Equipment Planning for Renewable Energy Wide-Area Network in Hokkaido and Consideration of Transmission Capacity for the Increase in the Amount of Introduction

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Abstract: In order to expand the introduction amount of renewable energy, it is necessary to solve various problems such as suppression of output fluctuation, cost of power supply compensator for reducing output fluctuation, and lack of transmission capacity. On the other hand, it is known that output fluctuation of renewable energy is leveled by interconnecting renewable energy dispersedly arranged in a wide area. Therefore, it is possible to reduce the cost of the system by optimally distributing and linking the renewable energy to a wide area. Therefore, in this study, we developed computer algorithms to optimize the location and introduction amount of renewable energy that will conduct wide area interconnections based on actual transmission network equipment. The target of the analysis was the Hokkaido area in Japan with extensive land and abundant natural energy. Using the proposed algorithm, we evaluate the relationship between economical renewable energy location and capacity, renewable energy supply rate and grid capacity. As a result, it was possible to realize an economical power system with a high percentage power supply ratio of renewable energy.

Key words: Renewable energy, genetic algorithm, wide interconnection, transmission capacity.

Nomenclature

F_{system}	Objective function of the system	Tp, dv	Power transmission
C_{gen}	Cost of power generation [JPY]	cps	Controllable power source
C_{tp}	Delivery Cost [JPY]	$need$	Demand
C_{sho}	Shortage of power Cost [JPY]	$loss$	Transmission loss
p	Power [MW]	$nomi$	Nominal voltage
Δp	Loss of power [MW]	$line, n$	Transmission line
u	Unit price of equipment [JPY/MWh]	$allow$	Allowable current
Δt	Interval of sampling time [hour]	sho	Shortage of power
V	Rated capacity [MW]	Re, r, dp	Renewable energy
I	Current	j	Number of solar power generation
R	Resistance	k	Number of wind power generation
l	Length of power transmission line	l	Cities with power accommodation
JPY	Japanese Yen	m	Cities receiving power accommodation
$cos\phi$	Power factor		

Subscript

$period$	Analysis period
$city, i$	Introduction city of a power source
pv	Solar farm
wp	Wind farm

1. Introduction

Recently, in Japan, due to the earthquake that occurred in 2011, nuclear power plants are stopped. Currently, there are 7 nuclear power plants in operation,

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and many nuclear power plants are still conducting inspections and reviews [2]. Fig. 1 shows the ratio amount of the electricity generated by each power source in Japan from 2010 (before the earthquake) to 2016 [3]. Nuclear power generation accounted for about 30% of the total in 2010 before the earthquake, but it decreased to 1.7% in 2016. On the other hand, thermal power generation including coal, petroleum, LNG, and LPG accounted for 61.8% of the total in 2010, but the proportion increased after the disaster, accounting for about 80% of Japan's generated electricity. As shown in Fig. 1, the electric power which the nuclear power plant has covered is covered by the increase in the thermal power plant. However, because the power supply of thermal power generation involves the emission of greenhouse gases, the increase in power generation due to increased firing of thermal power plants is feared to promote global warming. So, in Japan, power supply by renewable energy does not emit greenhouse gases paying attention. However, there are problems to increase renewable energy introduction. For example, output fluctuation occurs due to climate change in the place where renewable energy is installed. The cost of compensation power

supply and energy storage device to suppress this fluctuation is expensive. Moreover, if we introduce a large amount of renewable energy in areas with low electricity demand, the capacity of the transmission line that cannot supply electricity due to insufficient capacity in existing network equipment is a problem. Therefore, in order to increase the ratio of the power supply by renewable energy, it is necessary to take measures against output fluctuations that cannot be predicted and set the capacity of the appropriate electricity transmission network. On the other hand, it is known that output fluctuation is leveled by interconnecting renewable energy dispersedly arranged in a wide area. From this, it is considered that by appropriately distributing and arranging renewable energy, it is possible to suppress the output fluctuation, reduce the equipment cost of the compensation power supply and the energy storage device, and construct a system with low cost. However, in order to properly distribute renewable energy, it is necessary to clarify the area to be installed and the type and capacity of renewable energy. Therefore, in this research, we aim to develop computer algorithms to optimize the introduction amount of renewable energy and

Fig. 1 The ratio amount of the electricity generated by each power source in Japan from 2010 to 2016.

compensation power supply from economical efficiency by using actual transmission network.

