CONTROL SYSTEM DESIGN FOR A SMALL PRESSURIZED WATER REACTOR

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ABSTRACT

Small Pressurized Water Reactors (SPWR) have unique designs from the commercial large Pressurized Water Reactors (PWRs). Integral design is adopted. There are no hot legs and cold legs between the reactor core and the steam generators like in the PWR. Strong interactions exist among different loops. The pressure vessel is large in volume and the coolant inventory is also in a large amount. The inertia of the coolant is large and it takes more time for the primary system to respond to disturbances. The steam generator adopts the once-through design and the water inventory is small. The steam generator is very sensitive to disturbances. These unique characteristics challenge the control system design of SPWR.

Relap5 is used to model the SPWR. Steady-state simulation is performed to verify the correctness of the model. In the reactor power control system, both the reactor fission power and the coolant average temperature are regulated by the control rod reactivity. In the feedwater flow control system, the coordination between the reactor and the turbine is considered and coolant average temperature is adopted as one measurable disturbance for the control system. The coolant pressure is adjusted based on the heaters and spray in the pressurizer. The water level in the pressurizer is controlled by the charging flow and the letdown flow is compensated to calculate the charging flow needed. Transient simulations are carried out to evaluate the control system performance. When the reactor is perturbed, the reactor can be stabilized under the control system.

Key Words: Small Pressurized Water Reactor; Thermal-hydraulic Model; Control System Design

1 INTRODUCTION

Small modular reactors (SMRs) are defined by the IAEA as those reactors with an output below 300 MWe [1]. Many countries, such as the USA, China, Argentina, and South Korea, have developed their own concepts. Among the different concepts, significant efforts have been put into Small Pressurized Water Reactors (SPWR). The applications of SPWRs include electricity supply for areas with a small grid, desalination, hydrogen production, and heat and power cogeneration.

The design of an SPWR is different from that of large commercial PWRs. An integral design is a general option. The reactor core, coolant pumps and steam generators are placed in the pressure vessel, and there are no hot legs or cold legs between the reactor core and the steam generators like in the PWR. Strong interactions exist among different loops. The pressure vessel is large in volume, and the coolant inventory is also large. The inertia of the primary coolant is large. Therefore, it takes more time for the primary system to respond to disturbances. The steam generators adopts a once-through design with straight or helical coil tubes, and the water inventory is small compared to that in the U-tube type steam generators. As a result, the steam generators are very sensitive to disturbances. These unique

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characteristics pose challenges to the control system design of the SPWR, as the traditional proportional-integral-derivative (PID) feedback control may not satisfy the control requirements. Especially for the feedwater control, the use of integrated control was proposed due to its high sensitivity to other process parameters [2]. Moreover, if the SPWR is designed for heat and power cogeneration, coordinated control may be needed to balance the dynamic coupling between different processes. Advanced control can be an alternative solution for the control of the SPWR [3].

In this paper, an SPWR is modeled using Relap5. Its control system with traditional PID controllers is designed. The transients with typical load patterns are simulated under the control system to evaluate the control performance. The feedwater control system is improved by introducing a feedforward controller with the average coolant temperature as the input and the feedwater flow rate as the output. Through comparisons, the steam temperature variation can be efficiently suppressed.

