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Simulation of the SMR Steam Extraction Operation for corresponding to Intermittency of Renewable Energy

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1. Introduction

Nuclear-Renewable Hybrid Energy System (NRHES) is a conceptual system that integrates the nuclear, fossil, renewables, energy storage and industry customers to maximize economical competiveness and operational stability [1]. Depending on the electricity demand and renewable energy generation, a portion of thermal energy utilization for electricity generation can be varied while the reactor operated constantly in the full power. The thermal energy of NPP can be extracted in a form of steam from the steam line and delivered to the process heat application facility.

NRHES can relieve the overload of the power grid and enables efficient utilization of energy. In the region where the proportion of renewable energy generation is large, the net load, which is total demand load excluding renewable energy, rapidly decreases during daytime. This net load curve is called a duck curve, because it ends up resembling a duck. When the duck curve phenomenon occurs, it is hard to predict net load and the operating cost of the electrical grid increases due to the intensifying output volatility caused by the overpower generation of the renewable energy sources during the daytime. In addition, the net load increases rapidly after the sunset additional baseload power generation is required. It causes that operational and maintenance costs would increase due to the operation suspension and repetition of baseload power generation. In Korea, the duck curve phenomenon is getting intensified as the renewable power generation facilities increase. If the duck curve phenomenon intensifies, the flexible operations would be required more to maintain the stability of the power system. In addition, the electricity demands in summer and winter would be higher because electricity demands for cooling and heating would be increased. Especially in Korea, in the rainy season, the both irradiation and wind would not be sufficient to produce the renewable energy generation. NRHES should be constructed in consideration of these annual characteristics.

In this study, an NRHES configuration is developed to correspond with the duck curve phenomenon and annual net load. The thermal energy storage system (TES) is added to SMR to extract nuclear power plant steam during the daytime, store thermal energy, and use it for process heat facilities to reduce the load on the electrical grid and use energy efficiently. A hypothetical NRHES consisting of one SMART and a renewable energy source is assumed in the Jeju Island area, and net load data of Jeju Island is created by scale down.

2. Net Load Analysis Considering Renewable Energy Generation

To ensure flexibility in the power system, the power supply and climate condition should be considered, and for this purpose, the daily and annual characteristics of net load are analyzed considering the renewable energy power generation.

2.1 Daily Characteristics of Net Load

In order to analyze the daily net loads, electricity demand and renewable energy generation in Jeju Island of 2021 are analyzed [2]. As a result of the trend of electricity demand and renewable energy generation in Jeju Island, the maximum electricity demand is at 20:00, 5:00, and 13:00. The maximum generation of renewable energy is at between 13:00 and 14:00, and minimum value is at dawn when the sun sets.

In addition, renewable energy generation increases significantly around 10:00 and decreases around 17:00. And the net load would be the peak around 20:00 when the demand for electricity is high and the amount of renewable energy generated is low. And the time when the Net load is smallest is around 13:00. **Fig.1** presents the maximum and minimum ranges of the net load in Jeju in 2021. And the daily maximum and minimum difference of net load is the largest at 584.02 MW on April 18 (**Fig.2**) and the smallest at 117.6 MW on January 23 (**Fig.3**).

