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ARTICLE

Dynamic modeling of HTGR-renewable hybrid system for power grid simulation

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A dynamic model of a high temperature gas-cooled reactor (HTGR) hydrogen cogeneration plant integrated with an electric grid is newly developed aiming to evaluate load frequency control (LFC) performance of the cogeneration plant. The HTGR cogeneration plant has potential to provide electric grid stability by compensating the intermittent and perturbating characteristic effects of the renewable energy power generation not by adding additional equipment but by taking advantages of two intrinsic design features of the HTGR system, namely, helium gas turbine power conversion system and the existential massive capacity of heat in the reactor graphite core. The model is developed with MATLAB/Simulink framework to fully utilize Institute of Electrical Engineers of Japan (IEEJ) Automatic Generation Control (AGC) 30 model which are widely used in grid simulations. Trial simulations are performed using the developed model. The results of simulations demonstrate the capability of dynamic model for the evaluation of LFC performance for HTGR system with a grid being incorporated with significant portfolios of renewable energy power generation.

Keywords: HTGR; helium gas turbine; power grid simulation

Nomenclature

A_m	Turbine inlet flow area
C_0	Theoretical gas velocity
D_m	Turbine blade average diameter
G	Mass flow rate
g	Gravitational acceleration
I	Moment of inertia
N	Gas turbine speed
P	Pressure
PR	Pressure ratio
R	Gas constant
T	Temperature
t	Time
U	Turbine average tip speed
W	Work of turbine and compressor
Z	Turbine stage number
κ	Adiabatic index
ρ	Density
τ	Torque
η	Efficiency
ω	Rotational speed

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c	Compressor
ci	Compressor inlet
co	Compressor outlet
t	Turbine
ti	Turbine inlet
to	Turbine outlet

1. Introduction

The Ministry of Economy, Trade and Industry (METI), in collaboration with other ministries and agencies, formulated the “Green Growth Strategy through Achieving Carbon Neutrality in 2050.” One Japan’s approach to Carbon Neutrality in 2050 is decarbonization of our electricity generation sector. Today, the sector highly depends on fossil fuels due to the low installed capacity of carbon-free power generators. Towards the decarbonization, the Green Growth Strategy sets a target of renewables’ share of power generation between 50% and 60% in 2050. To enable such high renewable penetration levels on electric grid, the imbalance between generation of the intermittent renewable sources, e.g. wind power and solar photovoltaic dispatchable generators and demands must be managed.

The priority dispatch rule in Japan designates an order of dispatching control. When power generation exceed the demand, control of generations in fossil fuel fired power plants is the primary option. However, the contribution of a fossil fuel fired power plant as compensation reserve will be significantly reduced due to its low capacity in a zero-CO_2 emission power system. Therefore, large increase in curtailment of renewable energy is expected. Results showed in the committee under METI reveal that the curtailment rate of renewables may rise more than

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30% when the penetration rate of intermittent renewables reach 46% even in a condition that sufficient capacity for power transmission line is developed [1].

JAEA has proposed a high temperature gas-cooled reactor (HTGR)-renewable hybrid system based on the GTHTR300C [2], a Generation IV commercial HTGR electricity and hydrogen cogeneration system [3]. The system is designed such that it is capable of providing electric grid stability by compensating the intermittent and perturbating characteristic effects of the renewable energy power generation.

The present study aims to develop the dynamic model of HTGR-renewable hybrid system integrated with a power grid to evaluate load frequency control (LFC) performance of the hybrid system under a condition with a large penetration of renewable energies. The model is based on detailed engineering datasets of GTHTR300C and incorporates original control strategies that are shown to be effective of variable power generation. The paper discusses approach and details of the modeling of the system. Trial simulations are also conducted to assess the capability for LFC simulations.

2. HTGR-renewable hybrid system

An HTGR-renewable hybrid system is designed to balance supply and demand on the power grid with large penetration of renewable power plants is based on GTHTR300C. **Figure 1** explains the system configuration of the GTHTR300C. The basic design of the GTHTR300C was completed together with major Japanese industries using experience and knowledge obtained through design, construction, and operation of the HTTR. The reactor applies a 600 MWth prismatic reactor core with reactor outlet temperature of 950°C. The reactor system employs a closed helium Brayton cycle and a power generating efficiency of 47% can be achieved. An intermediate heat exchanger (IHX) which transfers heat to a hydrogen production plant is devised upstream of the gas turbine.