2 AN INTRODUCTION TO THE SPWR

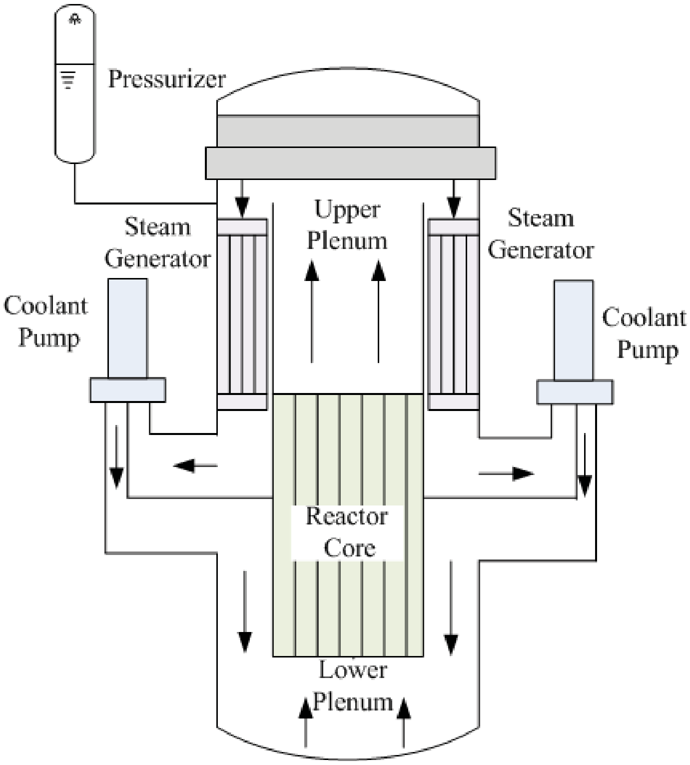

Figure 1 Diagram of the coolant system

An illustrative diagram of an SPWR is shown in Figure 1. The SPWR adopts an integral design. The steam generators, coolant pumps and reactor core are located inside the pressure vessel, and the pressurizer is placed outside of the vessel. The coolant is driven by the coolant pumps and flows downwards to the lower plenum through the downcomer. Then, it goes upwards through the reactor core and absorbs the heat generated in the fuel rods by the fission reaction. The heated coolant is collected in the upper plenum and sent to the once-through steam generators. Heat is released to the secondary fluid of the steam generator, and the cooled coolant goes back the pumps to start the next cycle.

The design parameters of the SPWR are shown in Table I. The thermal power is 310 MWt, the fuel is ≤4.45% in enrichment, and its active height is 2.15 m. There are 57 fuel assemblies, which are in a 17×17 square structure. The reactor is operated at 15 MPa. The coolant enters the reactor core at 282°C and exits at 323°C There are 4 vertical canned coolant pumps and 16 double-tube type once-through steam generators.

Table I. Design Parameters of the SPWR

Parameters	Values
Thermal Power	310 MWt
Electrical Power	100 MWe
Fuel Enrichment	≤4.45%
Coolant Pressure	15 MPa
Coolant Inlet Temperature	282°C
Coolant Outlet Temperature	323°C
Coolant Flow Rate	1353 kg/s

3 RELAP5 MODELING OF THE SPWR

The system code Relap5 is applied to the SPWR transient calculation. The control system will also be implemented in Relap5 to evaluate the control performance. The Relap5 nodalization for modeling of the SPWR is shown in Figure 2. The coolant is pumped by the coolant pumps and goes downwards through the downcomers modeled by control volumes 100 and 200 to the reactor core. The reactor core is modeled with three separate channels: hot, average and bypass channels. They are represented by control volumes 115, 116 and 117, respectively. The red parts associated with control volumes 115 and 116 are modeled as the fuel rods, in which heat is generated. The heated coolant flows upwards to the upper plenum and then goes into the steam generators. Control volumes 122, 123, 125 and 128 are used to model the upper plenum. After the heat is released to the secondary fluid, the coolant returns to the coolant pumps.

The 16 steam generators are divided into two sets, each containing 8 steam generators that share one steam line. The hot coolant flows downwards and into the double-tube zone (control volumes 163 and 164) through the upper single-tube zone (control volumes 160 and 162). It goes back to the coolant pumps after passing through the lower single-tube zone (control volumes 165 and 167). For the secondary side of the steam generators, the feedwater flow comes from the time dependent volume 180. The feedwater first flows through the feedwater line (control volumes 184 and 186) and then enters the heat transfer area, where the feedwater absorbs heat from the double-tube zone (control volume 192) and the lower single-tube zone (control volumes 188 and 190). Superheated steam is collected in the steam line (control volume 550) after passing through the upper single-tube zone (control volumes 194 and 196). The steam is sent to the outlet boundary 567.

