The automatic control design and simulation of reactor control system in small modular reactor

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Abstract: In China, the development and application goals of Small Modular Reactor (SMR) aim at electricity generation area, heat supply area, and seawater desalination area, etc. The main technical features of the SMR are as follows: integrated pressurized water reactor, reactor coolant pump and reactor pressure vessel connected by short pipe, steam generator sets in reactor pressure vessel, control rod drive mechanism (CRDM), pressure vessel, reactor internals, Once-Through Steam Generator(OTSG), and canned motor pump are all mature technology. Based on the characteristic of the reactor and OTSG, the automatic control design of the SMR is discussed in this paper, and the simulation results are presented to illustrate the control scheme.

Keyword: small modular reactor, control system, integrated pressurized water reactor, once-through steam generator

1 Introduction

Nowadays the demands and applications of Nuclear Power Plant (NPP) are not only concentrated on the electricity generation but also on some enormous power consumption by non-electricity applications, such as seawater desalination, civil and industrial heat supply. Therefore more and more countries are developing the advanced Small Modular Reactor(SMR) to meet the extensive and diverse energy needs[1]. The SMR development project in China aims at innovation based on the existing PWR technology, by adapting an integrated and modular reactor design which makes the SMR capable of reaching large power by several modular combinations to meet the diverse demands. [2]

According to the Chinese SMR design, it has eliminated the primary pipeline and integrated the One-Through Steam Generator (OTSG) into the Reactor Pressure Vessel (RPV). Therefore, it is different from the typical separated loop-type PWR design of present time. Both of these factors influence the characteristic of the control process of the reactor power and steam generator feed water flow, and accordingly bring new challenges to the control system design. During the normal operation and operational transients, the reactor power and feed water flow are under automatic control of the Reactor Power Control (RPC) system and the SG Feed Water Control (FWC) system. The RPC and FWC cooperate with each other so as to carry out the energy conversion from the primary loop to the secondary loop and meanwhile maintain the reactor and other primary system stably running. Thus the automatic control design of the RPC and FWC is mostly affected by the particular characteristic of the integrated layout and the OTSG.

In this paper, the basic functionality and the preliminary scheme of the RPC and FWC are discussed based on the general control scheme for NSSS of the SMR. A simulation study is also introduced, which has been conducted by applying the safety analysis code RELAP5 for the scheme of the SMR model, wherein the simulation results indicate good performance of the control scheme for a set of different transients.

2 System description

2.1 Main configuration of the SMR

According to the Chinese SMR design, 4 coolant pumps are set in order to force the circulation between the reactor core and the OTSG, and the length of the coolant loop is much shorter than the separated loop-type PWR design. The OTSG is made up of thousands of one-through tubes which are divided into 4 groups. Each group of the OTSG tubes has one set

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of the feed water pipes and steam pipes. The feed water of the secondary loop is heated and turned into superheated steam in the OTSG pipes. Comparing with the separated loop-type PWR, the SMR has fewer water inventory and its thermal-hydraulic process is rather more adverse and rapid.

2.2 The general control scheme

The general control scheme for NSSS of the SMR is the automatic control combined with the manual control. The control systems of the NSSS have an automatic control range from 0 to 100% Full Power (FP), except the RPC and FWC, where the manual scheme is applied below 20%FP instead of the automatic scheme. The NSSS is operated at the corresponding power level according to the different load level. During the load following mode, the primary control principle is to maintain the main steam pressure and the average temperature of the reactor coolant at the specific constant respectively. According the control system design, the reactor is capable of returning to the equilibrium condition automatically through the load variations transient in steps of ±10% FP or in continuous ramps with a gradient of ±5%FP/min.

3 The Automatic control design

3.1 The Reactor Power Control system (RPC)

The reactor power control (RPC) system includes two control channels: the temperature channel and the power mismatch channel. The temperature channel receives the average temperature measurement computed and adjusted from the core inlet and outlet temperature measurements, and compares it with the reference temperature (a fixed setpoint). The error between these two signals is the primary control signal of the RPC system. The power mismatch channel is a forward channel. This channel receives the nuclear power signal and the total feed water flow of the secondary side and adds their error to the temperature error signal. The final error signal is processed by the rod speed program, and then produces the control rod travel speed signal and two direction logic signals. The control scheme for the RPC is shown as Fig. 1.

