible to discharge it when it is necessary. Therefore, as long as the capacity is not insufficient, it is considered that there is no need to deploy multiple battery functions used by each microgrid. As for the specific number and capacity of the battery function, it is likely to depend on the management plan of the operator to deploy it. For example, based on the viewpoint of cost and ease of operation management, it is possible to deploy a small number of battery functions with the large capacity or deploy a large number of battery functions with small capacity.

In this chaper, we propose a method to find optimal locations of battery functions to reduce the transmission loss in the case of interconnected microgrids that exchange the power. Therefore, it is assumed the situation to trade the power between microgrids in the future.

In the evaluation, the power loss associated with transmission is assumed to depend on the power amount and the transmission distance, and the transmission load (transmission amount * distance) is set as an objective function, and it is minimized. In this evaluation, the battery function to be deployed is assumed the same performance, but it is possible to extend the method to a different performance. On the other hand, the proposed method does not consider the cost of constructing a microgrid or the construction of transmission lines for wide-area connections. Therefore, we assume the stage where the interconnected microgrids were constructed. In this case, the proposed method to find optimal locations of battery functions and to control power transmission between microgrids is effective.

In this section, the proposed model is able to evaluate the power loss reduction by transmission by the assumption that there is no performance difference of the charge-discharge function. In the evaluation setting, each of microgrids that supply and consume electricity are deployed in 10 locations. As an evaluation, the number of microgrids for deploying the charge-discharge function is changed from 5 locations to 10 locations, and the amount of power loss is evaluated. As a result, when deploying the charge-discharge function to 10 microgrids, the amount of power loss was the smallest result. Further, in the case of deploying the minimum charge-discharge capacity required, it is evaluated by changing the combination of the product of the capacity and the number of deployments of the charge-discharge function. As a result, when deploying the charge-discharge function in 10 microgrids, it was the result of the minimum power loss. In addition, in the case of deploying both the charge-discharge function of the small capacity in 20 microgrids or the charge-discharge function of the large capacity in 2 microgrids, the amount of power loss was a result of increasing. In this evaluation setting, it is the best result when the charge-discharge function of the appropriate capacity is deployed to 10 microgrids. From this result, it has been verified existence of suitable capacity and the number of microgrids for deploying the charge-discharge function depending on the topology and power trade conditions. In particular, in the case of deploying a large number of charge-discharge functions whose capacity is small, or a small number of charge-discharge functions whose capacity is large, it became clear that the power loss due to transmission is increased.

In this evaluation, it is best to deploy the charge-discharge function to the microgrid of 10 locations. Therefore, it is considered the result of dependent on the configuration of the topology and power trading conditions. The deployment position of the charge-discharge function, it is considered to depend on the number of independent power transmission paths. If the transmission paths are crossed and there is no problem with the capacity, by deploying the charge-discharge function at its intersection, it is considered possible to reduce the number of deployments. However, the capacity and number of deployments of the optimum charge-discharge function, to depend on the topology and power supply and demand, etc., it is necessary to calculate each time. The proposed method can calculate the amount of power loss by transmission even when the topology and power supply and demand patterns are changed. Therefore, it is necessary to calculate the capacity and number of the optimal charge-discharge function for each power supply and demand pattern by using the proposed method.

On the other hand, compared with the method of determining the deployment position of the charge-discharge function clustering power supply and demand microgrids (k-means based method), the proposed method has become possible power loss reduction of up to 20%. Therefore, although in part, it is considered that the effectiveness of the proposed method capable of performing power loss reduction based on the transmission distance has been verified.

At present, it is the stage where a single microgrid is being constructed. In the future, it is thought that the proposed method is useful in the advanced stage that multiple microgrids are widely connected and the power is traded between microgrids.

2.6. Related Work

Much microgrid-related research has been conducted to achieve efficient power utilization by mutually trading power. For example, [37] used a peer to peer (P2P) network for microgrid control. In addition, [38] managed a power network by using the analogy of a communication network. In particular, a system that has a plug-and-play function of a distributed power supply and charge-discharge equipment has been considered.

Reference [39] focused on multiple power generation sides to mutually control the amount of power generated and minimize currents transmission. There have been many studies related to smart homes. For example, efficient power use control using smart meters and charge-discharge functions has been studied [40]. In addition, [41] used microgrids with charge-discharge functions to minimize the payment generated by each microgrid purchasing power from other microgrids. Furthermore, the optimal deployment of energy storage for power supply and demand in multiple regions and that for radiation topologies considering demand response have been conducted [42], [43].

There have been many studies focusing on the routing of power in power network. For example, [44] focused on the routing control of energy on the basis of graph theory in a local area. Reference [45], [46] focused on power packet transmission. Specifically, header and footer information are attached to the power packet of a payload, and the packets are transmitted to a destination by generating a signal using header information.

The aforementioned studies focused on transmitting power in both directions as well as in the directions where easy power transmission control is achieved. Research from the point of view of power supply and demand has been mainly promoted, such as reducing costs and using multiple types of energy more efficiently.

The research [37]–[41] is related to this paper in terms of efficient use of power, but it is different in developing efficient power use by optimally deploying the battery function. The research [44] is related to this paper in terms of reducing losses due to transmission. However, it is different from the viewpoint of effectively using the power generated by the battery function. Specifically, temporarily charging the surplus power in the battery function, which is dynamically deployed, and discharging the power that was accumulated at the stage where the power is insufficient are different. Research [45], [46] is a study of packet-power transmission of electricity and is related in terms of power transmission. However, it differs from the viewpoint of effective use of electric power by using the battery function.

On the other hand, for research [42], [43], it is similar in terms of optimally deploying the battery function, and the similarities and differences are compared using Table V. Symbols “a” through “i” in Table V show the evaluation point.

Table V Comparison between Related Studies and Our Proposal

	a	b	c	d	e	f	g	h	i
Research [42]	○	○		○		○	○		
Research [43]	○			○				○	
Proposal	○		○		○	○			○

a: Deploy the battery function optimally

b: Set the power line capacity as a decision variable

c: Set the capacity of the power lines as constants as constraints

d：Deploy battery to power supply point and demand point

e：Deploy battery only between power supply and demand

f：Focus on a large power network such as interconnected microgrids

g：Minimize life-cycle costs for the entire system

h：Minimize life cycle costs for storage functions

i：Minimize power loss due to transmission

The research [42] is a study that minimizes life-cycle costs for the entire large-scale power system (f) (g). It is evaluated including the cost of the transmission line laying, and the capacity of the transmission line is treated as a decision variable for optimization (b). It is the configuration to deploy the battery function including power supply point and demand point (d). On the other hand, in this paper, the transmission capacity is treated as a constant (upper limit) as a restriction condition (c) in order to deploy the battery function optimally and to minimize the power loss associated with transmission. Therefore, the research [42] and our proposal have become different purposes and means.

The research [43] is a study that minimizes the life-cycle cost for battery (h) in a single microgrid (small-scale, radiation topology). An integrated evaluation both the facility cost for battery and the operational gain by reducing the peak of power consumption is executed. By minimizing the life cycle cost as an evaluation function, the optimum position of the battery is determined in the microgrid, including the supply point of power (d). On the other hand, our proposal is intended to be a large-scale configuration with interconnected microgrids (f). To minimize the power loss associated with power transmission between microgrids that supply and demand power (i), the multiplication of "power transmission" and "transmission distance" is minimized as an evaluation function. As a result, the optimum position of the battery function is determined (e) in the range of the specified number. Therefore, the research [43] and our proposal have become different purposes and means.

In the above comparison, the research [42] focuses on the viewpoint of the entire system operator such as power generation facilities and transmission facilities and calculates a battery function arrangement which contributes to minimizing the life cycle cost. The research [43] focuses on the viewpoint of the operator of the battery function and calculates the arrangement of the battery function that contributes to minimizing the life cycle cost. On the other hand, in our proposal, the battery is optimally deployed from the point of view of the transmission network operator as a new point. The generated power is primary charged in the battery placed in the transmission network, and electricity is effectively used by discharging power when the power generation is lack. In the specified battery function number, a method of optimally deploying the battery function to minimize the power loss associated with transmission is proposed.

2.7. Conclusion

In this chapter, in a situation where power generation and demand patterns are different, we proposed a high-efficiency electric power-use method that enables power trading by using the battery function and reduces transmission power loss in the interconnected microgrids. In the proposed method, it is possible to determine the optimal microgrids for the power relay that deploy the battery functions by minimizing the transmission load that is defined by the multiplication of the "volume of power transmission" and "transmission distance", as an objective function when transmitting from multiple power supply microgrids to the demand microgrids. In addition, it is possible to calculate the optimal transmission paths and the capacities to be equipped with battery functions. The proposed method was evaluated for a topology where 49 microgrids were connected to lattice-like (7x7). As a result, it was verified that the optimal battery locations, capacities, and transmission paths were able to be calculated to minimize the transmission load.

However, the capacity and number of deployments of the optimal charge-discharge function to minimize the transmission loss depends on the topology and power trade, etc. Therefore, it is necessary to calculate the capacity and number of the optimal charge-discharge function for each power trade pattern by using the proposed method. On the other hand, compared with the method of determining the deployment position of the charge-discharge function clustering power supply and demand microgrids, the proposed method has become possible power loss reduction of up to 20%. Therefore, although in part, it is considered that the effectiveness of the proposed method capable of performing power loss reduction based on the transmission distance has been verified.

Chapter 3

Power Loss Reduction for Power Trading between Interconnected Microgrids Using Batteries

3.1. Introduction

As described in the previous chapter, interconnected microgrids [12], which trade electric power between multiple microgrids, are considered promising. However, power transmission loss increases when the transmission distance increases between multiple microgrids. In addition, the loss also increases if low-efficiency batteries are used. It is necessary to preferentially utilize a high charge-discharge efficiency battery. Therefore, a method of simultaneously reducing the power loss due to the transmission, charging, and discharging is a crucial problem.

In our paper [33], the authors proposed and discussed a method to reduce the power transmission loss between interconnected microgrids. Specifically, we focused on RE and reducing power transmission loss between microgrids by minimizing loads. Such loads are defined by the multiplication of "volume of power transmission" and "transmission distance" as an objective function of a linear programming model. In our paper above, the power loss reduction method was proposed under the assumption that there was no difference in battery performance.

In this chapter, assuming that there is difference in battery performance in the interconnected microgrids, we propose a scheme to reduce the power loss by transmission and charge-discharge. Specifically, by assuming that multiple batteries are deployed in selected microgrids, an integrated function of the power loss due to the transmission, charging, and discharging of power as a mathematical programming problem is minimized. Thus, the total power loss is minimized by determining optimal battery utilization controls and transmission amount between microgrids.

This chapter is organized as follows. In Sec. 3.2, issues for interconnected microgrids and the policy to solve them are discussed. In Sec. 3.3, the new method to reduce power loss by transmission, charge, and discharge is proposed. Section 3.4 presents the evaluation results of the proposed method and discussion. In Sec. 3.5, we discuss the results. We conclude with a summary in Sec. 3.6.

3.2. Issue of Interconnected Microgrids and Solution

3.2.1. Overview of Microgrid

Figure 3.1 shows an example of a microgrid, which is composed of a power switch, multiple photovoltaic equipment, power consumption equipment, and batteries. Microgrids are interconnected with others via the power switch. If the amount of power generated in a microgrid is greater than that consumed inside, the power can be supplied to other microgrids that lack power.

Figure 3.2 shows the changes in the amount of photovoltaic power generation as an example. The horizontal axis shows the time over a three-day period, and the vertical axis shows the amount of power generated in kWh. In this example, the increases in power generation are repeated due to the sunlight from good weather conditions. The amount of power generated per day is 100 kWh.

Figure 3.3 shows an example of the changes in electric power consumption at home. The axes are the same as those shown in Fig. 3.2. This example shows a pattern in which power consumption increases slightly in the morning and substantially in the night. The amount of power consumed per day is 100 kWh.

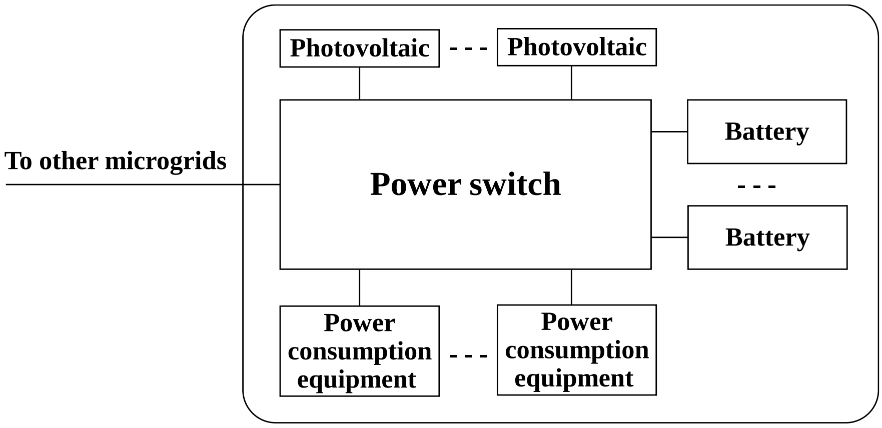

Figure 3.1 Example of a microgrid.

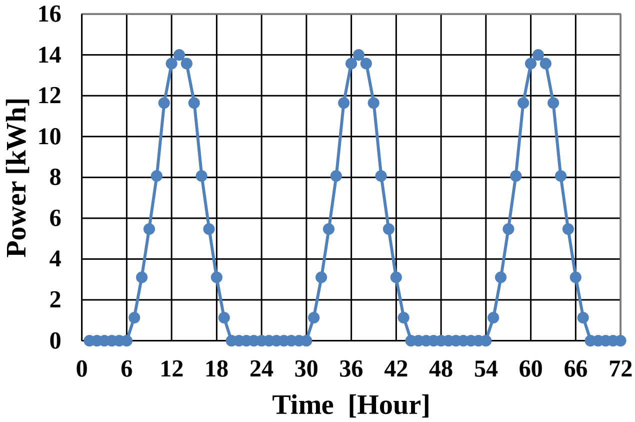

Figure 3.2 Predicted power supply cycle in a microgrid.

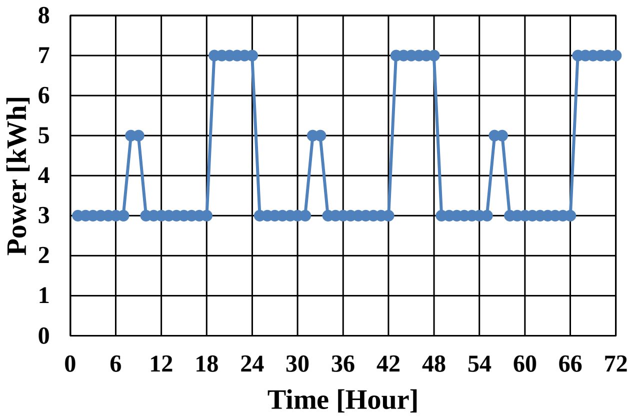

Figure 3.3 Predicted power demand cycle in a microgrid.

3.2.2. Issue for Effective Use of Electric Power

The green line (Battery) in Fig. 3.4 shows the charge-discharge amount required when the power generated is temporarily charged and discharged at required times. The blue and red lines (Supply, Demand) represent the amount of power generation and consumption, respectively.

As shown in Fig. 3.2, it is not possible to generate electric power when there is insufficient sunlight, and it cannot correspond to the power demand shown in Fig. 3.3. Therefore, it is necessary to charge to an initial value; this amount is 21.77 kWh as shown in Fig. 3.4. When there is no charge-discharge function, excessively generated power that is not consumed for each time is discarded. To effectively use the electric power generated during the day, it is necessary to charge the power during that time and discharge it to cope with a large amount of power demand from the evening onward. In such a situation, the capacity to temporarily charge the unconsumed power is required, which is shown as 62.64 kWh in Fig. 3.4. In the case where the power supply and demand amounts do not match at each point in time, it is necessary to use batteries to shift the power needed.

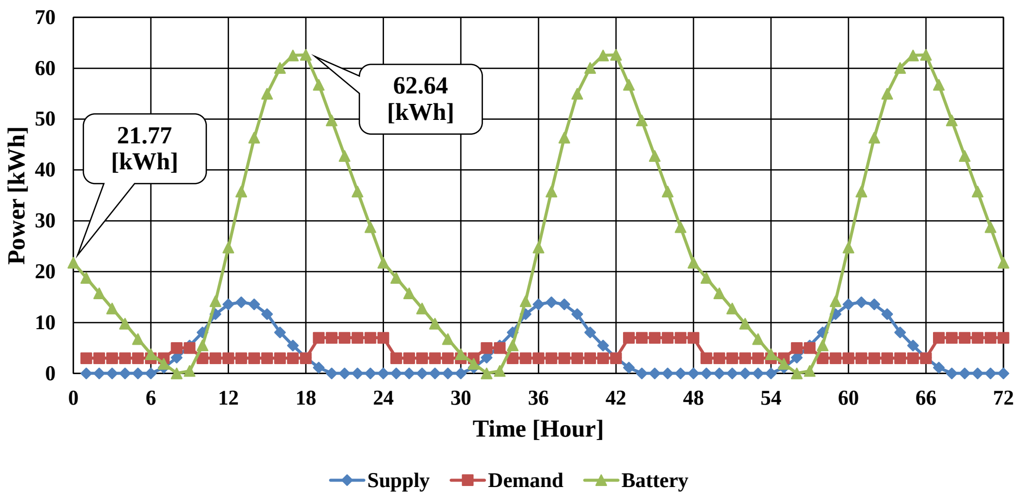

Figure 3.4 Power relation among supply, demand, and batteries.

3.2.3. Challenge for Interconnected Microgrids

An example of interconnected microgrids is shown in Fig. 3.5. The topology of the power network is set up in reference to the Japan Photonic Network Model [47]. In the model, multiple prefectures are connected to each other. When each prefecture is considered as a microgrid, it is possible to simulate the power trading between microgrids. In Fig. 3.5, each circle corresponds to a microgrid in each prefecture. Blue microgrids (1, 7, 8, 12, 24, 25, 36, 44, 45, 47) represent those in which the power is excessive in the power balance and supplying power to other microgrids is possible. In addition, the amount shown in Fig. 3.2 is used as an example to simulate the power generation pattern caused by sunlight. Pink microgrids (9, 10, 11, 13, 23, 26, 28, 34, 35, 41) represent those in which the power is insufficient in the power balance, and demand power from other microgrids. In addition, the amount shown in Fig. 3.3 is used as an example to simulate the power demand pattern.

In actual microgrids, the difference between the amount of power generated and that consumed is the amount that can be supplied or demanded. Here, as an example of simulating the different states in different microgrids, the power generation and consumption shown in Figs. 3.2 and 3.3, respectively, are used. In Fig. 3.5, white microgrids represent those in which there is no shortage of power balance, and the power relay is possible.

For each microgrid constituting the interconnected microgrids, if the power supply and demand amounts in each time do not match, a battery function is required to charge the surplus power generated temporarily, corresponding to power demands at different time. However, if the battery function is not deployed in an appropriate position, the power loss by transmission can increase. This is because the power is temporarily charged in the battery that exists along the path, which is not the shortest, between the power supply and demand microgrids. In addition, the power loss by charge-discharge is increased when a low-efficiency battery function is used. Therefore, it is necessary to reduce the power loss by using an appropriate battery function in the power trading between interconnected microgrids.

The purpose in this chapter is to propose a method to reduce both transmission and charge-discharge power loss for the trading of power between interconnected microgrids by an optimal deployment of the battery function, charge-discharge control, and transmission path.

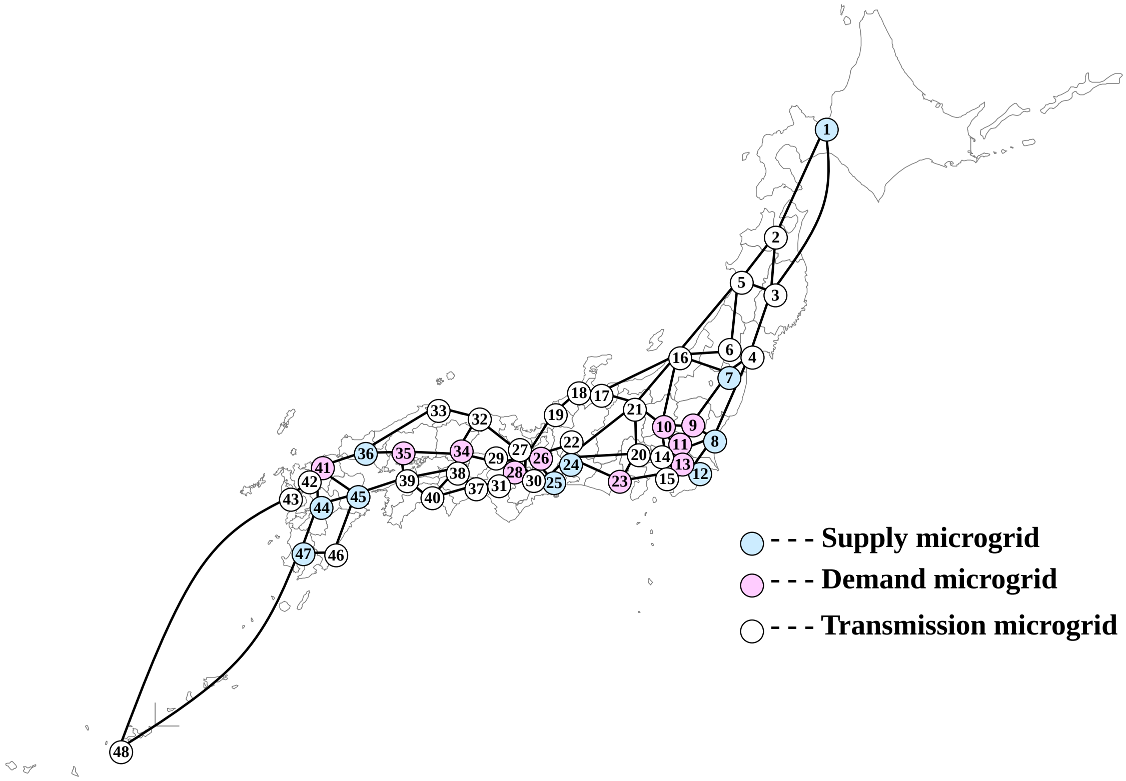

Figure 3.5 Example of interconnected microgrids.