The concept of HTGR-renewable hybrid system is shown in **Figure 2**. The HTGR co-generation plant is connected to an electric grid which are also integrated with renewable power plants including solar PV power plants and wind power plants. The outputs of renewable power plants considerably vary on a time scale of seconds to days. The HTGR co-generation plant provides values of kWh, kW and ΔkW to the grid. The HTGR cogeneration plant can maintain a fixed reactor thermal power during the operation commanded economic dispatch control (EDC) by varying the amount of secondary production such as hydrogen. The plant also can used for load frequency control (LFC) at constant reactor power by fully utilizing heat storage capability in the reactor core. In order to utilize the storage capacity is to change heat

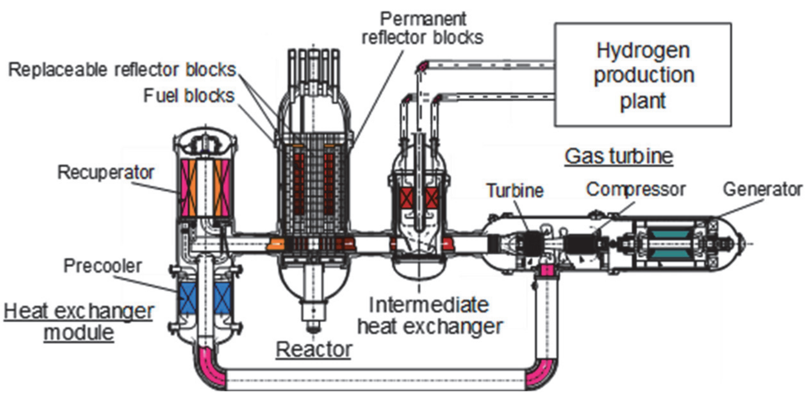

Figure 1. GTHTR300C plant layout.

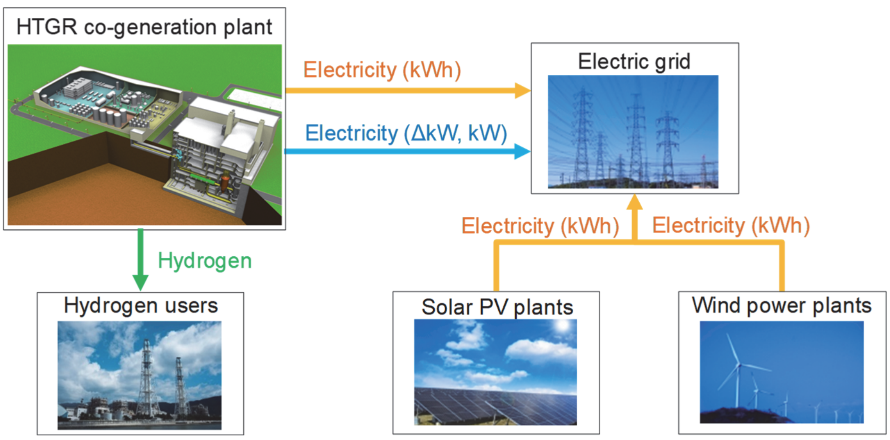

Figure 2. HTGR-renewable hybrid system.

transfer rate between reactor core and coolant by altering coolant flow rate. The primary pressure control is employed for the manipulation of reactor coolant flow rate because it is able to maintain gas turbine operation at the optimum point due to the characteristics of helium coolant. The plant also can cope with second time scale variation mainly by inertia of the gas turbine with a help of governor. A turbine bypass control is used as the governor. The control approaches and their advantages are described in the past study [3] and will not be repeated here.

3. Modeling approach for power grid simulation

3.1. Power grid

In order to demonstrate the capability of the hybrid system to maintain the stability of a grid with a large penetration of renewable energies, modeling and simulation of the LFC for a power grid is necessary. **Figure 3** shows the schematic of simulation model for the power grid with a HTGR cogeneration plant and other generators including renewable power plants.

