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Design of a generator control system for small nuclear distributed generation

Dong-Hee Yoon* and Gilsoo Jang†

Abstract – Small-scale reactors have recently attracted attention as a potential power generation source for the future. The Regional Energy Research Institute for Next Generation is currently developing a small-scale reactor called Regional Energy rX 10 MVA (REX-10). The current paper deals with a power system to be used with small-scale reactors for multi-purpose regional energy systems. This small nuclear system can supply electric and thermal energy like a co-generation system. The electrical model of the REX-10 has been developed as a part of the SCADA system. REX-10's dynamic and electromagnetic performance on the power system is analyzed. Simulations are carried out on a test system based on Ulleung Island's power system to validate REX-10 availability on a power system. RSCAD/RTDS and PSS/E software tools are used for the simulation.

Keywords: Small-scale reactor, Nuclear power plant, Power system dynamic performance, Co-generation, REX-10 system, Real-time simulator

1. Introduction

Coal, oil, and uranium, are used to generate a large proportion of electricity in the Korean power system. However, there is overconsumption of these natural resources, resulting in a number of environmental problems like global warming and acid rain. The demands of local electrical energy such as distributed generation are also increasing. Therefore, a small and reliable energy generation method is necessary.

In recent years, nuclear reactor technology has advanced substantially due to the increasing interest in nuclear power [1]. Research on distributed generation, which includes a small nuclear reactor, is being conducted in several countries. In fact, some eastern European countries have conducted studies on local nuclear heating power plants, and Japan and the United States have also commenced research on new, small nuclear power plants.

Recently, Korea has also started to follow suit. The Korean peninsula has many small islands, so a small-scale reactor as a distributed power generation source can be a stable source of energy for this region. To validate a small reactor installation on a small electrically isolated island, the implementation of an electrical model is necessary.

The present paper focuses on the development of an electrical model of a small nuclear power plant and the evaluation of its dynamic performance in a power distribution system. The electrical characteristics of a regional power system which includes small-scale reactor, the Regional Energy rX 10 MVA (REX-10) system, are analyzed. New turbine control systems are necessary for this distributed nuclear generation in which the steam turbine parameters are different from those of the conventional co-generation system. In the present paper, calculation of the parameters of the turbine model is performed.

A prototype electrical model of a small-scale reactor is proposed in the current work, with the power system of Ulleung Island used as the test bed. This power system is designed using the PSS/E software tool, and the electrical models are developed by RSCAD/RTDS, an electromagnetic real-time simulator.

2. REX-10 System

A stable operation is necessary for the implementation of a small-scale reactor system in a local area. The following are the requirements for REX-10's operation:

First, REX-10 must be stable. It is specially designed to be installed underground only because of the risks associated with nuclear radiation. Second, the amount of radioactive waste should be small. In the current study, the life span of the REX-10 reactor is expected to be over 10 years. Third, the operational life of the reactor should be as long as possible. Finally, REX-10 must be economically feasible.

Co-generation refers to the combined production of electricity and heat in an energy conversion facility. It is regarded as distributed generation, and its present source is mainly fossil fuel. In the present work, the REX-10 system also presents a form of co-generation. Co-generation is used for applications in which there is continuous demand for heat near the co-generation facility [2–3].

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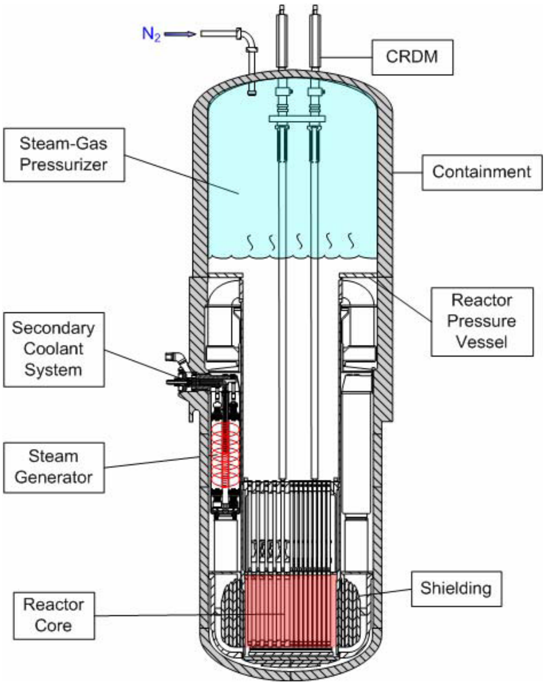

