Study on Suppression of Frequency Fluctuation of Microgrid Interconnected With Photovoltaic Power Generation by SOFC Triple Combined Cycle and Storage Battery

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Abstract: *In this paper, research reports on frequency fluctuation in case of introducing SOFC triple combined cycle and storage battery (lead storage battery or nickel metal hydride storage battery or lithium ion battery) into independent micro grid interconnected with photovoltaic power generation will be conducted. Through numerical analysis in this paper, the introduction amount of SOFC triple combined cycle and photovoltaic power generation and storage battery, which can keep the frequency variation of independent microgrid within the allowable range are investigated.*

Keywords: *Storage battery, Photovoltaic, Microgrid, SOFC triple combined cycle*

1. Introduction

Construction of a distributed electric power system linking a large amount of renewable energy is expected from the concern about the environmental impact on the centralized electric power system centered on thermal power generation and the risk of power loss during accident. However, since the output of renewable energy is unstable, in practice, the introduction capacity to the distributed power system is largely restricted. The purpose of this research is to construct a micro grid with a high proportion of Photovoltaic power generation (PV) by linking a solid oxide fuel cell (SOFC) triple combined cycle (SOFC-TCC) to an independent micro grid including PV. SOFC-TCC is a highly efficient power generation system that combines SOFC with gas turbine (GT) and steam turbine (ST). There are several examples of research on SOFC-TCC [1][2]. However, there are few researches on suppression of frequency fluctuation of micro grid interconnected with renewable energy by SOFC-TCC and storage battery. Therefore, in this paper, numerical analysis is conducted to investigate the limit introduction amount of PV and storage battery which can accommodate frequency fluctuation of independent microgrid interconnecting SOFC- TCC and PV in an allowable range. In the analysis of this paper, the frequency fluctuation when introducing lead-acid battery, nickel-metal hydride storage battery, and lithium ion battery into proposed system respectively are investigated.

2. Configuration of Proposed System

Figure 1 shows the structure of an independent microgrid proposed in this paper. The installation location of the independent microgrid assumed in this paper is Kitami city of Hokkaido of Japan. The fuel (methane gas after desulfurization) of the SOFC-TCC to be introduced in the proposed system is supplied directly to only the SOFC portion in order to keep the power generation efficiency high. Also, the storage battery to be introduced in the proposed system is a lead storage battery or a nickel-metal storage battery, or a lithium ion battery.

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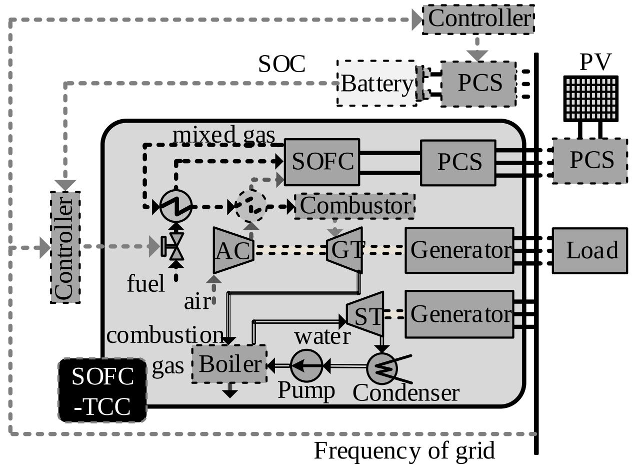

Fig. 1: Configuration of the proposed system.

3. Analysis Model

Figure 2 shows an analysis model of frequency variation in the proposed system. The frequency in the proposed system is calculated in the frequency calculation block based on the deviation of the total supply power and the electric power load. In the proposed system, the output of the storage battery and the SOFC-TCC is controlled so that the frequency becomes equal to the reference value of the frequency. Here, the output of the storage battery is adjusted by PWM control of the inverter in order to cope with the short cycle fluctuation of the PV output. On the other hand, the output of the SOFC-TCC is adjusted by controlling the fuel flow rate so that both the state of charge (SOC) of the storage battery and the frequency of the microgrid are kept at the reference values. By changing the characteristic equation in the battery model in Fig. 2, it is possible to express the characteristics of lead storage battery, nickel-metal hydride storage battery, storage battery of lithium ion battery. The analysis model was created by MATLAB / Simulink R2014a.

