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Original Article

Design of the flexible switching controller for small PWR core power control with the multi-model

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ABSTRACT

Small PWR can be used for power generation and heating. Considering that small PWR has the characteristics of flexible operating conditions and complex operating environment, the controller designed based on single power level is difficult to achieve the ideal control of small PWR in the whole range of core power range. To solve this problem, a flexible switching controller based on fuzzy controller and LQG/LTR controller is designed. Firstly, a core fuzzy multi-model suitable for full power range is established. Then, T-S fuzzy rules are designed to realize the flexible switching between fuzzy controller and LQG/LTR controller. Finally, based on the core power feedback principle, the core flexible switching control system of small PWR is established and simulated. The results show that the flexible switching controller can effectively control the core power of small PWR and the control effect has the advantages of both fuzzy controller and LQG/LTR controller.

1. Introduction

Small Pressurized Water Reactor (SPWR) is a highly secure distributed energy supply system with compact structure and wide application. Steam generators, pressurizer, control rod drive mechanisms, etc. are installed in reactor pressure vessel, and main coolant pump is directly connected with pressure vessel. Main pipeline and main gate valve are canceled, and flow resistance of primary circuit working medium is reduced. Natural circulation capacity of primary circuit is improved, and inherent safety of system is improved. With the refueling maintenance cycle long, SPWR can supply power and heat energy stably for a long time. As SPWR has the characteristics of flexible operating conditions and complex operating environment, it needs fast load following and anti-disturbance ability in the operation process, which puts forward high requirements for the design of power control system of SPWR[1]. The traditional core power controller is mainly designed based on the core linearization model under a certain power level, which is suitable for a small operating range [1]. When the core power changes in a large range or the transient load changes in any operating condition, it is difficult to achieve a good control of the core power in all operating conditions. Therefore, it is necessary to design more reasonable core power controller to ensure the safe operation of SPWR.

In recent years, several researchers have studied for the core power control of SPWR. Liao and Wang designed the core power internal model robust controller of SPWR based on the multi-model strategy [1]. Hu et al. used the coordinated control strategy of control rod adjustment system, feedwater control system of once through steam generator (OTSG) and speed control system of feedwater pump for SPWR nuclear power plant [2]. Tai et al. established an improved implicit multi-model predictive control system for mobile nuclear power plant [3]. Li et al. built a core power flexible control system for PWR core nonlinear model using Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) control strategy [4]. Zeng et al. designed a functional variable universe fuzzy proportional-integral-derivative (PID) controller for PWR core power control based on the multi-model strategy [5].

In order to integrate the performance advantages of the LQG/LTR controller and the fuzzy controller, a control scheme with LQG/LTR

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Nomenclature

t	time
T	temperature
n	neutron density
c	delayed neutron precursor density
P	core power
f	share of the reactor core fuel heat production
e	the relative power error (δP_{set}-δP_r)
U	fuzzy output of fuzzy controller
ec	the relative power error derivative
W_p	core coolant flow
C_p	specific heat capacity at constant pressure

Greek symbols

β	total delayed neutron fraction
Λ	neutron generation time
λ	decay constant
ρ	reactor core reactivity
μ	total heat capacity
Ω	heat transfer coefficient between fuel and coolant
α	temperature feedback coefficient
δ	Small perturbation

Subscripts

r	value relative to the initial value
f	Fuel
c	coolant
$c1$	the coolant average
$c2$	the coolant outlet
set	the set value
0	the initial value
lp	the coolant inlet
rod	control rod
$fuzzy$	fuzzy controller
LQG	LQG/LTR controller

controller and fuzzy controller weighting or switching is developed. First of all, according to the references [4–6], based on the multi-model modeling method, a multi-model of SPWR core suitable for the full power range is established. Then, based on LQG/LTR controller and fuzzy controller, the flexible switching controller are designed by the T-S fuzzy switching rule. Finally, the dynamic characteristics of the SPWR core power control is simulated.

The rest of this paper is organized in the following sequence. Section 2 describes the establishment of the fuzzy multi-model of SPWR core. In Section 3, the core power flexible switching control system for SPWR is established. The simulation analysis of the core power control system of SPWR is in Section 4. Section 5 is the conclusion.

2. Fuzzy multi-model of SPWR core

2.1. The nonlinear model of reactor core

The nonlinear mathematical model of reactor core includes neutron dynamics model, thermal hydraulic model, reactivity model. The point reactor dynamics with one group of delayed neutron precursors is established with the reactivity feedback of coolant temperature and fuel temperature [7,8].