Fig. 1. Schematic diagram of REX-10

The design of the REX-10 system is based on the System-integrated Modular Advanced ReacTor (SMART). Its system pressure and capacity are properly set according to the requirements for a regional energy reactor [4]. The REX-10 reactor is an integral-type pressurized-water reactor (PWR) as shown in Fig. 1. The integral reactor concept involves the entire primary system components such as the core, pumps, main heat exchangers (steam generators), and pressurizer, among others, arranged in a single pressure vessel. Therefore, the risk of a large loss-of-coolant accident (LOCA) can be excluded. Unlike SMART, REX-10 is designed to remove heat from the nuclear fuel by natural circulation and to be operated with low system parameters compared with the traditional PWR. The proliferation resistance of the fuel is a very important feature of the REX-10 system. Therefore, thorium fuel is the best candidate fuel for a small power reactor [5].

The detailed design parameters of the REX-10 reactor are determined based on the system pressure, total thermal power, and the natural circulation system. Table 1 shows the detailed parameters of the REX-10 design [6].

Table 1. REX-10 design parameters [6]

Primary circuit	Cooling mode	Natural circulation
	Coolant flow rate	64.9 kg/s
	Core inlet temperature	165 ℃
	Core outlet temperature	200 ℃
Secondary circuit	Type	Helical-coiled once-through
	Steam temperature	198.3 ℃
	Steam pressure	1.5 MPa
	Feedwater temperature	99.6 ℃
	Feedwater flow rate	4.37 kg/s

3. REX-10 System Model

3.1 Concept of the REX-10 System Model

There are three parts in the REX-10 Model: the generation part, the inner plant load which is necessary for the operation and maintenance of the REX-10 system, and the emergency generation part. A simple diesel generator is selected for the modeling of the REX-10 system. About 80% of REX-10 output is used for the heat load, and 20% is used for power generation. Under normal conditions, the REX-10 reactor is operated as a base-load generator. However, unlike a large nuclear power generator, the output of the REX-10 system can be controlled by changing the heat-electricity ratio. By controlling the amount of steam, a degree of load-following is possible [7]. Almost all power plants perform load-following control to adjust the power output depending on the demand for electricity variation. To achieve the purpose of REX-10's installation as a dispersed generation, load-following is necessary for the stable operation of the power system. In the current paper, the electrical modeling of REX-10 was performed to realize the function of load-following. This modeling also includes some calculations of the suitable parameters for REX-10.

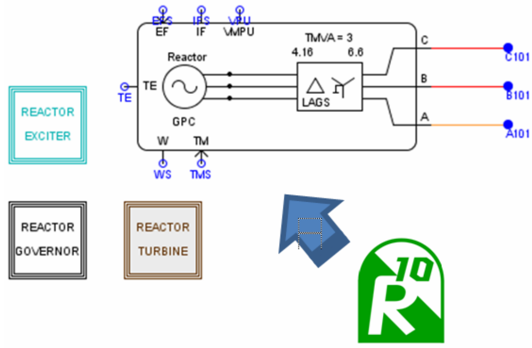

Fig. 2. Electrical REX-10 module in the RTDS model

The developed REX-10 model should be used as a part of a SCADA system in this project, so the electrical REX-10 model is developed using RTDS, a real-time simulator. The REX-10 modules in the RTDS simulator are shown in Fig. 2 and 3 [6, 8].

