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Power and Temperature Control of Nuclear Power Plant Based on Transfer Function Matrix Method

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ABSTRACT The paper presents the simple and efficient analysis method of frequency-domain to control the core power and coolant temperature of Nuclear Power Plants (NPPs). In order to properly describe the neutron kinetic and thermal transmission of NPPs, a one-dimensional dynamic model has been accomplished by using the linearizing in time domain and discretizing in spatial domain, and then the transfer function matrix can be obtained through Laplace transform. Based on the transfer function matrix of NPPs, the effective of different system inputs: reactivity and feed water mass flow, can be analyzed by Nyquist method. On this basis, the power and temperature control system are presented, and the stability is proved in frequency domain. The proposed method is verified by RELAP5 that confirm its performance.

INDEX TERMS Nuclear power plant, power and temperature control system, control strategy, RELAP5.

I. INTRODUCTION

Generally, nuclear power plants (NPPs) operate as the primary base energy source in electricity grids, which means in most cases, the core power or electrical power of NPPs need to keep constant [1]. In this case, the control system is designed for resisting the perturbation of power and coolant temperature. However, with the development of nuclear technology, the share of nuclear energy source in the energy balance of the electricity grid has a significant increase [2]. Therefore, there is a tendency for NPPs to adjust the core power and coolant temperature flexibly. High control performance can be achieved by improving the existing control algorithms via applying advanced and most modern control technologies.

Considering the complexity of the NPP model, the high performance power and temperature control system based on advanced control technologies will face many difficulties [3]–[4]. Therefore, a simple and efficient approach for power and temperature control system design need to be developed. For this purpose, a control oriented model of NPPs is needed. The most dynamic simulation codes cannot be satisfied with this demand, because the dynamic model build by these codes cannot be analysis by control theory. Although large scale three-dimensional dynamic model is sufficiently accurate, it is too complex to be linearized through small perturbation method. Thus one-dimensional distributed parameter thermal model is employed to be linearized in time domain, discretized in Spatial Domain for transfer function modeling [5]. Based on this dynamic model, the transfer function model was developed by the Laplace Transformation. Through the transfer function model, frequency domain analysis method is used to analyze the stability and design the temperature control strategies. The simulation with RELAP5 verifies the performance of the power and temperature control system based on the frequency domain method.

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II. MATHEMATICAL MODEL

In this section, the discussion is only aimed at the transfer function modeling of the neutron kinetic and coolant behavior in NPPs. For the sake of simplicity, a single phase heat exchange tube model is referenced. The other models, such as core, primary and secondary Steam Generator, are formally equivalent.

A. NEUTRON KINETICS MODEL

The mathematical model has a single computational node of neutron kinetics. The purpose of this node is to calculate the average neutron density or power. The node is defined by the following differential equations:

$$\frac{dn(t)}{dt} = \frac{\delta(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i C_i(t) \tag{1}$$

$$\frac{dc_i(t)}{dt} = \frac{\beta}{\Lambda} n(t) - \lambda_i C_i(t) \tag{2}$$

where, n means the averaged neutron density, δ means the reactivity, $\beta = \sum_{i=1}^{6} \beta_i$ means the total yield of the delayed neutron precursors, β_i are the delayed neutron fraction, l is the averaged neutron generation time, λ_i means the delayed neutron precursors decay constant, C_i are the ith group of the delayed neutron precursors concentrations, t means time. With the linear method based on Taylor expansion, and Laplace transform, the transfer function of neutron kinetics can be shown as equation 3:

$$\frac{\Delta n(s)}{\Delta \delta(s)} = \frac{n_0}{\left[\Lambda s + \beta - \sum_{i=1}^{6} \frac{\lambda_i \beta_i}{(s+\lambda_i)}\right]} \tag{3}$$

where, Δ means the increment, n_0 means the initial averaged neutron density. The average thermal power generated in the nuclear reactor P is directly proportional to the average neutron density $\Delta P = \xi \Delta n$, where ξ is the constant coefficient.

Considering the reactivity feedback from coolant and fuel temperature increment, the reactivity increment can be described as follows:

$$\Delta\delta = \Delta\delta_{input} + \Delta\delta_{temp} \tag{4}$$

where, $\Delta\delta_{input}$ means the reactivity introduced by control rod, which can be regarded as the input of the power control system; $\Delta\delta_{temp}$ means the reactivity feedback from coolant and fuel temperature.

B. THERMAL-HYDRAULIC MODEL

1) HEAT CONDUCTION IN REACTOR CORE

A one-dimensional single channel core thermal model is built in figure 1. A n nodes heat transfer model with some simplifying hypotheses, include single fuel, gap, clad, coolant, has been implemented with neglect of axial heat conduction. In this model, the coordinate of fuel rods central axis is zero.