1 Neutron dynamics model

$$\frac{dn_r}{dt}=\frac{\rho-\beta}{\Lambda}n_r+\frac{\beta}{\Lambda}c_r \tag{1}$$

$$\frac{dc_r}{dt}=\lambda n_r-\lambda c_r \tag{2}$$

2 Thermal hydraulic model

$$\mu_f\frac{dT_f}{dt}=fP_0P_r-\Omega\left(T_f-T_{c1}\right) \tag{3}$$

$$\frac{\mu_c}{2}\frac{dT_{c1}}{dt}=\frac{1}{2}\left[(1-f)P_0P_r+\Omega\left(T_f-T_{c1}\right)\right]+W_pC_{p,c}\left(T_{lp}-T_{c1}\right) \tag{4}$$

$$\frac{\mu_c}{2}\frac{dT_{c2}}{dt}=\frac{1}{2}\left[(1-f)P_0P_r+\Omega\left(T_f-T_{c1}\right)\right]+W_pC_{p,c}(T_{c1}-T_{c2}) \tag{5}$$

3 Reactivity model

$$\rho=\rho_{rod}+\alpha_f\left(T_f-T_{f0}\right)+\frac{\alpha_c}{2}[(T_{c1}+T_{c2})-(T_{c10}+T_{c20})] \tag{6}$$

Taking P_r to be P/P_0, the relation between P_r and n_r could be described as follows,

$$n_r(t)=P_r(t) \tag{7}$$

2.2. The transfer function model of reactor core

Based on the core steady-state operating point, Eqs. (1)–(6) are linearized by the perturbation theory. The linearization mathematical model of reactor core is obtained. The multi-input multi-output (MIMO) system is established by selecting the core relative power deviation, coolant average temperature deviation as the output, reactivity and core coolant inlet temperature as the input. The input parameters, state parameters and output parameters are defined as follows,

$$\boldsymbol{u}=\left[\delta\rho,\delta T_{lp}\right]$$

$$\boldsymbol{x}=\left[\delta P_r,\delta C_r,\delta T_f,\delta T_{c1},\delta T_{c2}\right]$$

$$\boldsymbol{y}=[\delta P_r,\delta T_{c2}]$$

The state space model is established at the core power levels of 20%FP(Full Power), 40%FP, 60%FP, 80%FP and 100%FP respectively.

Table 1
The parameters of SPWR at various steady state power levels.

Parameter	100% FP	80% FP	60% FP	40% FP	20% FP
P_{r0}	1.0	0.8	0.6	0.4	0.2
T_{c1}(°C)	302	298.6	295	291.8	288.4
α_f(°C^{-1})	−2.9e-5	−3.2e-5	−3.3e-5	−3.5e-5	−3.8e-5
α_c(°C^{-1})	−6.3e-4	−5.59e-4	−5.56e-4	−5.22e-4	−4.86e-4
μ_f(J/°C)	2.25e7	2.21e7	2.18e7	2.14e7	2.1e7
Ω(W/°C)	3.94e6	4.16e6	4.38e6	4.61e6	4.85e6
μ_c(J/°C)	6.9e7	6.8e7	6.7e7	6.61e7	6.53e7

Then, the state space models are transformed into the core transfer function models. Finally, the transfer function matrix is recorded as follows,

$$\begin{bmatrix} \delta P_r \\ \delta T_{c2} \end{bmatrix} = \begin{bmatrix} G_{r11,i} & G_{r12,i} \\ G_{r21,i} & G_{r22,i} \end{bmatrix} \cdot \begin{bmatrix} \delta\rho \\ \delta T_{lp} \end{bmatrix} i = 1,2,3,4,5$$

where, subscripts 1, 2, 3, 4, and 5 represent transfer functions at the core power levels of 20%FP, 40%FP, 60%FP, 80%FP, and 100%FP, respectively.

2.3. The fuzzy multi-model of reactor core

Considering the characteristics of SPWR, such as multivariable, nonlinear and wide operating range, the model of reactor core under single power level can't accurately describe the dynamic response of SPWR core under the whole operating condition. To solve the problem, the multi-model modeling method that approximates the actual system by weighting the several transfer functions with the fuzzy membership function is adopted. In this paper, to build the fuzzy multi-model of reactor core, the transfer function models at 20%FP, 40%FP, 60%FP, 80%FP and 100%FP power level are selected as the local models, and the triangular membership function is used to weight the local models to establish the fuzzy multi-model of SPWR [1,4–6,9]. The parameters of SPWR at various steady state power levels are shown in Table 1 [3].

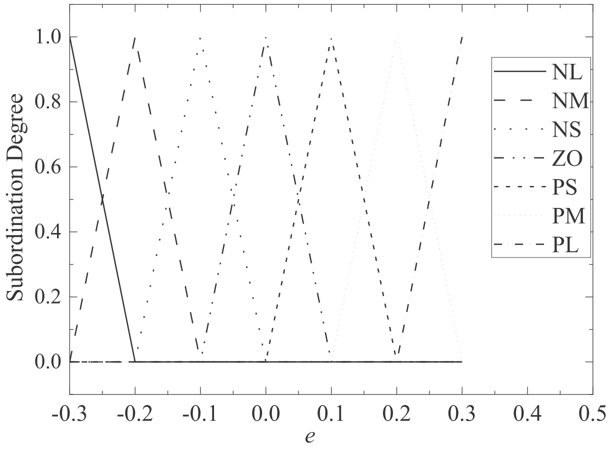
3. Design of the flexible switching control system for SPWR core

The flexible switching control system for SPWR core power is designed with the core control rod speed as the input and the core relative power deviation as the output. The T-S fuzzy rule is used to realize the flexible switch between the fuzzy controller and the LQG/LTR controller.