3.2 Steam turbine model

The nomenclature is as follows:

CV : Control valve
δ_i : Angle by which the q-axis leads the stator terminal voltage phasor (radians)
E_{FD} : Field voltage (pu)
I_{FD} : Field current (pu)
K_A : Overall gain
K_C : Constant
K_G : Speed governor gain

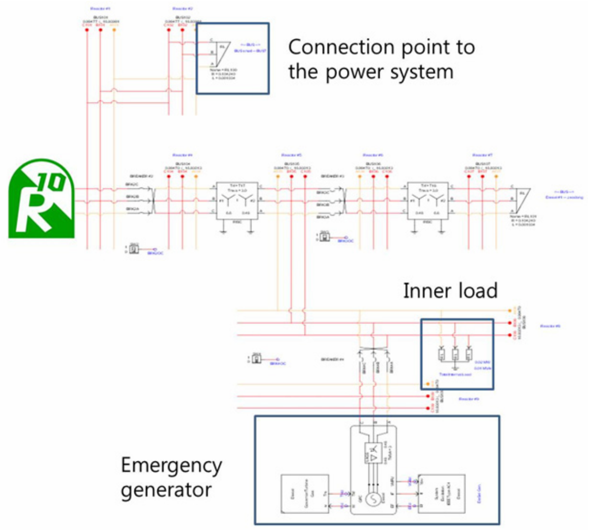

Fig. 3. REX-10 system in an RTDS simulation

L_{C1}, L_{C2}	: Rate limits (pu/s)
l	: Length of the tube (m)
P	: Pressure of steam in the vessel (kPa)
P_0	: Rated pressure (kPa)
P_{CH}	: Pressure of the steam generator (pu)
P_M	: Mechanical power (pu)
P_{M_REF}	: Mechanical power reference (pu)
ρ	: Density of steam (kg/m^3)
Q	: Steam mass flow rate (kg/s)
Q_0	: Rated flow-out of the vessel (kg/s)
Q_{CH}	: Steam mass flow rate of the steam generator (kg/s)
Q_{in}	: Input steam mass flow rate (kg/s)
Q_{out}	: Output steam mass flow rate (kg/s)
r	: Radius of the tube (m)
T_A	: Time constant (Time constant associated with the regulator and firing of thyristors) (s)
T_B	: Lag time constant (s)
T_C	: Lead time constant (s)
T_{CH}	: Time constant of the steam generator (s)
T_M	: Mechanical torque (pu)
T_R	: Time constant of rectification and filtering of the synchronous machine terminal voltage (s)
T_{SM}	: Time constant of the servomotor (s)
T_{SR}	: Time constant of speed relay (s)
t	: Time (s)
V	: Volume of the vessel (m^3)
V_{CH}	: Volume of the steam generator (m^3)
V_{i_Max}	: Voltage limits, maximum (pu)
V_{i_Min}	: Voltage limits, minimum (pu)
V_{PU}	: Machine voltage (pu)
V_{REF}	: Voltage regulator reference (pu)
V_{R_MAX}	: Exciter output limit, maximum (pu)
V_{R_MIN}	: Exciter output limit, minimum (pu)
W	: Weight of steam in the vessel (kg)
ω	: Rotor speed (pu)
$\Delta\omega$	: Rotor speed deviation (pu)

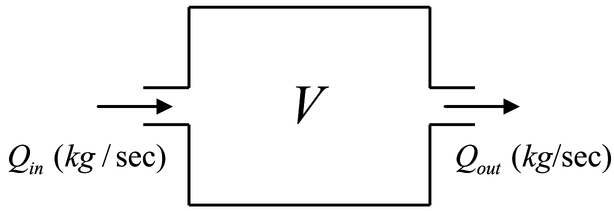

Fig. 4. Steam vessel [9]