The evaluation model is developed based on the Institute of Electrical Engineers of Japan (IEEJ) Automatic Generation Control (AGC) 30 model [4] because the model is widely used for power grid simulations by electric utility companies and enables to handle time domain for the LFC. The AGC 30 model is built under a MATLAB /Simulink framework and covers time dependent behaviors of electricity demand, generator power outputs, power flows with other power grids through inter connection line and controls of generator by load dispatch center such as Economic Dispatch Control (EDC) and LFC. Since the IEEJ AGC 30 model considers nuclear power plants as base load plants, a plant model for HTGR cogeneration plant is newly developed.

Figure 4 shows a schematic of HTGR cogeneration plant model connected to the AGC 30 model. The model is built to consider variation of generator speed, plant

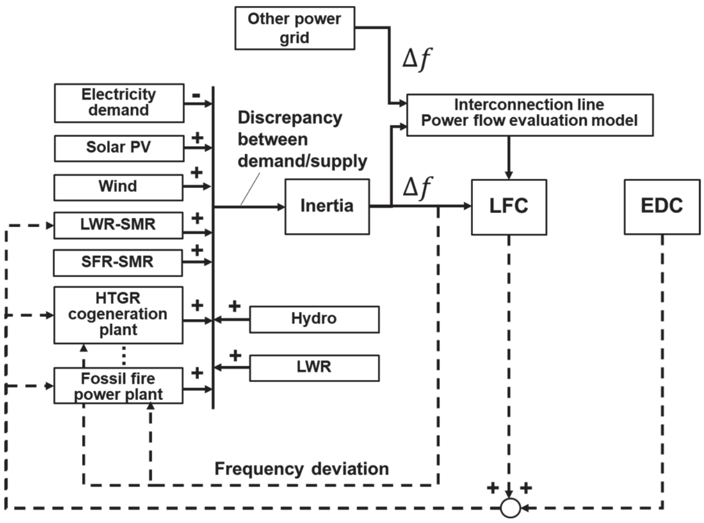

Figure 3. Power grid simulation model combined with HTGR cogeneration plant model.

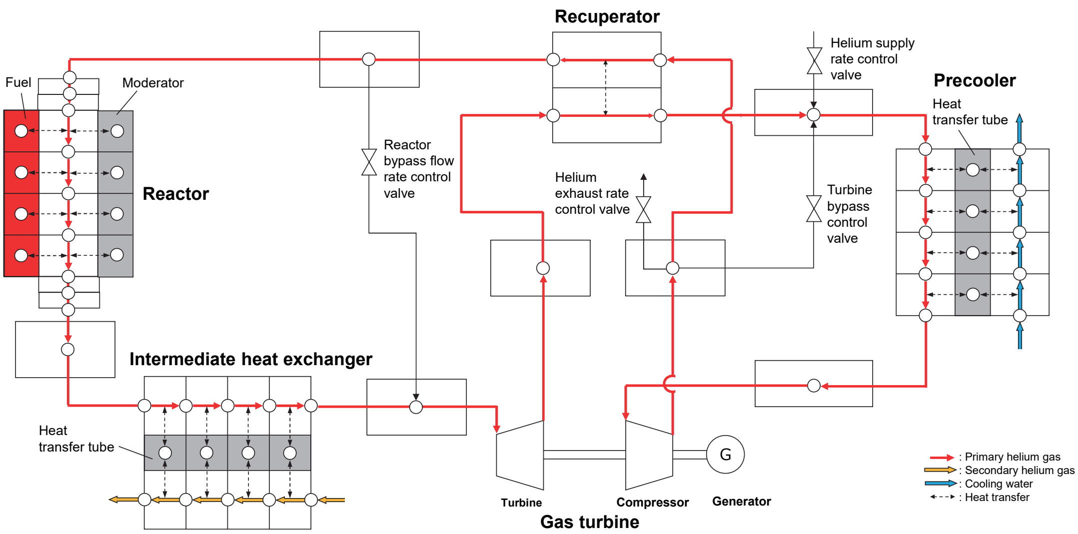

Figure 4. Schematic of HTGR cogeneration plant model.

controls corresponding to LFC and time dependent behaviors of power output. Interactions between two models, i.e. the grid simulation model and the HTGR cogeneration model are evaluated by exchanging the request of power output by EDC, grid frequency and power output calculation results at each time step.