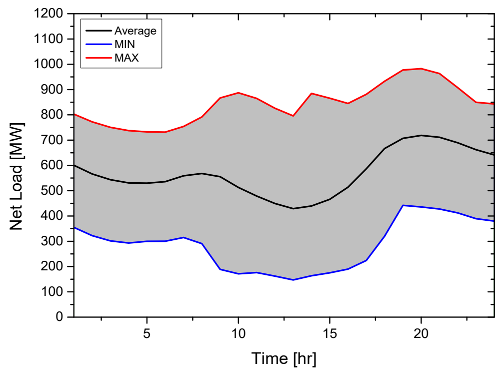

Fig.1 The Maximum and Minimum Ranges of the Net load in Jeju Island

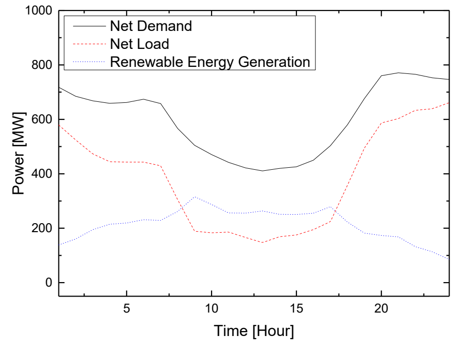

Fig.2 The Day of the Maximum Net Load Difference

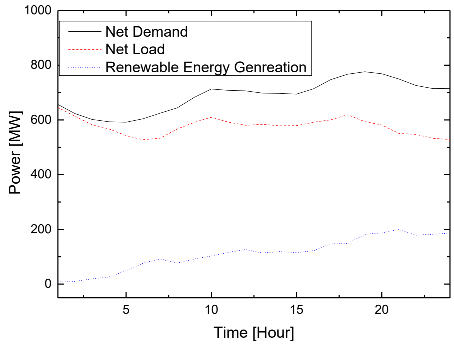

Fig.3 The Day of the Minimum Net Load Difference

2.2 Annual Characteristics of Net Load

The annual characteristics of the net load are analyzed combining the annual characteristics of electricity demand, solar power generation, and wind power generation. As a result of the analyzing the annual electricity demand (based on the daily maximum electricity demand) from 2017 to 2021, the electricity demand is the largest in summer (August: 1,012 MW as of 2021) and low in spring and autumn (May: 659 MW as of 2021) (**Fig.4**). The monthly cumulative net demand is the largest at 495,937 MWh in August and the smallest at 349,576 MWh in May. In other words, it is found that the net load is the largest in summer and the smallest in spring and autumn. The trend of net load is similar to that of electricity demand because the proportion of renewable power generation is not large at 10-20% of electricity demand (**Fig.5**).

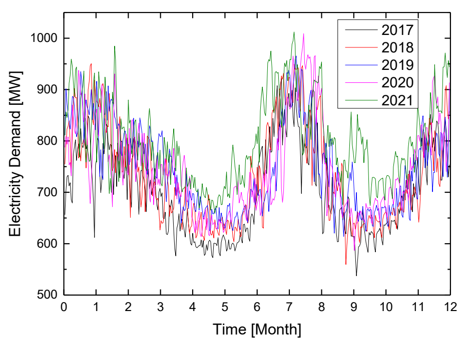

Fig.4 Electricity demand in Jeju Island (2017 ~2021)

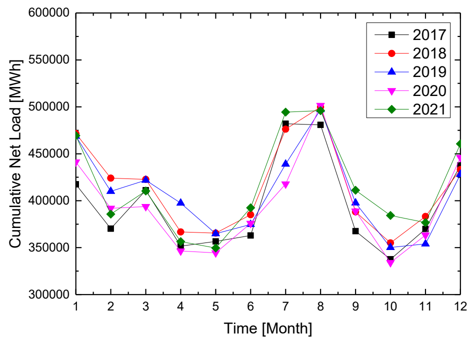

Fig.5 Monthly Cumulative Net Load in Jeju Island (2017 ~2021)

3. Numerical Demonstration

The integrated system combining SMART100 and TES to correspond to net load variation is configured (**Fig.6**) and simulation model is developed using Modelica [3] and pre-developed SMART 100 model [4]. The SMART100 generated power is controlled by the steam extraction rate following to the net load.