Fig. 4 shows the diagram of a steam vessel. The time constant T_V of a steam turbine is calculated from the relationships

$$\frac{dW}{dt} = V\frac{d\rho}{dt} = Q_{in} - Q_{out} \tag{1}$$

$$Q_{out} = \frac{Q_0}{P_0}P \tag{2}$$

$$\begin{aligned} Q_{in} - Q_{out} &= V\frac{\partial\rho}{\partial P}\frac{dP}{dt} \\ &= V\frac{\partial\rho}{\partial P}\frac{P_0}{Q_0}\frac{dQ_{out}}{dt} \\ &= T_V\frac{dQ_{out}}{dt} \end{aligned} \tag{3}$$

$$T_V = \frac{P_0}{Q_0}V\frac{\partial\rho}{\partial P} \tag{4}$$

The change in the density of the steam with respect to pressure can be determined from the steam tables in reference [9, 10] and the relationships

$$\frac{\partial\rho}{\partial P} = \frac{\partial}{\partial P}\left(\frac{1}{v_{steam}}\right)\bigg|_{T_0}, \tag{5}$$

where v_{steam} is the specific volume per unit mass of steam (m3/kg) [9, 11], and

$$\frac{\partial\rho}{\partial P} = \frac{\partial}{\partial P}\left(\frac{1}{v_{steam}}\right)\bigg|_{T_0} = \frac{\frac{1}{v_2} - \frac{1}{v_1}}{P_2 - P_1}\bigg|_{T_0}, \tag{6}$$

where v_1 and v_2 are the specific volumes corresponding to P_1 and P_2.

3.3 Time constant calculation

Among the required parameters for the setup of the generator, some that can be deduced from REX-10 characteristics are calculated next. For a parameter setting, REX-10 time constant calculation is carried out from Table 2, reference [9], and the water table in reference [10].

$$P_{CH} = 100kPa = 0.1MPa \tag{7}$$

$$Q_{CH} = 0.84kg/s \tag{8}$$

Table 2. REX-10 steam generator parameter

Pressure of the vessel	100 kPa
Temperature in the vessel	140 ℃
No. of tubes	12
Mass flow rate	0.840 kg/s (for each tube : 0.070 kg/s)

At 140 ℃, the following values are calculated from the table of reference [10]. In [11], the methods are given for obtaining the following values:

$$P_1 = 50kPa\ ,\ \ v_1 = 3.7948 \tag{9}$$

$$P_2 = 200kPa\ ,\ \ v_2 = 0.9348 \tag{10}$$

From (6), $(\partial\rho/\partial P)$ is calculated from the equation

$$\frac{\partial\rho}{\partial P} = \left.\frac{\frac{1}{v_2}-\frac{1}{v_1}}{P_2-P_1}\right|_{T_0} = 5.3749\times10^{-6}(s^2/m^2) \tag{11}$$

Table 3. Tube parameter of the steam generator

	1st row	2nd row	3rd row
No. of tubes	3	4	5
Tube diameter(mm)	7.745	7.745	7.745
Length (m)	4.3769	4.3769	4.3816

The steam generator is composed of a three-tube set. Each tube set has 12 tubes. The total volume of the tubes is calculated from the relationships

$$V_{CH} = \pi r^2 l = 2.4756\times10^{-3}(m^3) \tag{12}$$

$$T_{CH} = \frac{P_{CH}}{Q_{CH}}V_{CH}\frac{\partial\rho}{\partial P} = 0.00158(s) \tag{13}$$

3.4 Generator control

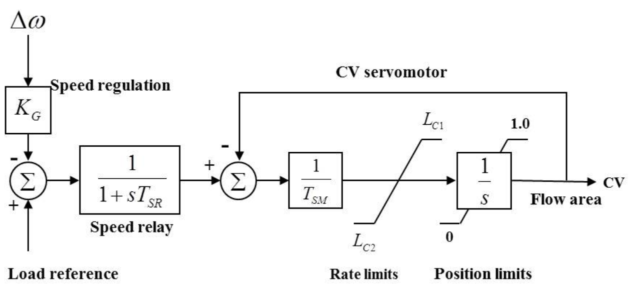

Fig. 5. Simplified mechanical-hydraulic speed governing system [9]

Fig. 5 shows the simplified mechanical-hydraulic speed governing system. When the REX-10 is operated as a load-following generator, the percentage of the speed regulation is 4%. The load reference is set to 0.95. REX-10 is regarded as a base load generator, so the load reference is close to 1.