According to the Heat Diffusion Equation, the transfer functions of heat transfer process from fuel to clad described by incremental form can be represented as follows:

where, α means coefficient of heat transfer; l means the length of coolant nodes; D means the diameter; ΔT means the temperature increment; Δq means the power density increment; m means the mass per unit length; c means the thermal capacity. The subscripts $fuel$, $clad$, gap mean the fuel pellet, clad surrounding the fuel pellet, and gap between fuel pellet and clad respectively.

According to the Boussinesq Approximation, the temperature depending on density can be accounted in natural circulation [6]:

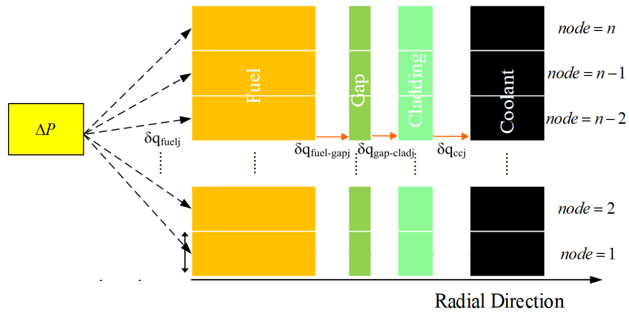


FIGURE 1. The one-dimension heat transfer model of reactor core. Heat transfer process in radial direction is neglected. In axial direction, fuel, gap, clad and coolant are divided into *n* nodes with length *l*.

$$\Delta T = \gamma \Delta\rho \tag{9}$$

$$\Delta T = \gamma \Delta\rho \tag{10}$$

where, γ is constant coefficient. Considering the (9) and (19) (dependence of fluid density on enthalpy), has:

$$\Delta T = \eta \Delta h \tag{11}$$

where, (5)–(8), as shown at the bottom of the next page.

The thermal power density q_{fuelj}, which is calculated by neutron kinetics equation, can be regarded as input of core heat transfer system. For another, temperature increments $\Delta T_{fuelj} \Delta T_{gapj} \Delta T_{cladj}$ which are calculated by heat transfer model (equation (5)-(8)), can be provided as feedback to neutron kinetics equation. Equation (4)-(11) constitutes the transfer function model of heat transfer process in reactor core (figure 1). Figure 2 shows the dynamic model of temperature in reactor core, including the fuel, gap, cladding and coolant.

2) THERMAL-HYDRAULIC DYNAMIC BEHAVIOR OF THE COOLANT

The next computational nodes are related to the determination of coolant temperatures in reactors. The first principle method of thermal-hydraulic has been considered to describe the thermal-hydraulic dynamic behavior of the coolant:

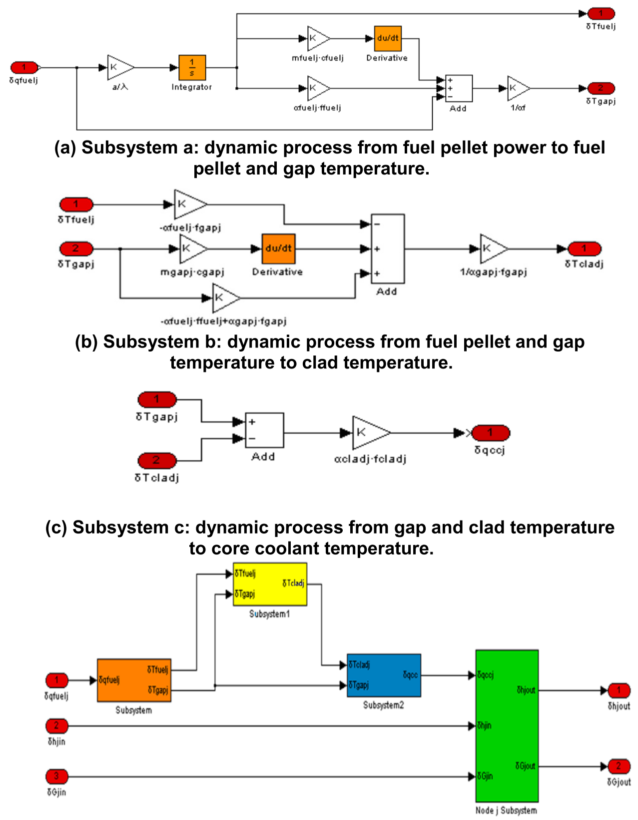
$$\frac{\partial\rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \tag{12}$$

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(Gh)}{\partial z} - q_l = 0 \tag{13}$$

where, ρ means coolant density, G means coolant mass flow rate; h means the coolant enthalpy; q_l means the power density. According to the method of Colombo in 2010 [7], equation (12) and (13) can be discretizated using a backward finite difference scheme in axial and time linearized as follows:

$$\frac{\partial\Delta\rho_{out}}{\partial t} + \frac{\Delta G_{out} - \Delta G_{in}}{l} = 0 \tag{14}$$

$$\frac{\partial(h_{out0}\Delta\rho_{out} + \rho_{out0}\Delta h_{out})}{\partial t}$$



(a) Subsystem a: dynamic process from fuel pellet power to fuel pellet and gap temperature.