If the amount of steam supplied to the turbine decreases, the turbine power decreases. High-pressure and low-pressure turbines are composed of multiple stages. Each stage is modeled as a simple turbine following Stodola's Law. When the amount of steam entering the turbine is lower than the design value due to steam extraction, the outlet pressure and outlet enthalpy increase by Stodola's Law and the turbine power is decreased. The extracted heat is stored in the thermal energy storage system (TES) by exchanging heat in the intermediate heat exchanger (IHX) and this heat can be used for the process heat facilities. In order to utilize high-temperature steam, steam is extracted from inlet of the high-pressure turbine, and the effect of the core reactivity due to steam extraction is evaluated. The heat transfer medium of TES is Therminol66. The steam extraction rate is controlled through a PID controller so that the power production of the low pressure/high pressure turbine follows the power net load data. The gain value of the PID controller is set to 1.0e-05.

A hypothetical NRHES composed of one SMART 100 unit (100 MWe) and renewable energy source in Jeju Island is assumed, and the hypothetical net load data of Jeju Island is generated by scale down. The maximum steam extraction rate is set to 10%. The maximum capacity of the renewable energy generation facility is assumed to be 30 MWe, composed of 10 MWe of wind power and 20 MWe of photovoltaic. And as an alternative base load, LNG power generation is assumed to be 200 MWe. The NRHES specification is presented in **Table I**.

Table I. (proposed) NRHES configuration

Power Source	Unit	Value
Nuclear		
Thermal Power	MWth	365
Electric Power	MWe	100
Renewable		
Wind	MWe	10
Photovoltaic	MWe	20
Fossil		
LNG	MWe	200
EES		
Storage Capacity	MWh	100
TES		
Storage Capacity	MWh	200

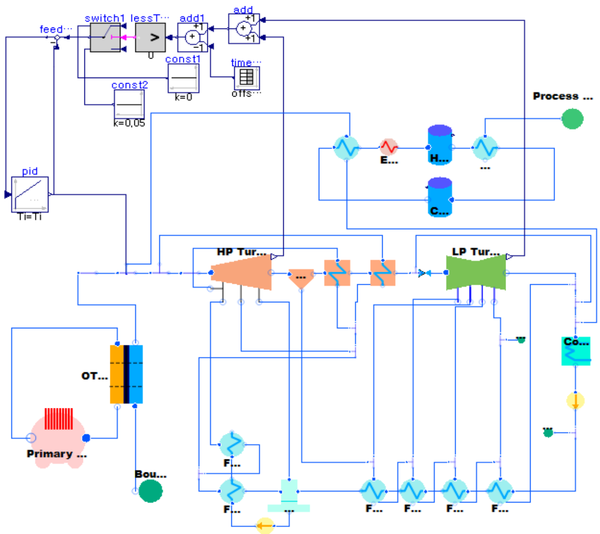

Fig.6 SMART-TES Steam Extraction Control System

When 10% of the steam flow rate on the secondary side is extracted, and a simulation of the behavior of the primary side is conducted in a situation where the flow rate on the secondary side increased. During steam extraction, the flow rate on the secondary side of the steam generator increases and the heat of the core is further cooled, thereby increasing reactivity. When the extraction flow rate is increased to 0-10% for 100 to 200 seconds **(Fig.7)**, the effect of the core by the extraction steam is evaluated to be negligible with a change in reactivity of less than 7.0e-6 (**Fig.8**).