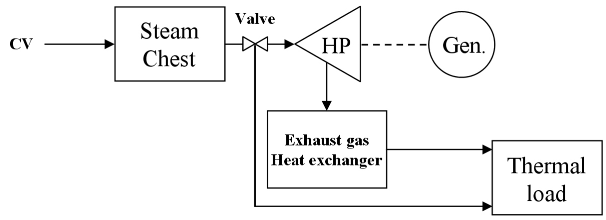

Fig. 6. Configuration of the steam turbine of REX-10

The REX-10 system has several features of co-generation. However, a fast increase in power output is not feasible because the resource for the system is thorium. A substantial amount of time is needed to increase the thermal output because of the reaction time of thorium. Therefore, REX-10 cannot have a complete load-following function like a general co-generation. In the case of power output decrease, however, the reduction in steam output to the generator is not a problem. The steam turbine model of REA-10 is shown in Fig. 7.

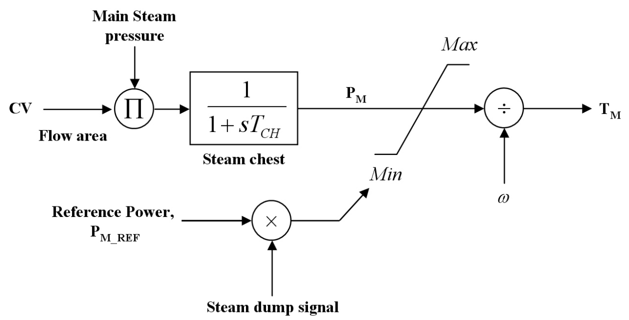

Fig. 7. Steam turbine model of REX-10

There are two operation modes in REX-10. One is a base load mode, and another is a load-following mode. For the implementation of those facts, the steam turbine model of REX-10 is suggested in Fig. 7. For the control of power output, steam dumping signal is used. If the steam dumping signal is equal to 1, the REX-10 system generates its maximum electrical output because the system serves as a base-load generator. In this condition, T_M is fixed as the rated figure regardless of the variation in CV. In the case of a power decrease as has been mentioned in the previous section, a reduction in steam is possible. The load-following function is operated in REX-10 using the steam dump signal. In this condition, the CV signal from the governing system is somewhat reflected in the calculation of T_M. However, a rapid increase in power is impossible. REX-10 is a nuclear power system, so the maximum generation is the rated operation for the system. If a temporary increase in power is required, REX-10 cannot adjust the imbalance in the power system.

An exciter model should also have two modes (base load, load-following) like a turbine model. When REX-10 is in load-following mode, its exciter performs field current control like a general exciter in the power system. In the present work, the IEEE Type AC4 exciter model is used for the simulations [8, 9]. If the REX-10 system is operated with base load generation, an exciter is set up for the maximum output of REX-10 regardless of the load variation.

4. Ulleung Island Power System

The transmission of electricity from land to a remote island is not only uneconomical but also a demanding task. Therefore, co-generation is preferable. A nuclear power system can also operate for a long time between fuel charges. Given these, the island power system on Ulleung Island is selected as the test bed in the present paper.