The pressurizer that controls the coolant pressure is also modeled as control volumes 512 and 520. Heaters are included inside the pressurizer and used to raise the pressure. A spray system is applied to reduce the coolant pressure and modeled as the time dependent volume 580. The charging flow is represented by time dependent volume 600 and adopted to regulate the water level of the pressurizer.

To compute the reactor fission power, a point reactor kinetics model with six groups of delayed neutrons is applied. Two reactivity feedback effects are considered: that of the fuel rod temperature and that of the moderator temperature.

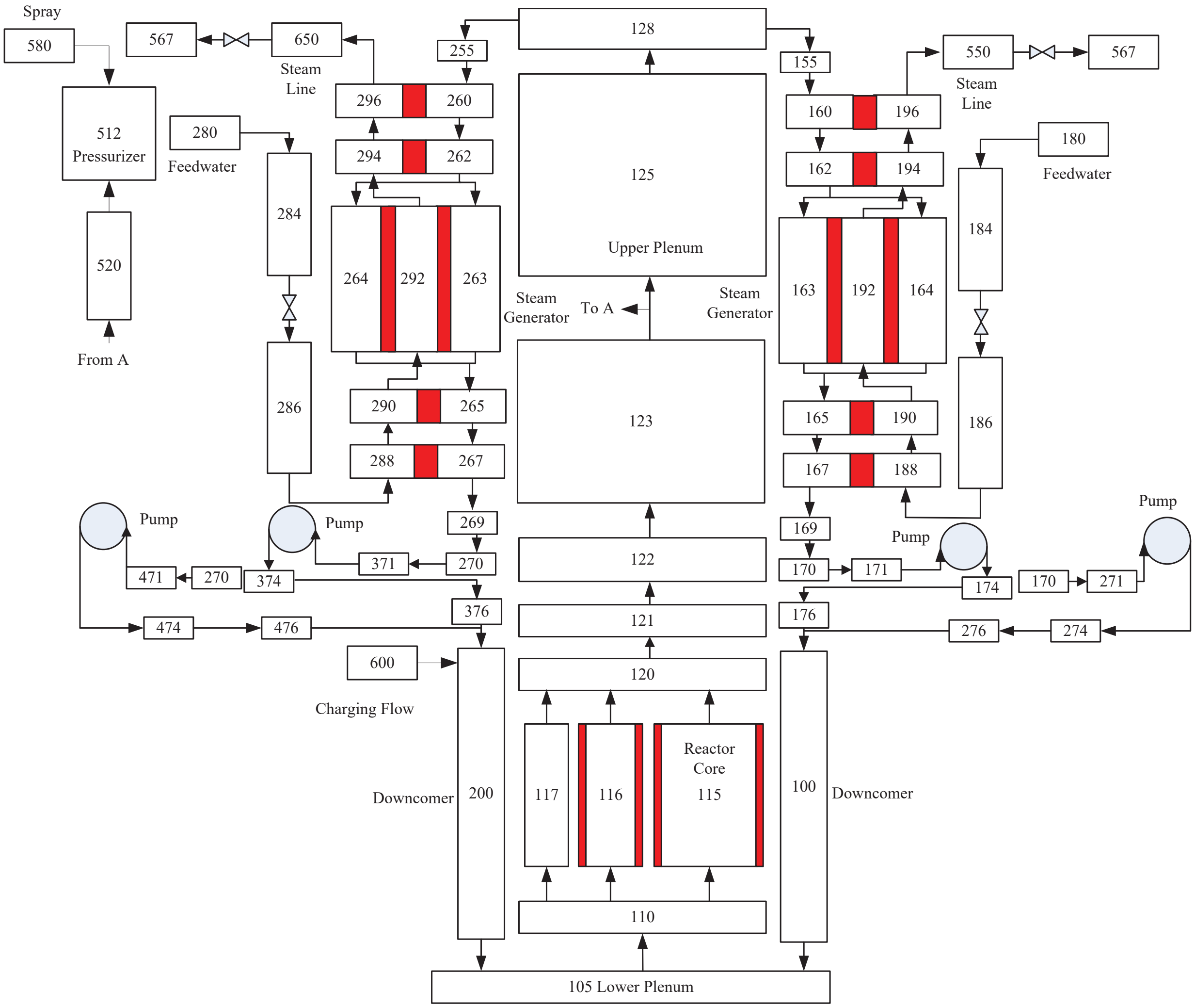

Figure 2 **Relap5 nodalization of the SPWR model**

4 THE SPWR CONTROL SYSTEM

4.1 Reactor Power Control

Turbine-following-reactor strategy is adopted. The reactor power is determined by the load demand. The coolant average temperature is required to be varied linearly with the power level. The relationship between them is shown in Figure 3. The control diagram of the coolant average is shown in Figure 4. The error between the coolant average temperature measurement and its setpoint is used as the drive signal for the control rod drive mechanism. The mismatch between the reactor power and its setpoint is also compensated in the coolant average temperature control system.

4.2 Feedwater Flow Control

The steam pressure is maintained at constant during the operation. Feedwater flow rate is regulated to stabilize the steam pressure. The feedwater flow control diagram is shown in Figure 5. The error between the steam pressure measurement and its setpoint is the input to the pressure controller. The mismatch between the steam flow and the feedwater flow is also compensated to generate the required feedwater flow.