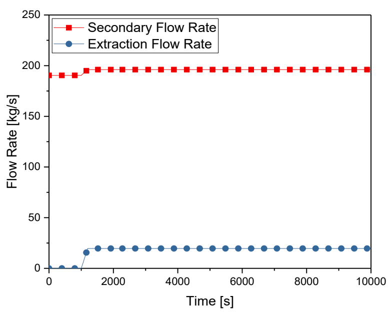

Fig.7 Change in flow rate on the secondary side

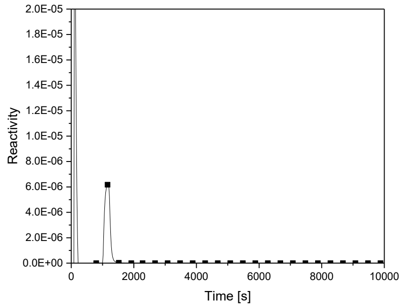

Fig.8 Change in Reactivity

Fig.9 presents the daily analysis of net load followings of the SMART-TES integrated system. the amount of steam extraction is controlled according to the net load, and the result of power generation following the net load can be verified. The heat source of TES is used to operate the process heat facility. The turbine power is controlled only by the change in steam supplied to the turbine by the change in the amount of extraction steam. **Fig.10** presents the annual net load, and the order of these value scales are summer, winter, autumn and spring. Simulation results present that larger amount of steam is extracted in spring and autumn storing more heat energy when the net load is relatively low among the four seasons and the amount of steam extraction is relatively reduced in summer and winter to produce more electricity (**Fig.11**). In addition, the simulation results show that electricity production that follows the net load is possible for four seasons (**Fig.12**).

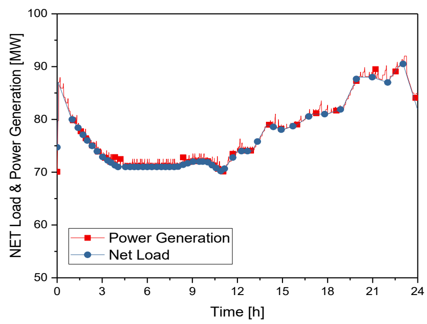

Fig.9 Net load in Jeju Island and Power Generation (Daily Analysis)

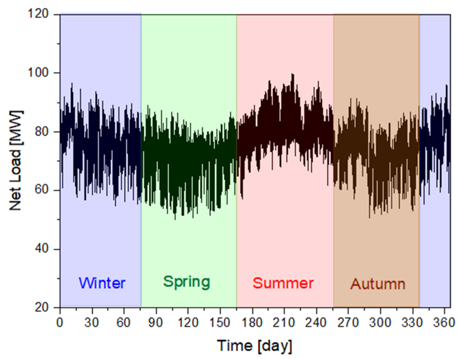

Fig.10 Net load in Jeju Island (Annual)

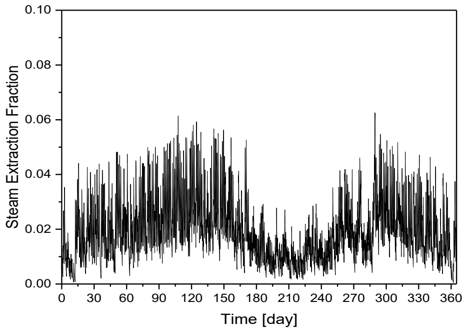

Fig.11 Steam Extraction Rate (Annual Analysis)

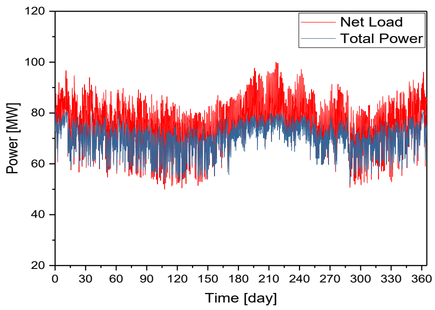

Fig.12 Net load in Jeju Island and Power Generation (Annual Analysis)

5. Conclusions

A NRHES simulation model consisting of SMART100 and thermal energy storage system (TES) has been developed to investigate the duck curve phenomenon and characteristic of the annual net load.

Daily and annual characteristics of net load in Jeju Island are analyzed considering the renewable energy power generation. And the integrated system combining SMART100 and TES to correspond to net load variation in Jeju Island is modeled and simulated. The simulation results show that electricity production that follows the net load is possible for net load of the daily and four seasons. It can be used to utilize the surplus thermal energy while mitigating the impact on the electrical power grid due to the intermittency of the renewable energy.

ACKNOWLEDGEMENT

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