3.2.4. Control Policy of Power Transmission, Charge, and Discharge

Transmission power loss is assumed to be proportional to the amount of power transmitted and the transmission distance. It is also assumed to be generated by the amount of charging and discharging. Therefore, as an objective function for evaluations, we will minimize the power loss by power charge-discharge and transmission load. The transmission load is defined by the multiplication of the "volume of power transmission" and "transmission distance" between microgrids. Specifically, when the power from the power-supply microgrid is charged to the battery function or consumed by the power-demand microgrid, the optimal transmission amount, transmission path, location of batteries, and power supply are determined to minimize the power loss. In the optimal deployment of battery functions, we search to minimize the power loss within the evaluation period on the basis of the number of deployments and capacities of the specified battery functions and determine the optimal position.

3.3. Proposal of a Method to Reduce Power Loss

This section presents a method to reduce the power loss due to transmission and charge-discharge by using a mathematical programming model. We define symbols to describe evaluation conditions and decision valuables to minimize the power loss. In order to find a minimum power loss, an objective function is defined and solved by using the symbols and decision valuables.

3.3.1. List of Symbols for Evaluation Model

Table VI shows a list of symbols specified for calculating the solution of the mathematical programming problem that minimizes the power loss by transmission, charge, and discharge. i indicates the microgrid number. When the time range to be evaluated is divided into T slots, t indicates the slot number. In addition, t=0 indicates the state of the initial value. r represents the loss rate of power to transmission per km, and $\rho(i)$ represents the loss rate of power to charge or discharge.

$C(i,j)$ shows the distance between adjacent microgrid i and j in the configuration where multiple microgrids are connected to each other. $L(i,j)$ shows the upper limit of the amount of power that can be transmitted between adjacent microgrids i and j. $P(i,t)$ shows the amount of power supplied by microgrid i at time t. $D(i,t)$ shows the amount of power consumed by microgrid i at time t. $W(i)$ shows the capacity of the charge-discharge deployed in microgrid i.

M represents the total number of microgrids with battery functions. V represents the total amount of charge as the initial value for supplying the power consumed before power generation for all microgrids. U represents the minimum required total charge capacity to charge the surplus power generated during the evaluation period.

Table VI List of Symbols

Symbol	Definition
i	Number of microgrid ($i = 1,\cdots, N$)
t	Number of time slot ($t = 0,\cdots, T$)
r	Power loss rate per km due to transmission
$\rho(i)$	Power loss rate by charge or discharge in microgrid i
$C(i,j)$	Distance between adjacent microgrid i and j (km)
$L(i,j)$	Limit of transmission amount between adjacent microgrid i and j (kWh)

$P(i,t)$	Amount of power supplied from microgrid i in time slot t (kWh)
$D(i,t)$	Amount of power consumed by microgrid i in time slot t (kWh)
$W(i)$	Battery capacity in microgrid i (kWh)
M	Number of microgrids with distributed battery functions, $M<N$
V	Initial value of the total amount of power in the distributed batteries (kWh) (Refer to (3-6))
U	Necessary capacity of the distributed batteries (kWh) (Refer to (3-7))

3.3.2. List of Decision Variables for Evaluation Model

The decision variables listed in Table VII are determined by the optimization problem described as follows. $Q(i,j,t)$ determines the amount of power transmitted from adjacent microgrid i to j at time t. $B(i,t)$ determines the amount of power remaining in the charge-discharge function of microgrid i at time t. $F(i,t)$ determines the control amount of the power supply of microgrid i at time t. The value of $\delta(i)$ is determined to be 1 or 0 if the battery function is deployed or not, respectively, in microgrid i.

Table VII List of Decision Variables

Variable	Definition
$Q(i,j,t)$	Amount of power transmitted from adjacent microgrid i to j in time slot t (kWh)
$B(i,t)$	Amount of power remaining in the battery of microgrid i in time slot t (kWh)
$F(i,t)$	Amount of reduced power supply for supply microgrid i in time slot t (kWh)
$\delta(i)$	Deployment/No deployment of battery in microgrid i (1/0)

3.3.3. Objective Function and Constraints

The proposed system aims to minimize power loss by transmission and charge-discharge as described in the previous section. By formulating and evaluating the problem as mathematical programming one, we can achieve high-efficiency power utilization by using the battery functions.

The objective function is shown as follows. The amount of transmission power loss is indicated by $r*C(i,j)Q(i,j,t)$. The amount of power loss due to charge-discharge is indicated by $\rho(i)|B(i,t)\text{-}B(i,t\text{-}1)|$. By deriving the minimum value of the objective function, the optimal placement and control of multiple battery functions can be calculated, and the power loss can be minimized.

$$Minimize$$

$$\sum_{t=1}^{T}\sum_{i=1,i\neq j}^{N}\{r * C(i,j)Q(i,j,t) + \rho(i)|B(i,t) - B(i,t-1)|\} \tag{3-1}$$

The constraints are described as follows.

1) Power balance condition: In time t, the amount of power supply and demand in microgrid i is equal to the sum of the power quantities $Q(k,i,t)$ and (-1)*$Q(i,k,t)$, and ($B(i,t$-1)-$B(i,t)$). $Q(k,i,t)$ represents the amount of power flowing from adjacent microgrid k. $Q(i,k,t)$ represents the amount of power flowing into microgrid k. $B(i,t$-1)-$B(i,t)$ indicates the amount of charge change in the battery. The supply amount from the microgrid supplying power is equal to (-1)*$P(i,t)$+$F(i,t)$. The amount of power consumed by the microgrid that requires power is equal to $D(i,t)$. In addition, the power balance is zero in microgrids for the relay that does not supply nor demand power.

$$\sum_{k} Q(k,i,t) - \sum_{k} Q(i,k,t) + B(i,t-1) - B(i,t)$$
$$= D(i,t) - P(i,t) + F(i,t) \tag{3-2}$$

2) Transmission quantity condition: In time t, the amount of power $Q(i,j,t)$ that is transmitted from adjacent microgrid i to j is less than or equal to the maximum value $L(i,j)$ that can be transmitted.

$$0 \leqq Q(i,j,t) \leqq L(i,j) \tag{3-3}$$

3) Battery function number condition: The number of microgrids for the relay to deploy the battery function is less than or equal to the specified number M.

$$\sum_{i=1}^{N} \delta(i) \leqq M \qquad (3-4)$$

4) Charge and discharge quantity condition: In time t, the amount of power $B(i,t)$ charged to microgrid i with the battery function is less than or equal to the specified capacitance $W(i)\ \delta(i)$.

$$0 \leqq B(i,t) \leqq W(i)\delta(i) \qquad (3-5)$$

5) Initial value of charge amount condition: The sum of the charge amount $B(i,0)$ is equal to the specified initial power amount value V to supply the power required before power generation.

$$\sum_{i=1}^{N} B(i,0) = V \qquad (3-6)$$

6) Capacity condition for battery function: The total capacity of the battery functions to be deployed is at least the minimum charge-discharge capacity U required to temporarily charge and hold surplus power generated during the period of evaluation.

$$\sum_{i=1}^{N} W(i)\delta(i) \geqq U \qquad (3-7)$$

3.4. Evaluation and Results

3.4.1. Overview of Evaluation

First, the total battery capacity to be deployed is fixed, and an appropriate combination of each battery capacity and number of batteries to be deployed is clarified to reduce the power loss. The total battery capacity to be deployed is defined by the multiplication of each battery capacity $W(i)$ and the number of microgrids with battery functions (M). As described in the previous section, a microgrid used for the power transmission is used as a deployable position of the battery function.

Second, we compare the minimum amount of power loss due to transmission and charge-discharge when the output of the microgrid supplying power is controllable and the power generation capacity is sufficient. This evaluation shows the output control of the power supply microgrid that minimizes the power loss.

Third, we change the number of microgrids with battery functions (M) and each battery capacity $W(i)$ to be deployed in the interconnected microgrids as parameters and compare the minimum amount of power loss due to transmission and charge-discharge in each case. The total battery capacity is not fixed. This evaluation clarifies the number of microgrids for which the battery function should be deployed and their required capacity.

3.4.2. Evaluation Model

Table VIII shows a list of the set values for the defined symbols. The configuration shown in Fig. 3.5 is used for the interconnected microgrids to perform the evaluations. Specifically, one microgrid is basically installed in each prefecture based on the Japan Photonic Network Model [47]. Tokyo Prefecture has two microgrids in consideration of its power scale. As a result, the number of microgrids to be deployed is 48.

For the time slots to be evaluated, the cycle of charge amount shown in Fig. 3.4 is considered. The charge amount is evaluated until t=56, which is the third period where the charge amount is 0. The power loss rate r by transmission is set to 0.0001 as 0.01% power loss per km by considering information of [36], [48]. In addition, two types of power loss rate $\rho(i)$ generated during charge or discharge are set. The power losses of the efficient and non-efficient storage batteries are set to 5 and 15%, respectively by considering information of [49].

The distance $C(i,j)$ between microgrids is based on the topology in Fig. 3.5, and is set to the distance between the locations of the prefectural government. The upper limit of the transmission amount $L(i,j)$ is set to 1,000 kWh as there is sufficient power transmission capacity in this evaluation. For the microgrids that can supply or demand power, ten locations are selected by referring to the power balance in each prefecture. The amount of power generated shown in Fig. 3.2 is used as $P(i,t)$ for power-supply microgrids. The amount of power consumed shown in Fig. 3.3 is used as $D(i,t)$ for power-demand microgrids. Although the forecast values should be used as the supply and demand values, in this evaluation, the values shown in Figs. 3.2 and 3.3 are used for convenience as predicted values.

When the power loss is evaluated at a constant of the total battery capacity (Evaluations 1 and 2), the capacity of each battery $W(i)$ to be deployed in the microgrid is set by considering the minimum required battery capacity U (626.4 kWh, described in the next section). Specifically, a combination of battery capacity $W(i)$ and the number of microgrids with battery functions (M) is set as 31.5*20, 42*15, 63*10, 126*5, 315*2, and 630*1. In addition, the value of $W(i)$ is set between 40 and 250 kWh when the total capacity of the deployed battery function is changed, and the power loss is evaluated (Evaluation 3). The number of microgrids with battery functions (M) is set to 5, 10, 15, and 20. The amount of power (V), for which the battery function is initially charged, is set to 217.7 kWh, and the total amount for the minimum required batteries is set to 626.4 kWh, in consideration of the graph in Fig. 3.4 and the power trading between ten microgrids.

Table VIII Value of Symbols

Symbol	Value
i	1,⋯, 48
t	0,⋯, 56
r	0.0001 (0.01% power loss per km)
$\rho(i)$	0.05 (i: Odd), 0.15 (i: Even)
$C(i,j)$	Distance between adjacent prefectural capitals or cities i and j in Japan (km)
$L(i,j)$	1,000 (kWh)
$P(i,t)$	Power supply cycle shown in Fig. 3.2
$D(i,t)$	Power demand cycle shown in Fig. 3.3
$W(i)$	Evaluation 1 and 2: 31.5, 42, 63, 126, 315, 630 (kWh) Evaluation 3: 40–250 (kWh)
M	Evaluation 1 and 2: 20, 15, 10, 5, 2, 1 Evaluation 3: 5, 10, 15, 20
V	217.7 (kWh)
U	626.4 (kWh)

3.4.3. Evaluation Results

3.4.3.1. Comparison of the power loss for a constant total battery capacity

The comparison results between the proposed method considering the transmission distance and charge-discharge efficiency and the method (Route-based method) focusing only on transmission distance is shown in Fig. 3.6. In this evaluation, the total capacity of batteries to be equipped is set to 630 kWh, considering the minimum required battery capacity *U* (626.4 kWh). The combinations of battery capacity and number of microgrids with battery functions are set to (1) 31.5 kWh*20, (2) 42 kWh*15, (3) 63 kWh*10, (4) 126 kWh*5, (5) 315 kWh*2, (6) 630 kWh*1. The power generation amount is controlled to be equal to the demand amount.

As shown in Fig. 3.6, compared with the route-based method considering transmission distance only, the proposed method results in an average of 26.7% improvements in terms of power loss reduction by transmission and charge-discharge. The best result is when the battery function of 126 kWh is deployed to five microgrids. When the battery function of 315 kWh is deployed to two microgrids, the performance results for both methods were the same. The reason is discussed in Sec. 3.5. The calculation result of the optimal arrangement when the battery function of 126 kWh is deployed to five microgrids is shown in Fig. 3.7. The green squares are the optimal positions to deploy the battery functions.

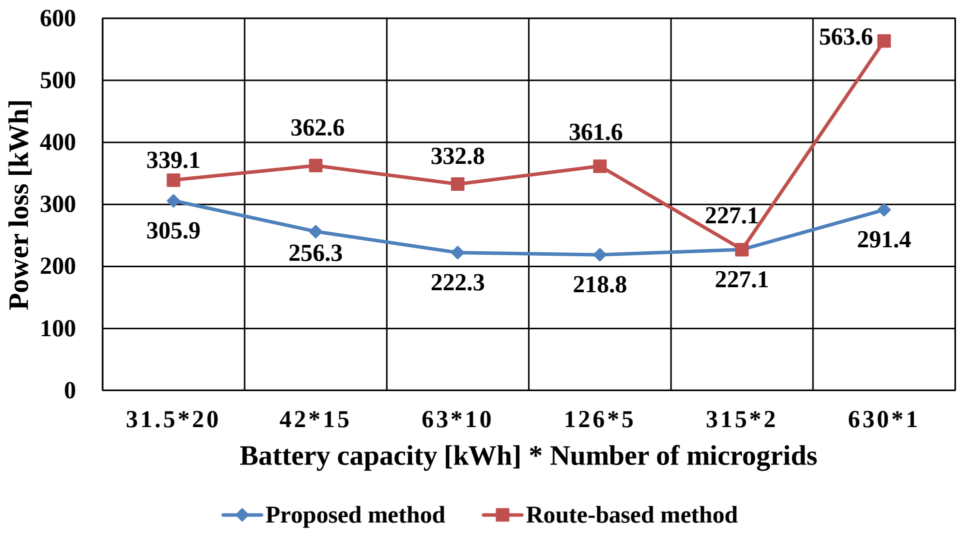

Figure 3.6 Comparison between proposed and route-based methods.

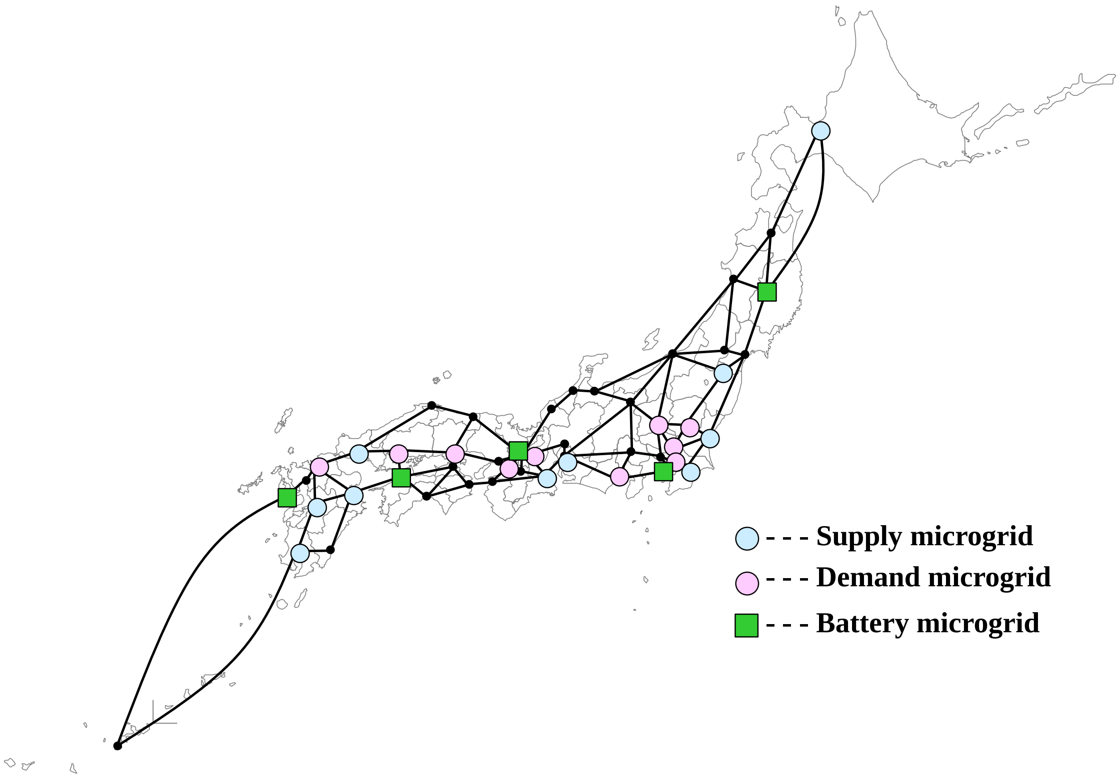

Figure 3.7 Optimal locations of 126 kWh*5 batteries.

3.4.3.2. Power loss evaluation by transmission and charge-discharge to power generation capacity

Figure 3.8 shows the result of comparing the amount of power loss caused by transmission and charge-discharge when the power generation capacity is changed from 1x (Supply 1.0) to 2x (Supply 2.0). The combinations of battery capacity and number of batteries used in the evaluation are the same as those in the previous evaluation. As shown in Fig. 3.8, the best result is when the power generation capacity is twice the demand. For any power generation capacity, deploying the battery function of 126 kWh to five microgrids achieves the best results.

Figure 3.9 shows a comparison of the amount of power supplied by each microgrid for power generation. As a condition, it is possible to supply power up to two times the demand amount. In addition, the battery functions of 126 kWh are deployed to five microgrids. The amount of power supplied by each microgrid resulted in unequal results. Another point of interest was the high-power supply from microgrids (12, 24, 25) in the vicinity of microgrids with high-power demand. When such a control is performed, the power loss by transmission and charge-discharge is minimized.

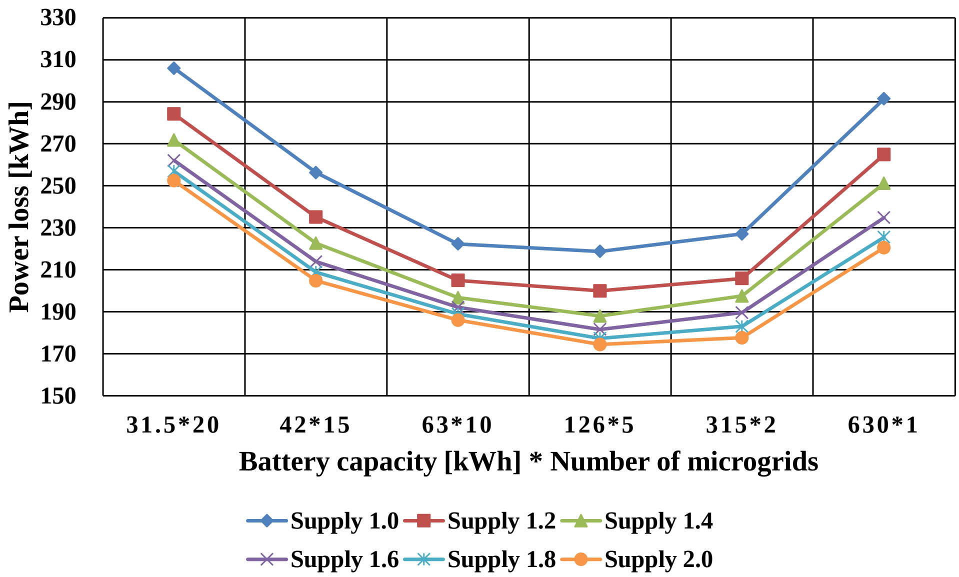

Figure 3.8 Power loss evaluation by changing power supply capability.

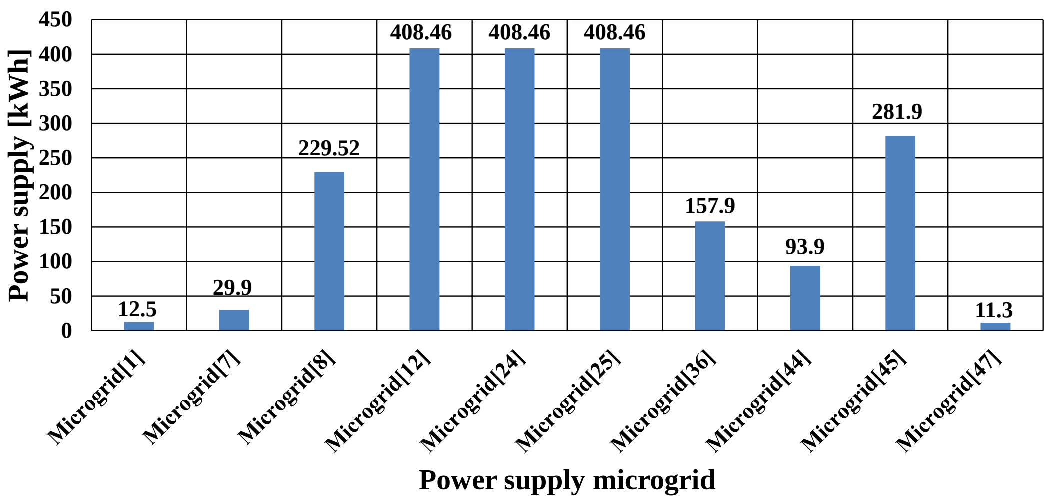

Figure 3.9 Power supply comparison among microgrids in the case of Supply 2.0 with 126 kWh*5 batteries in the microgrids.

3.4.3.3. Power loss evaluation by transmission and charge-discharge by changing total battery capacity

Figure 3.10 shows the results of the evaluation of power loss by transmission and charge-discharge by changing the number of microgrids and each battery capacity. The power supply capability is set to two times the amount of power demand. If the multiplication of each battery capacity and the number of deployments is less than the minimum required capacity U, the optimum value is not calculated.

When the battery functions are deployed to 5, 10, 15, and 20 microgrids, their power loss by transmission and charge-discharge is almost all the same amounts as shown in Fig. 3.10. However, the amount of power loss increased as the capacity of the battery function to be deployed decreases. In particular, when the battery function of 40 kWh is deployed to 20 microgrids, the power loss becomes the result of a surge.