4. Energy Balance Calculation of SOFC-TCC

In this paper, the capacity of each system of SOFC-TCC is determined so that the rated output of SOFC-TCC is equal to the maximum power demand (121.5 MW) of Kitami city by energy balance calculation. Here, the maximum power demand of Kitami city is the maximum value of electricity demand for one year in Kitami city. This was obtained from the historical power demand record of Hokkaido and the population of Kitami city. Equations (1) and Eq. (2) show the power balance equation and the heat balance equation of SOFC, respectively.

$$P_{SOFC} = \eta \cdot N \cdot N_0 \cdot I \cdot V \tag{1}$$

$$\sum_{i=1}^{7} [q_{i,sf} \cdot h_{c,i}] = \sum_{i=1}^{7} [q_{i,r} \cdot h_{r,i} + q_{i,sf} \cdot \int_0^{T_{sf}} c_i dT - q_{i,r} \cdot \int_0^{T_r} c_i dT] \tag{2}$$

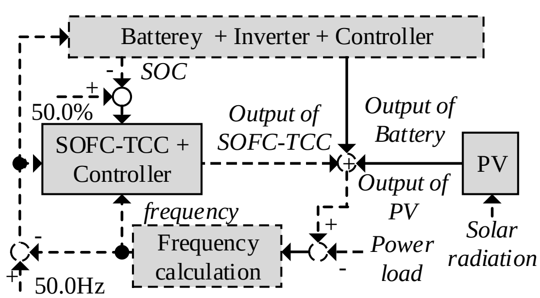

Fig. 2: Analytical model of the proposed system.

TABLE I: Rated power of SOFC-TCC

Types of generators	Rated output[MW]
SOFC	84.36
GT	16.50
ST	21.35
Total	122.2

In the Eq. (1), the P_{SOFC} [W] is the DC output of the SOFC, η is the efficiency of the power conditioner, N and N_0 are the stack number and the number of cells of the SOFC respectively, V [V] is the voltage, I [A] is the current. In the Eq. (2), $q_{i,sf}$ [kg/s] is the flow rate of the component i of the gas during power generation, and $q_{i,r}$ [kg/s] is the flow rate of the component i of the gas at reforming. Further, c_i [J/(kg·K)] is the specific heat of the component i of the gas, T_{sf} [K] is the temperature during power generation of the SOFC, T_r is the temperature [K] during reforming, $h_{c,i}$ [J/kg] is the generation reaction heat of gas component i, $h_{r,i}$ [J/kg] is the reforming reaction heat of gas component i. Similarly to the above, energy balance calculation is performed for other equipment as well. Table 1 shows the results of energy balance calculations. In this paper, analysis is performed when introducing SOFC-TCC with the rated output shown in Table 1.

5. Analysis method

5.1. How to set PV introduction amount and introduction amount of storage battery

PV introduction capacity in this analysis is fixed at 33.3 MW. This value is the limit capacity that can be handled only by SOFC-TCC without peak shifting by storage battery against long - period fluctuation of load and photovoltaic power generation. However, when this PV capacity is introduced, the short-period fluctuation of the PV output becomes large, and when the storage battery is not introduced, the frequency fluctuation deviates from the allowable range. In this paper, frequency fluctuation analysis is performed when changing the number of storage batteries introduced in the proposed system, and the minimum capacity of the storage battery that can accommodate the frequency fluctuation within the specified range (50 ± 0.3 Hz) in Hokkaido is investigated. The above PV capacity (33.3 MW) is the capacity calculated from the minimum output of SOFC-TCC obtained from the analytical model and the electric load of 1 year in Kitami City and solar radiation. The power load in Kitami City for one year was obtained from the historical power demand in Hokkaido and the population of Kitami City.