2. System Overview

2.1 Power System

Fig. 2 shows proposed power grid in this study. We built a distributed the proposed power grid with a wide area interconnection of the solar power generation and the wind power generation in the target Hokkaido area in Japan. Hokkaido has extensive land and abundant natural energy. Therefore, in this study, we target Hokkaido in Japan with a high potential for the introduction of renewable energy. We categorize Hokkaido area into 14 cities based on the transmission line, the meteorological characteristics and population distribution. We propose a power grid that is connected to each area in the transmission. The capacity of the transmission line is decided with reference to actual tidal current record [4], the population of each city and Hokkaido's maximum

electric power demand. Electric power is supplied from the solar power generation and the wind power generation installed in each city and if it covers the electric power demand of each city. When electric power supplied from renewable energy falls below power demand, electric power is supplied from another city through power transmission line or electric power is supplied from a power supply compensator. When the power supplied from renewable energy exceeds the electric power demand, electric power would be transferred through the transmission line to the other cities which are short electricity.

2.2 Distributed Power Supply Network

Fig. 3 shows an example of distributed power network. The solar power generation and the wind power generation are installed in each city, and the generated electricity is supplied to customers in each city via transmission lines. In addition, when renewable energy output exceeds electricity demand, electricity

Fig. 2 Proposed power grid.

Fig. 3 Distributed power network in the proposed interconnected power system.

will be exchanged between the cities via the grid interconnection device. At this time, if the interchangeable power exceeds the transmission capacity, power exceeding the transmission capacity will not be transmitted. Also, if it cannot cover the demand with the renewable energy or interchange power from other cities in each city, supply power from the power supply compensator is installed in each city. If power supply compensator is installed in the city, power will be supplied from a power supply compensator installed in another city.

3. Analysis Method

3.1 Optimization Analysis by Genetic Algorithm

In the power grid with distributed and connected renewable energy, output of the solar power generation and the wind power generation installed in many areas varies due to weather conditions such as solar radiation amount and wind speed in each city. Therefore, it is necessary to optimize the output ratio of each power source having nonlinear characteristics based on the objective function. In this analysis, we will develop an optimization algorithm based on genetic algorithm (GA) that can deal with multiple variables simultaneously. From the analysis result, we compare the utilization ratio of renewable energy cost and power supply compensator introduction amount and capacity of transmission line with the actual tidal current performance which minimizes the objective function.

3.2 Chromosome Model

Fig. 4 shows the individual model to be introduced into the GA. The individual which is composed of a chromosome represents the output of the renewable energy of all cities, chromosome expressing the priority order of cities conducting power interchange and determining the transmission path. Fig. 5 shows the respective chromosomes.

(a) The chromosome representing the output of renewable energy in Fig. 5a is constituted of a group

of genes represented by 0 or 1 and shows the output ratio of the solar power generation and the wind power generation in each area. The output of the solar power generation and the wind power generation for each sampling time of each area is expressed by multiplying the output of the solar power generation and the wind power generation calculated from the weather conditions of each city with the information expressed by each chromosome.

(b) If surplus electricity is generated in multiple cities, it is uncertain which delivery cost of electricity will be the lowest when electricity is interchanged from any city. Therefore, in this study, when surplus electricity is generated in multiple cities, we also make chromosomes which randomly decide which cities to exchange power. The chromosome expressing the priority order of the cities that perform electric power accommodation in Fig. 5b represents each city by numbers from 0 to 13, the numbers being arranged at random. This chromosome is not crossover in the GA operation and leaving a combination that is the lowest cost.

(c) When transmitting electricity to a city, if there are multiple power transmission paths, it is unclear which route can be selected to reduce the delivery cost. Therefore, when there are multiple transmission lines when transmitting electricity, a chromosome to randomly select the route is created. This chromosome is represented by numbers 0, 1 and 2, and each represents a route for power transmission. This chromosome is not crossover in the GA operation and leaving a combination that is the lowest cost.

3.3 Analysis Flow

Fig. 6 shows a flow chart of the system analysis

Fig. 4 Individual model of the proposed GA.

Fig. 5 Each chromosome model in the individual.

Fig. 6 Analysis flow.

based on GA in this study. Eq. (1) is the objective function F_{system} of the proposed system. It consists of the sum total of renewable energy and power generation cost of compensating power source C_{gen} [ten thousand yen], power consignment cost C_{tp} [ten thousand yen] and cost C_{sho} [ten thousand yen] due to

an occurrence of shortage power. In this study, the optimal solution is the configuration of the system that minimizes the value of Eq. (1).