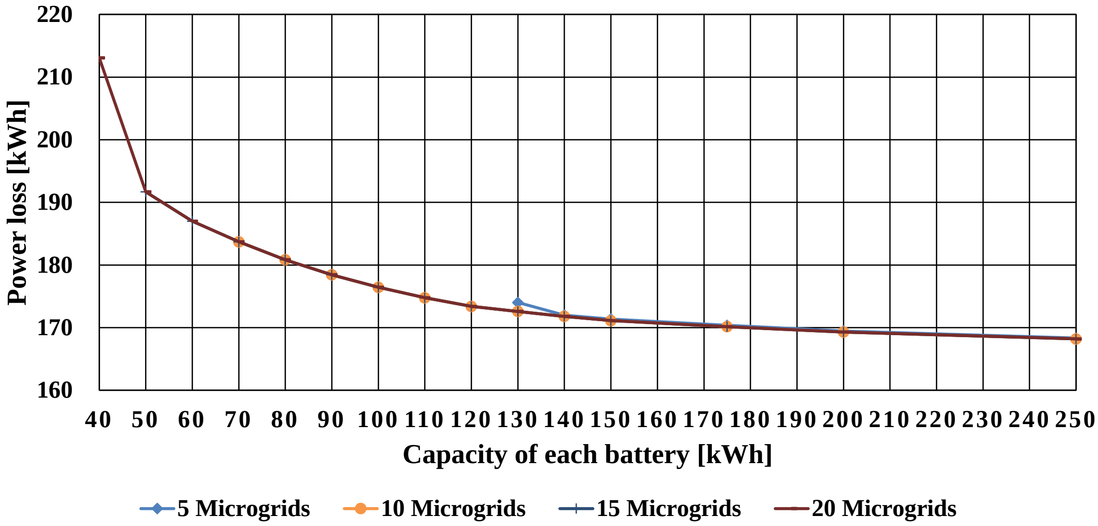

Figure 3.10 Power loss evaluation by changing the capacity of each battery and number of microgrids.

3.5. Discussion of Evaluation Results

From Fig. 3.6, compared with the route-based method considering transmission distance, the proposed method considering transmission distance and charge-discharge efficiency achieved a generally good result. In the route-based method, the charge-discharge functions on the shortest path between power supply and demand microgrids are used. This is the control used even if the battery function used is not efficient. In the proposed method, the battery function is selected so that the power loss by transmission and charge-discharge is minimized. Therefore, it is thought that the proposed method results in reduced power loss. When the battery function of 315 kWh is deployed in two microgrids, both methods have the same result as shown in Fig. 3.6. This is because the battery functions that exist on the shortest route chosen by the root-based method are conveniently all efficient battery functions. When the battery function of 630 kWh is deployed in one microgrid, the power loss in the route-based method is greatly increased. This is the result in which the battery functions that exist on the shortest path are coincidentally inefficient.

As shown in Fig. 3.8, when the power generation capacity is twice as much as the demand, the best result is achieved. In the evaluation, ten microgrids are set up as places to demand power. When each power generation capacity is one-fold to the power demand, it is necessary to supply the maximum power generated from all ten microgrids locations. Also, when the microgrid supplying power is far from that demanding power, the transmission distance and power loss increases accordingly.

When it is assumed that each power generation capacity is double as shown in Fig. 3.9, the power supply amount can be increased in the region where the power demand is high. As a result, it is possible to reduce the power supply from the microgrid that exists far from the region where the power demand is high. Therefore, it is possible to reduce the power loss. In addition, it becomes possible to construct microgrids that increased the amount of equipment for power generation in consideration of both the distribution of the region with a lot of power demand and the that where power generation by renewable energy is easy. Therefore, it is possible to reduce power loss by transmission and charge-discharge.

From Fig. 3.10, the power loss by transmission and charge-discharge resulted in no differences for 5, 10, 15, and 20 microgrids where the battery functions are to be deployed. The results shown in Fig. 3.8 are the best results when the battery function of 126 kWh is deployed to five microgrids in the current evaluation setting. Therefore, if there is sufficient battery capacity, even if the number of battery deployments is increased to more than necessary, it is considered to be a result that does not contribute to power loss reduction. However, when the battery function of 40 kWh is deployed in 20 microgrids, the need to use a non-efficient battery function occurs and the amount of power loss increases greatly.

As shown in the evaluation results of Fig. 3.6, compared with the method for minimizing the transmission distance (Route-based method), the proposed method has become possible to reduce the power loss of 26.7% on average. Therefore, although in part, the effectiveness of the proposed method is considered to have been verified. In this evaluation, when deploying the charge-discharge function to the microgrid of five locations, it is the best result. In addition, in the case of deploying a large number of charge-discharge functions whose capacity is small, or a small number of charge-discharge functions whose capacity is large, it became clear that the power loss due to transmission and charge-discharge is increased. The capacity and number of deployments of the optimal charge-discharge function to minimize the power loss due to transmission and charge-discharge depends on the topology and power trade, etc. Therefore, it is necessary to calculate the capacity and number of the optimal charge-discharge function for each power supply and demand pattern by using the proposed method.

From the evaluation results of Fig. 3.8, if the power generation capacity is higher than the demand amount, it is verified to obtain the reduction of power loss by transmission and charge-discharge. Further, from the evaluation results of Fig. 3.9, it is verified to obtain a high power supply amount from the microgrid close to the microgrid with a large amount of power demand. From the above results, when it is possible to plan the deployment of the power supply amount, and to enhance the power generation capacity in the vicinity of the area with a large power consumption, it was clarified that it is possible to reduce the power loss.

3.6. Conclusion

In this chapter, we investigated a method to reduce power loss and to efficiently use power generated by renewable energy by using battery functions. Specifically, we proposed a method to reduce the power loss due to power trading between multiple microgrids for excessive power generation and shortage of power. In the proposed method, by solving the mathematical programming problem that minimizes the power loss by transmission and charge-discharge, it calculates the optimal arrangement and the use control of multiple battery functions. In addition, in the case where the power generation capacity is surplus to demand, the optimal output control of the power supply function is calculated to reduce the power loss due to power trading.

To evaluate the proposed method, we simulated the interconnected microgrids by connecting multiple prefectures in Japan and evaluated the power loss by transmission and charge-discharge. In the first evaluation, we evaluated the power loss by fixing the total capacity of batteries to be deployed. As a result, we clarified the appropriate combination of each battery capacity and number of microgrids with battery functions to reduce the power loss due to power trading. In the second evaluation, by assuming that the power generation capacity is sufficiently present for demand and that the output from the microgrid supplying power can be controlled, we evaluated the power loss by transmission and charge-discharge. As a result, when the power generation capacity is large for demand, we confirmed that the power loss associated with the power supply can be reduced by controlling the appropriate amount of power generation. In the third evaluation, we evaluated the power loss by transmission and charge-discharge by changing the number of microgrids with battery functions and each battery capacity. When many small battery functions are used, a situation in which a non-efficient battery function is used occurs. This clarified that the power loss associated with power trading would increase substantially.

However, the capacity and number of deployments of the optimal charge-discharge function to minimize the power loss due to transmission and charge-discharge depends on the topology and power trade, etc. Therefore, it is necessary to calculate the capacity and number of the optimal charge-discharge function for each power trade pattern by using the proposed method. As shown by the evaluation results, when it is possible to plan the deployment of the power supply amount, and to enhance the power generation capacity in the vicinity of the area with a large power consumption, it is possible to reduce the power loss. In addition, compared with the method for minimizing the transmission distance (Route-based method), the proposed method has become possible to reduce the power loss of 26.7% on average. Therefore, although in part, the effectiveness of the proposed method is considered to have been verified.

Chapter 4

Long-term Power Loss Reduction for Power Trading between Interconnected Microgrids Considering Deterioration of Charge-discharge Efficiency

4.1. Introduction

In our research [33], [34], we proposed schemes to reduce power loss due to transmission and charge-discharge for a short term. In this chapter, we focus on the interconnected microgrids and propose a high-efficiency power utilization method that reduces the power loss by transmission and charge-discharge for a long term. Specifically, we propose a reduction method of the power loss by transmission and charge-discharge considering the long-term operation and the deterioration of the charge-discharge efficiency.

This chapter is organized as follows. In Sec. 4.2, issues for interconnected microgrids and the policy to solve them are discussed. In Sec. 4.3, the new method to reduce power loss by transmission and charge-discharge for a long term is proposed. Section 4.4 presents the evaluation results of the proposed method. In Sec. 4.5, we discuss the results. We conclude with a summary in Sec. 4.6.

4.2. Issue of Power Trading for Interconnected Microgrids

4.2.1. Overview of Microgrid

Figure 4.1 shows an example of a microgrid that has the same structure shown in Fig. 3.1. Microgrids are interconnected with others via the power switch. If the amount of power generated in a microgrid is greater than that consumed inside, power can be supplied to other microgrids that lack power.

Figure 4.2 shows an example of the changes in the amount of photovoltaic power generation that has the same power supply pattern shown in Fig. 3.2. However, the amount of generation is different. The amount of power generated per day is 120 kWh.

Figure 4.3 shows an example of the changes in electric power consumption that has the same power demand pattern shown in Fig. 3.3. However, the amount of consumption is different. The amount of power consumption per day is 120 kWh. The power consumption in the time zone which does not generate electricity is supported by the power supply from batteries.

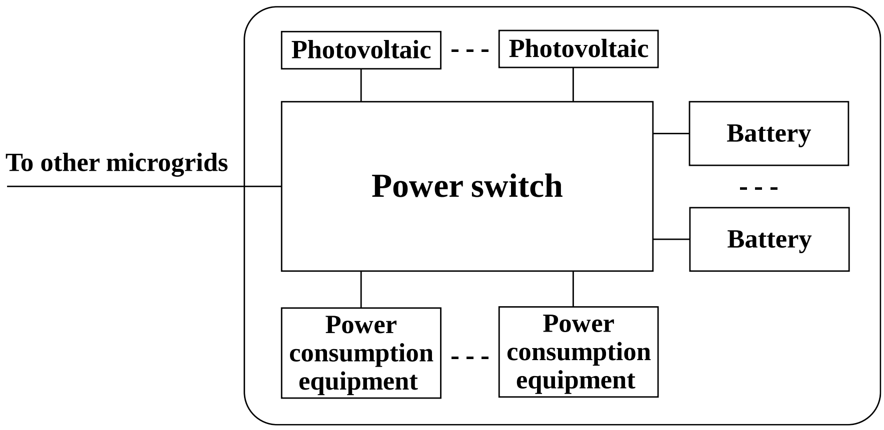

Figure 4.1 Example of a microgrid.

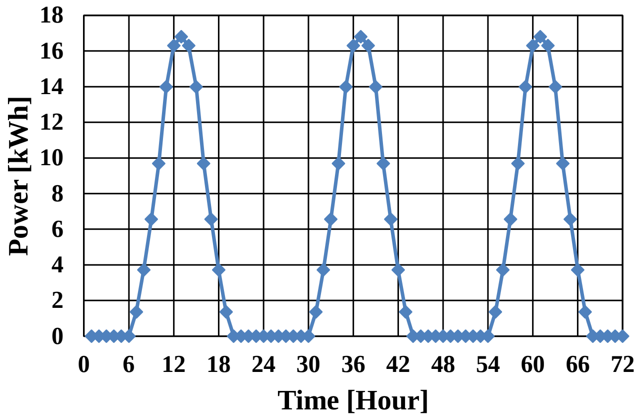

Figure 4.2 Predicted power supply cycle in a microgrid.

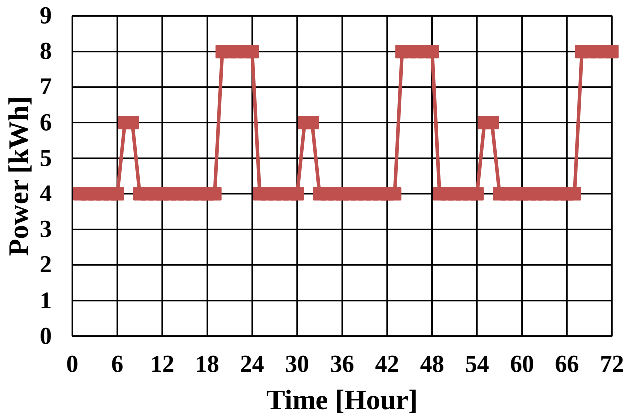

Figure 4.3 Predicted power demand cycle in a microgrid.

4.2.2. Issue for Effective Use of Electric Power

The green line (Battery) in Fig. 4.4 shows the charge-discharge amount required when the power generated is temporarily charged and discharged at required times based on the supply in Fig. 4.2 and demand in Fig. 4.3.

As shown in Fig. 4.2, it is not possible to generate electric power when there is insufficient sunlight, and it cannot correspond to the power demand shown in Fig. 4.3. Therefore, it is necessary to charge to an initial value; this amount is 30.92 kWh as shown in Fig. 4.4.

To effectively use the electric power generated during a day, it is necessary to charge the power during that time and discharge it to cope with a large amount of power demand from the evening onward. In such a situation, the capacity to temporarily charge the unconsumed power is required, which is shown as 73.84 kWh in Fig. 4.4. In the case where the power supply and demand amounts do not match at each point in time, it is necessary to use batteries to shift the power needed.

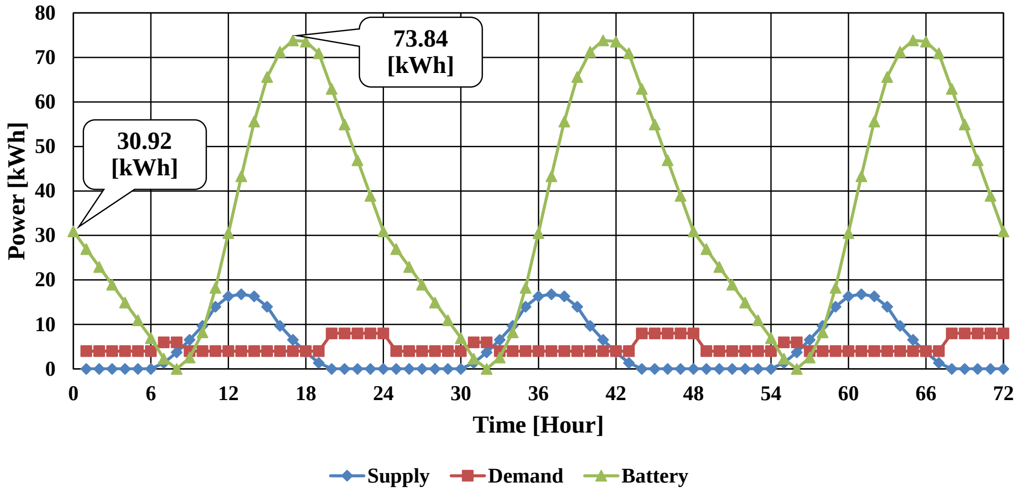

Figure 4.4 Power relation among supply, demand, and battery.

4.2.3. Overview of Interconnected Microgrids and Challenge

An example of interconnected microgrids is shown in Fig. 4.5. Each square with a number corresponds to a microgrid shown in Fig. 4.1. The interconnected microgrids are composed of 49 microgrids and they are connected in lattice form (7x7).

In Fig. 4.5, microgrids (2, 5, 9, 13, 21, 24, 32, 35, 38, 43) that have “S” character represent those in which the power is excessive in the power balance and supplying power to other microgrids is possible. In addition, the amount shown in Fig. 4.2 is used as an example to simulate the power generation pattern caused by sunlight. Microgrids (3, 7, 11, 17, 23, 27, 33, 37, 44, 46) that have “D” character represent those in which the power is insufficient in the power balance, and demand power from other microgrids. In addition, the amount shown in Fig. 4.3 is used as an example to simulate the power demand pattern.

In actual microgrids, the difference between the amount of power generated and that consumed is the amount that can be supplied or demanded. Here, as an example of simulating the different states in different microgrids, the power generation and consumption shown in Figs. 4.2 and 4.3, respectively, are used. In Fig. 4.5, other microgrids with no character represent those in which there is no shortage of power balance, and the power relay is possible.

For each microgrid constituting the interconnected microgrids, if the power supply and demand amounts in each time do not match, a battery function is required to charge the surplus power generated temporarily, corresponding to power demands at different time. However, if the battery function is not deployed in the appropriate position, power loss by transmission can increase. This is because the power is temporarily charged in the battery that exists along the path, which is not the shortest, between the power supply and demand microgrids.

In addition, power loss also increases if low-efficiency batteries are used to charge excess power and to discharge it when it is needed. Besides, it is necessary to consider the deterioration of the charge-discharge efficiency for a long term. Therefore, it is necessary to reduce the power loss by using an appropriate battery function in the power trading between interconnected microgrids.

We propose a scheme to reduce the power loss due to transmission and charge-discharge considering the deterioration of the charge-discharge efficiency by deciding appropriated battery location and power transmission for a long term.

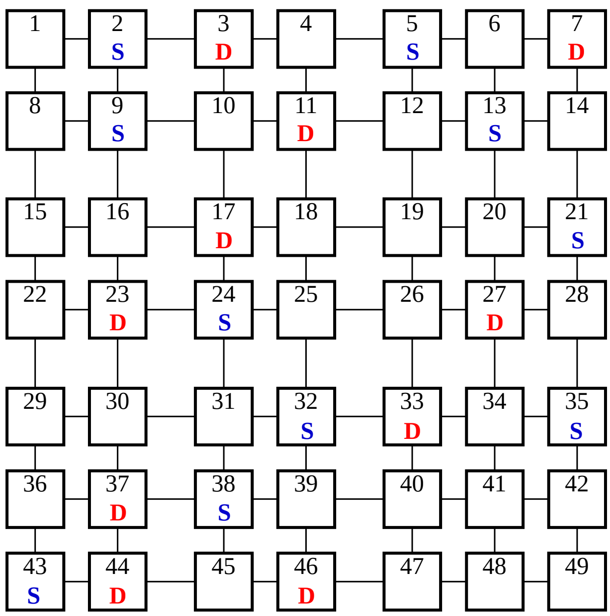

Figure 4.5 Example of interconnected microgrids.

4.2.4. Control Policy of Power Transmission, Charge, and Discharge

Transmission power loss is assumed to be proportional to the amount of power transmitted and the transmission distance. It is also assumed to be generated by the amount of charging and discharging. Moreover, it is assumed that the charge-discharge efficiency deteriorates in proportion to the amount of power charged-discharged. Therefore, as an objective function for evaluations, we will reduce the power loss by transmission and charge-discharge.

Specifically, when the power from the power-supply microgrid is charged to the battery function or consumed by the power-demand microgrid, proper transmission amount, transmission path, location of batteries, and charge-discharge amount are determined to reduce the power loss. In addition, based on the constraints such as the number of deployments and capacity of the specified charge-discharge function, the objective function is reduced to the total amount of power transmitted between microgrids.

4.3. Proposal of a Method to Reduce Power Loss for a Long Term

This section presents a method to reduce the power loss due to transmission and charge-discharge for a long term by using a mathematical programming model. We define symbols to describe defined conditions and decision valuables to reduce the power loss. In order to reduce the power loss for a long term, an objective function that is a nonlinear is defined. In addition, to calculate the power loss reduction by the objective function, we propose a scheme for calculating approximate values for the nonlinear function.

4.3.1. List of Symbols for Evaluation Model

Table IX shows a list of symbols specified for calculating the solution of the mathematical programming problem that reduces the power loss by transmission, charge, and discharge. i indicates the microgrid number. When the time range to be evaluated is divided into T slots, t indicates the slot number. In addition, t=0 indicates the state of the initial value. r represents the loss rate of power to transmission per km. $\rho(i,t)$ represents the power loss rate for charge or discharge after charging or discharging in microgrid i in time slot t. e indicates the deterioration rate of charge or discharge efficiency caused by charging and discharging.

$C(i,j)$ shows the distance between adjacent microgrid i and j in the configuration where multiple microgrids are connected to each other. $L(i,j)$ shows the upper limit of the amount of power that can be transmitted between adjacent microgrids i and j. $P(i,t)$ shows the amount of power supplied by microgrid i in time slot t. $D(i,t)$ shows the amount of power consumed by microgrid i in time slot t. $W(i)$ shows the capacity of the charge-discharge deployed in microgrid i.

M represents the total number of microgrids with battery functions. V represents the total amount of charge as the initial value for supplying the power consumed before power generation for all microgrids. U represents the minimum required total charge capacity to charge the surplus power generated during the evaluation period.

Table IX List of Symbols

Symbol	Definition
i	Number of microgrid ($i = 1,\cdots, N$)
t	Number of time slot ($t = 0,\cdots, T$)
r	Power loss rate per km due to transmission
$\rho(i,t)$	Power loss rate for charge or discharge after charging or discharging in microgrid i in time slot t
e	Deterioration rate of charge or discharge efficiency caused by charging and discharging
$C(i,j)$	Distance between adjacent microgrid i and j (km)
$L(i,j)$	Limit of transmission amount between adjacent microgrid i and j (kWh)
$P(i,t)$	Amount of power supplied from microgrid i in time slot t (kWh)
$D(i,t)$	Amount of power consumed by microgrid i in time slot t (kWh)
$W(i)$	Battery capacity in microgrid i (kWh)
M	Number of microgrids with distributed battery functions, ($0<M<N$)
V	Initial value of the total amount of power in the distributed batteries (kWh)
U	Necessary capacity of the distributed batteries (kWh)

4.3.2. List of Decision Variables for Evaluation Model

The purpose of this chapter is to determine the proper placement of the battery function to reduce the power loss by transmission and charge-discharge. Therefore, it is necessary to have a variable whether to allocate the battery function for each microgrid. Since the electric power loss by transmission is dependent on the amount of power transmitted, variables are needed to reduce the amount of power transmitted between microgrids for each time. In addition, variables are needed to decide charge or discharge power for each time. By setting variables to determine the proper battery position, transmission amount, and charged electric power, it is possible to evaluate the power loss by transmission and charge-discharge.

The decision variables listed in Table X are determined by an objective function described as follows. The value of $\delta(i)$ is determined to be 1 or 0 if the battery function is deployed or not, respectively, in microgrid i. $Q(i,j,t)$ determines the amount of power transmitted from adjacent microgrid i to j in time slot t. $B(i,t)$ determines the amount of power remaining in the battery function of microgrid i in time slot t. i of $\delta(i)$ and $B(i,t)$ indicates the number of the microgrid for the relay that does not supply and demand power.

Table X List of Decision Variables

Variable	Definition
$\delta(i)$	Deployment/No deployment of battery in microgrid i (1/0)
$Q(i,j,t)$	Amount of power transmitted from adjacent microgrid i to j in time slot t (kWh)
$B(i,t)$	Amount of power remaining in the battery of microgrid i in time slot t (kWh)

4.3.3. Objective Function and Constraints

The proposed system aims to reduce power loss by transmission and charge-discharge as described in the previous section. The decision variables are decided by formulating and evaluating the objective function of a mathematical programming problem.