(b) Subsystem b: dynamic process from fuel pellet and gap temperature to clad temperature.

(c) Subsystem c: dynamic process from gap and clad temperature to core coolant temperature.

(d) Coupling system of heat transfer in reactor core.

FIGURE 2. Dynamic model of thermal and temperature in reactor core.

$$+\frac{(h_{out0}\Delta G_{out}+G_{out0}\Delta h_{out})-(h_{in0}\Delta G_{in}+G_{in0}\Delta h_{in})}{l}$$
$$-\Delta q_l = 0 \tag{15}$$

where, the subscripts *out* and *in* mean the outlet and inlet of coolant nodes respectively. The higher order terms are neglected. This linear time-invariant thermal hydraulic dynamic model can be passed from time domain to frequency domain by Laplace transform method (considered the initial condition is zero):

$$A\begin{pmatrix}\Delta\rho_{out}(s)\\ \Delta h_{out}(s)\\ \Delta G_{out}(s)\end{pmatrix} = B\begin{pmatrix}\Delta q_l(s)\\ \Delta h_{in}(s)\\ \Delta G_{in}(s)\end{pmatrix} \tag{16}$$

where,

$$A = \begin{pmatrix} sl & 0 & 1\\ slh_{out0} & sl\rho_{out0}+G_{out0} & h_{out0}\end{pmatrix} \tag{17}$$
$$B = \begin{pmatrix} 0 & 0 & 1\\ l & G_{in0} & h_{in0}\end{pmatrix} \tag{18}$$

Δq_l, Δh_{in} and ΔG_{in} are regarded as the system inputs, $\Delta\rho_{out}$, Δh_{out} and ΔG_{out} are regarded as system outputs. According to the linear system theory, as the result of matrix A and B are 2 × 3 matrixes, the output vector has no unique solution. Therefore, the fluid density depending on enthalpy can be accounted [8]:

$$\Delta\rho = \beta\Delta h \tag{19}$$

where, β means the constant coefficient between $\Delta\rho$ and Δh. One has:

$$\begin{pmatrix}\Delta h_{out}(s)\\ \Delta G_{out}(s)\end{pmatrix} = Tf\begin{pmatrix}\Delta h_{in}(s)\\ \Delta G_{in}(s)\\ \Delta q_l(s)\end{pmatrix} \tag{20}$$

where,

$$Tf = \begin{pmatrix} \frac{G_{out0}}{l\rho_{out0}s+G_{out0}} & \frac{h_{in0}-h_{out0}}{l\rho_{out0}s+G_{out0}} & \frac{1}{l\rho_{out0}s+G_{out0}}\\ \frac{-\beta lG_{out0}s}{l\rho_{out0}s+G_{out0}} & \frac{[\rho_{out0}-\beta(h_{in0}-h_{out0})]ls+G_{out0}}{l\rho_{out0}s+G_{out0}} & \frac{-\beta ls}{l\rho_{out0}s+G_{out0}}\end{pmatrix} \tag{21}$$

Equation (20) and (21) are the linear time-invariant thermal hydraulic transfer function model which links the three system inputs to the two system outputs. Single phase tube has *n* nodes can be described as follow equations:

$$Th_{jout} = Tf_j \times Th_{jin} \tag{22}$$
$$Th_{(j+1)in} = \begin{pmatrix} Th_{jout}\\ \Delta q_{(j+1)l}(s)\end{pmatrix} \tag{23}$$

where, Tf_j means the transfer function matrix of *j*th node in the tube, $1 \le j \le n$. The transfer process can be shown as figure 3:

Some defects of the transfer function model based on time domain and spatial domain, such as non-conservation of energy, non-minimum phase behavior, have been discussed by Colombo *et al.* [7]. In this section, the non-causal behavior [6] brought by momentum balance equation will be discussed.