The functionality of the temperature channel and the power mismatch channel is firstly to stabilize the system, and furthermore to optimize the control performance. The temperature channel uses a Lead-Lag function to adjust the phase of the temperature signal, meanwhile bring back the error between the reference temperature and the measurement temperature within the deadband. The power mismatch channel accelerates the reactor's response to the load in virtue of the High-Pass filter. Besides in order to improve the stability margin and avoid frequent rod motion from low level to high level nuclear power, two changeable gains are introduced to achieve a proper gain for the power mismatch, and guarantee an acceptable range of parameter change during the normal transient. Since the OTSG produces superheated steam, the steam flow cannot be simply considered as an indication of the energy consumed, nevertheless the feed water flow with a constant water temperature almost approximates the demand of the mass and energy of the OTSG, thus the RPC introduces the feed water flow as the load signal.

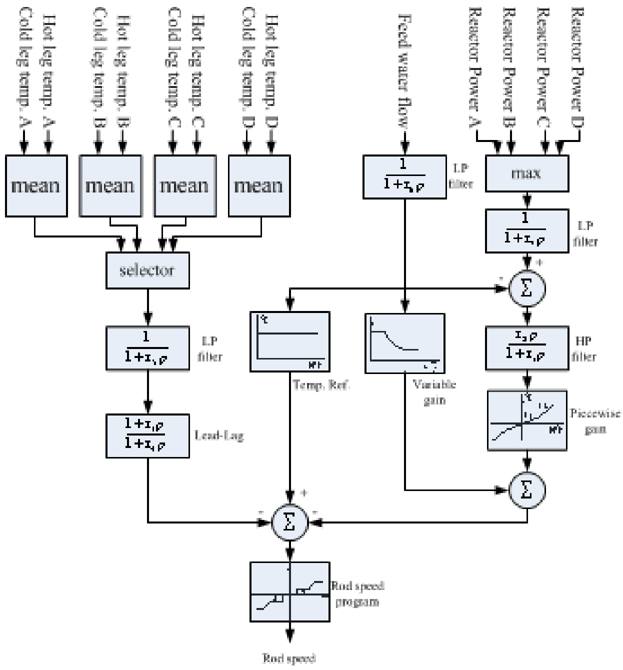


Fig.1 The control scheme for the RPC.

3.2 The SG Feed Water Control system (FWC)

The functionality of the OTSG feed water control system is to maintain a fixed setpoint of the OTSG's secondary side pressure and to make the feed water flow accommodate the load requirements by regulating the OTSG's feed water flow.

During 0 to 20%FP, the feed water flow is controlled manually. A bypass control valves are used to adjust the feed water flow manually through the startup feed water line and the startup feed water pump. During the 20%FP to 100%FP, the feed water flow is regulated automatically through the main Feed Water Pump (FWP), main Feed Water Valve (FWV) and the main feed water line. The bypass feed water channel is not at operation simultaneously.

The three-element feed water controller regulates the main valve opening by using the error between the steam pressure and a constant setpoint. The error is introduced into the Proportion-Integral controller to achieve a good transient and steady-state regulation behavior within closed loop. The error between the feed water flow and the steam flow directly reflects the unbalance of the mass in the OTSG, thus is also introduced to regulate the FWV, by adding it to the output of the Proportion-Integral. The control scheme for the FWV controller is shown as Figure 2.

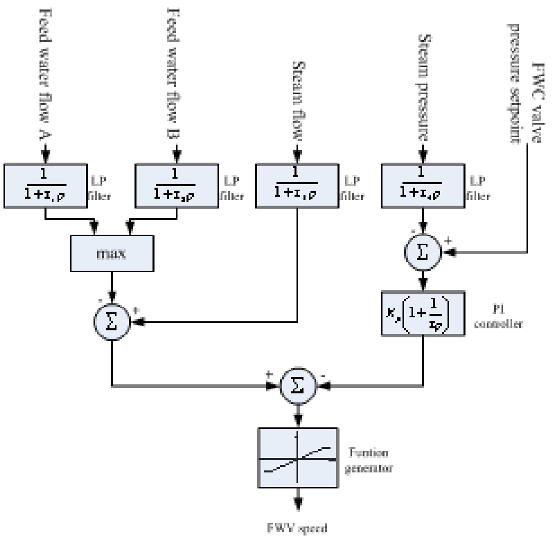


Fig.2 The control scheme for the FWV.