The objective function is shown as follows. In equation (4-1a), $r*C(i,j)Q(i,j,t)$ indicates the amount of transmission power loss. $\rho(i,t-1)|B(i,t)-B(i,t-1)|$ indicates the amount of power loss due to charge-discharge. Equation (4-1b) shows the detail of $\rho(i,t)$ in equation (4-1a). $\rho(i,t)$ indicates a power loss rate for charge or discharge after charging or discharging in microgrid i in time slot t. $\rho(i,0)$ indicates initial value of power loss rate for charge or discharge.

$Minimize$

$$\sum_{t=1}^{T}\sum_{i=1,i\neq j}^{N}\{r * C(i,j)Q(i,j,t)\} +$$

$$\sum_{t=1}^{T}\sum_{i=1}^{N}\{\rho(i,t-1)|B(i,t)-B(i,t-1)|\} \qquad (4-1a)$$

$$\rho(i,t) = \rho(i,t-1) + e\{|B(i,t)-B(i,t-1)|\} \quad (t \geq 1) \qquad (4-1\text{b})$$

The constraints are described as follows.

1) Power balance condition: In time *t*, the amount of power supply and demand in microgrid *i* is equal to the sum of the power quantities *Q*(*k,i,t*) and (-1)**Q*(*i,k,t*), and (*B*(*i,t-1*)-*B*(*i,t*)). *Q*(*k,i,t*) represents the amount of power flowing from adjacent microgrid *k*. *Q*(*i,k,t*) represents the amount of power flowing into microgrid *k*. *B*(*i,t*-1)-*B*(*i,t*) indicates the amount of charge change in the battery. The supply amount from the microgrid supplying power is equal to (-1)**P*(*i,t*). The amount of power consumed by the microgrid that requires power is equal to *D*(*i,t*). In addition, the power balance is zero in microgrids for the relay that does not supply nor demand power.

$$\sum_{k}Q(k,i,t) - \sum_{k}Q(i,k,t) + B(i,t-1) - B(i,t)$$
$$= D(i,t) - P(i,t) \qquad (4-2)$$

2) Transmission quantity condition: In time *t*, the amount of power *Q*(*i,j,t*) that is transmitted from adjacent microgrid *i* to *j* is less than or equal to the maximum value *L*(*i,j*) that can be transmitted.

$$0 \leqq Q(i,j,t) \leqq L(i,j) \qquad (4-3)$$

3) Battery function number condition: The number of microgrids for the relay to deploy the battery function is less than or equal to the specified number *M*.

$$\sum_{i=1}^{N} \delta(i) \leqq M \qquad (4-4)$$

4) Charge and discharge quantity condition: In time t, the amount of power $B(i,t)$ charged to microgrid i with the battery function is less than or equal to the specified capacitance $W(i)$ $\delta(i)$.

$$0 \leqq B(i,t) \leqq W(i)\delta(i) \qquad (4-5)$$

5) Initial value of charge amount condition: The sum of the charge amount $B(i,0)$ is equal to the specified initial power amount value V to supply the power required before power generation.

$$\sum_{i=1}^{N} B(i,0) = V \qquad (4-6)$$

6) Capacity condition for battery function: The total capacity of the battery functions to be deployed is at least the minimum charge-discharge capacity U required to temporarily charge and hold surplus power generated during the period of evaluation.

$$\sum_{i=1}^{N} W(i)\delta(i) \geqq U \qquad (4-7)$$

4.3.4. Evaluation Policy

Equation (4-1) is a quadratic expression of the amount of change in charge-discharge. In addition, the constraint conditions include an integer variable to decide whether to deploy or not a battery function for each microgrid. Equality and inequality constraints are also included. Therefore, this problem is a nonlinear problem of the integer mixture type and very complicated. On top of this, in the interconnected microgrid as shown in

Fig. 4.5, the number of decision variables is enormous when calculating a solution to meet the long-term power loss reduction such as 1000 days.

For example, in the topology shown in Fig. 4.5, there are 84 links to connect the microgrids, and they need to determine the transmission amount in two directions, and a total of 168 decision variables exist. We also need to determine the amount of charge for the 29 microgrids that exist as microgrids for relaying, and there are 29 decision variables. If the above variables are determined for 24 hours and about 1000 days, there are decision variables for the total 4,728,000 ((168 + 29) * 24 * 1000). In addition, it is also necessary to decide whether to deploy the battery function to 29 of the relay microgrids.

Therefore, we propose a method to calculate the approximation to equation (4-1) in a simple and fast manner.

4.3.5. Proposal for reduction of power loss considering charge-discharge efficiency deterioration

Figure 4.6 shows a method to reduce power loss due to transmission and charge-discharge, considering the deterioration of charge-discharge efficiency for a long term. In this method, for example, if the evaluation process of 1000 days is performed, the optimization process of one day is executed 1000 times. Specifically, the deterioration of the charge-discharge function after power trading for one day is calculated and used for the next optimization, and this procedure is repeated for 1000 days. In addition, microgrids that deployed the battery function calculated in the optimization processing of each day are recorded, and the evaluation of 1000 days is executed to avoid exceeding the specified number of the microgrids.

In our case, as a prerequisite, the amount of electricity generation and consumption per day is equal by using a charge-discharge function although the amount of electricity generation and consumption per hour is not equal as shown in Fig. 4.4. This is because we are assuming a power balance control for supply and demand for each day based on a contract between power supply and demand. Therefore, even if the processing to execute the optimization every day is performed, it is thought that the approximation of the power loss calculation for evaluating power loss generation tendency is possible. In addition, a long-term evaluation is carried out that adheres to the constraint equation such as the upper capacity of charge-discharge function. As a result, it is possible to evaluate tendency of power loss generation while complying with the specified constraints by using the optimization for each day.

On the other hand, if there is a surplus supply power in the case of the evaluation per day, it is thought that the processing of whether to charge-hold or dispose of the surplus power is necessary. In this case, the appropriate control depends on how long the power balance between the power supply and demand is assessed. For example, if the power balance is assessed every week, it is possible to execute a long-term evaluation by repeating a weekly optimization. Thus, by setting the optimization period according to the balance period of the power trading, it is considered possible evaluation. And it is not always necessary to fix the evaluation period, and if the evaluation period fluctuates, it is possible to cope with the method of performing optimization according to it.

However, if one optimization period is prolonged, deterioration of the charge-discharge efficiency will not be renewed in the meantime, and it is likely that the amount of generated power losses will be underestimated. Therefore, it is considered desirable to update the charge-discharge efficiency in a short period of time. When repeating the processing of optimization, in the next optimization, the deterioration of the charge-discharge efficiency is incorporated based on the amount of the charge and discharge power. Therefore, in view of the trend of power loss generation by transmission and charge-discharge, it is considered possible evaluation.

The processing of the proposed method is described in detail in accordance with the figure below.

A) The process to reduce the power loss is started.
B) The initial settings required to perform the optimization for one day are performed. Specifically, in the interconnected microgrid, the distance between microgrids, the power loss rate due to transmission, the initial value of the power loss rate due to charge or discharge, and constants such as evaluation period are set.
C) The objective function to evaluate the power loss by transmission and charge-discharge for one day is set.
D) The constraint conditions such as power supply and demand, power transmission between microgrids, and the number of microgrids with battery function are set.
E) Transmission and charge-discharge control to minimize the power loss for one day are calculated by using the objective function.
F) Microgrids that deployed the battery function by the optimization for one day are recorded.

G) The number of microgrids that deployed the battery function is determined whether the specified upper limit has been reached. If the specified limit is reached, processing H) is executed, and if the maximum limit is not reached, the processing I) is executed.

H) If the number of microgrids with battery functions reaches the specified upper limit, candidates for microgrids that can be deployed for battery functions are limited in accordance with the history.

I) It is determined whether performed evaluation of the specified time period. If the evaluation is performed, the power loss evaluation is terminated as processing M). If it is determined that the planned evaluation has not been completed, processing J) is executed.

J) Deterioration of the charge-discharge function is calculated based on the charge and discharge amount utilized.

K) In accordance with the deterioration of the charge-discharge function, the loss rate of the power by charging or discharging in the next optimization process for one day is updated.

L) History of the deployment position for the battery functions that have been used in the past is recorded.

M) The process to reduce the power loss is terminated.

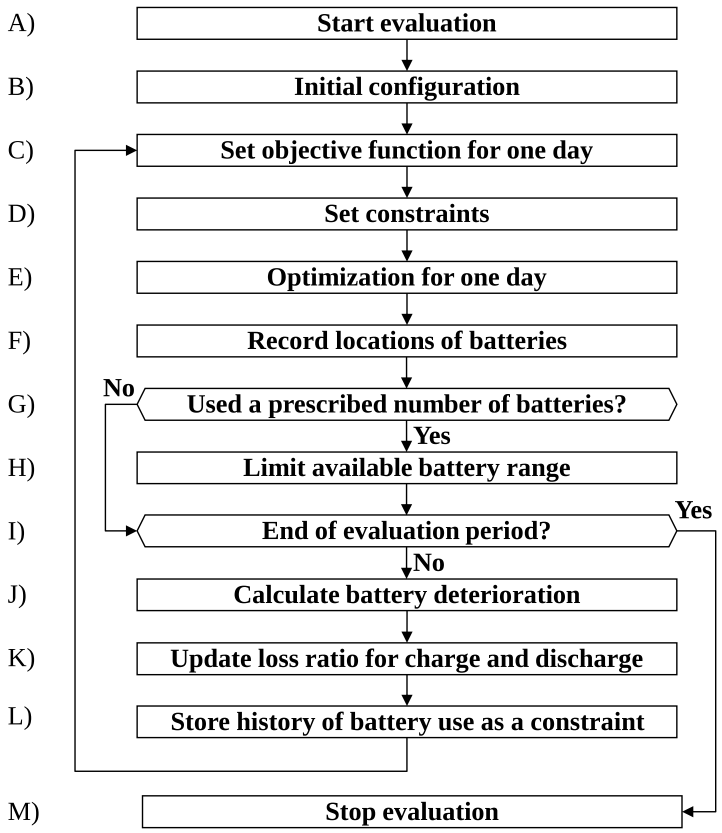

Figure 4.6 Power loss reduction method.

4.4. Evaluation and Results

4.4.1. Overview of Evaluation

First, the relationship between the allocations of battery functions deployed to the interconnected microgrids and the power loss is clarified in order to reduce the long-term power loss by transmission and charge-discharge. In this evaluation, we change each battery capacity and the number of battery functions to be deployed to the interconnected microgrids, and compare the value of the objective function for each case, and evaluate the proper capacity and the number of the battery functions. In particular, a large number of small battery functions of the capacity and a small number of large battery functions of the capacity are evaluated. It is clarified which case has a high effect of reducing the long-term power loss by transmission and charge-discharge. Therefore, the product of the number of microgrids (M) and each battery capacity $W(i)$ is fixed to a constant value. The effect of the long-term power loss reduction is evaluated by changing the combination of the number of microgrids (M) and each battery capacity $W(i)$. In this evaluation, the product of the number of microgrids (M) and each battery capacity $W(i)$ is set by considering the value of U that is the minimum required capacity.

Second, in the case where the amount of battery capacity to be deployed is redundant to the minimum required capacity, it is evaluated the effect of reducing the long-term power loss. In order to continue power trading even in the case where some battery functions don't work, it is thought that battery functions with redundant capacity are deployed. Therefore, in this evaluation, the product of the number of microgrids (M) and each battery capacity $W(i)$ is set to about twice of U that is the minimum required capacity. The effect of the long-term power loss reduction is evaluated by changing the combination of the number of microgrids (M) and each battery capacity $W(i)$.

4.4.2. Evaluation Model

Table XI shows a list of the set values for the defined symbols. To decide a topology for the interconnected microgrids, we consider the number of prefectures in Japan and conditions of research [41], [42], [43] that respectively used 18 distribution power networks, 21 regions, and 34 nodes,. As a result, we use the configuration shown in Fig. 4.7 as the interconnected microgrids for the evaluation. Specifically, the number of microgrids N to be deployed is 49. The microgrids for power supply and demand are set to 10 locations, respectively.

For the time slots to be evaluated, the cycle of charge amount shown in Fig. 4.4 is considered. Specifically, the power loss is evaluated from t=8 to 32 to eliminate the effect of the initial charge amount. In addition, the time number is shifted by 8. Then the new time number is from t=0 to 24. In the evaluation, this one-day power trading is repeated for 1000 days.

The power loss r by transmission is set to 0.01% (0.0001) as it is proportion to the transmission length by considering information of [36], [48]. For the power loss rate $\rho(i,t)$ by charge or discharge, as initial value (t=0), 5% of the power loss is set when the number i of a microgrid is odd, and 15% of the power loss is set when i is even by considering information of [49]. When t equals to 1 or more, it is set to increase according to the amount of power charged and discharged as shown in Equation (4-1b). For e, the deterioration rate for charge or discharge is set to 5% (equivalent to about 10% for charge-discharge) when the charge-discharge procedure is executed in 1000 times of battery capacity $W(i)$. When the charge and discharge for the battery capacity is executed for each day, 1000 times is equivalent to less than three years.

The distance $C(i,j)$ between adjacent microgrids is set 10 km or 50 km as shown in Fig. 4.7. The upper limit of the transmission amount $L(i,j)$ is set to 1,000 kWh as there is sufficient power transmission capacity in this evaluation. As a pattern 1, power is supplied from 10 microgrids (i = 2, 5, 9, 13, 21, 24, 32, 35, 38, 43) and the amount of power generated shown in Fig. 4.2 is used as $P(i,t)$ for every power-supply microgrids. In addition, as a pattern 1, power is consumed at 10 microgrids (i = 3, 7, 11, 17, 23, 27, 33, 37, 44, 46) and the amount of power consumed shown in Fig. 4.3 is used as $D(i,t)$ for every power-demand microgrids. In the evaluation 1, a combination of battery capacity $W(i)$ and the number of microgrids with battery functions (M) is set as 37.5*20, 50*15, 75*10, 150*5, 375*2, and 750*1. In the evaluation 2, a combination of them is set as 75*20, 150*10, 375*4, and 750*2.

In the evaluation, a term from t=8 to 32 is repeated for 1000 times. Therefore, the amount of power (V), for which the battery function is initially charged, is 0 kWh. The total amount for the minimum required batteries is set to 738.4 kWh, in consideration of the graph in Fig. 4.4 and the power trading between ten microgrids.

Table XI Value of Symbols

Symbol	Value
i	1,⋯, 49
t	0,⋯, 24 (24 hours, 1000 days)
r	0.0001 (0.01% power loss per km)
$\rho(i,t)$	Refer to equation (4-1b): 0.05 (i: Odd), 0.15 (i: Even) at t = 0
e	0.05 for each W(i)*1000*2
$C(i,j)$	Distance between adjacent microgrids i and j as shown in Fig. 4.7 (10km/50km)
$L(i,j)$	1,000 (kWh)
$P(i,t)$	Power supply cycle shown in Fig. 4.2: i = 2, 5, 9, 13, 21, 24, 32, 35, 38, 43 (Pattern 1 shown in Fig. 4.7) (kWh)
$D(i,t)$	Power demand cycle shown in Fig. 4.3: i = 3, 7, 11, 17, 23, 27, 33, 37, 44, 46 (Pattern 1 shown in Fig. 4.7) (kWh)
$W(i)$	Evaluation 1: 37.5, 50, 75, 150, 375, 750 (kWh) Evaluation 2: 75, 150, 375, 750 (kWh)
M	Evaluation 1: 20, 15, 10, 5, 2, 1, Evaluation 2: 20, 10, 4, 2

V	0 (kWh)
U	738.4 (kWh)

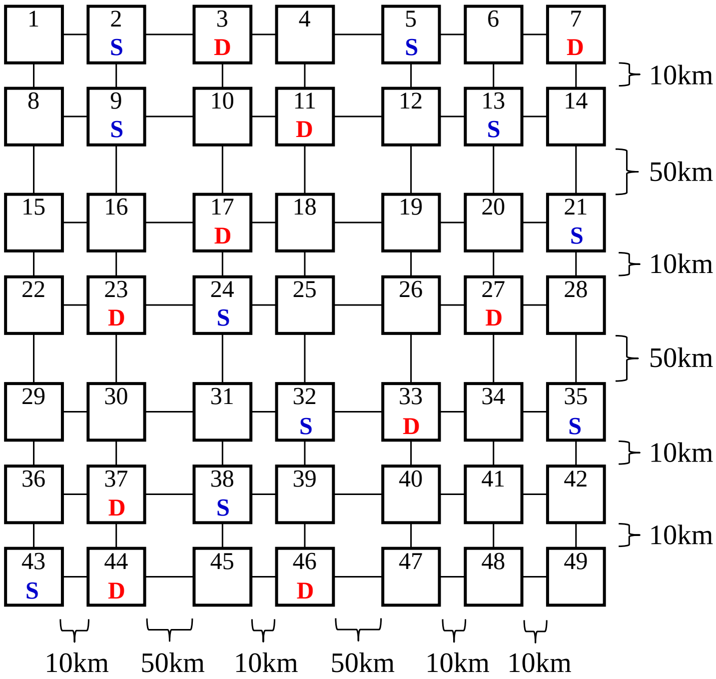

Figure 4.7 Distance between microgrids.

4.4.3. Evaluation Results

4.4.3.1. Power loss evaluation to combination of battery capacity and the number of microgrids to deploy battery functions

Figure 4.8 shows the result of the evaluation of the amount of power loss for each day for the combination of battery capacity and the number of microgrids. In this evaluation, a total battery capacity for the combination of each battery capacity and the number of microgrids is set 750 kWh by considering minimum required capacity (U). In the evaluation shown in Fig. 4.8, a total of five patterns combined with four different patterns than that shown in Fig. 4.7 are evaluated, and the average value is shown as the result.

It was confirmed that the amount of power loss of each day continued to increase from the evaluation result of 1000 days. When the battery function of 75 kWh is deployed to 10 microgrids, the amount of power loss at each day is smaller than others. When a small battery function of the capacity is deployed in 20 microgrids, the amount of power loss at each day is increased compared with other cases.

Figure 4.9 shows the result of the evaluation of the amount of accumulated power loss for each day for the combination of battery capacity and the number of microgrids. In this evaluation, a total battery capacity for the combination of each battery capacity and the number of microgrids is set 750 kWh. In the evaluation shown in Fig. 4.9, a total of five patterns combined with four different patterns than that shown in Fig. 4.7 are evaluated, and the average value is shown as the result.

From the evaluation results of 1000 days, the amount of accumulated power loss continued to increase, and the increase was confirmed as shown in Fig. 4.8. When the battery function of 75 kWh is deployed to 10 microgrids, the accumulated amount of power loss at each day is smaller than others. When a small battery function of the capacity is deployed in 20 microgrids, the accumulated amount of power loss at each day is increased compared with other cases.

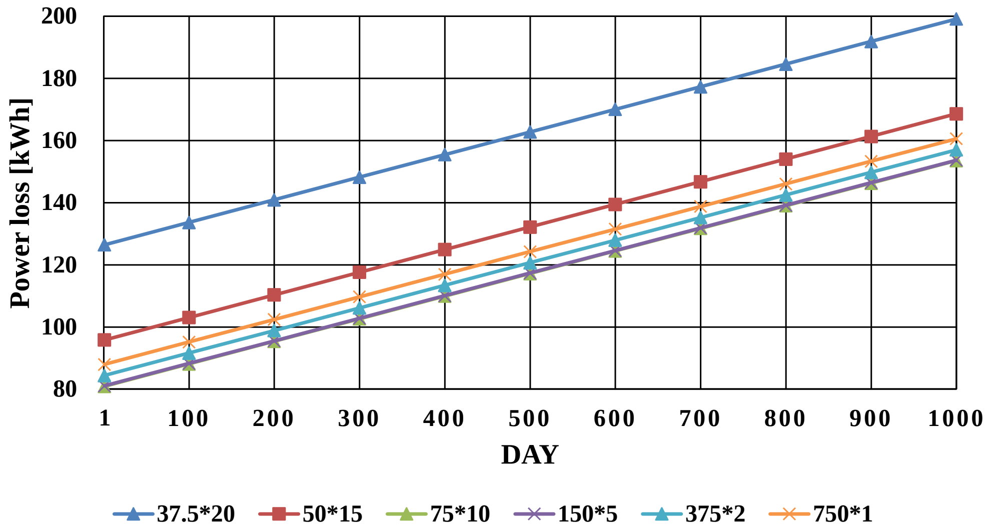

Figure 4.8 Evaluation of power loss for each day at the capacity required for charge-discharge.

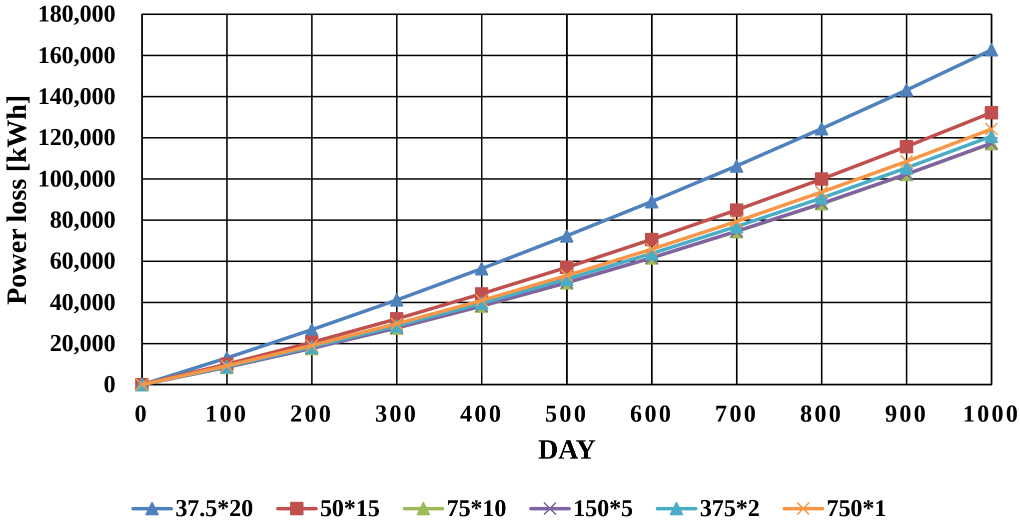

Figure 4.9 Evaluation of accumulated power loss at the capacity required for charge-discharge.