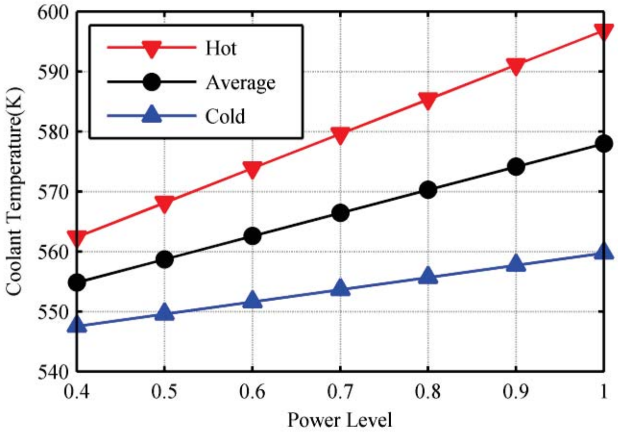

Figure 3 Relationship between coolant average temperature and power level

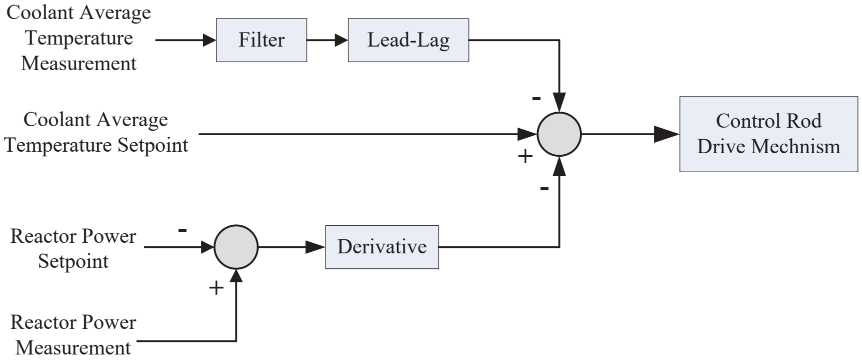

Figure 4 Coolant average temperature control diagram

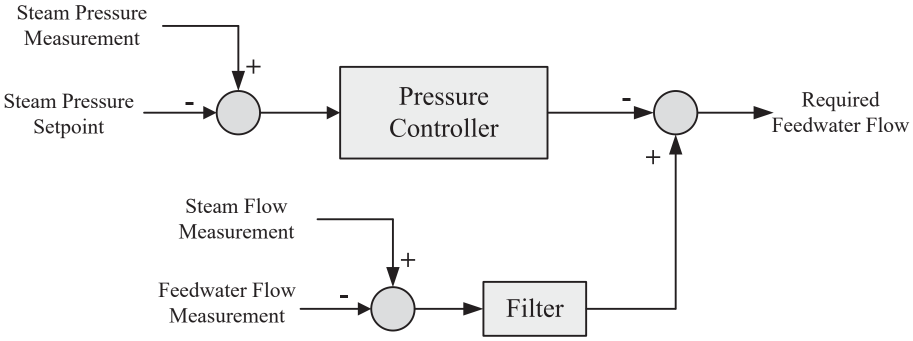

Figure 5 Feedwater flow control diagram

4.3 Pressurizer Pressure and Water Level Control

The pressure in the pressurizer is controlled by the spray and heaters. The compensated pressure error is calculated by the pressure controller taking the error between the pressure measurement and its setpoint as the input. The compensated pressure error drives the control actions. When the error is positive and larger than a certain limit, the spray works to decrease the pressure while the heaters is to increase the pressure when it is less than one certain value as shown in Figure 6. The water level of the pressurizer is controlled by the charging flow. The control diagram is shown in Figure 7. The error between the level measurement and its setpoint is the input of the level controller. The required feedwater flow is obtained from the level controller and compensated by the mismatch between the charging flow and the letdown flow.