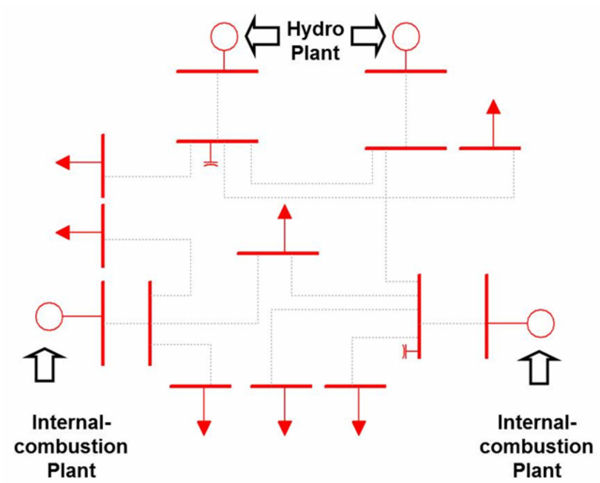

Fig. 8. Ulleung Island power system

Ulleung Island is in the East Sea. It is located 130 km east of the Korean peninsula. There are 4 generators and 15 buses in the power system of Ulleung Island. The PSS/E program is used to develop the power system, and Fig. 8 shows a one-line diagram of the Island's power system. The simulation result of power flow is verified by information acquired from the inspection of Ulleung Island [12].

Table 4. Electrical load in Ulleung Island

	Active power (MW)	Reactive power (MVar)
Bus 3 Gun-lib	0.794	0.252
Bus 4 Do-dong	1.428	0.453
Bus 7 Ju-dong	1.82	0.88
Bus 8 Bu-dae	1.027	0.44
Bus 13 Chun-bu	0.327	0.229
Bus 14 Hyun-po	0.111	0.211
Bus 15 Tae-ha	0.4	0.109

RSCAD/RTDS, a real-time simulator, is used for the simulation of the REX-10 system. After verification of the power flow results, the power system of Ulleung Island is transformed into RSCAD/RTDS file format for extensive simulation by RSCAD/RTDS. The RTDS simulator is a fully digital electromagnetic transient power system simulator used to conduct closed-loop testing of physical devices such as protection equipment and control equipment, and to perform analytical system studies. The RTDS Simulator allows users to examine the effects of disturbances on power system equipment and networks so that outages or complete failure can be prevented.

Of paramount importance is the fact that the RTDS simulator works in a continuous, sustained real time. Therefore, it can solve power system equations fast enough to produce output conditions continuously, which represent the real conditions in the network. The solution is in real time so the simulator can be connected directly to the power system control and protective relay equipment [8].

5. Case Studies

5.1 Scenario 1 – normal condition

The settings of a Runtime option of the RTDS simulator are as follows:

- Time interval : 50 seconds
- Meter update frequency 1000 milliseconds

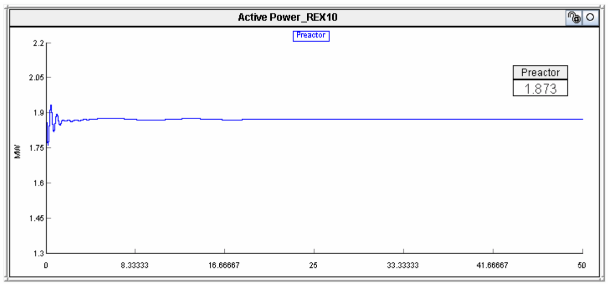

Fig. 9. REX-10 active power

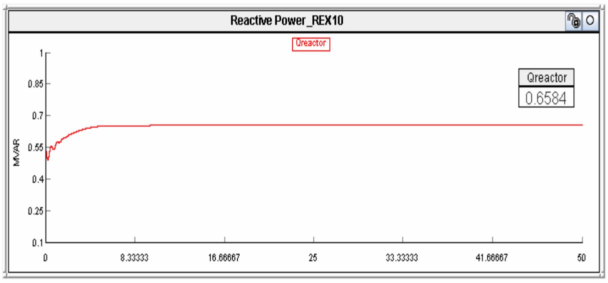

Fig. 10. REX-10 reactive power

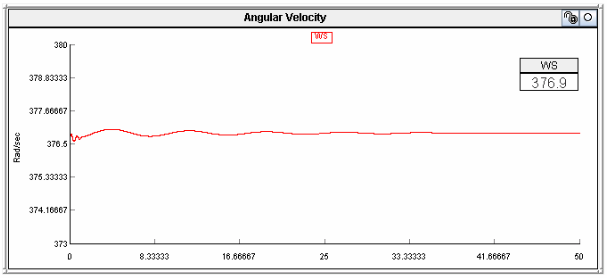

Fig. 11. REX-10 frequency

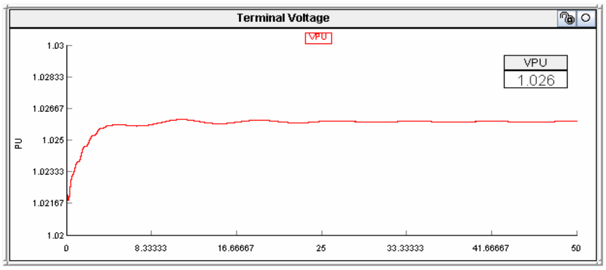

Fig. 12. Terminal voltage

5.2 Scenario 2 – load increase

In this scenario, the contingency of a load increase is simulated. The amount of load increase is 0.46 MW and 0.27 MVar in the Bu-Dae area. As can be seen, the output of REX-10 is limited to 2MVA.

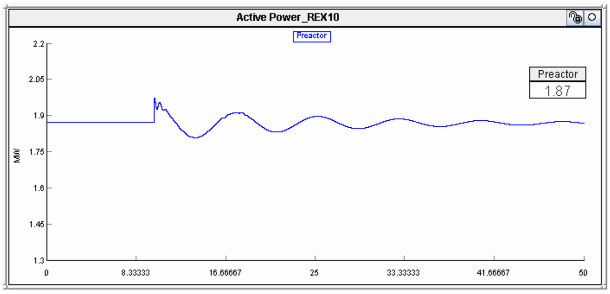

Fig. 13. REX-10 active power

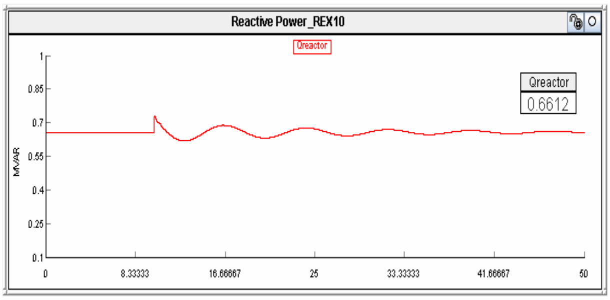

Fig. 14. REX-10 reactive power

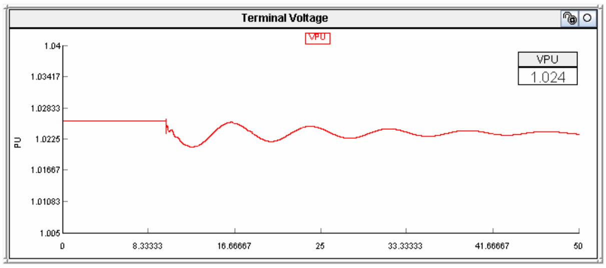

Fig. 15. REX-10 terminal voltage

5.3 Scenario 3 – load decrease, no dumping mode

In this scenario, the contingency of a load decrease is simulated. The amount of load reduction is 1.05 MW and 0.45 MVar. REX-10 is operated in the no dumping mode. Although the load is reduced in the power system, the active power output is not decreased in the no dumping mode.