4.4.3.2. Power loss evaluation in the case of redundant battery capacity

Figure 4.10 shows the result of the evaluation of the amount of power loss for each day for the combination of battery capacity and the number of microgrids. In this evaluation, a total battery capacity for the combination of each battery capacity and the number of microgrids is set 1500 kWh that is about twice of the minimum required capacity (*U*) as redundant battery capacity. In the evaluation shown in Fig. 4.10, a total of five patterns combined with four different patterns than that shown in Fig. 4.7 are evaluated, and the average value is shown as the result.

When the battery function of 150 kWh is deployed to ten microgrids, the amount of power loss at each day is smaller than others. In addition, when the battery function of 75 kWh is deployed to 20 microgrids, the amount of power loss on each day after 124 days was very large.

Figure 4.11 shows the result of the evaluation of the amount of accumulated power loss for each day for the combination of battery capacity and the number of microgrids. In this evaluation, a total battery capacity for the combination of each battery capacity and the number of microgrids is set 1500 kWh. In the evaluation shown in Fig. 4.11, a total of five patterns combined with four different patterns than that shown in Fig. 4.7 are evaluated, and the average value is shown as the result.

When the battery function of 150 kWh is deployed to 10 microgrids, the accumulated amount of power loss at each day is smaller than others. In addition, when the battery function of 75 kWh is deployed to 20 microgrids, the accumulated amount of power loss on each day after 257 days was very large.

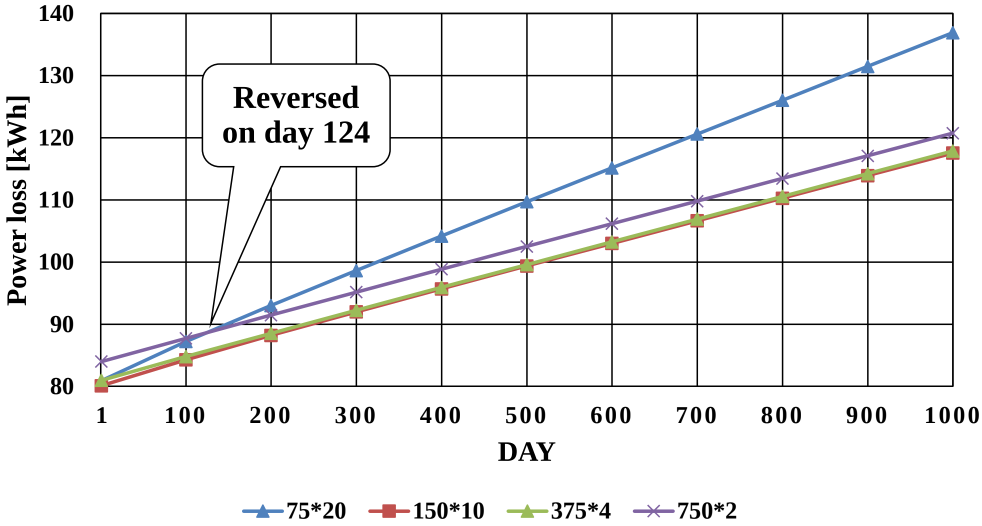

Figure 4.10 Evaluation of power loss for each day at about twice the capacity required for charge-discharge.

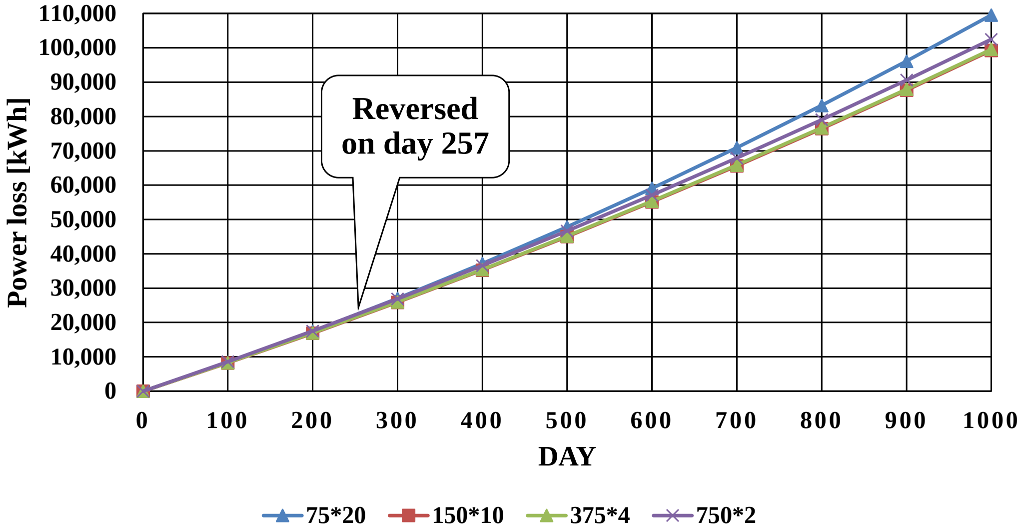

Figure 4.11 Evaluation of accumulated power loss at about twice the capacity required for charge-discharge.

4.5. Discussion of Evaluation Results

In the evaluations shown in Figs. 4.8 and 4.9, when the battery function of 75 kWh was deployed to 10 microgrids, the amount of long-term power loss was reduced compared with other results. When the capacity of 37.5 kWh and 50 kWh of battery function was deployed in 20 and 15 microgrids, respectively, the amount of long-term power loss was increased.

In these evaluations, microgrids for the relay which do not supply and demand of power are set up as candidate places for deploying the battery function. Therefore, 29 relay microgrids are candidates for the battery function. As the initial rate of charge and discharge efficiency for battery functions deployed in the relay microgrids whose identifiers are odd numbers, the power loss of 5% is set. On the other hand, as the initial rate of charge and discharge efficiency for the relay microgrids whose identifiers are even numbers, the power loss of 15% is set. In this evaluation, five patterns of topology are evaluated. The relay microgrid that is equipped with a good efficient charge-discharge function exists in 13.6 locations as an average. On the other hand, there are 15.4 locations as an average for relay microgrids that are equipped with a charge-discharge function that is not efficient. When the battery function of the capacity of 37.5 kWh or 50 kWh is deployed in 20 or 15 microgrids, respectively, it is necessary to use a charge-discharge function that is not efficient. Therefore, it is thought that power loss increased.

In these evaluations, the battery function of 750 kWh that is equivalent to the minimum required capacity is only deployed. Therefore, it is necessary to use the deployment setting of the battery function determined by the calculation of the first day to reduce the power loss for the long-term. Continuous use is performed for the battery function deployment selected on the first day, and the charge-discharge efficiency deteriorates continuously. It is thought that the performance for power loss reduction to the combination of battery capacity and the number of microgrids is decided on the first day and continues for a long term. Therefore, in the case of deploying a battery function of 75kWh in 10 microgrids, the long-term power loss by transmission and charge-discharge is considered to be smaller than others.

In the evaluations shown in Figs. 4.10 and 4.11, when the battery function of 150 kWh was deployed to ten microgrids, the amount of long-term power loss was reduced compared with other results. In these evaluations, the battery function of 1500 kWh that is equivalent to about the twice capacity to the minimum required capacity is deployed.

Therefore, within the specified number of microgrids for relay to deploy the battery function, it is possible to use different battery functions on each evaluation term.

However, the efficient battery function has only been deployed in 13.6 relay microgrids as an average. Even if the battery function with a small capacity of 75 kWh can be deployed to 20 relay microgrids, it is considered that the efficient 13.6 relay microgrids are mainly used. Therefore, the use of a portion of the total battery capacity that can be used is repeated, and the efficiency of the battery function utilized is rapidly deteriorated. As a result, when the battery function of 75 kWh is deployed to 20 relay microgrids, compared with the case of the combination of other battery capacity and number of deployments, long-term power loss amount is expected to increase.

In particular, from the results of Fig. 4.10, when the battery function of 75 kWh is deployed in 20 microgrids, compared with the case of deploying the battery function of 750 kWh in 2 microgrids, the amount of power loss generated on each day is small until the 123 days. When the battery function of 750 kWh is deployed in 2 microgrids, the amount of power loss as a whole is likely to be high in the initial stage due to the large amount of power loss by the transmission distance. On the other hand, as described above, when the battery function of 75 kWh is deployed in 20 microgrids, it is thought that the charge-discharge efficiency of the battery functions deteriorates rapidly because it continues to use the part of the battery functions that are available. As a result, in the case of deploying the battery function of 75 kWh in 20 microgrids, it is thought that the amount of power loss generated for each day became larger than others after 124 days. In addition, from the results of Fig. 4.11, it is thought that the accumulated amount of power loss became larger than others after 257 days.

From the above evaluation results, when deploying the charge-discharge function of a small volume to many microgrids, the possibility of utilizing an inefficient charge-discharge function is increased. Also, the power loss amount due to transmission and charge-discharge is increased even in the case of deploying a large capacity of the charge-discharge function to a few microgrids. Therefore, it is necessary to deploy the charge-discharge function in a range between not extremely at least and not too much compared with the number of microgrids to be supply and demand. Further, by performing the charge-discharge function deployment of the capacity to be selected only an efficient charge-discharge function, it is possible to reduce the power loss amount by transmission and charge-discharge.

4.6. Conclusion

In this chapter, we proposed a high-efficiency power utilization method to reduce the power loss by long-term transmission and charge-discharge by considering the deterioration of the battery function for the interconnected microgrids. In the proposed method, the amount of power loss generated by transmission and charge-discharge is set as the objective function, and the optimization process of one day is repeated. Moreover, the long-term power loss reduction is evaluated by calculating and retaining the deterioration of the battery function by the charge-discharge execution of power, and using it in the next optimization for one day.

For the evaluation of the proposed method, 49 microgrids were targeted for the topology connected to lattice-like (7x7). We have verified that it is possible to calculate deployment of battery functions and transmission routes to reduce the amount of power loss due to transmission and charge-discharge for 1000 days.

In order to reduce the amount of the power loss, it is necessary to deploy the charge-discharge function in a range between not extremely at least and not too much compared with the number of microgrids to be supply and demand. Further, by performing the charge-discharge function deployment of the capacity to be selected only an efficient charge-discharge function, it is possible to reduce the power loss amount by transmission and charge-discharge.

In addition, we evaluated the amount of power loss for the combinations of battery capacity and the number of deployments. When the charge-discharge efficiency deterioration by the charging and discharging was advanced, it was confirmed that "power loss amount generated on each day" and "accumulation of power loss amount" are reversed during the evaluation period among the combinations of battery capacity and the number of deployments of it. As a result, it was clarified that the use setting of the battery function based on long-term evaluation is necessary.

Chapter 5

Effective Utilization for Color-managed Electric Power by Optimized Battery Location and Transmission Management

5.1. Introduction

Net zero emission to reduce greenhouse gases is being promoted as a global direction. Increasing of the utilization rate for renewable energy (RE) to power consumption is being promoted. However, the use of electric power generated by RE, and the use of charge-discharge equipment has problems such as stability and costs of power generation.

Therefore, it is desirable to use a variety of power supplies. Moreover, since the amount of power generated by RE varies, the power consumption by RE might be controlled according to the amount of power generated. As a result, the utilization rate of RE is likely to be set at various values depending on the situation of power generation and consumption.

In the supply and demand of electric power, it is thought that the generated power is only consumed to the demand amount even if the power generation capacity is higher than the demand amount. In addition, if the demand side tries to contribute to net zero emissions, it is likely to increase the utilization rate of RE in phases, considering costs. Therefore, it is important to reduce the power loss by the transmission and charge-discharge at each stage of the rate of RE used by the demand side. The percentage of utilization rate of RE is calculated by evaluating the ratio between consumed power by RE and the amount of consumed power for an evaluating period.

In this chapter, we focus on the interconnected microgrids and propose a high-efficiency power utilization method that reduces power loss by the transmission and charge-discharge for power trading between the microgrids. In the proposed method, the target rate of RE utilization on the demand side of electric power is achieved. In addition, the power loss is reduced by solving a mathematical programming problem with an objective function of power loss by the transmission and charge-discharge between microgrids.

Through the evaluation of the proposed method, we discuss the optimal position of multiple charge-discharge functions to be deployed and the effect of power loss reduction on each percentage of RE use. In addition, a specified utilization rate (from 0% to 100%) of RE is achieved on a demand side.

This chapter is organized as follows. In Sec. 5.2, issues for interconnected microgrids and the policy to solve them are discussed. In Sec. 5.3, the new method to achieve a specified utilization rate of RE and to reduce power loss by transmission, charge, and discharge is proposed. Section 5.4 presents the evaluation results of the proposed method. In Sec. 5.5, we discuss the results. We conclude with a summary in Sec. 5.6.

5.2. Issue of Effective Use of Electric Power and Measure Policy

5.2.1. Overview of Microgrid

Figure 5.1 shows an example of a microgrid. It is composed of a power switch, multiple photovoltaic equipment for generation of fully renewable energy (Hereinafter referred to as FRE), other power generators for non-renewable energy (Hereinafter referred to as NRE), batteries, and power consumption equipment. Each microgrid can trade power with other microgrids by way of the power switch. When the amount of power generated in the microgrid is greater than the power consumption, power can be supplied to other microgrids where power is insufficient.

Figure 5.2 shows the changes in the amount of photovoltaic power generation (Hereinafter referred to as FRE power) and other power generation (Hereinafter referred to as NRE power) as examples. The horizontal axis shows the time over a three-day period, and the vertical axis shows the amount of power generated in kWh. In this example, the increases in FRE power generation are repeated due to the sunlight from good weather conditions. On the other hand, stable power generation in other generators for NRE power is assumed.

Figure 5.3 shows an example of the changes in electric power consumption in a microgrid. The horizontal axis shows the time over a three-day period, and the vertical axis shows the amount of power consumed in kWh. This example shows a consumption pattern in which power consumption increases slightly before going to work and substantially after coming back to home. The power consumption in the time zone which does not generate electricity is supported by power supply from batteries.

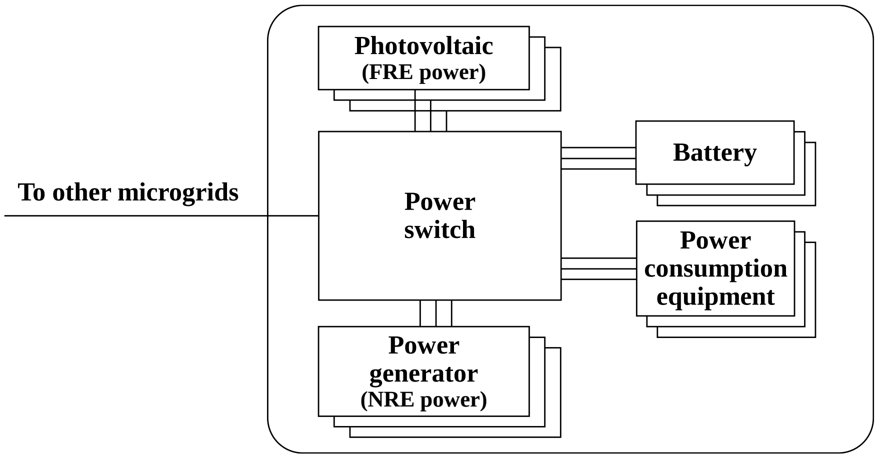

Figure 5.1 Example of a microgrid.

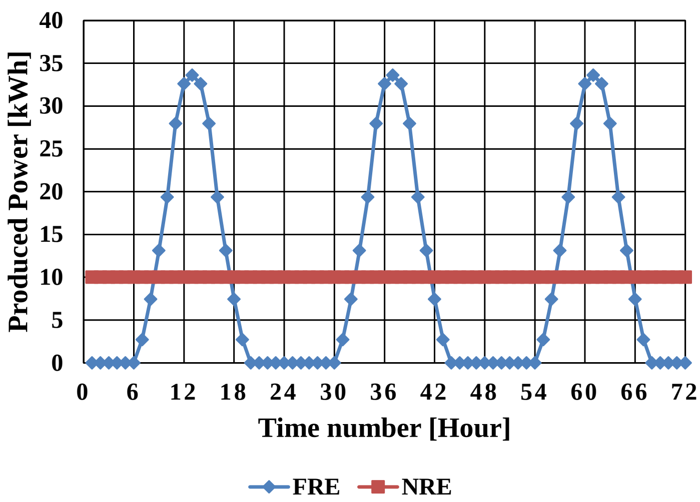

Figure 5.2 Predicted power supply cycle in a microgrid.

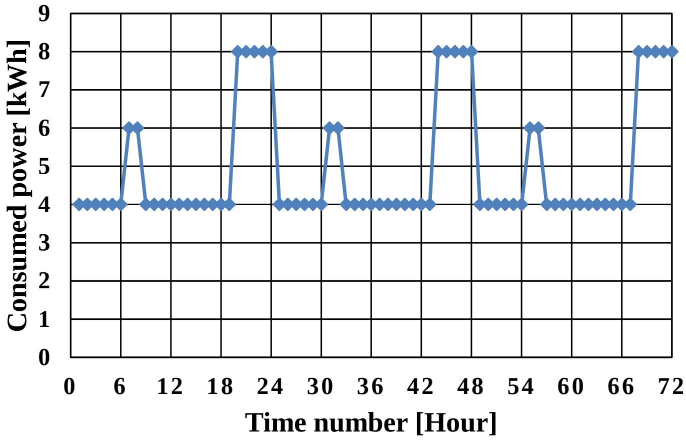

Figure 5.3 Predicted power demand cycle in a microgrid.

5.2.2. Overview of Interconnected Microgrids and Challenge

An example of interconnected microgrids is shown in Fig. 5.4. Each square with a number corresponds to a microgrid shown in Fig. 5.1. The interconnected microgrids are composed of 49 microgrids and they are connected in lattice form (7x7).

In Fig. 5.4, microgrids (2, 9, 21, 32, 38) that have “S1” character represent those in which FRE power is excessive in the power balance and supplying power to other microgrids is possible. In addition, the amount shown in Fig. 5.2 as FRE power is used as an example to simulate the power generation pattern caused by sunlight. Microgrids (5, 13, 24, 35, 43) that have “S0” character represent those in which NRE power is excessive in the power balance and supplying power to other microgrids is possible. In addition, the amount shown in Fig. 5.2 as NRE power is used as an example to simulate the power generation pattern.

Microgrids (3, 7, 11, 17, 23, 27, 33, 37, 44, 46) that have “D” character represent those in which the power is insufficient in the power balance, and demand power from other microgrids. In addition, the amount shown in Fig. 5.3 is used as an example to simulate the power demand pattern.

In actual microgrids, the difference between the amount of power generated and that consumed is the amount that can be supplied or demanded. Here, as an example of simulating the different states in different microgrids, the power generation and consumption shown in Figs. 5.2 and 5.3, respectively, are used. In Fig. 5.4, other microgrids with no character represent those in which there is no shortage of power balance, and the power relay is possible.

For each microgrid constituting the interconnected microgrids, if the power supply and demand amounts in each time do not match as shown in Figs. 5.2 and 5.3, a battery function is required to charge the surplus power generated temporarily, corresponding to power demands at different time. However, there are various types of devices capable of charging and discharging power, and performance deteriorates due to the number of years and conditions of use. For example, in the reference [49], it is shown that the charge-discharge efficiency is degraded by about 10%, and it is desirable to use efficient charge-discharge function. Therefore, it is necessary to use the charge and discharge function of the battery equipment which is deployed in interconnected microgrids.

In the case where the charge-discharge function which exists in the appropriate position is not selectively used, it is temporarily charged to the microgrid that exists in the route not the shortest path between power supply and demand microgrids, the transmission distance is increased. As a result, there is a problem that power loss by transmission is increased.

In addition, there is a problem that the power loss by charge and discharge of power is increased when the charge-discharge function which does not have a good efficiency is used. In this chapter, when the utilization rate of RE, for example, 80% (RE 80%) is specified by the microgrid on a demand side, it is necessary to be able to achieve by using FRE power and NRE power generated in the microgrid.

We propose a method to determine the optimal position and transmission path for the charge and discharge function to achieve the utilization rate of RE required by temporarily charging and discharging FRE and NRE power generated. This reduces the power loss by transmission and charge-discharge by using preferentially efficient charge-discharge function.

Specifically, our purpose is to enable a power transmission operator to use the microgrids that do not provide and demand power and to reduce the power loss by transmission and charge-discharge by allocating charge and discharge functions to optimal locations.

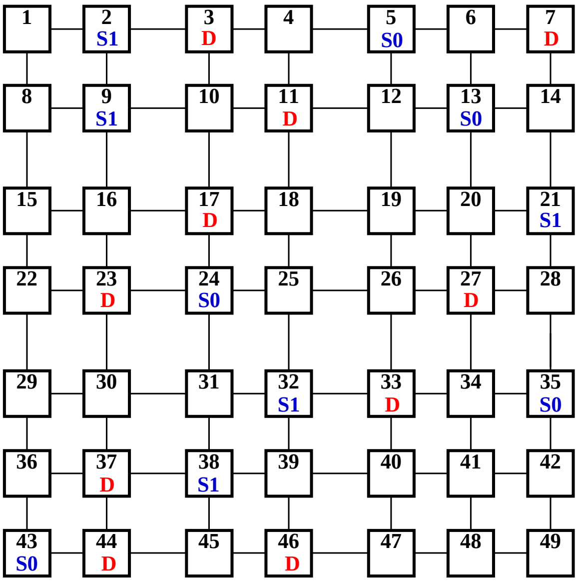

Figure 5.4 Example of interconnected microgrids.

5.2.3. Optimal Transmission Path and Battery Function Deployment Policy

The purpose in this chapter is to reduce the power loss by the transmission and charge-discharge by deploying battery functions. Here, we assume that the power loss by transmission is proportional to the amount of power transmitted and transmission distance by considering the reference [36]. The power loss by charge and discharge is assumed to be proportional to the amount of power charged or discharged by considering the reference [50].

Therefore, we define an objective function for evaluation that includes "power loss in proportion to the amount of transmitted power and distance" and "power loss in proportion to the amount of charged and discharged power". In particular, power generated by FRE and NRE power are distinguished, and the power loss accumulated for each power traded between power supply and demand microgrids.

As a proposed method, all power (FRE and NRE power) supplied by the microgrids on a power supply side is charged to the battery functions or consumed at the microgrids on a demand side, and optimal transmission paths are calculated by minimizing the objective function. In addition, in the deployment of battery functions, the optimal deployment position is determined by minimizing the objective function for the total amount of power transmitted between the microgrids based on the specified number of deployments and capacities of them.

5.3. Proposal to Reduce Power Loss for Specified Rate of Renewable Energy

This section presents a method to reduce power loss for specified rate of RE by using a mathematical programming model. We define symbols to describe defined conditions and decision valuables to minimize the power loss. In order to find a minimum power loss, an objective function is defined and solved by using the symbols and decision valuables.