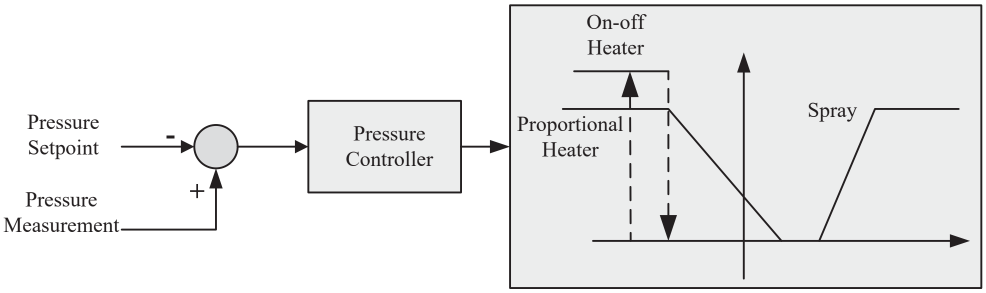

Figure 6 **Pressurizer pressure control diagram**

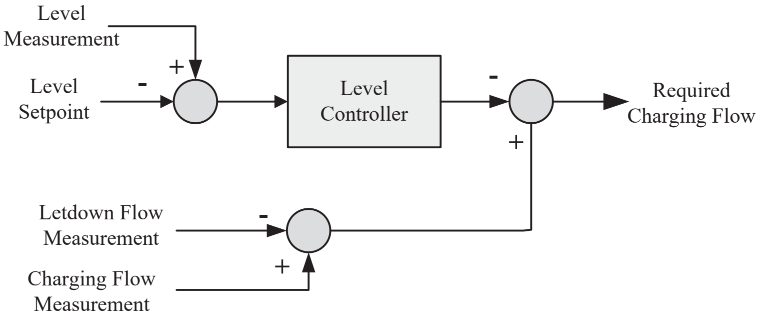

Figure 7 **Pressurizer water level control diagram**

5 SIMULAITON RESULTS

5.1 Steady-state Simulation Results

To ensure the correctness of the Relap5 nodalization, the steady-state simulation is performed. The steady-state results are shown in Table II and compared with the design values. The relative errors are less than 1%. It is shown that the Relap5 model can be used to perform the thermal-hydraulic simulation of the SPWR.

Table II. Steady-state Results of the Relap5 Model

Parameters	Calculated Values	Design Values	Error(%)
Thermal Power(MW)	310	310	0
Coolant Inlet Temperature (°C)	284.9	282.6	0.8
Coolant Outlet Temperature (°C)	325.2	323.4	0.6
Coolant Flow Rate (kg/s)	1354	1353	0.1

5.2 Transient Simulation results

To test the control performance of the designed control system, two load patterns are introduced: a 10% step decrease and a 5%/min ramp decrease.