(a) Input as initial data and analysis conditions, the output by the photovoltaic power generation and the wind power generation in each city, power demand,

power generation cost of various power sources, power consignment cost, cost of insufficient power and GA parameter are input.

(b) Generate the population shown in Fig. 4 by the number specified by GA parameter. In addition, the value of genes in the chromosome representing the output of renewable energy generated in the early generation is randomly determined. Furthermore, chromosomes representing the priority order of cities that will accommodate electric power are randomly determined.

(g)~(i) Calculate the compensating power source and the amount of interchangeable power by giving the output of the solar power generation and the wind power generation to Eq. (2), decided based on information on the chromosome. In the case where the power supply cannot be sufficiently accommodated by the entire system due to the shortage of the transmission capacity, the electric power that cannot be covered is set as the insufficient electric power. However, the interchange power from other cities is calculated using Eq. (3). Eq. (4) is used for the transmission loss. Line current I_{line} is the power dissipated to other cities divided by the nominal voltage of each transmission line. The resistance value of each transmission line was referred to the value corresponding to the allowable current when the transmission capacity was obtained from the Eq. (5) [5].

(l) Calculate the generation cost from the output of the solar power generation, the wind power generation and power supply compensator installed in each city in Eq. (6). In Eq. (7), the consignment cost necessary for power interchange among cities is calculated. In Eq. (8), the cost of insufficient power is calculated.

(m) The fitness of each individual is determined from the objective function of Eq. (1) given from the sum of the power generation cost of each power source, the power consignment cost and the cost of the insufficient power. In this study, in order to construct

a system with excellent economic efficiency, individuals with lower objective function values should have higher fitness.

(o) Rearrange the fitness of each individual determined by (m) in descending order of evaluation.

(p) From the collection of individuals sorted by (o), according to the selection operation determined by the GA parameter, we will eliminate the lower population and increase the higher population.

(q) In the crossover operation, extract the two chromosomes in accordance with crossover probability set in advance from the chromosomes of the solar generation and the wind power generation in all individuals. Then, replace the front and rear of randomly selected genes in the extracted chromosome. By doing this operation, we will make a new individual.

(r), (s) Analyze the number of generations set with the GA parameter and extract individuals with the highest fitness from the final generation population as optimal solutions. By doing this, we get the amount of photovoltaic power generation, wind power generation and compensating power supply in each city and the interchangeable electricity amount between areas.

$$F_{system} = C_{gen,period} + C_{tp,period} + C_{sho,period} \quad (1)$$

$$\sum_{t=0}^{N_{period}} \left\{ \sum_{i=1}^{N_{city}} \left(\sum_{j=1}^{N_{pv}} P_{pv,i,j,t} + \sum_{k=1}^{N_{wp}} P_{wp,i,k,t} + \sum_{l=1}^{N_{tp}} P_{tp,i,l,t} + P_{cps,i,t} \right) \cdot \Delta t \right\} \\ = \sum_{t=0}^{N_{period}} \left\{ \sum_{i=1}^{N_{city}} \left(\Delta P_{need,i,t} + \sum_{m=1}^{N_{city}} \Delta P_{tp,i \rightarrow m,t} \right) \cdot \Delta t \right\} \quad (2)$$

$$P_{tp,i,l,t} = P_{tp,l \rightarrow i,t} - \sum_{n=1}^{N_{line}} P_{loss,l \rightarrow i,n,t} \quad (3)$$

$$P_{loss,l \rightarrow i,n,t} = 3 \cdot I_{line,n,t} \cdot R_n \cdot l_n \quad (4)$$

$$P_{tc} = \sqrt{3} \cdot V_{nomi} \cdot I_{allow} \cdot \cos\phi \quad (5)$$

$$C_{gen,period} = \sum_{t=0}^{N_{period}} \sum_{i=0}^{N_{city}} \{ (u_{pv} \cdot P_{pv,i,t} + u_{wp} \cdot P_{wp,i,t} + u_{cps} \cdot P_{cps,i,t}) \cdot \Delta t \} \quad (6)$$

$$C_{tp,period} = \sum_{t=0}^{N_{period}} \sum_{i=0}^{N_{city}} (u_{dv} \cdot P_{tp,i,t} \cdot \Delta t) \quad (7)$$

$$C_{sho,period} = \sum_{t=0}^{N_{period}} \sum_{i=0}^{N_{city}} (u_{sho} \cdot P_{sho,i,t} \cdot \Delta t) \quad (8)$$

4. Analysis Conditions

4.1 Power Demand

In this study, the analysis period is one year. Fig. 7 shows the demand pattern of electricity on the first day of each month. This power demand pattern was based on past power supply by the Hokkaido Electric Power Company. The electricity demand in each city was considered from the population of each city.