5.3.1. List of Symbols for Evaluation Model

As shown in Fig. 5.4, we focus on the interconnected microgrids. The purpose of this chapter is to minimize the power loss due to transmission and charge-discharge by appropriately allocating batteries in the microgrids for relay. To solve this problem, we set five decision variables. The first one is a variable whether to deploy a battery function in a microgrid for the relay. The second and third ones are variables that control the amount of FRE and NRE power in battery functions. The fourth and fifth ones are variables that control the amount of FRE and NRE power transmitted between microgrids. An objective function to solve the problem is formulated by using these decision variables.

In the formulation, it is necessary to identify the microgrid for power supply, demand, and transmission. It is necessary to identify the time to charge excessively generated power and to discharge power when it is lack. Since the transmission capacity is finite and the power loss by transmission depends on the amount of power to be transmitted and the transmission distance, it is necessary to specify the power transmission capacity and transmission distance between microgrids. In the process to transmit FRE and NRE power generated by microgrids and to evaluate the power transmission loss, it is necessary to define the changes in the amount of power for generation and consumption in the microgrid as well as a power loss rate for the transmission. The battery functions are used to temporarily charge surplus electric power and to discharge when it is necessary. Since the capacity of the battery function is finite, the capacity as the upper limit must be defined. In addition, it is necessary to specify the total number of microgrids to deploy the battery function. When calculating the power loss associated with charge and discharge, it is necessary to define the loss rate of power in each charge and discharge function. It is necessary to specify the total amount of charge as the initial value for supplying FRE and NRE power consumed before power generation, and the minimum required total charge capacity to charge the excessively generated power. It is also necessary to specify the utilization rate of FRE power to the power consumption in the microgrid on the demand side. In addition, it is necessary to specify the time period for evaluating the amount of FRE power contained in the consumed power. It becomes possible to deal with more specific problems by making the above settings. The solution to solve the issue is described in detail later in the following sections.

Table XII shows a list of symbols specified for calculating the solution. i indicates the microgrid number when there are N microgrids. When the time range to be evaluated is divided into T slots, t indicates the slot number. $C(i,j)$ shows the distance between adjacent microgrid i and j in the configuration where multiple microgrids are connected to each other. $L(i,j)$ shows the upper limit of the amount of power that can be transmitted between adjacent microgrids i and j. $P_0(i,t)$ and $P_{100}(i,t)$ show the amount of power supplied by microgrid i at time t for FRE and NRE, respectively. $D(i,t)$ shows the amount of power consumed by microgrid i at time t. r represents a loss rate of power due to transmission. $W(i)$ shows the capacity of the charge-discharge function deployed in microgrid i. M represents the total number of microgrids with battery functions. Therefore, there is a relation of $0<M<N$. $\rho(i)$ shows a loss rate of power due to charge and discharge in microgrid i. V_0 and V_{100} represent the total amount of FRE and NRE power charge as the initial value to supply the power consumed before power generation for all microgrids. U represents the minimum required total charge capacity to charge the surplus power generated during the evaluation period. *REX* represents RE utilization rate in power consumption. *SPAN* represents an interval to evaluate the utilization of RE. For the total evaluation period to evaluate the power loss, the value of *SPAN* is the period of the number of factors. For example, if the total evaluation period is 48 hours, a value such as 1 hour, 2 hours and 12 hours is set as *SPAN*.

Table XII List of Symbols

Symbol	Definition
i	Number of microgrid ($i = 1,\cdots, N$)
t	Number of time slot ($t = 1,\cdots, T$)
$C(i,j)$	Distance between adjacent microgrid i and j (km)
$L(i,j)$	Limit of transmission amount between adjacent microgrid i and j (kWh)

$P_0(i,t)$	Amount of NRE power supplied from microgrid *i* in time slot *t* (kWh)
$P_{100}(i,t)$	Amount of FRE power supplied from microgrid *i* in time slot *t* (kWh)
$D(i,t)$	Amount of power consumed by microgrid *i* in time slot *t* (kWh)
r	Loss rate of power due to transmission
$W(i)$	Battery capacity in microgrid *i* (kWh)
M	Number of microgrids with distributed battery functions, $0<M<N$
$\rho(i)$	Loss rate of power due to charge and discharge in microgrid *i*
V_0	Initial value of the total amount of NRE power in the distributed batteries (kWh) (Refer to (5-16))
V_{100}	Initial value of the total amount of FRE power in the distributed batteries (kWh) (Refer to (5-17))
U	Necessary capacity of the distributed batteries (kWh) (Refer to (5-18))
REX	Renewable energy utilization rate in power consumption
SPAN	Interval to evaluate the utilization of renewable energy

5.3.2. List of Decision Variables for Evaluation Model

The purpose of this chapter is to determine the optimal placement of the battery function to reduce FRE and NRE power loss by transmission and charge-discharge. Therefore, it is necessary to have a variable whether to allocate the battery function for each microgrid. Since the electric power loss by transmission is dependent on the amount of power transmitted, variables are needed to optimize the amount of FRE and NRE power transmitted between microgrids for each time. In addition, variables are needed to optimize charge or discharge FRE and NRE power for each time. By setting variables to determine the optimal battery position, transmission amount, and charged electric power, it is possible to calculate optimal solution and to evaluate the power loss by transmission.

The decision variables listed in Table XIII are determined by the optimization problem described as follows. The value of $\delta(i)$ is determined to be 1 or 0 if the battery function is deployed or not, respectively, in microgrid *i*. $Q_0(i,j,t)$ and $Q_{100}(i,j,t)$ determine the amount of NRE and FRE power transmitted from adjacent microgrid *i* to *j* at time *t*, respectively. $B_0(i,t)$ and $B_{100}(i,t)$ determine the amount of NRE and FRE power remaining in the battery function of microgrid *i* at time *t*, respectively. *i* of $B_0(i,t)$, $B_{100}(i,t)$, and $\delta(i)$ indicates the number of the microgrid for the relay that does not supply and demand power.

Table XIII List of Decision Variables

Variable	Definition
$\delta(i)$	Deployment/No deployment of battery in microgrid *i* (1/0)
$Q_0(i,j,t)$	Amount of NRE power transmitted from adjacent microgrid *i* to *j* in time slot *t* (kWh)
$Q_{100}(i,j,t)$	Amount of FRE power transmitted from adjacent microgrid *i* to *j* in time slot *t* (kWh)
$B_0(i,t)$	Amount of NRE power remaining in the battery of microgrid *i* in time slot *t* (kWh)
$B_{100}(i,t)$	Amount of FRE power remaining in the battery of microgrid *i* in time slot *t* (kWh)

5.3.3. Objective Function and Constraints

The proposed system aims to minimize the power loss by transmission and charge-discharge as described in the previous section. By formulating and evaluating the problem as mathematical programming one, we can achieve high-efficiency power utilization by using the battery functions.

The objective function is shown as follows. The first part is a term to accumulate power loss due to transmission and charge and discharge to NRE power, the second part is a term to accumulate power loss to FRE power. The amounts of FRE and NRE power loss by transmission are indicated by $r*C(i,j)Q_0(i,j,t)$ and $r*C(i,j)Q_{100}(i,j,t)$, respectively. The amounts of FRE and NRE power loss by charge-discharge are indicated by $\rho(i)|B_0(i,t)-B_0(i,t-1)|$ and $\rho(i)|B_{100}(i,t)-B_{100}(i,t-1)|$, respectively. By deriving the minimum value of the objective function, the optimal placement and control of multiple battery functions can be calculated, and the power loss can be minimized.

$$Minimize$$

$$\sum_{t=1}^{T}\sum_{i=1,i\neq j}^{N}\{r*C(i,j)Q_0(i,j,t)+\rho(i)|B_0(i,t)-B_0(i,t-1)|\}+$$
$$\sum_{t=1}^{T}\sum_{i=1,i\neq j}^{N}\{r*C(i,j)Q_{100}(i,j,t)+\rho(i)|B_{100}(i,t)-B_{100}(i,t-1)|\} \quad (5-1)$$

The constraints are described as follows.

1) Power balance condition for relay microgrid: At all times, the amount of power flowing into a microgrid must be equal to the sum of the amount of power flowing out and the amount of power discharged. Equation (5-2) indicates the balance condition of inflow and outflow for NRE power. In time t, the sum of the power quantities $Q_0(k,i,t)$ and (-1)*$Q_0(i,k,t)$, and ($B_0(i,t-1)$-$B_0(i,t)$) is equal to zero. $Q_0(k,i,t)$ represents the amount of NRE power flowing from adjacent microgrid k. $Q_0(i,k,t)$ represents the amount of power flowing into microgrid k. $B_0(i,t-1)$-$B_0(i,t)$ indicates the amount of charge change in the battery. Equation (5-3) indicates the balance condition of inflow and outflow for FRE power.

$$\sum_k Q_0(k,i,t) - \sum_k Q_0(i,k,t) + B_0(i,t-1) - B_0(i,t) = 0 \qquad (5-2)$$

$$\sum_k Q_{100}(k,i,t) - \sum_k Q_{100}(i,k,t) + B_{100}(i,t-1) - B_{100}(i,t) = 0 \qquad (5-3)$$

2) Power balance condition for power supply microgrid: At all times, the amount of power flowing into a microgrid must be equal to the sum of the amount of power flowing out and the amount of power generated. Equation (5-4) indicates the balance condition of inflow and outflow for NRE power. In time t, the sum of the power quantities $Q_0(k,i,t)$ and (-1)*$Q_0(i,k,t)$ is equal to the sum of the power generation. The supply amount from the microgrid supplying NRE power is equal to (-1)*$P_0(i,t)$*(1-REX). By the way, for NRE power, the value of (1-REX) is multiplied by the NRE power generation amount $P_0(i,t)$ in order to change the percentage of power generated by RE and to make the NRE power supply volume to the same amount in the NRE power consumed by the demand side.

Similarly, equation (5-5) indicates the balance condition of inflow and outflow of FRE power. For FRE power, the value of REX is multiplied by FRE power generation amount $P_{100}(i,t)$ in order to change the percentage of power generated by RE and to make the FRE power supply volume to the same amount in the FRE power consumed by the demand side.

$$\sum_k Q_0(k,i,t) - \sum_k Q_0(i,k,t) = -P_0(i,t) * (1 - REX) \qquad (5-4)$$

$$\sum_k Q_{100}(k,i,t) - \sum_k Q_{100}(i,k,t) = -P_{100}(i,t) * REX \qquad (5-5)$$

3) Power balance condition for power demand microgrid: At all times, the amount of power flowing into a microgrid must be equal to the sum of the amount of power flowing out and the amount of power consumed. Equation (5-6) indicates the balance condition of inflow and outflow for NRE and FRE power. In time *t*, the sum of the power quantities $Q_0(k,i,t)$ and $Q_{100}(k,i,t)$ is equal to the sum of the power quantities $Q_0(i,k,t)$, $Q_{100}(i,k,t)$, and $D(i,t)$.

On the other hand, it is necessary to set the period (*SPAN*) to evaluate a ratio of the amount of power generated by renewable energies (hereinafter referred to as RE-degree) in the amount of power consumed by the demand microgrid. For example, it is necessary to set the time period such as one hour or two hours to evaluate RE-degree.

Equation (5-7) indicates the balance condition of NRE power on the demand side when RE-degree is set by *REX*. When RE-degree is set by *REX*, NRE power consumption is the value multiplied by (1-*REX*) value for *D* (*i*,*t*). The period to accumulate the amount of power for outflow and inflow is from n**SPAN*+1 to (n+1)**SPAN*. n is the value of 0, 1, 2, ⋯. For example, in the case of *SPAN*=4 as the period to be accumulated here, when n=0, the outflow and inflow are accumulated during the period from *t*=1 to 4. The sum of the amount of electricity that is flowed in during that period is equal to the amount of NRE power consumption. When n=1, the outflow and inflow are accumulated during the period from *t*=5 to 8. The sum of the amount of electricity that is flowed in during that period is equal to the amount of NRE power consumption. *SPAN* value is selected by the divisor for all evaluation periods. For example, if the total evaluation period is 48 hours, then *SPAN* is set one of values such as one hour, two hours, four hours, eight hours, 12 hours, and 24 hours. Also, n and *SPAN* are selected as the last time of the evaluation to satisfy (n + 1)**SPAN*=48.

Similarly, equation (5-8) indicates the balance condition of FRE power on the demand side when RE-degree is set by *REX*. When RE-degree is set by *REX*, FRE power consumption is the value multiplied by *REX* for $D(i, t)$.

$$\sum_k Q0(k,i,t) - \sum_k Q0(i,k,t) + \sum_k Q100(k,i,t) - \sum_k Q100(i,k,t) = D(i,t) \qquad (5-6)$$

$$\sum_{t=n*SPAN+1}^{(n+1)*SPAN} \left\{ \sum_k Q0(k,i,t) - \sum_k Q0(i,k,t) \right\} = \sum_{t=n*SPAN+1}^{(n+1)*SPAN} D(i,t) * (1 - REX) \qquad (5-7)$$

$$\sum_{t=n*SPAN+1}^{(n+1)*SPAN} \left\{ \sum_k Q100(k,i,t) - \sum_k Q100(i,k,t) \right\} = \sum_{t=n*SPAN+1}^{(n+1)*SPAN} D(i,t) * REX \qquad (5-8)$$

4) Transmission quantity condition: In time *t*, the amount of power that is transmitted from adjacent microgrid *i* to *j* is less than or equal to the transmission capacity between microgrids. Equation (5-9) indicates the transmission quantity condition for NRE power. The amount of power $Q_0(i,j,t)$ is less than or equal to the maximum value $L(i,j)$. Similarly, equation (5-10) indicates the transmission quantity condition for FRE power. The amount of power $Q_{100}(i,j,t)$ is less than or equal to the maximum value $L(i,j)$. In addition, equation (5-11) indicates the transmission quantity condition for the amount of NRE and FRE power.

$$0 \leqq Q_0(i,j,t) \leqq L(i,j) \qquad (5-9)$$

$$0 \leqq Q_{100}(i,j,t) \leqq L(i,j) \qquad (5-10)$$

$$0 \leqq Q_0(i,j,t) + Q_{100}(i,j,t) \leqq L(i,j) \qquad (5-11)$$

5) Battery function number condition: It is necessary to deploy optimal battery functions in the range of the number of deployments set as a plan for them. Equation (5-12) indicates the battery function number condition. The number of microgrids for the relay to deploy the battery function is less than or equal to the specified number *M*.

$$\sum_{i=1}^{N} \delta(i) \leqq M \qquad (5-12)$$

6) Charge and discharge quantity condition: The amount of power charged to microgrid *i* with the battery function is less than or equal to the specified capacitance. Equation (5-13) indicates the charge and discharge quantity condition for NRE power. In time *t*, the amount of power $B_0(i,t)$ charged to microgrid *i* with the battery function is less than or equal to the specified capacitance $W(i)\ \delta(i)$. Similarly, equation (5-14) indicates the charge and discharge quantity condition for FRE power. In addition, equation (5-15) indicates the charge and discharge quantity condition for the amount of NRE and FRE power.

$$0 \leqq B_0(i,t) \leqq W(i)\delta(i) \qquad (5-13)$$

$$0 \leqq B_{100}(i,t) \leqq W(i)\delta(i) \qquad (5-14)$$

$$0 \leqq B_0(i,t)+B_{100}(i,t) \leqq W(i)\delta(i) \qquad (5-15)$$

7) Initial value of charge amount condition: In order to supply the necessary power in a time zone with insufficient power generation, it is necessary to charge the minimum necessary power beforehand. Equation (5-16) indicates the initial value of charge amount condition for NRE power. The sum of the charge amount $B_0(i,0)$ is equal to the specified initial power amount value V_0 to supply the power required before power generation. Similarly, equation (5-17) indicates the initial value of charge amount condition for FRE power.

$$\sum_{i=1}^{N} B_0(i,0) = V_0 \quad (5-16)$$

$$\sum_{i=1}^{N} B_{100}(i,0) = V_{100} \quad (5-17)$$

8) Capacity condition for battery function: In order to charge the surplus power generated at a certain time without discarding it, it is necessary to deploy the charge-discharge capacity as a whole more than the minimum necessary. Equation (5-18) indicates the capacity condition for battery function. The total capacity of the battery functions to be deployed is at least the minimum charge-discharge capacity U required to temporarily charge and hold surplus power generated during the period of evaluation.

$$\sum_{i=1}^{N} W(i)\delta(i) \geqq U \quad (5-18)$$

5.3.4. NRE and FRE Power Supply and Demand Management Overview

Figure 5.5 shows an overview of supply and demand management of NRE and FRE power using the constraints described in previous section. In the proposed method, in order to manage the utilization rate of RE specified by a demand side, it manages power flows by distinguishing NRE and FRE power fundamentally. Specifically, different variables are introduced to separately manage NRE and FRE power for both power flows and charge-discharge functions, and NRE and FRE power supply and demand are distinguished. However, for the charge-discharge function, it is necessary to limit the charging amount not to exceed the charge-discharge capacity because it is assumed to share the battery for both NRE and FRE power. In addition, for the power transmission, it is necessary to limit the transmission amount not to exceed the transmission capacity between microgrids because it is assumed to share the transmission path for both NRE and FRE power. In the power consumption, it is necessary to control the consumption ratio of NRE power and FRE power in order to achieve the utilization rate of RE specified by the demand side.

In the setting shown in Fig. 5.5, NRE power (P_0) and FRE power (P_{100}) are supplied from the power supply side. In addition, the power consumption of the specified RE-degree is assumed in the demand side. On the other hand, when the amount of power supplied and the amount of demand power is not consistent at each time, it is assumed that the surplus NRE and FRE power are temporarily charged to the battery function and discharged when power is insufficient.

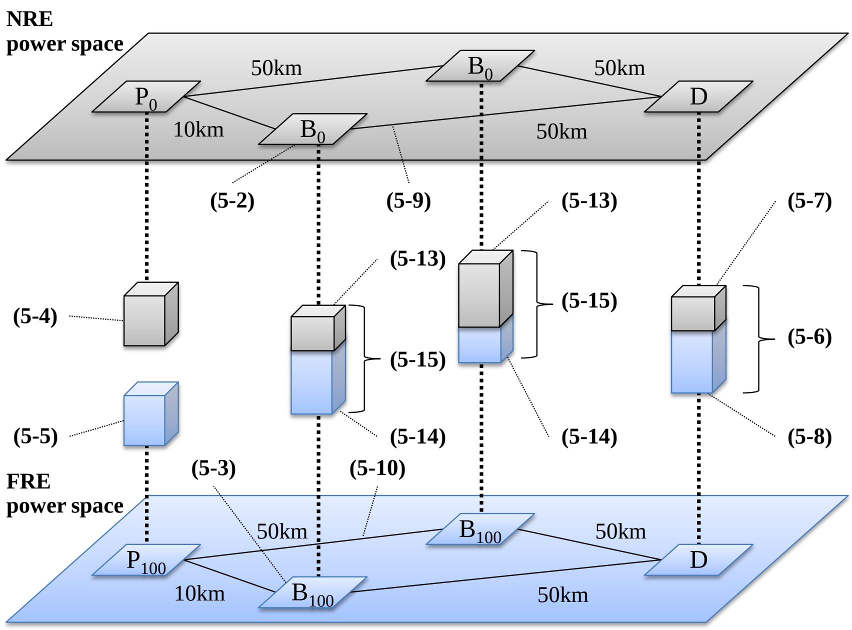

Figure 5.5 NRE and FRE power supply and demand management.

Regarding the above-mentioned power supply and demand control, especially in the case of achieving the power consumption of RE-degree specified in the demand side, it is necessary to achieve by properly mixing NRE and FRE power as the color-managed power. Therefore, it is necessary to distinguish NRE and FRE power, and NRE and FRE power space are introduced as shown in Fig. 5.5.

NRE and FRE power are basically managed separately in NRE and FRE power space. Surplus NRE and FRE power are temporarily charged to the battery function and discharged when power is insufficient. However, it is necessary to control the total charge of NRE and FRE power not to exceed the allowable capacity of the battery function. Moreover, in order to perform power consumption at the specified RE-degree on the demand side, it is necessary to control the power consumption to achieve the ratio of the consumed amount of NRE and FRE power during the evaluation period.

Specifically, in the NRE power space, NRE power supply control is executed by equation (5-4) in the microgrid which supplies power. NRE power charge control is executed by equation (5-13) in the microgrid to charge and discharge NRE power. In addition, the amount of NRE power for outflow and inflow is controlled by equation (5-2). The amount of NRE power transmission between microgrids is controlled by equation (5-9). NRE power consumption on the demand side is controlled by equation (5-7).

Regarding the FRE power space, the FRE power supply control is executed by equation (5-5) in the microgrid which supplies power. The FRE power charge control is executed by equation (5-14) in the microgrid to charge and discharge FRE power. In addition, the amount of FRE power for outflow and inflow is controlled by equation (5-3). The amount of FRE power transmission between microgrids is controlled by equation (5-10). FRE power consumption on the demand side is controlled by equation (5-8).

On the other hand, regarding the power space including both NRE and FRE power, the amount of demand as the sum of NRE and FRE power is controlled by equation (5-6). The amount of charge in the battery function as the sum of NRE and FRE power is controlled by equation (5-15). In addition, the sum of NRE and FRE power transmitted between microgrids is controlled by equation (5-11), although not illustrated. The total number of battery functions deployed in the microgrids is controlled by equation (5-12).

5.4. Evaluation and Results

5.4.1. Overview of Evaluation

In the first evaluation, we clarify the relationship between the allocations of battery functions deployed to the interconnected microgrids and the power loss in order to minimize the power loss by transmission and charge-discharge. In this evaluation, we change each battery capacity and the number of battery functions to be deployed to the interconnected microgrids, and compare the minimum value of the objective function for each case, and evaluate the optimal capacity and the number of the battery functions. In particular, a large number of small battery functions of the capacity and a small number of large battery functions of the capacity are evaluated. It is clarified which case has a high effect of reducing the power loss by transmission and charge-discharge. Therefore, the product of the number of microgrids M and each battery capacity $W(i)$ is fixed to a constant value. The effect of power loss reduction is evaluated by changing the combination of the number of microgrids *M* and each battery capacity *W*(*i*). In addition, in order to verify the effectiveness of the proposed method, we compare our new method and a route-based method that minimizes only the transmission length. In the first evaluation, the power loss reduction is evaluated in the case of RE-degree = 100% where the utilization of the battery function is the highest.