The rotation speed of the Feed Water Pump is controlled by the pressure error between the inlet and outlet of the FWV. The error is designed to remain constant which provides a linear mapping relationship between the feed water flow and the FWV opening position. The response of the FWP controller should be fast enough to change the feed water heading and lead the feed water flow, so that the pressure error between the inlet and outlet of the FWV would only vary within a acceptable range, and avoid a unwilling deviation of the feed water flow to the FWV opening position. One Proportion-Integral (PI) controller is introduced to do the regulation automatically, where the control scheme for the FWP is shown as Fig. 3.

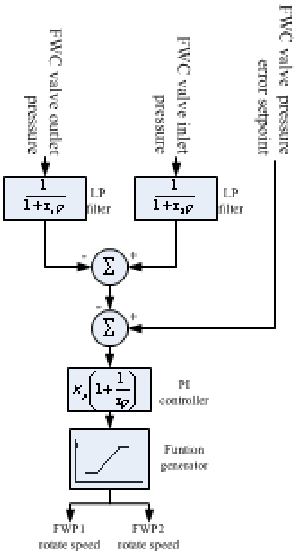
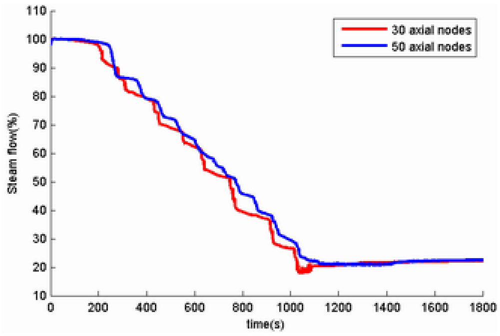


Fig.3 The control scheme for the FWP.

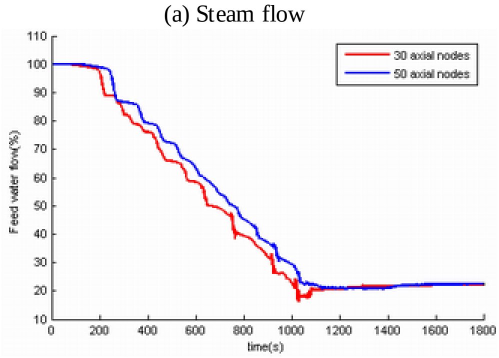
4 Simulation study

The closed-loop control performance of the above control schemes are tested under a simulation bench combined with RELAP5 and Matlab/Simulink. The control process model is built in RELAP5, and the control system model is built in Simulink. Since these two models running in two different programs with two different and changeable time steps. A synchronization mechanism for data exchange between RELAP5 and Simulink is developed via SQL database, which guarantees accurate exchanges of the data between these two programs at every simulation advance.

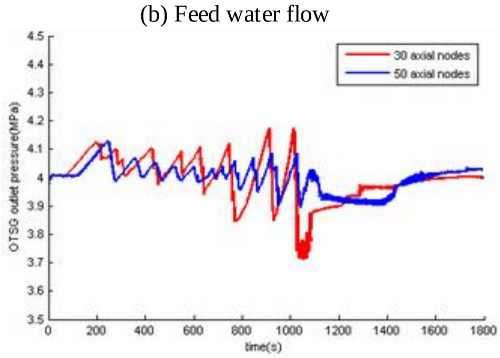
In this case, there is one factor that influences the modeling characteristic most for the control system simulation: the number of the axial nodes both for the reactor core and the OTSG. Since the SMR is a pressurized water reactor, the reactivity feedback of the moderator fluid temperature change is rather distinct, especially for few axial nodes of the reactor core in the simulation model. Therefore the reactor core has been densely nodalized in order to calculate the temperature of the moderator fluid more precisely in the simulation. The simulation of the OTSG also needs the same way of nodalization in order to catch the possible two-phase phenomenon in every node by using the correct flow regime and heat transfer formula. The simulation comparison of 30-50 axial nodes of the OTSG in Fig. 6 shows that more nodes can attain better continuity in the simulation of OTSG such as in the flow of the feed water and the steam, and the steam pressure. Meanwhile a dense nodalization makes the parameters responding more smoothly in the transient.