4.2 Cost Setting

Table 1 shows the cost of various power supplies, the delivery cost of power and the shortage of power cost used in this study. The power costs of various power supplies and the delivery cost of power were values published by the Meti [6] and Hokkaido Electric Power Company [7]. The power generation cost of power supply compensator was decided based on the amount of electricity that coal and oil-fired power maintained in Hokkaido currently generate on an annual average. In addition, since power outage occurs when shortage power, the shortage powers costs are set higher than other costs so that this does not occur.

4.3 GA Parameters

Table 2 shows the GA parameters used in this analysis. The sampling time is 1 hour, and the genetic operation is performed under the conditions shown in Table 2.

Fig. 7 Power demand of Hokkaido area in Japan.

Table 1 Various cost.

Type of generator and cost	Power generation cost ($\times 10^4$ JPY/MWh)
Photovoltaics	2.42
Wind power generator	2.16
Compensation power (Coal and oil-fired)	2.43
Delivery cost of electricity	0.41
Shortage of power cost	5.00

Table 2 GA parameters.

Generation number	1,000
Number of individuals	1,000
Interval of sampling time	1 hour
Probability of cross-over	95%
Probability of mutation	0.2%
Selection	
Individuals with maximum of adaptive value	15% in all the individuals
Individuals with the 2nd to 5th place of adaptive value	5% in all the individuals

5. Analysis Result

Fig. 8 shows total demand electric energy and total generated electric energy by renewable energy in this session. It can be seen from Fig. 8 that the electricity supply by renewable energy in each city does not exceed the electricity demand. In addition, since the generated power is larger for cities with greater electricity demand, it is considered that local production of electricity was done. According to the analysis, the amount of electricity generated by renewable energy was 33.1% of the total generated electricity. This result greatly exceeded the total electricity generation amount of renewable energy in present Hokkaido by 15.0%.

Fig. 8 Total demand electric energy and total generated electric energy in this session.

Fig. 9 Average utilization of transmission lines.

Fig. 9 shows the average of utilization of transmission lines. The average utilization of transmission lines in this system was 20.8%. This result is a much lower value than the utilization rate 37.0% obtained from the actual tidal current record of the transmission line used in this study. In particular, the average utilization rate of transmission lines after surplus power has been interchanged was 6.2%, which is a considerably low value. The reason for this is that local production of generated electricity was carried out to suppress electricity consignment cost. Therefore, it can consider that surplus electric power did not occur much. It seems that the electric power that is

interchanged to other cities became smaller than the actual tide current record.

Fig. 10 shows the maximum utilization rate of the transmission capacity when surplus power by renewable energy is exchanged. From Fig. 10, it can be seen that the utilization rate between the routes C-D, C-E, D-E, E-I, I-J, J-K and K-N is 100%. These results show that it is expected that by increasing the capacity of these transmission lines, power interchange by renewable energy will increase. Also, the rate of the power supply by renewable energy will increase. In addition, since no energy storage device is used in this analysis, it is thought that it will be possible to use electric

Fig.10 The maximum utilization rate of transmission line after surplus power interchanged.

power exceeding the transmission capacity by providing an energy storage device such as a heat storage tank in the future. As a result, it is thought that the usage rate of the compensation power supply will decrease, and the generation ratio of renewable energy will increase.

6. Conclusion

We developed a computer algorithm by using GA to analyze the economically optimal installation location and installed capacity of renewable energy by distributing renewable energy to a wide area. By analyzing this computer algorithm, the following conclusions were obtained.

(1) A large amount of renewable energy was installed in cities where electricity demand is high, because local production of electricity was planned to reduce the delivery cost of power.

(2) Electricity supply rate of renewable energy was 33.1% of the total electricity supply, which was a very high rate.

(3) Since the local production of electricity was carried out to reduce the power consignment cost, the average utilization rate of the transmission line in this analysis was 20.8%. It was lower than the average

utilization rate of the transmission line installed in Hokkaido area.

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