3.2. HTGR cogeneration plant

The HTGR cogeneration plant consists of reactor, heat exchangers, gas turbine and control systems. The system is modeled by mass and energy conservation equations using Simscape libraries that can be used under Matlab/ Simulink. The HTGR cogeneration plant model developed with MALAB/Simulink is shown in Figure 4. The detail of modeling is described in the following.

(1) Reactor

The reactor model utilizes a single channel approximation and consists of a fuel, a coolant channel, and a graphite moderator. The heat generated in the fuel region by nuclear fission reaction is modeled using a point kinetic equation considering reactivity feedbacks including Doppler reactivity, moderator reactivity and control rod reactivity. Volume average temperature of fuel and moderator are used to calculate the Doppler and moderator reactivities. The control reactivity is evaluated by the reactor outlet temperature control system model which calculates control rod position according to deviation between measured value and set point of controller. The block diagram of control system can be found in the past study [5]. Reactor kinetic parameters and power distributions required for the analysis are defined based on the nuclear design results of GTHTR300C. The Simscape does not have capability to model heat exchanges between a flow channel and two structures and therefore a user defined model is newly built with Matlab/Simulink. Heat transfer equations are incorporated for the heat transfer between the fuel/ graphite moderator and coolant channel [5].

(2) Heat exchanger

The IHX, recuperator, and precooler are modeled using the heat exchanger component in Simscape library. As for the secondary helium flow in IHX and cooling water flow in precooler, temperature, pressure and mass flow rate are set as boundary conditions at the inlet of each component. Heat transfer correlations used in the heat exchanger design of GTHTR300C are employed in the model.

(3) Gas turbine

The gas turbine consists of a turbine, a compressor and generator connected to a single shaft. The gas turbine model is newly incorporated by user defined Matlab scripts. The generator speed is evaluated by solving an angular momentum equation considering torques of each component as shown in Eq. (1). The turbine and compressor works are modeled using pressure ratios and efficiencies of each component as described in Eqs. (3) and (4).

$$\sum I_i \frac{d\omega}{dt} = \sum \tau_i \tag{1}$$

$$\tau_i = \frac{W_i}{\omega} \tag{2}$$

$$W_t = -\eta_t \frac{P_{ti}}{\rho_{ti}} G_t \left(\frac{\kappa}{\kappa - 1}\right) \left\{ \left(\frac{P_{to}}{P_{ti}}\right)^{\frac{\kappa-1}{\kappa}} - 1 \right\} \tag{3}$$

$$W_c = -\frac{1}{\eta_c} \frac{P_{ci}}{\rho_{ci}} G_c \left(\frac{\kappa}{\kappa - 1}\right) \left\{ \left(\frac{P_{co}}{P_{ci}}\right)^{\frac{\kappa-1}{\kappa}} - 1 \right\} \tag{4}$$

The pressure ratio and efficiency of turbine are evaluated by using the following Eqs.

$$\eta_t = f\left(\frac{U}{C_0}\right) \tag{5}$$

$$PR_t = \left(1 - \frac{{C_0}^2 Z}{2g \frac{\kappa}{\kappa - 1} RT_{ti}}\right)^{\frac{\kappa}{1-\kappa}} \tag{6}$$

$$C_0 = \frac{\pi D_m \frac{N}{60}}{\left(\frac{\phi}{0.208}\right)^{\frac{-1}{1.25}}} \tag{7}$$

$$\frac{U}{C_0} = \left(\frac{\phi}{0.208}\right)^{\frac{-1}{1.25}} \tag{8}$$

$$\phi = \frac{\frac{G_t \sqrt{T_{ti}}}{P_{ti\_kgm2}}}{\frac{N}{\sqrt{T_{ti}}} \frac{\pi D_m}{60} A_m \frac{1}{R}} \tag{9}$$

The compressor pressure ratio and efficiency are estimated by using the performance map of GTHTR300C gas turbine design [6].