5.2. Equipment specification

The specifications of various storage batteries per 1 unit to be introduced in the proposed system are shown below. Table 2 shows specifications of lead-acid battery. Table 3 shows specifications of nickel-metal hydride battery. Table 4 shows specifications of lithium ion battery.

TABLE II: Specification of lead storage battery

Parameter	Value
Nominal Voltage {V}	12.0
Rated capacity [Ah]	50.0
Mass [kg]	23.0

TABLE III: Specification of nickel-metal hydride storage battery

Parameter	Value
Nominal Voltage {V}	1.20
Rated capacity [Ah]	6.50
Mass [kg]	0.170

TABL IV: Specification of lithium ion battery

Parameter	Value
Nominal Voltage {V}	28.8
Rated capacity [Ah]	25.0
Mass [kg]	17.5

5.3. Input pattern and reference frequency

Figure 3 shows the solar radiation amount waveform for 10 minutes used in this analysis. The waveform of the amount of solar radiation was prepared as follows to simulate the fluctuation of the short cycle / minute cycle of wide area connected PV. First, in order to simulate the short cycle fluctuation of the solar radiation amount W_{solar} [W], the solar radiation amount at each sampling time t [s] is calculated by the following equation.

$$W_{solar} = 0.789 - 0.1 \cdot (0.1/60) \cdot t \tag{3}$$

Subsequently, at each sampling time, data randomly fluctuating according to a normal distribution (the average value is calculated by the equation (2), standard deviation is 0.08 kW/m^2) is calculated over 10 minutes. Finally, data is filtered so as to satisfy the change rate limit of ±0.2 kW/(m^2·s) in order to reflect the smoothening effect [1] of the minute periodic output fluctuation during PV wide area interconnection.

The power load is analyzed as constant at 63 MW. This value is the power load in Kitami City at the time when the output of SOFC-TCC comes closest to the lowest output in one year.

The reference frequency in the analysis is 50 Hz which is the reference value in the Hokkaido pipe. The allowable value of the frequency deviation is ± 0.3 Hz.

6. Analysis result

Figure 4 shows the results of this analysis. Figure 4 shows the minimum rated output and rated capacity of various storage batteries whose frequency fluctuation falls within the allowable range in the proposed system including 122.2 MW SOFC-TCC and 33.3 MW PV. From Fig. 4, it can be seen that the rated output of the storage battery is the smallest (5.01 MW) in the proposed system when the nickel-metal hydride storage battery is introduced. The reason for this is that the output response speed of the nickel-metal hydride storage battery is larger than that of other storage batteries. On the other hand, from Fig. 4, it can be seen that the minimum rated capacity of the storage battery (0.382 GJ) in the proposed system is the case where a lithium ion battery is introduced. The reason for this is that the maximum output per unit capacity of the lithium ion battery is larger than that of other storage batteries. From Fig. 4, it can be seen that the ratio of the rated capacity of the nickel-metal hydride battery to the rated capacity of the lead-acid battery and the ratio of the rated capacity of the lithium ion battery are 9.17% and 0.211%, respectively. Figure 5 to Fig. 7 show the frequency fluctuations in the proposed system incorporating various storage batteries of the equipment capacity in Fig. 4. These results indicate that frequency fluctuation of independent microgrid including large capacity PV (rated output of 27.3% of rated output of SOFC-TCC) by interconnecting storage battery and SOFC-TCC and controlling output can suppress.

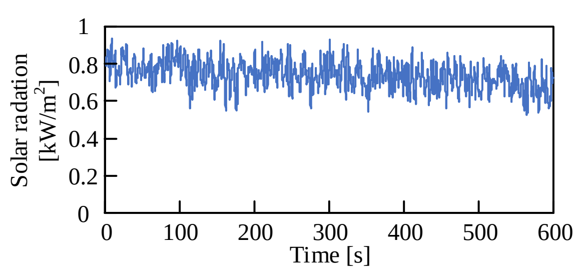

Fig. 3: Solar radiation.