Second, the power loss reduction is evaluated by changing RE-degree from 0 to 100%. The combination of the number of microgrids *M* and each battery capacity *W*(*i*) is the same setting of the evaluation one. The combination of the number of microgrid *M* and each battery capacity *W*(*i*) that minimizes the amount of power loss for each requested RE-degree is clarified.

Third, the effect of power loss reduction is evaluated by changing RE-degree required by the demand side from 0 to 100% and changing the evaluation period. For example, if RE 50% is requested on a demand side, and RE-degree is evaluated every hour, it is necessary to control FRE power by 50% and NRE power 50% per hour. On the other hand, in the case of evaluating RE-degree every two hours, in the situation where the power generation of FRE power is low, the NRE power is supplied 100% in the first hour of the first half, FRE power in the second half of the phase where the power generation of FRE power is increased can be controlled to supply 100%. In the difference of such a control, we evaluate the difference of the amount of power loss generated. Therefore, as the period for evaluating RE-degree in the power consumption on the demand side, the most effective evaluation period for the power loss reduction is clarified for multiple evaluation periods, such as every hour, two hours, and eight hours.

5.4.2. Evaluation Model

Table XIV shows a list of the set values for the defined symbols. To decide a topology for the interconnected microgrids, we consider research [42], [43] that used 21 regions and 34 nodes and the number of prefectures in Japan. As a result, we use the configuration shown in Fig. 5.6 as the interconnected microgrids for the evaluation. As a similar structure, the power network topology in Europe [51] is capable of mutually electric power exchange between neighboring countries and regions. In the research [41], evaluations are executed in a topology where 18 distribution networks are mutually connected. The topology on the lattice assumed by this paper is a structure being capable of mutual power trade between adjacent microgrids, and it is selected as a topology for evaluation since it is considered as a typical topology with similarities of other researches. The power supply microgrid (S1, S0) and the demand microgrid (D) shown in Fig. 5.6 are arranged randomly. The number of microgrids to be deployed is 49 (identifiers: 1 to 49). In the evaluation, a total of five patterns combined with four different patterns than that shown in Fig. 5.6 are evaluated, and the average value is evaluated as the result.

Table XIV Value of Symbols

Symbol	Value
i	1,⋯, 49
t	0,⋯, 48
$C(i,j)$	Distance between adjacent microgrids i and j as shown in Fig. 5.6 (10km/50km)
$L(i,j)$	1,000 (kWh)
$P_0(i,t)$	NRE power supply cycle shown in Fig. 5.2: i = 5, 13, 24, 35, 43 (Pattern 1 shown in Fig. 5.6) (kWh)
$P_{100}(i,t)$	FRE power supply cycle shown in Fig. 5.2: i = 2, 9, 21, 32, 38 (Pattern 1 shown in Fig. 5.6) (kWh)
$D(i,t)$	Power demand cycle shown in Fig. 5.3: i = 3, 7, 11, 17, 23, 27, 33, 37, 44, 46 (Pattern 1 shown in Fig. 5.6) (kWh)
r	0.0001 (0.01% power loss per km)
$W(i)$	37.5, 50, 75, 150, 375, 750 (kWh)
M	20, 15, 10, 5, 2, 1
$\rho(i)$	Evaluation shown in Fig. 5.8: 0.05 (i: Odd), 0.15 (i: Even), Evaluation shown in Fig. 5.9: Randomly set 5%, or 15% power loss by half
V_0	40, 36, 32, 28, 24, 20, 16, 12, 8, 4, 0 (kWh)
V_{100}	0 (kWh)
U	738.4 (kWh)
REX	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 (%)
$SPAN$	1, 2, 4, 8, 12, 24, 48 (Hour)

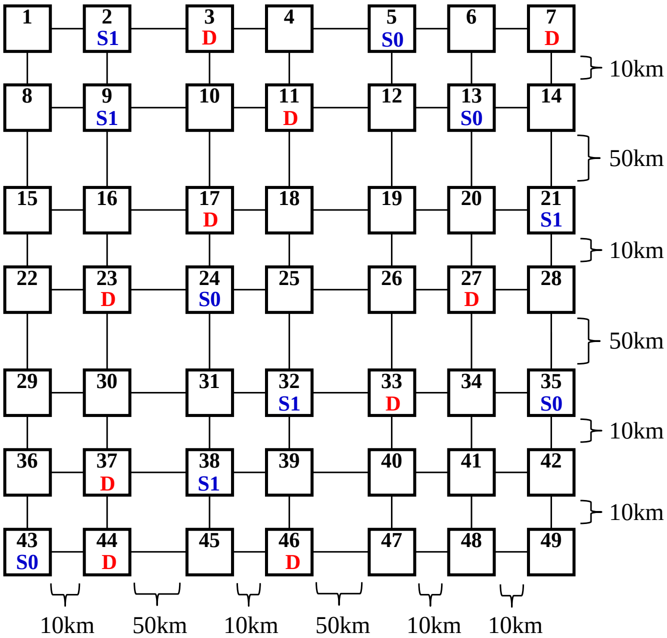

Figure 5.6 Distance between microgrids.

In order to decide the period of evaluation (*t* range), two patterns were pre-evaluated by deploying the power demand shown in Fig. 5.3 in 10 microgrids. In the first case (corresponding to 100% FRE demand), all the power demand is satisfied by deploying FRE power supply shown in Fig. 5.2 in 5 microgrids. In the second pattern (corresponding to 100% NRE demand), all the power demand is satisfied by deploying NRE power supply shown in Fig. 5.2 in 5 microgrids. Under these conditions, it was evaluated in advance the change in power remaining in the battery function. The evaluation results are shown in Fig. 5.7. In order to suppress the influence of the initial state, the time number of 48 hours of 8 to 56 was selected as the evaluation period since the charge of FRE electric power repeats 0. Then, the period is set to t=0 to 48.

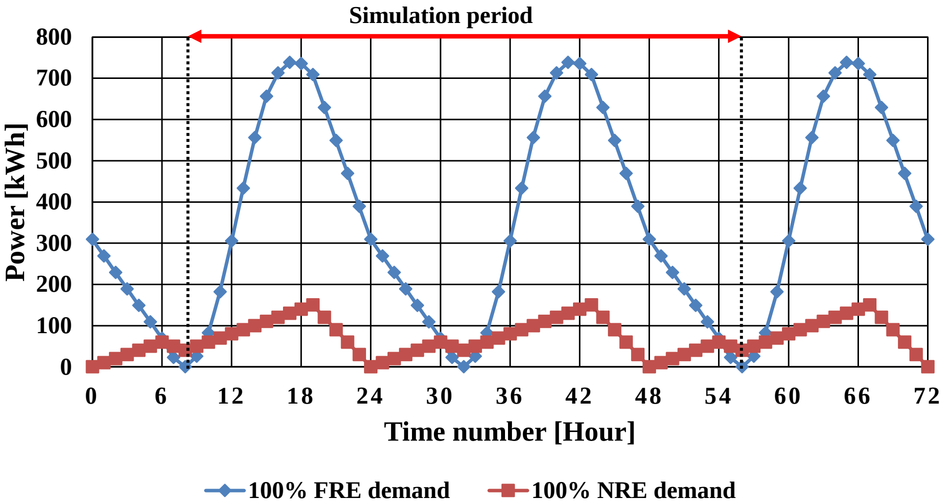

Figure 5.7 Change in battery charge volume.

In this evaluation, we set 48 hours for evaluating the objective function shown in equation (5-1) and calculate optimal locations of battery functions and transmission paths which give the minimum by integrating the amount of power loss generated every one hour. In this calculation, the control of the power transmission and the charge-discharge every one hour is assumed. On the other hand, it is possible to evaluate it by using the objective function shown in equation (5-1) by setting the value of 0 to 96 when assuming the control of 30 minutes, for example.

The distance $C(i,j)$ between adjacent microgrids is set 10 km or 50 km as shown in Fig. 5.6. The upper limit of the transmission amount $L(i,j)$ is set to 1,000 kWh as there is sufficient power transmission capacity in this evaluation.

As a pattern 1, the NRE power $P_0(i,t)$ is supplied from five microgrids (i = 5, 13, 24, 35, 43), and the NRE power generation amount shown in Fig. 5.2 is used as the respective supply amount. In addition, the FRE power $P_{100}(i,t)$ is supplied from five microgrids (i = 2, 9, 21, 32, 38), and the NRE power generation amount shown in Fig. 5.2 is used as the respective supply amount. The amount of power consumed shown in Fig. 5.3 is used as $D(i,t)$ for every power-demand microgrids. The power demand microgrids are set to 10 microgrids (i = 3, 7, 11, 17, 23, 27, 33, 37, 44, 46). Although the forecast values should be used as the supply and demand values, in this evaluation, the values shown in Figs. 5.2 and 5.3 are used for convenience as predicted values.

The power loss r by transmission is set to 0.01% (0.0001) by assuming it is proportion to the transmission length by considering information of [36], [48]. The capacity of each battery $W(i)$ to be deployed in the microgrid is set by considering the results shown in Fig. 5.7. Specifically, as the total capacity, combinations of M and the capacity $W(i)$ of the battery functions to be 750 kWh are selected since the minimum amount required for the excess power charge-discharge is 738.4 kWh. Specifically, combinations of battery capacity $W(i)$ and the number of microgrids with battery functions (M) are set as 37.5*20, 50*15, 75*10, 150*5, 375*2, and 750*1.

For the power loss $\rho(i)$ by charge-discharge, as the first pattern, 5% of the power loss is set when the number i of the microgrid is odd, and 15% of the power loss is set when i is even (Fig. 5.8 evaluation) by considering information of [49]. As the second pattern, the power loss $\rho(i)$ is randomly set 5%, or 15% power loss by half, without relying on a number i (Fig. 5.9 evaluation). In the reference [50], 70%, 80%, 90% as charge-discharge efficiency are considered. The power loss of 5% or 15% generated in the charge or discharge in this evaluation corresponds to 90% and 70% as the charge-discharge efficiency. In this evaluation, 5% power loss in charge or discharge is set as an example of high performance. In the case of low efficiency, a 15% power loss is set for charge or discharge.

The amount of power V_0 and V_{100} that the battery function must first be charged is calculated that the following pre-charge is necessary from the preliminary evaluation shown in Fig. 5.7. Specifically, if the demand side changes RE-degree from 0 to 100% at 10% intervals, V_0 changes with 40, 36, 32, 28, 24, 20, 16, 12, 8, 4, 0 (kWh). On the other hand, for the pre-charge amount of FRE power, since the change of charge amount in Fig. 5.7 is set to start the evaluation from the time of 0 charge, the value of V_{100} is 0.

The minimum total charge capacity U which is required to temporarily charge and hold all power generated in surplus in the period of evaluation is calculated from the preliminary evaluation of the charge amount shown in Fig. 5.7. From the results of Fig. 5.7, the minimum total charge capacity U is 738.4 kWh. *REX*, which is RE-degree of power consumption specified by the demand side microgrid, is set from 0 to 100% at 10% interval. In addition, *SPAN*, which is the period for evaluating RE-degree, is set to seven patterns of 1, 2, 4, 8, 12, 24, and 48 hours since the total evaluation period is 48 hours.

5.4.3. Evaluation Results

5.4.3.1. Power loss evaluation to combination of battery capacity and the number of microgrids to deploy battery functions

Figures 5.8 and 5.9 show the results of the power loss evaluation when the capacity and the number of deployments of the battery function are changed. Specifically, the amount of power loss is evaluated under the condition that the combination of the battery capacity and the number of microgrids to be deploy the battery functions is equal to 750 kWh that is slightly larger than the minimum required capacity *U*. In order to verify the effectiveness of the proposed method, the comparison with the route-based method [33] which deploys the battery functions to minimize transmission distance is shown.

In the evaluation shown in Fig. 5.8, a total of five patterns combined with four different patterns than that shown in Fig. 5.6 are evaluated, and the average value is shown as the result. In the evaluation shown in Fig. 5.9, the different charge or discharge efficiency (5% loss, 15% loss) is randomly set at random by half to each microgrid in the topology shown in Fig. 5.6. The average value of the evaluated five times is shown as a result. In this evaluation, a control of the supply and demand of power to satisfy RE-degree (100%) specified every 1 hour as a value of *SPAN* is executed.

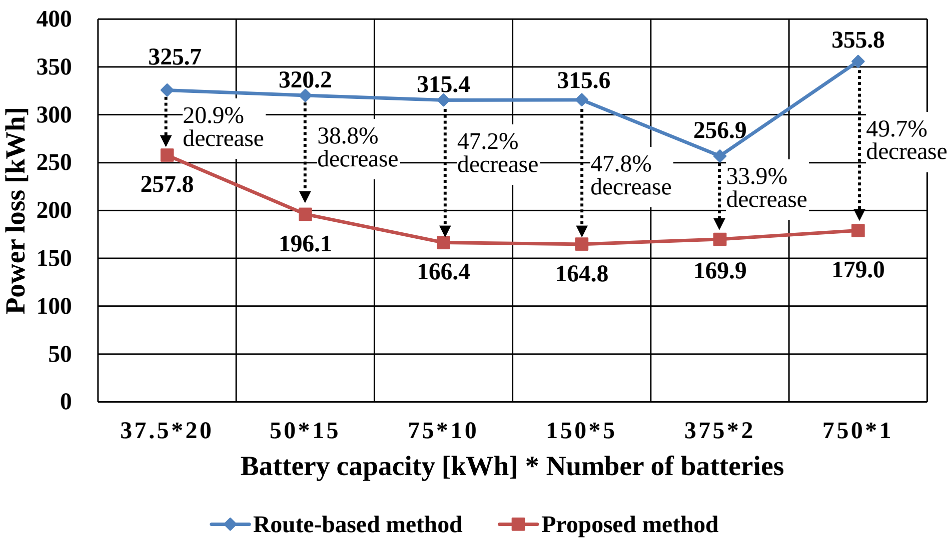

Figure 5.8 Power loss evaluation (1) by changing capacity and number of batteries.

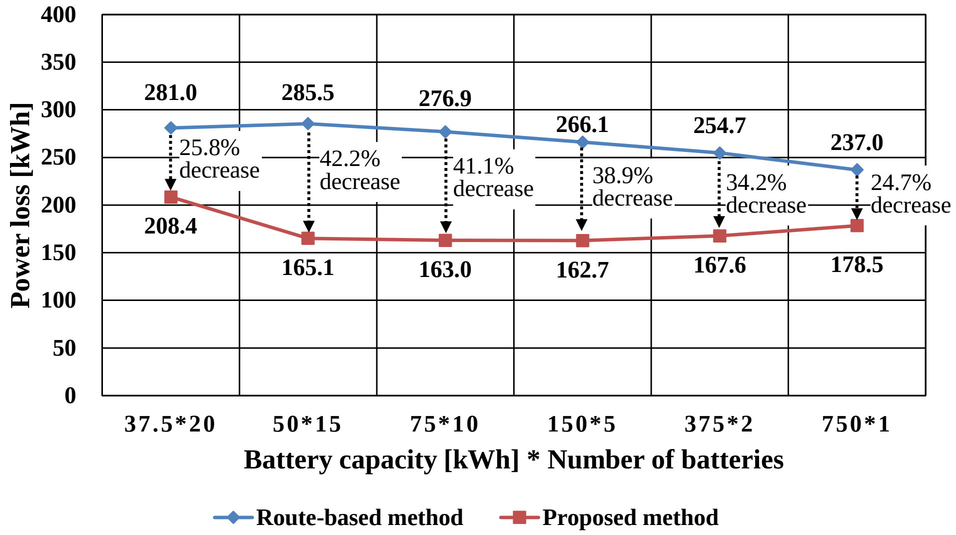

Figure 5.9 Power loss evaluation (2) by changing capacity and number of batteries.

In the evaluation of the proposed method shown in Fig. 5.8, when the battery function of 150 kWh is deployed to five microgrids, the result of the minimum amount of power loss by transmission and charge-discharge is 164.8 kWh. In addition, when the battery function is deployed in 20 or 15 microgrids, the amount of power loss is significantly increased compared with the case of deploying to 5 microgrids. Similarly, in the evaluation of the proposed method shown in Fig. 5.9, when the battery function of 150 kWh is deployed to five microgrids, the result of the minimum amount of power loss by transmission and charge-discharge is 162.7 kWh.

Regarding the power loss evaluation of Figs. 5.8 and 5.9, variance comparisons between the proposed method [P] and the route-based method [R] which deploys the battery functions to minimize transmission distance are shown in Table XV and Table XVI. Among all 12 evaluations, the proposed method resulted in a smaller variance in 11 different types of evaluations. In the proposed method, when the number of battery functions is large, the variance tends to increase. On the other hand, in the case of the route-based method, variance tends greatly increased when the number of battery functions was small.

In this evaluation, the total capacity of the battery function to be deployed is constant (750kWh), and evaluations are executed by changing the combination of individual battery capacity and number of battery deployments. For example, it is possible to evaluate both cases of deploying a large number of small battery functions of the capacity and a small number of large battery functions of the capacity. Therefore, it is possible to evaluate which type of battery deployment pattern provides efficient power utilization. In the evaluations, the best result is when the battery function of 150 kWh is deployed to five microgrids. In addition, when a large number of battery functions are deployed in 20 or 15 microgrids, the amount of power loss by transmission and charge-discharge tends likely to be increased. As shown in Figs. 5.8 and 5.9, compared with the route-based method considering transmission distance only, the proposed method results in an average of 20% or more improvements in terms of power loss reduction by transmission and charge-discharge. As a result, the advantage of the proposed method is confirmed.

Table XV Variance Comparison (1) of Evaluation Results in Route-based Method [R] and Proposed Method [P]

Method	37.5*20	50*15	75*10	150*5	375*2	750*1
[R]	845	513	520	678	4698	20309
[P]	580	625	30	35	12	17

Table XVI Variance Comparison (2) of Evaluation Results in Route-based Method [R] and Proposed Method [P]

Method	37.5*20	50*15	75*10	150*5	375*2	750*1
[R]	1026	896	2878	4700	5073	13958
[P]	377	2	2	1	0	1

5.4.3.2. Power loss evaluation by changing RE-degree at constant battery capacity

Figure 5.10 shows the evaluation result of the power loss by transmission and charge-discharge when the power consumption at RE-degree specified by the demand side is achieved under the condition of the total battery capacity constant (750 kWh). In this evaluation, the average value for the arrangement of five different topology patterns is evaluated as the result. The supply and demand of the power is controlled to satisfy RE-degree specified every one hour as a value of *SPAN.* In this evaluation, it is possible to evaluate the relationship between RE-degree demanded by the demand side and the amount of power loss generated for the combination of the battery capacity and the number of deployments.

As shown in Fig. 5.10, the amount of power loss by transmission and charge-discharge tends to increase as the demand side increases of RE-degree from 0 to 100%. In addition, if RE-degree is more than 60% and battery functions are deployed in 15 or more microgrids, the amount of power loss is significantly increased. In addition, when a small number of battery functions with large capacity such as 375 or 750 kWh are deployed in microgrids, the amount of power loss is also increased.

In the evaluation conditions set, the amount of power loss is increased by deploying a large number of battery functions of a small capacity when RE-degree is higher than 60%. It is possible to prevent the increase of the amount of power loss by deploying the battery functions of the capacity which does not become a large number of deployments of 20 or 15 microgrids. Moreover, if RE-degree demanded by the demand side is 50% or less, the amount of power loss generated results in less impact on the capacity and number of deployments of the battery functions.

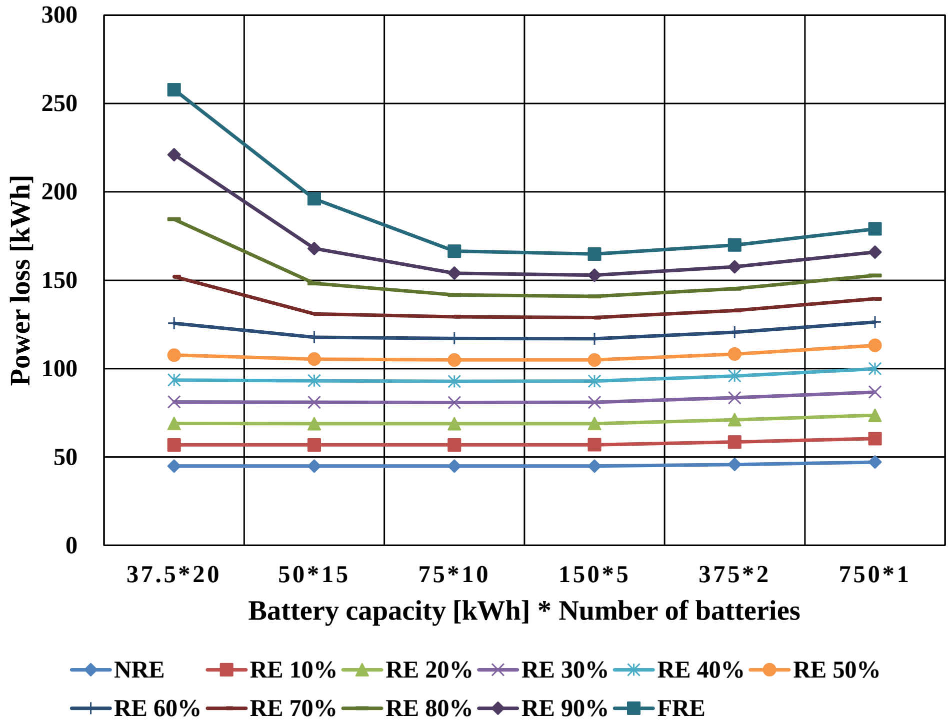

Figure 5.10 Evaluation of power loss for RE-degree at constant battery amount.

In Fig. 5.11, when the power demand of RE 50% is requested in the configuration shown in Fig. 5.6 as an example, it shows the calculation result of the optimal arrangement when the battery function of 150 kWh is deployed to five microgrids. In the figure, the “B” character is described and microgrids (ID = 1, 15, 19, 29, 39) enclosed by the thick red frame are the optimal locations to be used by deploying the battery functions. In this evaluation, the battery function which deploys to an even microgrid generates 15% power loss for charge or discharge, and the battery function which deploys to an odd microgrid generates 5% power loss. Therefore, the efficient battery function in the microgrid of the odd number is selected with priority even if it is located a little bit far location by comparing the power loss by between transmission and charge-discharge.