(4) Plant control

Plant control systems for reactor outlet temperature, turbine bypass flow, primary coolant inventory and reactor bypass flow are modeled with MATLAB/Simulink based on control block diagrams and control parameters of GTHTR300C design.

The reactor outlet temperature control system is modeled with cascade-connected two control loops. The outer loop determines the set point of reactor power for the inner loop corresponding to the error observed in reactor outlet temperature. The outlet temperature is controlled at 950°C by adjusting control rod positions. The inner loop calculates control rod reactivity and the output is used for reactor kinetic calculations.

The primary coolant inventory control system is modeled with helium supply and discharge flow rate control

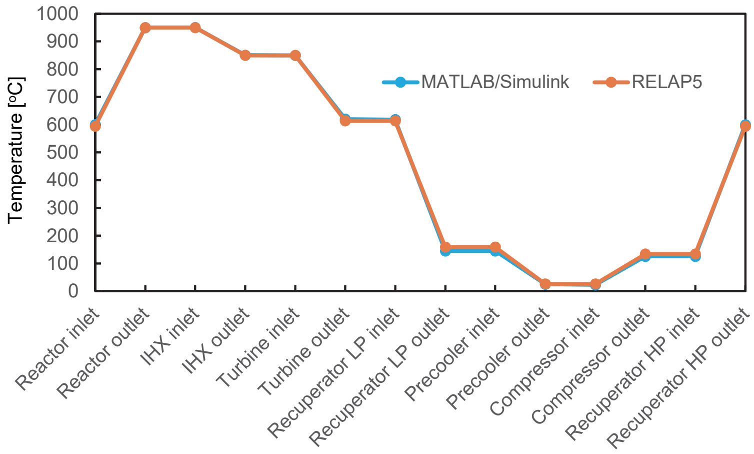

Figure 5. Comparative results of temperature distributions in the primary system between MATLAB/Simulink and RELAP5 steady state simulations.

block diagrams and stem positions of control valves for helium supply and discharge are adjusted corresponding to the signal from primary pressure controller. Pressure set points are scheduled in accordance with electrical load schedule requested by EDC in the AGC 30 model.

The control systems for turbine bypass and reactor bypass are modeled with PI controllers. Stem positions of the control valves for turbine bypass and reactor bypass are adjusted by deviations between set points and monitored values.

4. Simulation results

In order to confirm the capability and robustness of the developed model for analysis of the LFC performance of HTGR-renewable hybrid energy system, a trial transient simulation is conducted. Firstly, the calculation results of MATLAB/Simulink model at the steady state condition are compared with RELAP5 model. The model of the RELAP5 GTHTR300C model employed here is same as the one developed by the author [5]. **Figure 5** shows comparative results for temperature distributions in the system. The largest temperature difference is observed at the low-pressure side of recuperator outlet, however, both simulation results well agreed as depicted in the figure.

Secondly, a dynamic calculation is performed using the developed model shown in Chapter 3. A simulation case is made based on the AGC model case 2 in the report [4] by replacing an LNG fire power plant by the HTGR cogeneration plant. The HTGR cogeneration plant is assigned as a generator for LFC. The simulation results are depicted in **Figure 6**.

The area requirement is evaluated considering electric demand, grid frequency variation, grid capacity and transmission line current variation. The LFC controller allocates LFC command to LFC generators based on the area requirement. The controller commands to change primary pressure of HTGR cogeneration plant to manipulate power generation rate. The temperature variations in reactor are small and reactor power is kept stable. The grid frequency variations are controlled with ±0.2 Hz. The results of simulation revealed that the modeling approach is acceptable for analysis of the LFC control capability of HTGR-renewable hybrid energy system. The model enables to evaluate an LFC performance of HTGR cogeneration plant against irregular frequency variations induced by intermittent renewable power generations that cannot be modeled in the sole plant dynamics code.