$$\Delta q_{lj}(s) = \frac{\alpha_{clad}f_{clad}(\Delta T_{cladj}(s)-\Delta T_{jin}(s))}{4l/D} \tag{5}$$
$$\Delta T_{cladj}(s) = \frac{\alpha_{gap}f_{gap}\Delta T_{gapj}(s)-(4l/D)\Delta q_{lj}(s)}{m_{cladj}c_{cladj}s+\alpha_{gap}f_{gap}} \tag{6}$$
$$\Delta T_{gapj}(s) = \frac{\alpha_{fuel}f_{fuel}\Delta T_{fuelj}(s)-(\alpha_{fuel}f_{fuel}+\alpha_{gap}f_{gap})\Delta T_{gapj}(s)+\alpha_{gap}f_{gap}\Delta T_{cladj}(s)}{m_{gapj}c_{gapj}s} \tag{7}$$
$$\Delta T_{fuelj}(s) = \frac{\Delta q_{fuelj}-\alpha_{fuel}f_{fuel}\Delta T_{fuelj}(s)+\alpha_{fuel}f_{fuel}\Delta T_{gapj}(s))}{m_{fuelj}c_{fuelj}s} \tag{8}$$

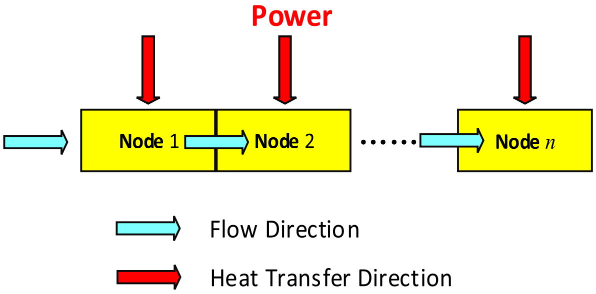


FIGURE 3. The structure of the single phase tube model. The length of each node is *l*, and the number of the nodes is *n*.

To the frictionless flow, the one-dimensional momentum balance equation can be shown as:

$$l\frac{\partial \Delta G_{out}}{\partial t} + 2v_{out}\Delta G_{out} - v_{out}^2 \Delta\rho_{out} - 2v_{in}\Delta G_{out} + v_{in}^2\Delta\rho_{in} = \Delta p_{in} - \Delta p_{out} + \Delta\rho_{out} lF \quad (24)$$

Using Laplace transform, the transfer function from $\Delta G_{in}(s)$ to $\Delta p_{out}(s)$ can be shown as:

$$Tf_{Gp} = (lf + v_{out}^2)\beta\frac{h_{in0} - h_{out0}}{l\rho_{out0}s + G_{out0}} - (ls + 2v_{out}) \times \frac{[\rho_{out0} - \beta(h_{in0} - h_{out0})]ls + G_{out0}}{l\rho_{out0}s + G_{out0}} \quad (25)$$

It can be noted that the system is non-casual because the extra zero brought by differential of mass flow. As the effect of mass flow differential cannot be neglected in momentum balance equation, the problem about non-casual system is inevitable once considering the pressure [8]. It can be concluded that the control-oriented model based on linearization in time domain and discretization in spatial domain can be used to analyze the variation of temperature and transfer process of energy, but it is impossible to analyze the variation of pressure.

3) HEAT EXCHANGER MODEL

The heat exchanger is simplified to straight tubes, single pass model (figure 4) where single phase water flow down on the primary side and two-phase water flow up on the secondary side. Therefore, the transfer functions of Steam Generator can be shown as:

$$\Delta T_{wj}(s) = \frac{\alpha_{ws}f_{ws}\Delta T_{sjin}(s) + \alpha_{wp}f_{wp}\Delta T_{pjin}(s)}{m_{wj}c_{wj}s - \alpha_{wp}f_{wp} + \alpha_{ws}f_{ws}} \quad (26)$$

$$\Delta q_{plj}(s) = \frac{\alpha_{wp}f_{wp}(\Delta T_{wj}(s) - \Delta T_{pjin}(s))}{4l_p/D_p} \quad (27)$$

$$\Delta q_{slj}(s) = \frac{\alpha_{ws}f_{ws}(\Delta T_{wj}(s) - \Delta T_{sjin}(s))}{4l_s/D_s} \quad (28)$$

where, the subscript p, w, and s mean the primary side, wall and secondary side. Equations (26)-(28) constitute the transfer function model of heat transfer process in heat exchanger. Figure 5 shows the dynamic model structure of the heat transfer process in steam generators, including primary and secondary sides.