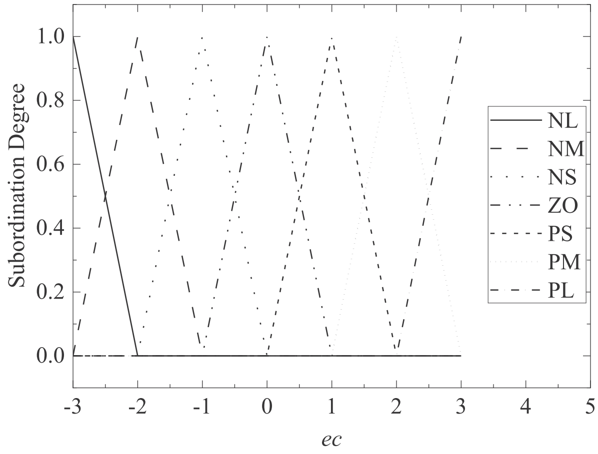
3.1. The fuzzy controller

In this paper, the two-dimensional fuzzy controller [10,11], is used to control the core power. The design of fuzzy controller can be divided into three steps,

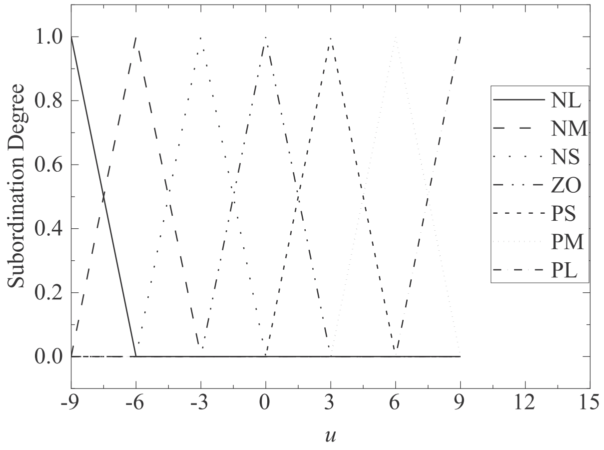
(1) Fuzzification : the controller transforms the accurate input value into the fuzzy input value which can be used in fuzzy logic inference. Set the fuzzy universe of the first input quantity i.e. core relative power error e as [-0.3,0.3], the fuzzy universe of the second input quantity i.e. core relative power error derivative ec as [-3,3], the fuzzy universe of the control output i.e. the control rod speed as [-9,9], select {negative large (NL), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive large (PL)} as the fuzzy set, and obtain the membership function as shown in Fig. 1.



（I）The membership function of relative power error



（II）The membership function of relative power error variation



（III）The membership function of control rod speed output

Fig. 1. The membership function of input and output of fuzzy controller.
Note: e: core relative power error; ec: core relative power error variation.

(2) Fuzzy inference: the core of fuzzy reasoning is fuzzy rules, which are the basis of fuzzy logic inference for fuzzy input of fuzzy controller. According to the fuzzy rules of reference [12], combining the selection of membership function and

Table 2
Fuzzy control rules of U_{fuzzy}.

ec	e						
	NL	NM	NS	ZO	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZO
NM	NL	NL	NM	NM	NS	ZO	PS
NS	NL	NM	NM	NS	ZO	PS	PM
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PM	PM	PL
PM	NS	ZO	PS	PM	PM	PL	PL
PL	ZO	PS	PM	PL	PL	PL	PL

Note: U_{fuzzy} represents the fuzzy output of the fuzzy controller.

the core dynamic characteristics of SPWR, the fuzzy rules as shown in Table 2 are formulated.

(3) Defuzzification: the fuzzy output obtained by fuzzy inference is transformed into accurate output through the maximum membership method and area centroid method or area bisection method [12,13]. For the method of defuzzification, the area centroid method is chosen as the following expression :

$$u=\frac{\int u^{*}\bullet\mu(u^{*})du^{*}}{\int\mu(u^{*})du^{*}}$$

where, u represents the precise output value, u^{*} represents the fuzzy output value, and $\mu(u^{*})$ represents the membership degree of the fuzzy output value.

3.2. The LQG/LTR controller

The LQG/LTR controller is a kind of linear robust optimal control based on state observer. LQG/LTR controller can deal with a series of linear control problems, such as disturbance noise, state variables that can't be measured directly, and reduce the system error as much as possible by using the minimum control energy [3,10,14]. The LQG/LTR controller is divided into the LQG controller and the LTR method. The LQG controller is the optimal control combining LQR controller and Kalman filter [4]. In the LTR method, firstly, the appropriate target loop (LQR controller loop or Kalman filter loop) is designed and selected. And the state feedback gain or filter gain is designed to make the open-loop transfer function of the system approximate to the target loop transfer function. The specific solution method is shown in the references [10,15].

3.3. Design of the flexible switching control system for SPWR core power

The core power flexible switching control system of SPWR is established, as shown in Fig. 2. Considering that the LQG/LTR controller is designed based on the transfer function at a certain power level, to realize the ideal control of core power at the full power range, the membership function which is the same as the local model weighting is used to weight the LQG/LTR controller designed at the power level of 20% FP, 40%FP, 60%FP, 80%FP and 100%FP to form a multi-mode LQG/LTR controller. As the fuzzy controller does not depend on the accurate mathematical model, only a single fuzzy controller is used. The fuzzy controller and the multi-mode LQG/LTR controllers are used to realize the core power control, and the flexible switching controller is used to realize the flexible switching between them.