5. Summary

A dynamic model of a HTGR hydrogen cogeneration plant integrated with electric grid is newly developed aiming to evaluate load frequency control performance of the cogeneration plant. The HTGR cogeneration plant has potential to provide electric grid stability by compensating the intermittent and perturbating characteristic effects of the renewable energy power generation not by adding additional equipment but by taking advantages of two intrinsic design features of the HTGR system, namely, helium gas turbine power conversion system and the existential massive capacity of heat in the reactor graphite core. The model is developed with MATLAB/Simulink framework to fully utilize IEEJ AGC 30 model which are widely used in grid simulations. Trial simulations are performed using the developed model. The results of simulations demonstrate the capability of the dynamic model for the evaluation of LFC performance for HTGR system with a grid being incorporated with significant portfolios of renewable energy power generation.

Acknowledgements

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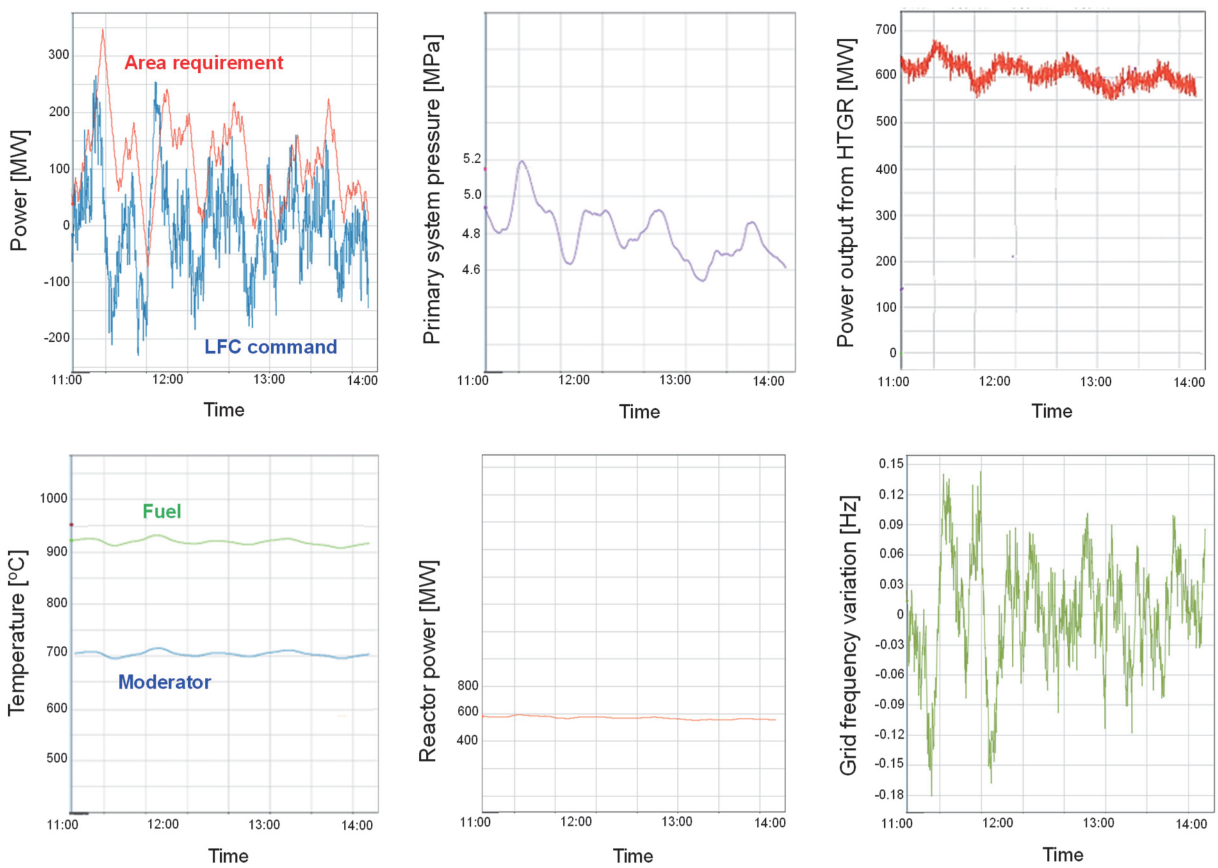

Figure 6. Transient simulation results of HTGR cogeneration plant model.

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