A 10% step decrease in the load is introduced at 0 second. The responses are shown in Figures 8 and 9 with solid lines. The reactor power responds to the load demand by inserting the control rods. Due to the inserted negative reactivity, the reactor power decreases promptly and stabilizes at 90% as shown in Figure 8(a). The coolant average temperature is also reduced with the decreased reactor power. The density of the coolant is increased. The water level in the pressurizer decreases as shown in Figure 9(d) and the pressure is reduced shown in Figure 8(d). Under the pressurizer level and pressure control system, the water level and pressure return to their setpoints. Under the steam pressure control system, the steam pressure is kept around its setpoint with slight variation by regulating the feedwater flow as shown in

Figure 9(a). The quick decrease in the feedwater flow and slow decrease in the coolant average temperature make the steam temperature significantly increase. The largest variation in the steam temperature is around 12.5°C.

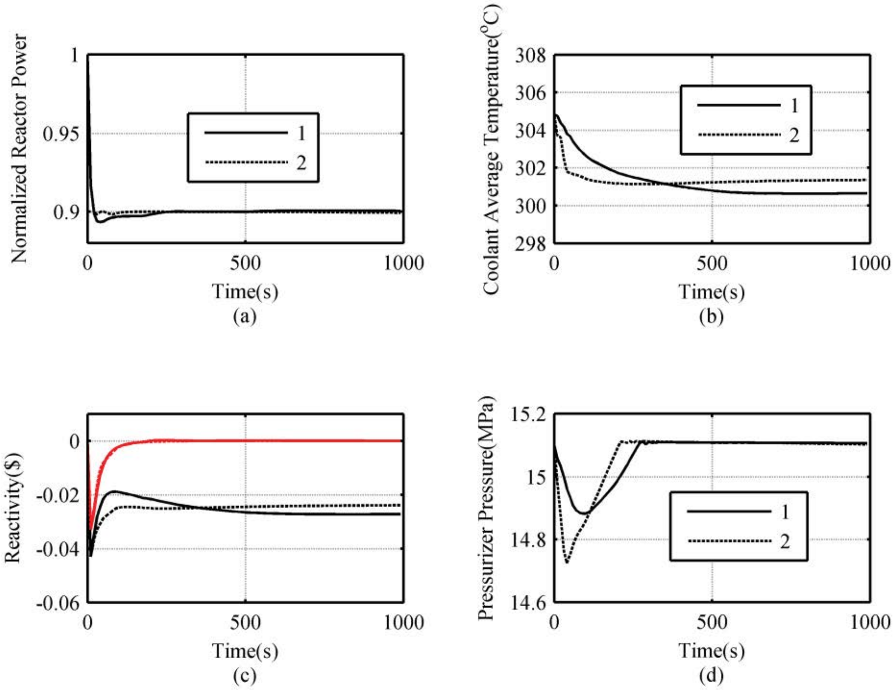

Figure 8 SPWR responses to a step load disturbance 1