(a) Steam flow



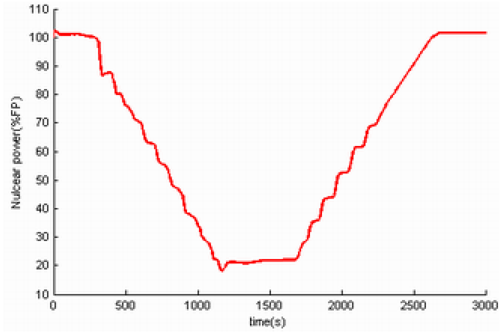
(b) Feed water flow



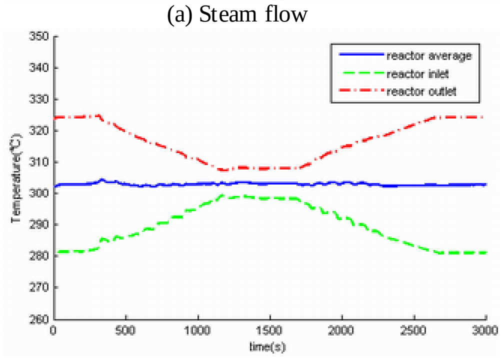
(c) Steam pressure

Fig.6 The simulation comparison of 30-50 axial nodes of the OTSG.

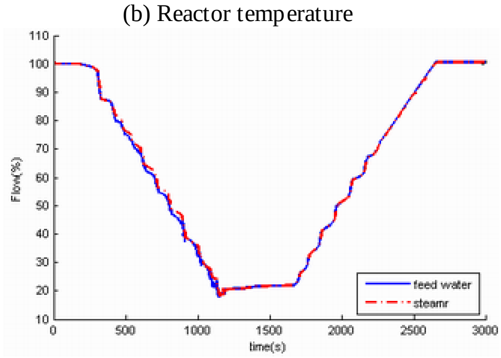
The closed-loop control performance of the control scheme for the RPC and FWC system is tested in the two transients required for by the SMR control system: ramp load change at 5%FP/min and step load change of 10%FP, which are shown as in Fig. 7 and Fig. 8 respectively. We can see that the steam flow and the pressure of the OTSG are both quickly responding to the regulation of the feed water, which mostly attributes to the small volume and few heat capacity of the OTSG. The nuclear power is also changing continuously during the transient since the feed water flow is introduced into the RPC system as the load signal. We can also see that the rotation speed of the FWP and the pressure error between the inlet and outlet of the FWV are both changing along with the OTSG pressure at the similar frequency. Accordingly the whole characteristic of the feed water system is evidently influenced by the OTSG, and appears to be more sensitive and coupled to the control actions.