Based on the T-S fuzzy rule, the flexible switching controller is used to realize the real-time distribution of the weight of the fuzzy controller and the multi-mode LQG/LTR controller according to the relative power error and its change. Therefore, the core of flexible switching controller design lies in the formulation of T-S fuzzy rules. Let the fuzzy subsets of *ec* be {NB, NS, ZR, PS, PB}, and the fuzzy subsets of *e* be {NB, ZR, PB}. Let L and F denote LQG/LTR controller and fuzzy controller respectively. The flexible switching controller switches to fuzzy control to play a leading role in case of large error, and LQG/LTR controller play a small control role. In case

Table 3
The fuzzy rules table.

e	ec				
	NB	NS	ZR	PS	PB
NB	L	L	L	L	F
ZR	L	L	L	F	F
PB	L	F	F	F	F

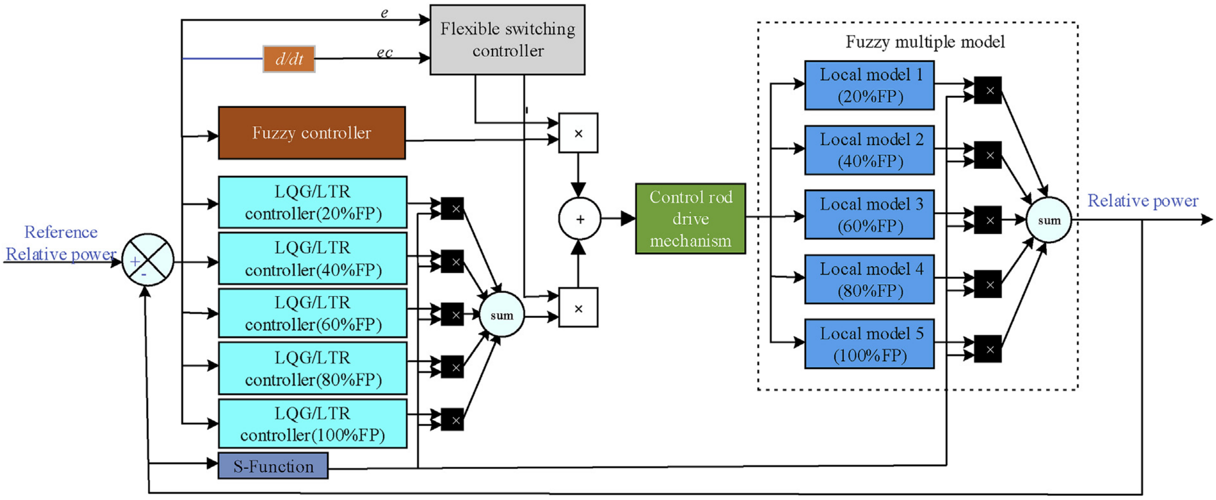


Fig. 2. The core power flexible switching control system of SPWR.