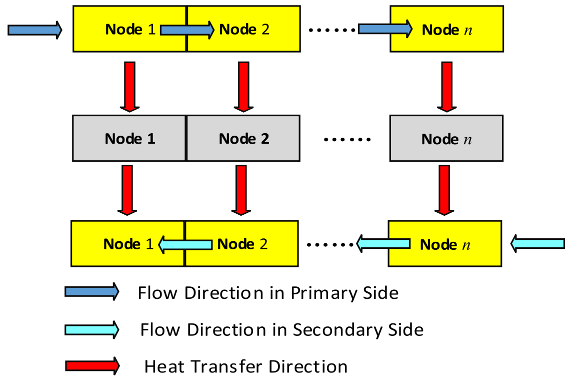


FIGURE 4. Structure of the heat exchanger model has *n* nodes, include primary side, secondary side and tube wall. In this model, heat transfer between adjacent nodes of tube wall is neglected.

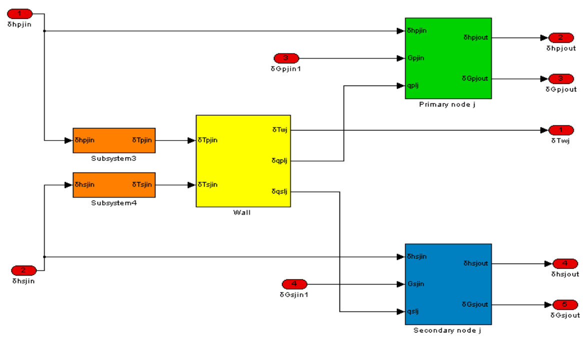


FIGURE 5. The *j*th node heat exchanger subsystem based on SIMULINK [9].

4) THE COOLANT CHANNEL MODELING

It is assumed that the coolant channel, include upper channel, upper plenum, down comer and down plenum, is thermal isolation, and heat transfer between adjacent tube wall nodes is neglected. According to the method in section 3.1(2), the jth coolant channel node transfer function modeling can be given with inserting $\Delta q_l = 0$:

$$\begin{pmatrix}\Delta h_{jout}(s)\\ \Delta G_{jout}(s)\end{pmatrix} = \begin{pmatrix}Tf_{hh} & Tf_{Gh}\\ Tf_{hG} & Tf_{GG}\end{pmatrix}\begin{pmatrix}\Delta h_{jin}(s)\\ \Delta G_{jin}(s)\end{pmatrix} \quad (29)$$

where,

$$Tf_{hh} = \frac{G_{jout0}}{l\rho_{jout0}s + G_{jout0}} \quad (30)$$

$$Tf_{Gh} = \frac{h_{jin0} - h_{jout0}}{l\rho_{jout0}s + G_{jout0}} \quad (31)$$

$$Tf_{hG} = \frac{-\beta lG_{out0}s}{l\rho_{jout0}s + G_{jout0}} \quad (32)$$

$$Tf_{GG} = \frac{[\rho_{out0} - \beta(h_{in0} - h_{out0})]ls + G_{out0}}{l\rho_{jout0}s + G_{jout0}} \quad (33)$$

The model build by SIMULINK is shown as figure 6.

5) COMPLETE COUPLED MODEL

The complete coupled model provides as input variables the reactivity and mass flow rate of the heat exchanger, which can be shown as figure 7.

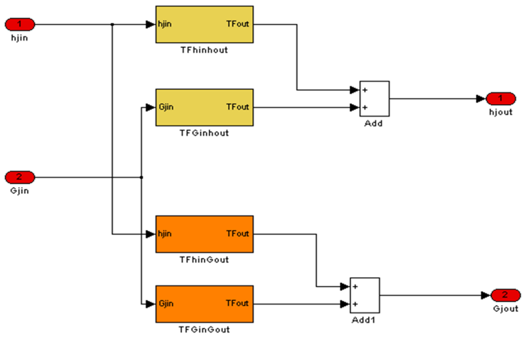


FIGURE 6. The jth node coolant channel subsystem based on SIMULINK.

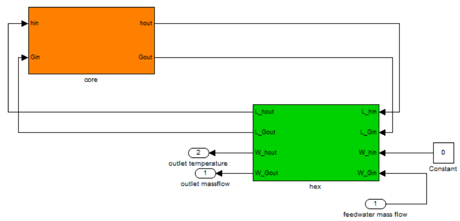


FIGURE 7. Complete coupled model based on SIMULINK.

III. TEMPERATURE AND POWER CONTROL STRATEGY DESIGN AND ANALYSIS

A. TEMPERATURE AND POWER CONTROL STRATEGY

In this work, the NPP design presented by Chen *et al.* [10] is regarded as the reference design. For simplifying the control-oriented model, the secondary side with single phase pressure water is introduced. The control strategy including power and coolant temperature control can be shown as figure 8. Where, the power control system can adjust the core power for load follow. However, because of the coupling effect, the coolant temperature will be changed with the power. In NPPs, the important controlled variable is the coolant temperature in reactor core, which can reflect the reactor safety and operation state to a large degree [11]. The main advantage of constant coolant temperature in core is to avoid the core meltdown or other accident in primary loop.