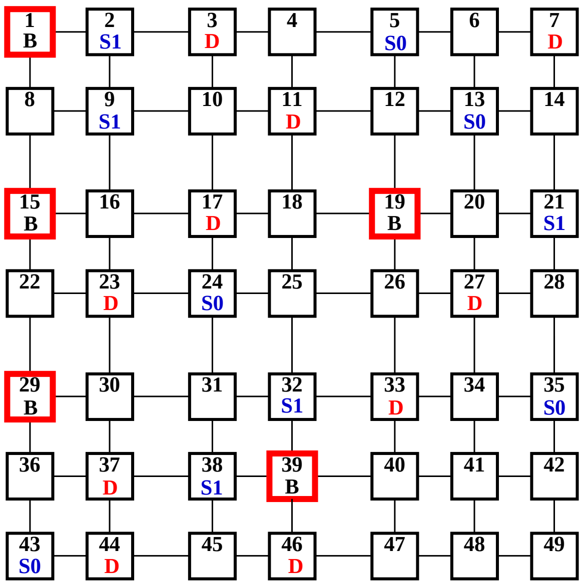

Figure 5.11 Optimal locations of 150kWh*5 batteries for RE 50% power demand.

As an example, when power demand of RE 50% is required under the condition that battery functions (ID = 1, 15, 19, 29, 39) are deployed as shown in Fig. 5.11, the change of remaining FRE and NRE power in the battery functions are depicted in Fig. 5.12 and 5.13, respectively. As a reference, the total charge remaining amount of FRE power (FRE all curve) and NRE power (NRE all curve) are displayed together. From the results of the figure, each battery function in the microgrid is confirmed to be able to charge and discharge by distinguishing between FRE and NRE power. As a result, it is confirmed that optimal transmission, charge-discharge, and deployment of the battery function considering RE-degree are possible since the charge-discharge and transmission are made by the time unit.

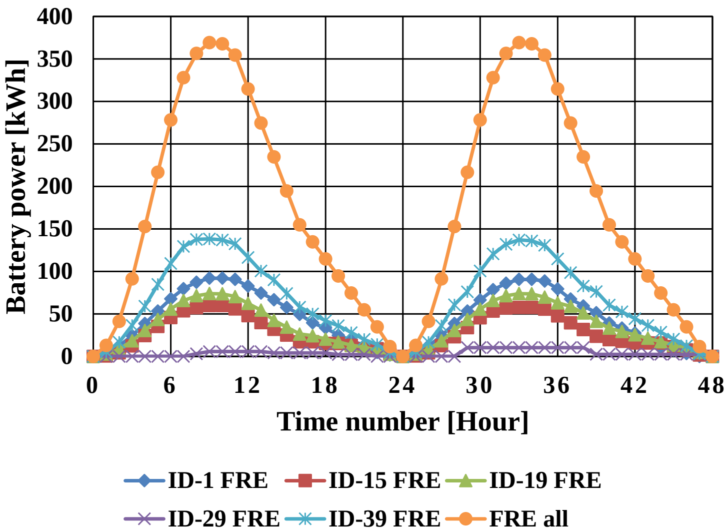

Figure 5.12 Change in FRE battery power amount for RE 50% power demand.

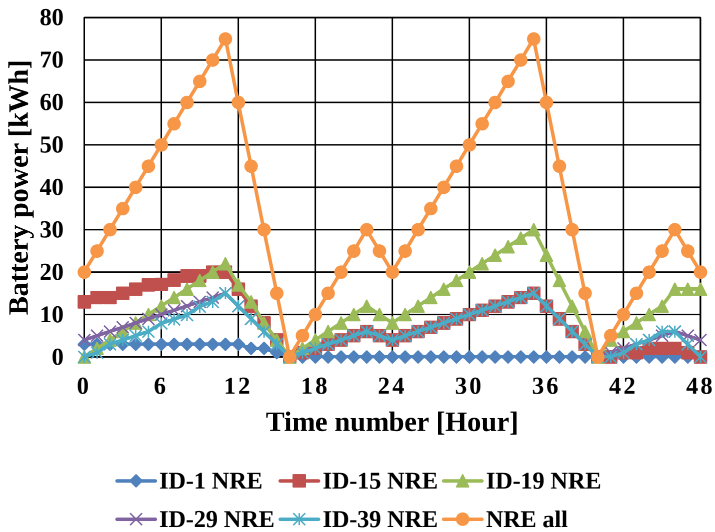

Figure 5.13 Change in NRE battery power amount for RE 50% power demand.

5.4.3.3. Power loss evaluation by changing a period for evaluating RE-degree

Figure 5.14 shows the evaluation result of the amount of power loss for the evaluation period of RE-degree demanded by the demand side. In this evaluation, a combination of the battery capacity and the number of deployments with the best power loss amount at the first evaluation shown in Fig. 5.8 is used. In other words, the case that the battery function of 150 kWh is deployed in five microgrids is evaluated as a representative of battery allocations. In this evaluation, the average value for the arrangement of five different patterns is evaluated as well as other evaluations. In this evaluation, it is possible to evaluate the relation between the power loss and the period achieving the requested RE-degree such as every hourly, every two hours, and eight hours.

As shown in Fig. 5.14, in the case of RE-degree of 10% to 90%, the power loss decreases as the period of evaluating RE-degree increases. In particular, in the case where the evaluation period of RE-degree is 12 hours, compared with the case of evaluating RE-degree every hour, the amount of generated power loss can be reduced by up to about 16%.

On the other hand, if RE-degree is 0% (NRE power) or 100% (FRE power), the color-managed power involved is only one of them, and is not able to compensate for each other, it is not reduced the amount of power loss. In addition, when RE-degree is 70% or more, the amount of generated power loss is reduced by less than 5% even if the evaluation period of RE-degree is set to 24 hours. In addition, when the evaluation period of RE-degree is compared with the case of 24 hours and 48 hours under the evaluation conditions set this time (supply and demand repeats every 24 hours), there is no change in the amount of power loss generated.

In the above-described evaluation conditions, it is obtained a relatively reduced amount of power loss in the case where RE-degree is 10% to 60% and the evaluation period of RE-degree is 12 hours.

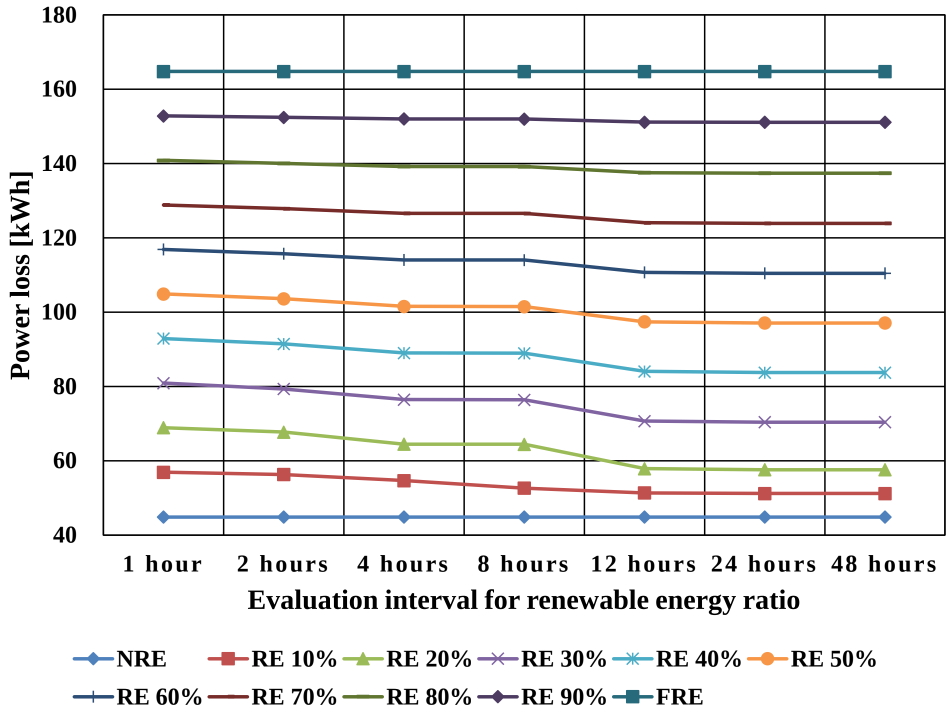

Figure 5.14 Evaluation of power loss for RE-evaluation interval.

5.5. Discussion of Evaluation Results

In the power loss evaluation for the combination of each battery capacity and the number of microgrids to be deployed battery function shown in Fig. 5.8 to Fig. 5.10, when the battery function of 150 kWh is deployed in five microgrids, the amount of power loss is minimized. When the battery function of the small capacity such as 37.5 kWh or 50 kWh is deployed in 20 or 15 microgrids, and the proposed power loss minimization method is used, it is set to prioritize the efficient battery function. However, when the number of deployments increases, it is thought that the battery function which does not have a good efficiency is used and the amount of power loss is increasing as a result. When a large-capacity battery function, such as 750 kWh, is deployed to a single microgrid, it is necessary to use the battery function which exists in the position which is not the shortest path connecting between the power supply and demand microgrids. As a result, the transmission distance is increased, and the amount of power loss is thought to increase.

In this evaluation, power supply functions for NRE and FRE are set in five microgrids, respectively. Ten microgrids are assigned for power demand. Therefore, in the case where the number of power supply and demand microgrids differ greatly, the optimal position of the battery function is considered to be different from the results, and evaluation is necessary for each setting.

On the other hand, in the case of the comparative evaluation the route-based method [33] in Fig. 5.8, the transmission distance is optimized, but the efficient battery function is not used preferentially. Since the battery function in a microgrid that exists on the shortest path between power supply and demand microgrids is used, there are both when using efficient battery functions and otherwise. As a result, it is thought that the power loss by transmission and charge-discharge increases. In addition, in the case of using the battery function of 750 kWh, the battery function in a microgrid to optimize the transmission distance is use. If the efficiency of the battery function is not good, it will be a significant power loss. Therefore, it is thought that even the average value of the evaluation for five patterns has resulted in a large amount of power loss.

Similarly, in the case of the comparative evaluation the route-based method [33] in Fig. 5.9, the transmission distance is optimized, but the efficient battery function is not used preferentially. On the other hand, the proposed method minimizes the power loss in consideration of the transmission distance and the efficiency of charge and discharge, and uses the efficient battery function preferentially. As a result, it is thought that the proposed method has a dominant result compared with the route-based method.

From the results of Table XV and Table XVI, in the proposed method, when the number of battery functions is large, the variance tends to increase. When the number of battery functions is increased, the arrangement and number of the efficient battery function varies with the arrangement pattern. Therefore, it is thought that the increase in the utilization of the non-efficient battery function occurs, resulting in increased variance due to the increase in power loss. In the case of a small number of battery functions to be used, when the arrangement of the microgrid for power supply and demand is different (Table XV), and the battery efficiency setting is random (Table XVI), the power loss is minimized by considering both the transmission distance and the battery efficiency. Therefore, it is thought that the increase of the variance is suppressed as a result that the power loss is not increased.

On the other hand, the route-based method tends to significantly increase the variance when the number of battery functions is small. In the route-based method, battery functions are selected to minimize the power transmission distance. If there is no efficient battery function on the shortest path, it utilizes a non-efficient battery function. Therefore, in the evaluation of Table XV and Table XVI, it happens to use a non-efficient battery function when the efficient battery function is not present on the shortest path. As a result, it is thought that the amount of power loss increased and the variance increased. In particular, if the number of battery functions used is one, whether the efficiency of the battery function on the shortest path is good or not affects the power loss reduction. Therefore, it is thought that the variance increased greatly depending on the allocation of efficient battery functions.

In the power loss evaluation, which changed RE-degree and the period of *SPAN* shown in Fig. 5.14, the amount of power loss is significantly reduced when specified RE-degree is 10% to 60% and RE-degree is evaluated in 12 hours interval. This is a result of flexibly adjusting the timing of each consumption for both NRE and FRE power as color-managed power in order to reduce the amount of power loss generated. When the power demand is only one of NRE and FRE power or one of NRE or FRE power supply is not sufficient, the use timing of the color-managed power cannot be adjusted. Therefore, it is thought that it is not possible to sufficiently reduce the amount of power loss even after changing the time period for RE-degree evaluation.

In the evaluations, the supply and demand amount of power are all the same in order to investigate the basic characteristics. However, in such a case, when the number of battery functions to be deployed is extremely small or deployed at a position not suitable, it is clarified that the power loss by transmission is increased. In addition, by assuming the efficient battery function (5% power loss by charge or discharge) and the non-efficient battery function (15% power loss by charge or discharge), it is clarified the amount of power loss increases when not efficient battery functions are used.

In addition, by evaluating the amount of power loss by changing RE-degree from 0 to 100%, the amount of power loss due to transmission and charge-discharge increases when RE-degree is higher. It is thought that the tendency to increase the amount of power loss rapidly when a lot of battery functions of a small capacity are deployed. Moreover, the time period for evaluating RE degrees is varied between 1 and 48 hours, and the amount of power loss is evaluated. In this evaluation condition which simulates the power generation by the sunlight, it is thought that the characteristic which can reduce the amount of power loss is clarified when the evaluation interval of about 12 hours is taken.

As a result of this formulation and evaluations, a certain value for the design policy of the interconnected microgrids with battery functions is obtained, and an effectiveness of this formulation could be verified. The proposed optimization method derives the solution of the transmission amount and the charge and discharge amount between the microgrids as a variable, and it is possible to apply it to a different type of topology because it does not depend on the topology as a solution. However, if the topology is different, it is considered to be a different result. In this evaluation, a solution can be derived from several tens of microgrids. Therefore, if the number of microgrids and the days of evaluation are extremely increased, the constraints are likely to occur in terms of computational time. On the other hand, the value of the supply and demand amount of the power in the microgrid is an input condition to calculate the solution, and it is thought that the derivation of the solution is possible even for different values of the input for each microgrid.

In relation to our research, there has been research [52], [53] to manage the attributes of power generation. An identifier is given to the power flow transmitted between each power supply and power consumption equipment, and researches on the stability control of the power supply and demand have been executed. In these papers, "color management" of power is proposed, which manages each power flow generated by different types of generators as a different power, and the supply and demand of power is controlled.

In this chapter, a power network capable of transmission control is assumed. We discuss the position control and transmission path control of the battery function to reduce power loss associated with power transmission and charge-discharge among power-supply, transmission, and power-demand business operators. Specifically, color-managed electric power (hereinafter referred to as colored power) transactions that distinguish power generation by RE and non-RE are achieved. In addition, a method to achieve the specified utilization rate of RE on the demand side is focused on. Moreover, we discuss a method to reduce the power loss associated with power transmission and charge-discharge in the control to supply and demand balance of electricity by temporarily charging the surplus colored-power and discharging at the stage where power is insufficient.

In the related research [52], [53], it is similar in terms of color management based on the attributes of power, but in our research, it is different in terms of identifying and managing power based on whether the power generated by RE. In addition, the power supply, charge-discharge, and consumption equipment are deployed in a wide area and the power loss by the transmission and charge-discharge is reduced by allocating battery functions to optimized locations in our research. Moreover, a control for the specified utilization rate of power by RE is also different. In our research, it is assumed that allocation of battery functions means to use the charge-discharge capacity that is equipped with in each microgrid.

By the way, the microgrid as a single unit is in the process of being built in recent years. In the future, in the advanced stage of operation for which multiple microgrids are connected to wide area and color-managed power is applied, this result is thought to be useful for the deployment position determination of the battery function, power transmission, and charge-discharge control, etc.

In summary, when the power rate by RE is increased in a demand side, the amount of using the charge-discharge function increases, the amount of power loss is increased. In particular, when the utilization rate of RE is 60% or more, when deploying a large number of charge-discharge function of small capacity, the power loss is extremely increased. Therefore, when the utilization rate of RE is high, operation that does not deploy a large number of charge-discharge functions of small capacity is important. On the other hand, when the utilization rate of RE is low, the influence of the power loss to the capacity of the charge-discharge function is small was confirmed. In addition, in the case where the utilization rate of RE is 90% or less, it was confirmed that the amount of power loss can be reduced by lengthening the period of evaluating the utilization rate of RE. In particular, if the utilization rate of RE is low, such as 10% to 50%, it was confirmed that the effect of reducing the amount of power loss is high. Therefore, if the utilization rate of RE is not high, reducing the power shift to comply with the specified RE rate in a short period, the control to consume without time shifting the power generated by RE is particularly important. In addition, it was clarified that the utilization rate of the renewable energy specified by the demand side and the reduction of power loss can be achieved concurrently.

5.6. Conclusion

In this chapter, we focused on an interconnected microgrids and proposed an effective utilization for color-managed power by optimizing allocation of battery functions and power transmission. In the proposed method, the power generated by RE or not is distinguished as color-managed power. In the case where the supply of power and the pattern of the demand are different, the battery function can be used to make power trading possible. It is also possible to reduce the power loss of FRE and NRE power due to transmission and charge-discharge.

The proposed method supplies color-managed power (FRE and NRE power) from multiple power supply microgrids to the power demand microgrid. By minimizing the power loss by transmission and charge-discharge as an objective function of the mathematical programming problem, it is possible to determine the optimal microgrids that are deployed battery functions, and to use selectively efficient battery functions. In addition, it is possible to consume power as specified RE-degree by controlling a ratio between FRE and NRE power consumed on the demand side.

The proposed method was evaluated for a topology in which 49 microgrids were connected to lattice-like (7x7). As a result, we confirmed that it is possible to optimally deploy the battery function to minimize the amount of power loss, to determine optimal power transmission paths, and to consume power as specified RE-degree. As a result of comparison of between the proposed method and route-based method (which deploys the battery function to minimize power transmission distance), the amount of power loss by transmission and charge-discharge was improved by 20% or more.

When the utilization rate of RE is high, it was clarified that operation that does not deploy a large number of charge-discharge functions of small capacity is important. In addition, if the utilization rate of RE is not high, reducing the power shift to comply with the specified RE rate in a short period, the control to consume without time shifting the power generated by RE is important. Furthermore, it was clarified that the utilization rate of RE specified by the demand side and the reduction of power loss can be achieved concurrently.

Chapter 6

Conclusion and Future Work

In this thesis, we focused on the interconnected microgrids in order to effectively use RE such as solar power. Specifically, we discussed the reduction of the power loss by transmission and battery charge-discharge under the conditions where power generation and demand patterns are different. We proposed schemes to decide transmission paths, battery locations, and control of charge-discharge in order to reduce the power loss. The results obtained in this study are summarized below.

In Chapter 2, the reduction of power loss by assuming the same performance for every charge-discharge function is discussed. We proposed a scheme that can reduce power transmission loss between microgrids by minimizing loads that are defined by the multiplication of “volume of power transmission” and “transmission distance” as an objective function of a linear programming model. The proposed method is evaluated for a topology where 49 microgrids are connected to lattice-like (7x7). It was confirmed that the proposed method improves the power transmission loss by up to 20% compared with the k-means based method at our evaluation conditions. By the proposed method, by deploying the charge-discharge function on the microgrid located on the path where the transmission distance is minimized, it was verified that it is possible to reduce the power loss by transmission. Therefore, it has been confirmed that our proposed method is beneficial as a method for reducing the power loss by transmission.

In Chapter 3, the reduction of power loss by assuming the different performance for every charge-discharge function is discussed. We proposed a scheme that can reduce the power loss by both transmission and battery charge-discharge. The power loss is reduced by minimizing an objective function of mathematical programming problem that is defined by a total power loss due to the transmission, charging, and discharging of power. To evaluate the proposed method, we simulated the interconnected microgrids by connecting multiple prefectures in Japan. It was verified that the proposed method resulted in an average of 26.7% improvements compared with the route-based method considering transmission distance only. By preferentially utilizing the efficient charge-discharge function and deploying the charge-discharge function in a microgrid that exists on a path to reduce the power transmission distance, it was clarified that it is possible to reduce the power loss by transmission and charge-discharge. Therefore, it has been confirmed that our proposed method is beneficial as a method for reducing the power loss by transmission and charge-discharge.

In Chapter 4, the reduction of power loss for a long term is discussed. We proposed a scheme to reduce the power loss by transmission and charge-discharge for a long term. The power loss is reduced by iterating minimization of an objective function of mathematical programming problem that is defined by a total power loss for one day considering battery efficiency deterioration. The proposed method is evaluated for one thousand days using the topology where 49 microgrids are connected to lattice-like (7x7). It is verified that it is possible to calculate a deployment of battery functions and transmission routes in order to reduce the amount of power loss due to transmission and charge-discharge for 1000 days. When the charge-discharge efficiency deterioration by the charging and discharging is advanced, it was confirmed that "power loss amount generated on each day" and "accumulation of power loss amount" are reversed during the evaluation period among the combinations of battery capacity and the number of deployments of it. As a result, it was confirmed that the use setting of the battery function based on long-term evaluation is necessary. In addition, the control of selecting the capacity and number, such as to use only efficient charge-discharge function, it has been clarified that it is possible to reduce the amount of power loss by transmission and charge-discharge.

In Chapter 5, under the condition that the rate of RE is specified by a demand side, the reduction of power loss is discussed. In the proposed method, the target rate of power consumption for RE is managed by the color management of power which distinguishes power generation by RE and non-RE. The power loss is reduced by minimizing an objective function of a mathematical programming problem that is defined by a total power loss by distinguishing power generation by RE and non-RE. Through the simulation, we confirmed that it is possible to optimally deploy the battery function to minimize the amount of power loss and to consume power as specified degree of RE. Compared with the route-based method, the proposed method is improved by 20% or more under our evaluation conditions. When the utilization rate of RE is high, it was clarified that operation that does not deploy a large number of charge-discharge functions of small capacity is important. In addition, if the utilization rate of RE is not high, reducing the power shift to comply with the specified RE rate in a short period, the control to consume without time shifting the power generated by RE is important. Furthermore, it was clarified that the utilization rate of RE specified by the demand side and the reduction of power loss can be achieved concurrently.

In this thesis, schemes to reduce the power loss by transmission and charge-discharge are discussed in detail for the interconnected microgrids by assuming that it is possible to control power transmission between microgrids. Therefore, a study to exactly control power transmission between microgrids as specified routing paths is needed.

In addition, it is also assumed that it is possible to control charging and discharging. Therefore, a study to exactly control power charging and discharging as specified by a result of minimization of a mathematical programming problem is needed.

Furthermore, the minimization of power loss is calculated based on the prediction of power generation and consumption by using a scheme of mathematical programming problem. For that reason, a study to predict power generation and consumption accurately is needed.

In this thesis, we proposed schemes to reduce the power loss by transmission and charge-discharge for effectively trading electric power between microgrids. Our result is a very small contribution for effectively using and trading power between microgrids. We hope that our research results can contribute even a little to the research and development of the interconnected microgrid field.

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