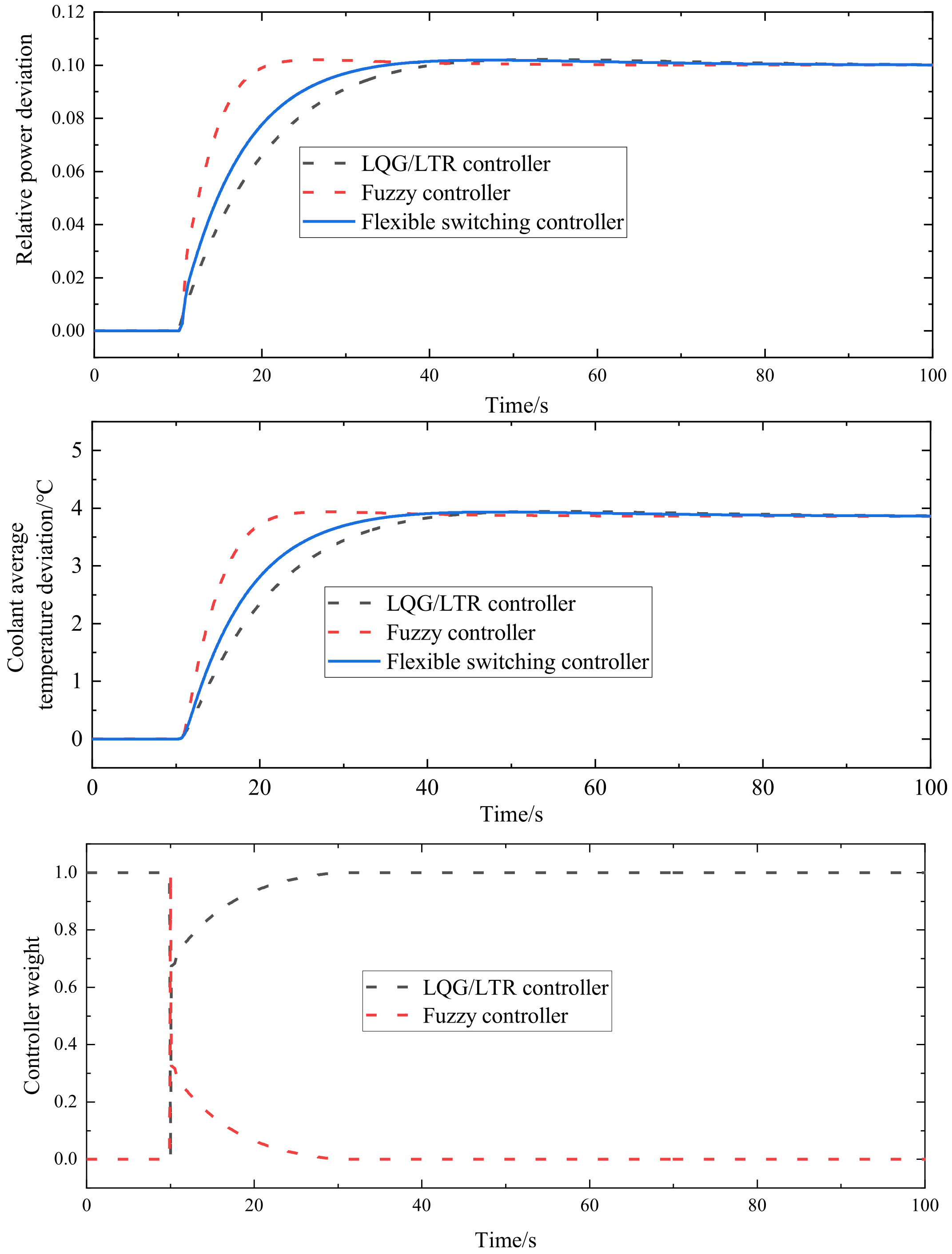


Fig. 3. Core reference relative power step change 10% FP at 60% FP power level.

of small error, the system will soon become stable, and the flexible switching controller switch to LQG/LTR controller to play a leading role, so as to specify the fuzzy rules as shown in Table 3 [16].

4. Simulation analysis

4.1. Core power step response

At the power level of 60% FP and 100% FP respectively, the core relative power step increases by 10% FP, and the simulation diagrams are shown in Figs. 3 and 4. The results show that when the core relative reference power changes, the core relative power error is large, and the fuzzy controller plays a leading role. As the core relative power error decreases, the weight of LQG/LTR controller keeps rising and gradually plays a leading role, and the flexible switching control curve tends to LQG/LTR control curve, reducing the overshoot of the controller as much as possible. At the same time, the core coolant outlet temperature also reaches a new stable level under the control of the controllers. The flexible switching control has both control advantages, which can not only obtain a shorter adjustment time, but also reduce the overshoot as much as possible, and optimize the control of core power.