B. FREQUENCY ANALYSIS

An appropriate analysis tool should be discussed firstly. Root locus is a classical analysis tools in the S-domain, while, there is a large number of zeros and poles in the transfer functions of figure 9, so that the root locus will become complicated. The amplitude-frequency curve (Nyquist, or Bode curves) is more suitable to the analysis for complex systems. However, because the system in figure 7 is the non-minimum phase system, the bode curve cannot reflect the stability accurately. Therefore, in this work we choice the Nyquist curve as the analysis tool. The linear analysis tool in Simulink is used for plotting Nyquist curves. From the Nyquist curves of $W_{reac-hextout}$ and $W_{feedwater-hextout}$ (figure 9(a)), the steady state gains of these two transfer functions is large enough, but the close loop transfer function $M_{reac-hextout}$ and $M_{feedwater-hextout}$ without any compensation are instability

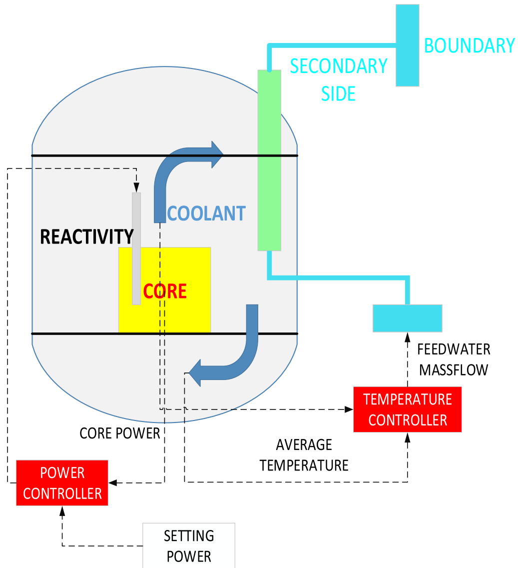


FIGURE 8. The overview of the power and temperature control system.

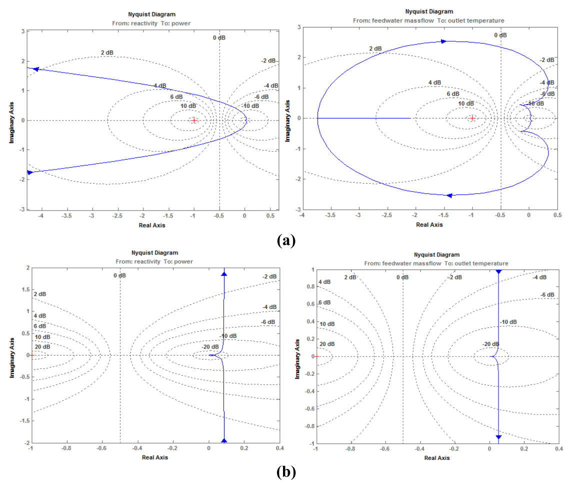


FIGURE 9. Nyquist curves of the open loop system, (a) original system; (b) power and temperature control system with $D_{reac-power}$ and $D_{feedwater-coretemp}$.

because $N^+ + Pol \neq 0$, where, N^+ is the number of clockwise encirclements of point (− 1, j0) by Nyquist curves of $W_{reac-power}$ and $W_{feedwater-coretemp}$, where, $W_{reac-power}$ and $W_{feedwater-coretemp}$ mean open loop transfer functions from the reactivity to the core power and the feed water mass flow rate to the average temperature in the reactor core. Pol is the number of poles of $W_{reac-power}$ and $W_{feedwater-coretemp}$ in the R.H.C.P.

To eliminate the steady state error caused by proportionality coefficient less than 1, Integral elements are introduced [12]–[13]. So, the controller can be given as:

$$Con_{reac-power} = Kp_{reac-power} + \frac{Ki_{reac-power}}{s} \tag{34}$$

$$Con_{feedwater-coretemp} = Kp_{feedwater-coretemp} + \frac{Ki_{feedwater-coretemp}}{s} \tag{35}$$