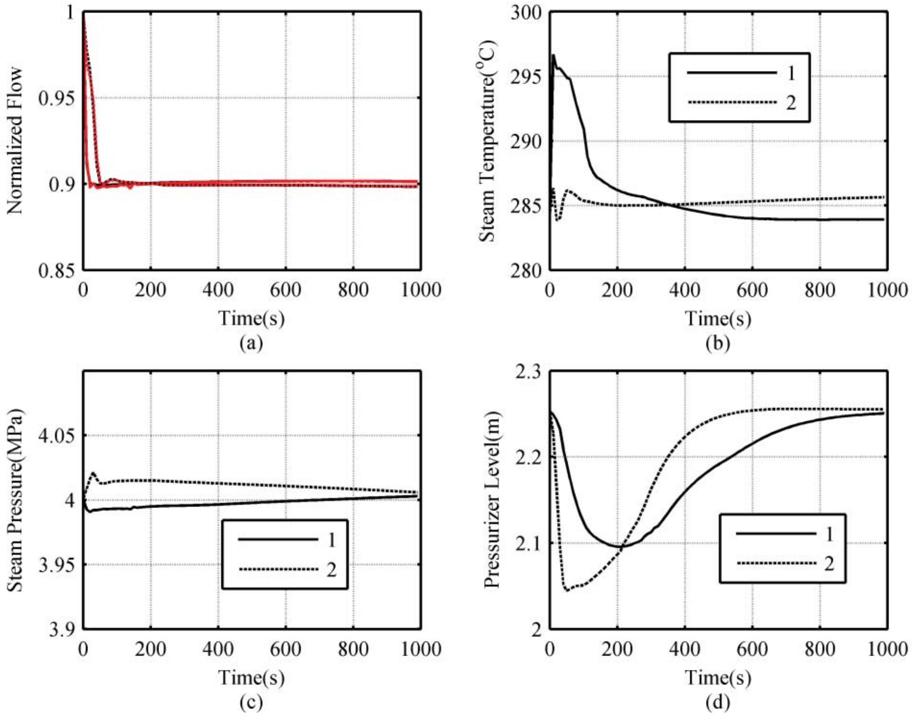

Figure 9 SPWR responses to a step load disturbance 2

A ramp decrease to 90% in the load at a rate of 5%/min is introduced at 0 second. The responses are shown in Figures 10 and 11 with solid lines. The reactor power responds to the load demand by inserting the control rods. Due to the inserted negative reactivity, the reactor power decreases linearly and stabilizes at 90% as shown in Figure 10(a). The coolant average temperature is also reduced with the decreased reactor power. The density of the coolant is increased. The water level in the pressurizer decreases as shown in Figure 11(d) and the pressure is reduced shown in Figure 10(d). Under the pressurizer level and pressure control system, the water level and pressure return to their setpoints. Under the steam pressure control system, the steam pressure is kept around its setpoint with slight variation by regulating the feedwater flow as shown in Figure 11(a). The quick decrease in the feedwater flow and slow decrease in the coolant average temperature make the steam temperature significantly increase. The largest variation in the steam temperature is around 8.3°C.