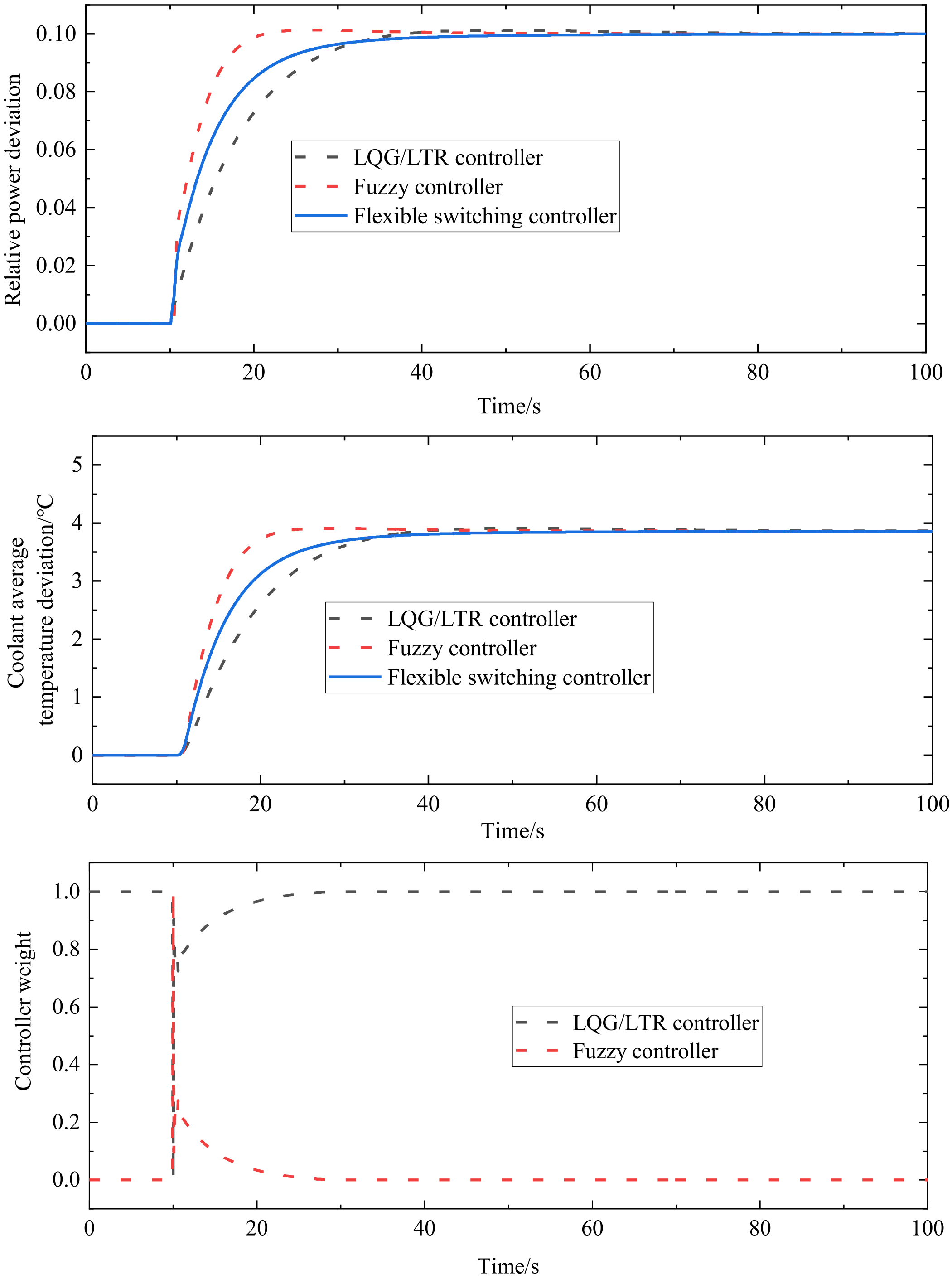


Fig. 4. Core reference relative power step change 10% FP at 100% FP power level.

4.2. Core coolant inlet temperature disturbance

At the power levels of 60% FP and 100%FP respectively, introducing the core coolant inlet temperature step change of 5 °C, the simulation diagrams are shown in Figs. 5 and 6. The results show that when the step core coolant inlet temperature is introduced, the core power and core outlet temperature can reach the new steady-state value quickly. From the figures, the results prove that the flexible switching control can combine the advantages of the two controllers to get better control effect.

4.3. Global range load following

Fig. 7 is the global range load following response of core relative power at a linear rate of 5%FP/min between the power levels of 30%FP-100%FP-30%FP with the flexible switching controller. As shown in Fig. 7, when the core power changes greatly, the designed flexible switching control system can also achieve ideal control effect, and achieve good following of the reference relative power change.

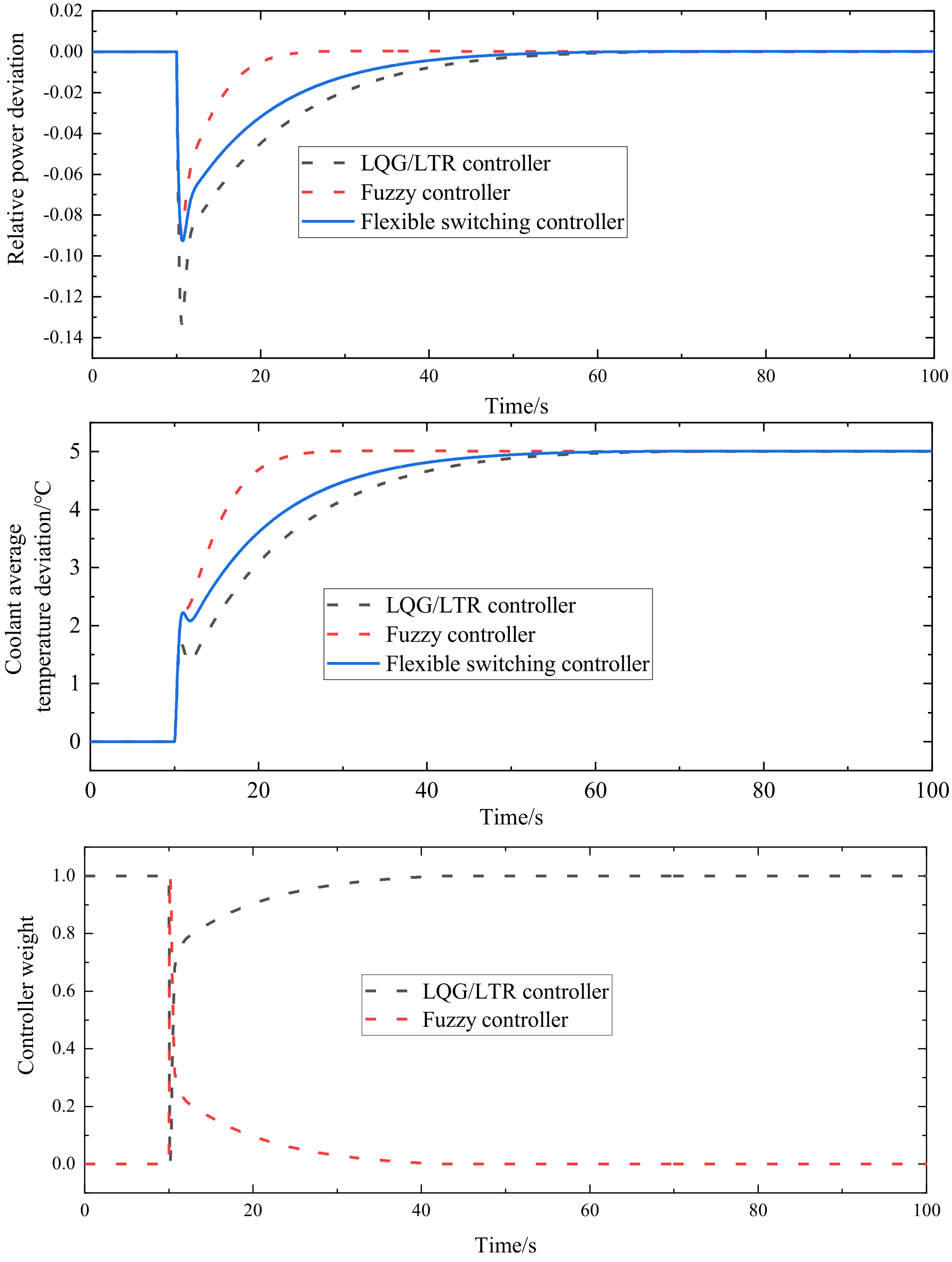


Fig. 5. The core coolant inlet temperature step change of 5 °C at 60%FP power level.