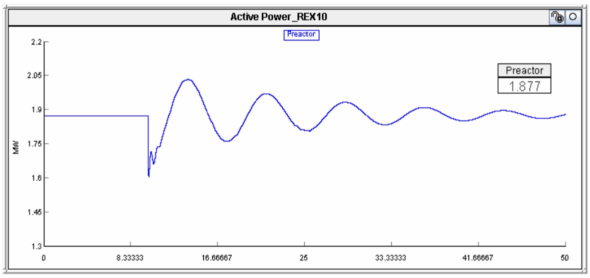

Fig. 16. REX-10 active power

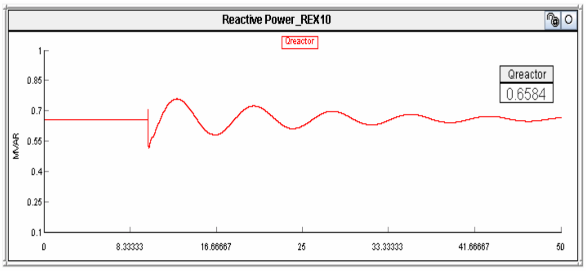

Fig. 17. REX-10 reactive power

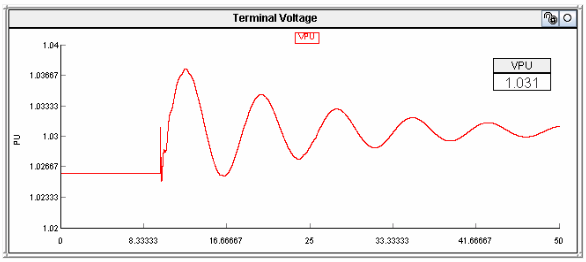

Fig. 18. REX-10 terminal voltage

5.4 Scenario 4 – load decrease, dumping mode

In this scenario, the contingency of a load decrease is simulated. The amount of load reduction is 1.05 MW and 0.45 MVar. REX-10 is operated in the dumping mode.

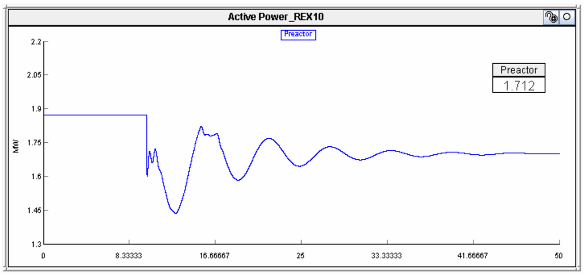

Fig. 19. REX-10 active power

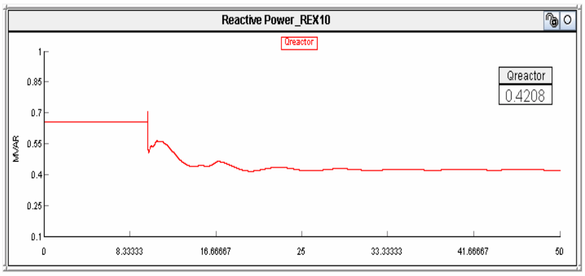

Fig. 20. REX-10 reactive power

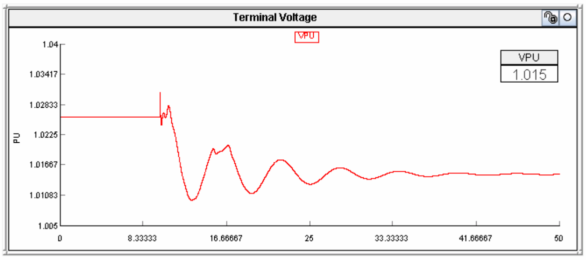

Fig. 21. REX-10 terminal voltage

6. Conclusion

The current work presented a regional power system with a small nuclear reactor, the REX-10 system. REX-10 was used as a co-generation system to supply heat and electricity to surrounding areas. A calculation method suitable for the evaluation of the characteristics of a small-scale reactor was proposed, and the electrical prototype model of a regional energy system with a small nuclear plant was developed. To validate the dynamic performance of the REX-10 system in an electrically isolated island, the power system of Ulleung Island was used. The proposed method will be applied for the analyses of a small nuclear system that will be constructed in the near future.

Acknowledgement

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