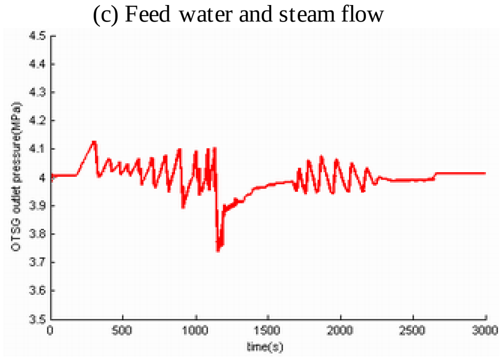
(a) Steam flow



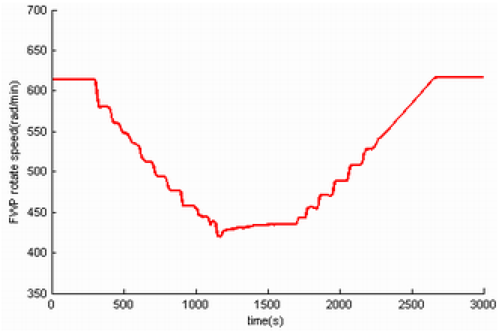
(b) Reactor temperature



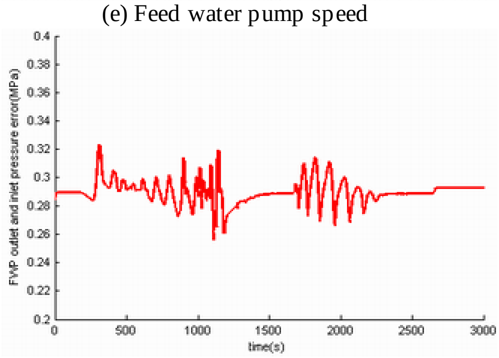
(c) Feed water and steam flow



(d) Steam pressure

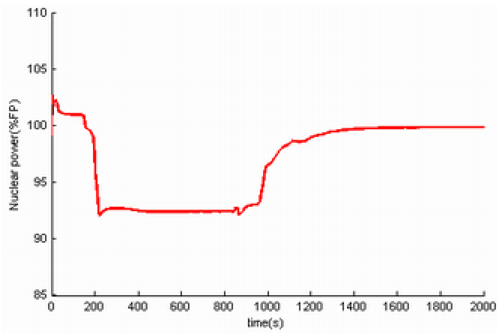


(e) Feed water pump speed

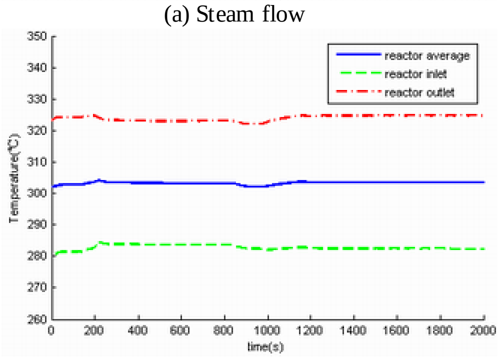


(f) Pressure error between inlet and outlet of the FWV

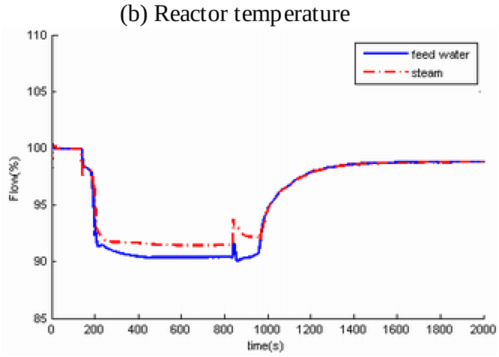
Fig.7 The simulation of ramp load change at 5%FP/min



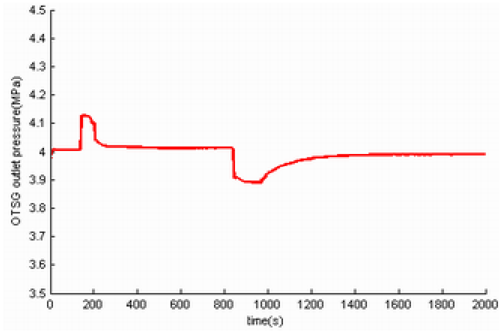
(a) Steam flow



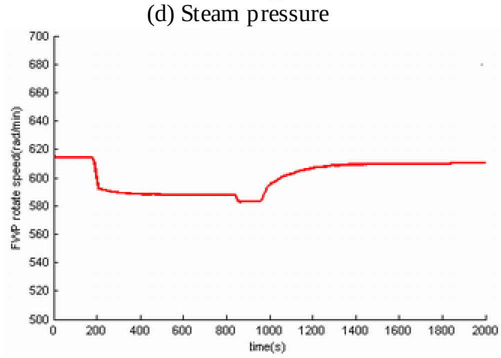
(b) Reactor temperature



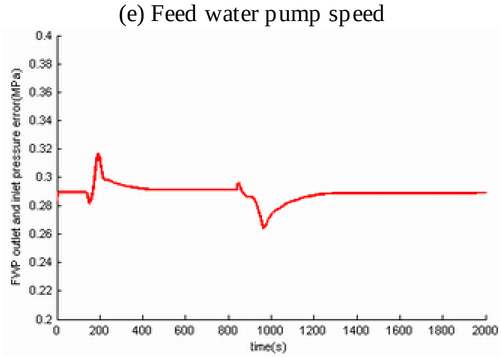
(c) Feed water and steam flow



(d) Steam pressure



(e) Feed water pump speed



(f) Pressure error between inlet and outlet of the FWV

Fig.7 The simulation of step load change of 10%FP

5 Conclusion

In this paper, the automatic control schemes of the reactor power control system and feed water control system for the Chinese SMR are proposed. The schemes are tested to be feasible within the simulation including specified large-scale ramp and step load change. The reactor power control is related to the feed water control through the feed water flow considered as the load signal. The control performance of both the primary and secondary loop is sensitive and closely coupled due to the transient of the integrated OTSG.

Nomenclature

SMR	Small Modular Reactor
OTSG	Once-Through Steam Generator
NPP	Nuclear Power Plant
RPC	Reactor Power Control
FWC	SG Feed Water Control

References

[1] HADID S.: IAEA Programme on Common Technology and Issues for SMRs, IAEA: Workshop on SMR Technology Assessment for Nuclear Term Deployment, 2011.

[2] ZHI C., DANRONG S.: The Progress of Instrumentation and Control System Development in Small Modular Reactor ACP100. In: IAEA. Proceedings of a Technical Meeting on Instrumentation and Control in Advanced Small and Medium Sized Reactors(SMRs), Vienna, IAEA, 2013.