5. Conclusion

It is very important to design a reasonable core power control system for a small PWR because of its complex operating conditions and high load tracking capability. In this paper, aiming at the problem that it is difficult to control the power of SPWR core well when it changes in a large range or the transient load changes under any working condition, several local linearization models are selected to establish the core fuzzy multi model. In order to design the core power control system of SPWR, a flexible switching controller based on LQG/LTR controller and fuzzy controller is designed. By comparing with LQG/LTR controller and fuzzy controller, the control performance of core power flexible switching control system is tested. The simulation results show that the fuzzy switching controller based on LQG/LTR controller and fuzzy controller can make the core power and core outlet temperature have smaller overshoot and shorter response time, and can achieve better core power control.

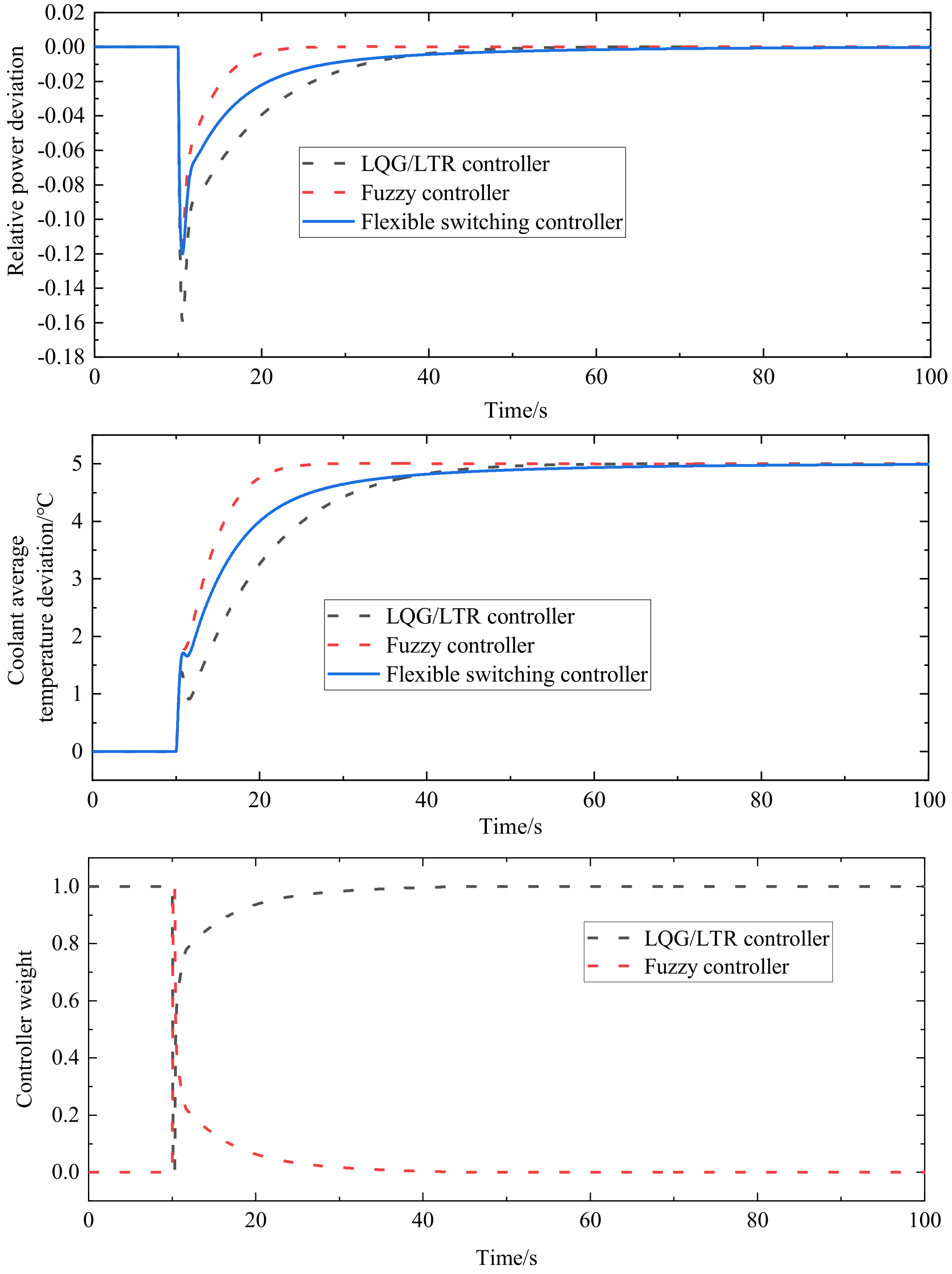


Fig. 6. The core coolant inlet temperature step change of 5 °C at 100%FP power level.