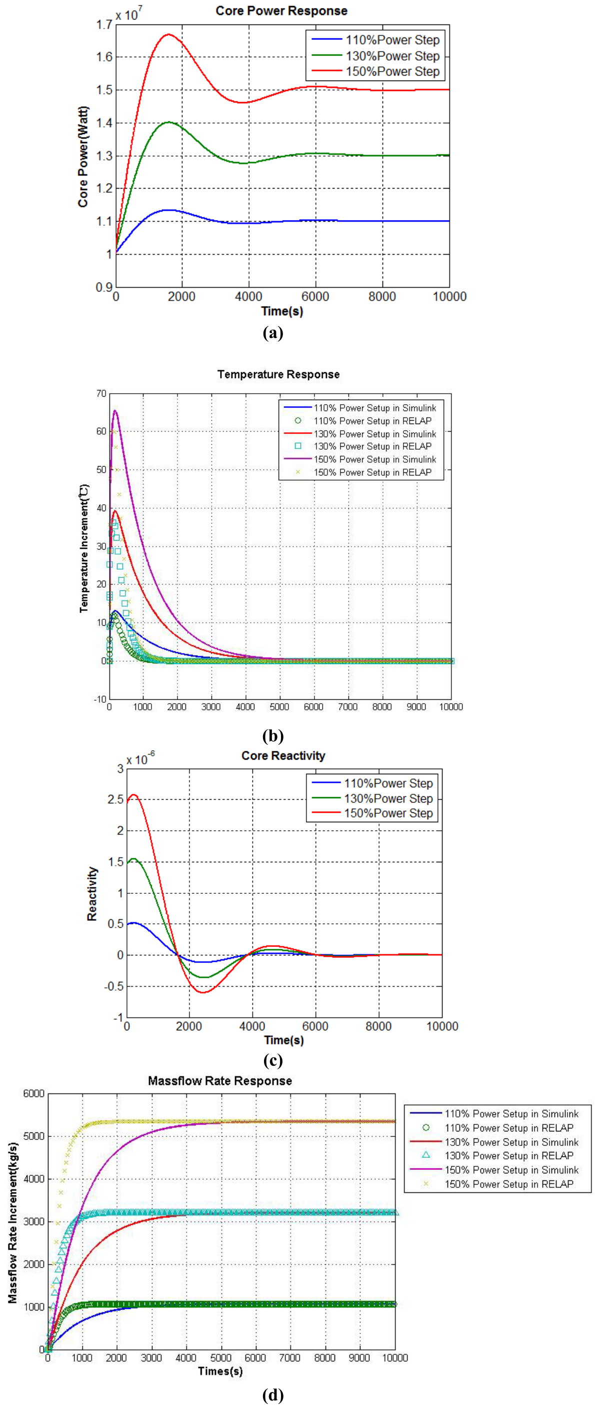


FIGURE 10. The response with the strategy of keeping average core temperature constant under 110%, 130% and 150% setting power step: (a) core power response; (b): average core temperature increment response;(c) core reactivity response under the controller $D_{reac-power}$; (d) mass flow rate response under the controller $D_{feedwater-coretemp}$.

where Con means controllers. $Kp_{reac-power}$, $Ki_{reac-power}$, $Kp_{feedwater-coretemp}$ and $Ki_{feedwater-coretemp}$ can bring great stability margin which can make system steady running when parameters drift in system devices. Actually, only the proportional term $Kp_{reac-power}$ and $Kp_{feedwater-coretemp}$ can keep the power and coolant temperature control system stability. However, the reactivity feedback from fuel and coolant temperature increment can decrease the steady-state accuracy. On the other hand, the introducing of integral elements improves the steady state characteristic, although $Ki_{reac-power}$ and $Ki_{feedwater-coretemp}$ may decrease the system stability. The Nyquist curves of open loop transfer functions $Con_{reac-power}W_{reac-power}$ and $Con_{feedwater-coretemp}W_{feedwater-coretemp}$ are shown as figure 9(b). It can be found that the power control system and core temperature control system are stability because of $N^{+} = 0, Pol = 0$.

IV. VERIFICATION AND DISCUSSION

To verify the efficiency of the control strategy and the capabilities of the designed controllers, the step change of setting power is simulated. The plant initially operates at 100%RFP and then the power steps to 110%, 130% and 150% RFP at 1st second. The system response can be shown as figure 10 based on Relap5-HD [14]. It can be found that under the power controller $D_{reac-power}$, the core power can track the setting power accurately; accordingly, under the temperature controller $D_{feedwater-coretemp}$, the average core temperature keeps constant with the action of $D_{feedwater-coretemp}$ (temperature changes are less than 3°C, 7°C and 12°C respectively), which means in the primary loop, the coolant is safety and has large margin although the core power changes significantly.