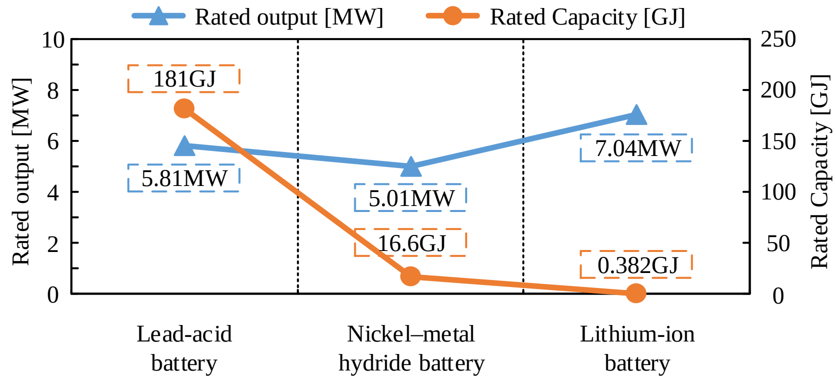

Fig. 4: The minimum amount of storage battery to be able to suppress frequency fluctuation.

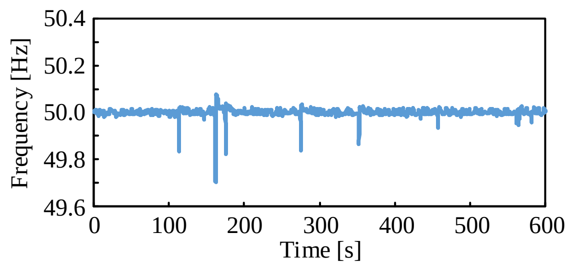

Fig. 5: Frequency fluctuation of the proposed system introducing Lead-acid battery.

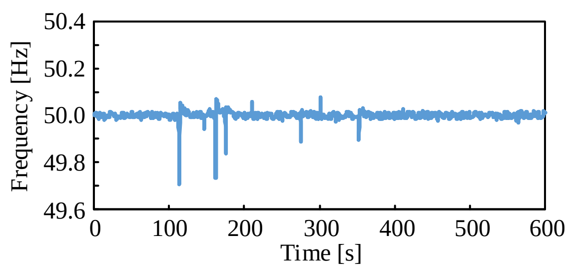

Fig. 6: Frequency fluctuation of the proposed system introducing Nickel-metal hydride battery.

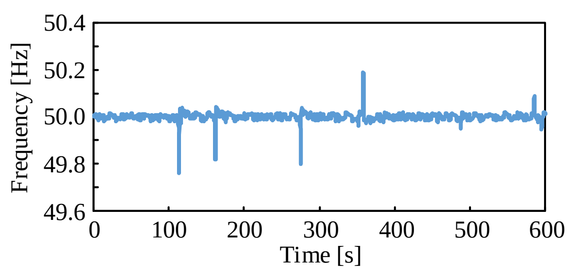

Fig. 7: Frequency fluctuation of the proposed system introducing Lithium-ion battery.

7. Conclusion

In this paper, numerical analysis was conducted to investigate the introduction amount of PV and the amount of storage battery that can accommodate the frequency fluctuation in an allowable range in independent microgrid interconnecting SOFC-TCC and PV. In the numerical analysis, analysis was carried out when three types of storage batteries, a lead storage battery, a nickel-metal hydride storage battery, and a lithium ion battery were respectively introduced into the proposed system. As a result, the following conclusion was obtained.

1) In the proposed system including 122.2 MW SOFC-TCC and 33.3 MW PV, the rated output of the storage battery required to suppress the frequency fluctuation is the smallest (5.01 MW) when nickel-metal hydride storage batteries are introduced.
2) In the proposed system, the rated capacity of the storage battery required to suppress the frequency fluctuation is the smallest (0.382 GJ) is when lithium ion batteries are introduced.

From now on, analysis of the economics of the microgrid with various storage batteries introduced together with SOFC-TCC and PV will be studied for optimal system configuration.

8. Acknowledgements

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9. References

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