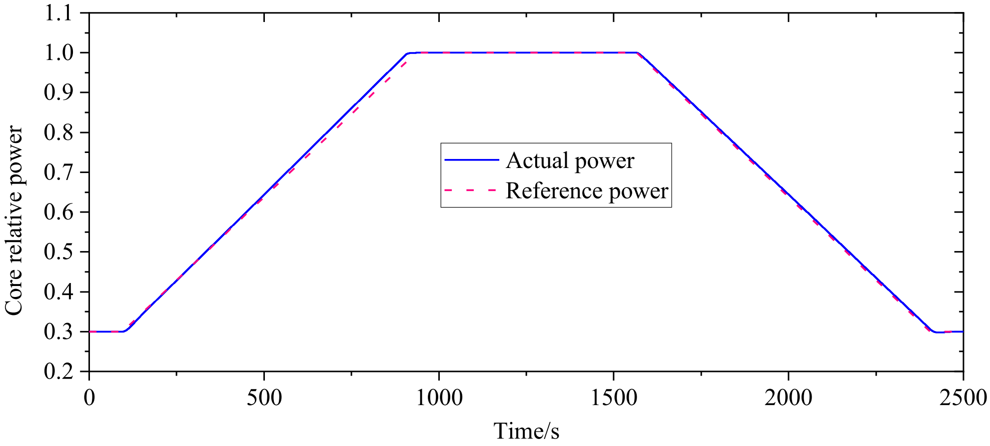


Fig. 7. The power levels of 30%FP-100%FP-30%FP with the linear rate of 5%FP/min.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2020.07.037.

References

[1] Liao Long-tao, Peng-Fei Wang, Study of multi-model internal model robust control for a small pressurized water reactor core, Autom. Instrum. 33 (2018) 76–79. + 94.

[2] Ping Hu, Fu-Yu Zhao, Tai Yun, Coordination control and simulation for small nuclear power plant, Prog. Nucl. Energy 58 (2012) 21–26, https://doi.org/10.1016/j.pnucene.2012.02.001.

[3] Tai Yun, Hou Su-xia, Li Chong, Fu-Yu Zhao, An improved implicit multiple model predictive control used for movable nuclear power plant, Nucl. Eng. Des. 240 (2010) 3582–3585, https://doi.org/10.1016/j.nucengdes.2010.05.003.

[4] Gang Li, Fu-Yu Zhao, Flexibility control and simulation with multi-model and LQG/LTR design for PWR core load following operation, Ann. Nucl. Energy 68 (2013) 193–203, https://doi.org/10.1016/j.anucene.2013.01.035.

[5] Wenjie Zeng, Qingfeng Jiang, Jinsen Xie, Yu Tao, A functional variable universe fuzzy PID controller for load following operation of PWR with the multiple model, Ann. Nucl. Energy 140 (2020), https://doi.org/10.1016/j.anucene.2019.107174.

[6] Lezhi Chen, Wenjie Zeng, Tao Yu, Jinsen Xie, Shangmian Du, Run Luo, Development and application of fuzzy multiple model simulation system for nuclear reactor core, Nucl. Power Eng. 40 (2019) 146–149.

[7] F. Dumortier, A. Van Cauwenberghe, L. Boullart, Computer Aided Design of Advanced Control Algorithms for Nuclear Reactor Control, 1994, https://doi.org/10.1109/CACSD, 04/1994.

[8] Andres Etcheparebordа, Jose Lolich, Research reactor power control design using an output feedback nonlinear design, Nucl. Eng. Des. 277 (2007) 268–276, https://doi.org/10.1016/j.nucengdes.2006.04.002.

[9] L. Wang, X. Wei, F. Zhao, X. Fu, Modification and analysis of load follow control without boron adjustment for CPR1000, Ann. Nucl. Energy 70 (2014) (2014) 317–328, https://doi.org/10.1016/j.anucene.2013.12.001.

[10] G. Li, X. Wang, B. Liang, X. Li, B. Zhang, Y. Zou, Modeling and control of nuclear reactor cores for electricity generation: a review of advanced technologies, Renew. Sustain. Energy Rev. 60 (2016) 116–128, https://doi.org/10.1016/j.rser.2016.01.116.

[11] Wenjie Zeng, Qingfeng Jiang, Jinsen Xie, Yu Tao, A fuzzy-PID composite controller for core power control of liquid molten salt reactor[J], Ann. Nucl. Energy 139 (2020), https://doi.org/10.1016/j.anucene.2019.107234.

[12] Yan-cheng Zhang, Research on Fuzzy Control and Simulation of Vehicle Active Suspension Based on Matlab/Simulink, Liaoning University of Technology, Liaoning, 2014.

[13] Chao-Jie Xie, Study of Membership Function Self-Adjusting Fuzzy Controller, Xi'an University of Electronic Science and Technology of China, Xi'an, 2014.

[14] Yu Hai-liang, The Application of LQG/LTR Method in Turntable System, Harbin Institute of Technology, Harbin, 2013.

[15] Wen-Jie Zeng, et al., LQG/LTR controller with simulated annealing algorithm for CIADS core power control, Ann. Nucl. Energy 142 (2020), https://doi.org/10.1016/j.anucene.2020.107422, 2020.

[16] Qiang Zhang, Multi-mode Soft Switching Variable Pitch Control of Wind Turbines Based on T-S Fuzzy Weighted, Lanzhou Jiaotong University, Lanzhou, 2019.