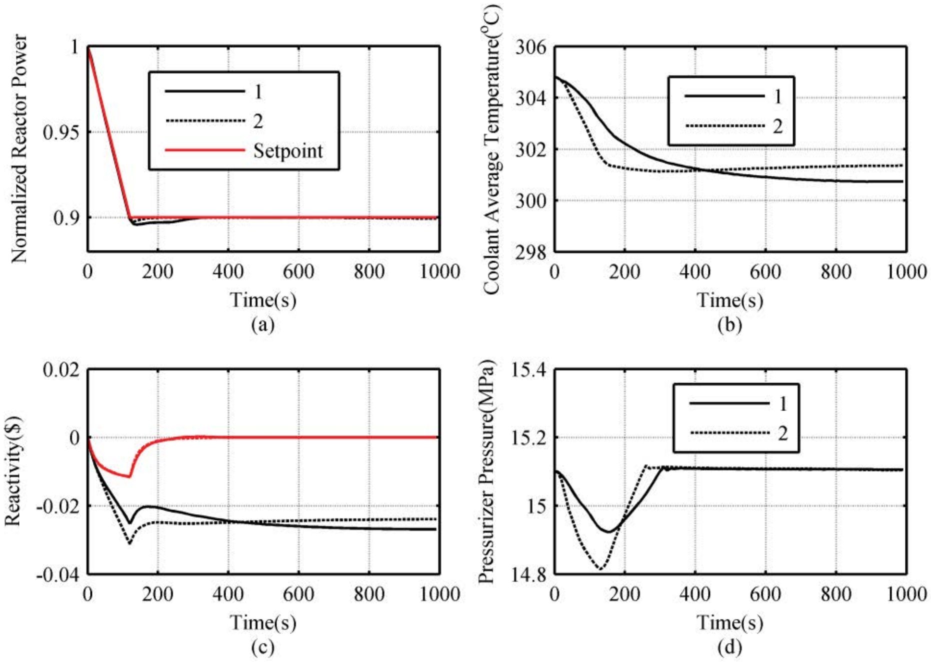

Figure 10 SPWR responses to a ramp load disturbance 1

6 IMPROVEMENTS ON FEEDWATER CONTROL

From the responses of the SPWR under the designed control system, it can be seen that the coolant average temperature responds to the load change slowly. The main reason is that the large coolant inventory has a large inertia and the once-through steam generator responds fast to disturbances. Therefore, the steam temperature has a large fluctuation. To suppress the steam temperature variation, improvements on the feedwater flow control is needed. If the coolant average temperature is larger than its setpoint, the feedwater flow should be increased to take more heat away from the coolant to reduce the coolant average temperature. Thus, a feedforward control is added to the feedwater flow control. The input signal of the feedforward control is the difference between the coolant average temperature and its setpoint. The output signal is the feedwater flow.

To test the control performance of the new control system, the same load patterns are introduced and the results are shown in Figures 8, 9, 10 and 11 with dashed lines. With the feedforward control system, the feedwater flow is larger than that without feedforward control as shown in Figure 9(a) and 11(a). As a result, the coolant average temperature reduces more quickly. The steam temperature variation is efficiently suppressed as shown in Figure 9(b) and 11(b).

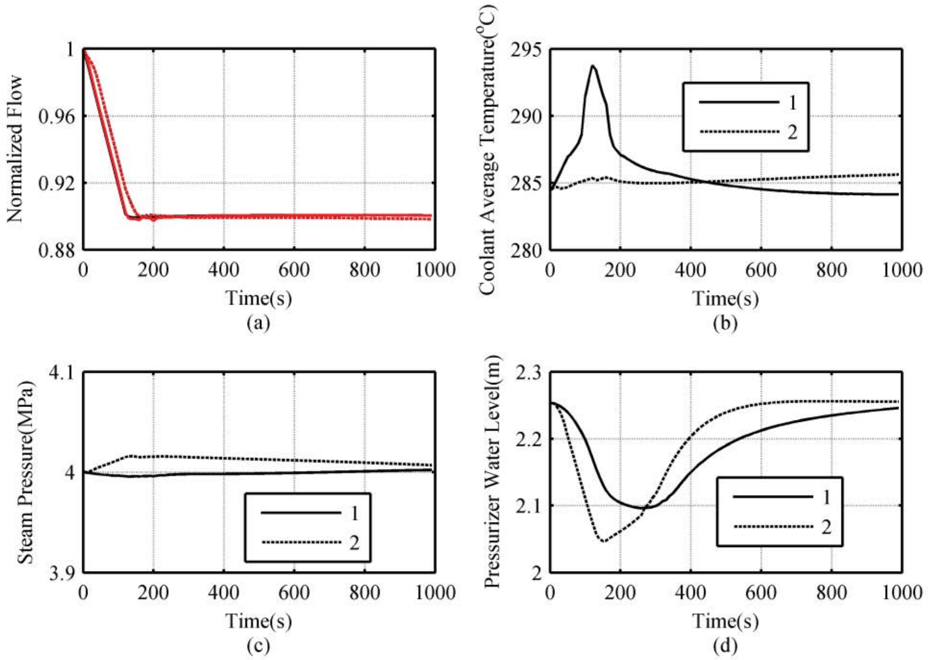

Figure 11 SPWR responses to a ramp load disturbance 2

7 CONCLUSIONS

The design of the SPWR is different from those of commercial PWR. The primary loop has a large time constant while the secondary loop has a small time constant. It is necessary to design an appropriate control system for SPWR. Relap5 is adopted to model the SPWR. Traditional PWR control system is applied to control SPWR. Through simulation, it is found that the average coolant temperature and steam temperature variation is large. To suppress the large variation, a feedforward control system is added with the coolant average temperature error as the input and the feedwater flow rate as the output to coordinate the relationship between the primary and secondary loops. It is concluded that the new control system can stabilize the SPWR and the control performance is satisfactory.

8 ACKNOWLEDGMENTS

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