V. CONCLUSION

A transfer function model, describing the main components of the nuclear reactor, has been analyzed in frequency domain based on the one-dimensional thermal-hydraulic equations. Based on the frequency analysis, a suitable control strategy has been also identified and validated by the Relap5HD code. The main requirement of this strategy is to maintain the fluid temperature in reactor core constant. The simulation shows the core power controller is valid when the setting power step. however, the coolant temperature will change greatly under the setting power step. To ensure the safety of reactor core, a average reactor core temperature controller is designed to keep the temperature constant. The results shown that the frequency analysis method is effective for nuclear reactor control system design.

In the future work, some research will be carried out:

(1) the transfer function model of nuclear reactor will be improved to include the momentum conservation equation;

(2) the accuracy of the transfer function model based on the first principal method will be verified through the thermal-hydraulic experimental loop.

APPENDIX: NOMENCLATURE

D	Diameter
C	Delay neutron precursor density
c	Thermal capacity
F	Mass force
G	Coolant mass flow rate
h	Coolant enthalpy

Ki	Integral coefficient
Kp	Proportionality coefficient
m	Mass per unit length
N^{+}	Number of clockwise encirclements of point (− 1, j0) by Nyquist curves
n	Averaged neutron density
n_0	Initial averaged neutron density
P	Thermal power
Pol	Number of poles
q	Power density
T	Temperature
Tf	Transfer function
l	Length of coolant nodes
v	Velocity of coolant
δ	Reactivity
α	coefficient of heat transfer
β	Delayed neutron fraction
ρ	Coolant density
Λ	Averaged neutron generation time
λ	Decay constant
Δ	Increment
ξ	Coefficient between ΔP and Δn
γ	Coefficient between ΔT and $\Delta\rho$

REFERENCES

[1] R. Ponciroli, A. Cammi, S. Lorenzi, and L. Luzzi, "A preliminary approach to the ALFRED reactor control strategy," *Prog. Nucl. Energy*, vol. 73, pp. 113–128, May 2014.
[2] Z. Dong, M. Liu, Z. Zhang, Y. Dong, and X. Huang, "Automatic generation control for the flexible operation of multimodular high temperature gas-cooled reactor plants," *Renew. Sustain. Energy Rev.*, vol. 108, pp. 11–31, Jul. 2019.
[3] G. Li, X. Wang, B. Liang, X. Li, B. Zhang, and Y. Zou, "Modeling and control of nuclear reactor cores for electricity generation: A review of advanced technologies," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 116–128, Jul. 2016.
[4] S. Yan, P. Wang, J. Wan, H. Fang, R. Luo, and F. Zhao, "Control strategy research and controllers design of the China lead alloy cooled reactor," *Prog. Nucl. Energy*, vol. 71, pp. 258–268, Mar. 2014.
[5] A. Cammi, L. Luzzi, A. A. Porta, and M. E. Ricotti, "Modelling and control strategy of the Italian LBE-XADS," *Prog. Nucl. Energy*, vol. 48, no. 6, pp. 578–589, Aug. 2006.
[6] P. Sabharwall, Y. J. Yoo, Q. Wu, and J. J. Sienicki, "Natural circulation and linear stability analysis for liquid-metal reactors with the effect of fluid axial conduction," *Nucl. Technol.*, vol. 178, no. 3, pp. 301–302, Jun. 2012.
[7] M. Colombo, A. Cammi, V. Memoli, D. Papini, and M. E. Ricotti, "Transfer function modelling of the lead-cooled fast reactor (LFR) dynamics," *Prog. Nucl. Energy*, vol. 52, no. 8, pp. 715–729, Nov. 2010.
[8] C. Benjamin, *Automatic Control Systems*. Hoboken, NJ, USA: Wiley, 2003.
[9] *SIMULINK Software*, Math Works, Natick, MA, USA, 2007.
[10] H. Chen, Z. Chen, C. Chen, X. Zhang, H. Zhang, P. Zhao, K. Shi, S. Li, J. Feng, and Q. Zeng, "Conceptual design of a small modular natural circulation lead cooled fast reactor SNCLFR-100," *Int. J. Hydrogen Energy*, vol. 41, no. 17, pp. 7158–7168, May 2016.
[11] S. Yan, H. Fang, P. Wang, C. Sun, F. Zhao, H. Huang, and Y. Wu, "Modeling and control strategy of the China accelerator driven subcritical reactor," *Prog. Nucl. Energy*, vol. 71, pp. 179–187, Mar. 2014.
[12] O. Yoshiaki, M. Haruki, and U. Mitsuru, *Nuclear Reactor Kinetics and Plant Control*. Tokyo, Japan: Springer, 2013.
[13] K. Ogata, *Modern Control Engineering*. Englewood Clifffs, NJ, USA: Prentice-Hall, 2002.
[14] *Relap5-HD Software*, GSE Syst., Sykesville, MD, USA, 2011.

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