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Flexibility control and simulation with multi-model and LQG/LTR design for PWR core load following operation

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ABSTRACT

The objective of this investigation is to design a nonlinear Pressurized Water Reactor (PWR) core load following control system. On the basis of modeling a nonlinear PWR core, linearized models of the core at five power levels are chosen as local models of the core to substitute the nonlinear core model in the global range of power level. The Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) robust optimal control is used to contrive a controller with the robustness of a core local model as a local controller of the nonlinear core. Meanwhile, LTR principles are analyzed and proved theoretically by adopting the matrix inversion lemma. Based on the local controllers, the principle of flexibility control is presented to design a flexibility controller of the nonlinear core at a random power level. A nonlinear core model and a flexibility controller at a random power level compose a core load following control subsystem. The combination of core load following control subsystems at all power levels is the core load following control system. Finally, the core load following control system is simulated and the simulation results show that the control system is effective.

1. Introduction

At present, energy generated by nuclear plants occupies an important part of the whole electricity production in the world. Meanwhile, the load following mode is becoming an increasingly important feature of nuclear plants. Some researchers (Meyer et al., 1978; Chari and Rohr, 1997) have worked on the load following operation of nuclear plants. The load following capability is to control and change the reactor power according to practical or predictable load demands on an electric network.

Controlling the reactor power in a load tracking mode is carried out by designing a suitable reactor power control system. Though a conventional reactor power control has been used in the base load mode, the performances and stability of the conventional control systems cannot be guaranteed in the load following mode. With the advancement of computer technologies and control theories over the decades, however, the sophisticated and desired control methods have been established, which give a bright future to the reactor load following control. Edwards et al. (1990, 1991), Arab-Alibeik and Setayeshi (2003), Ben-Abdennour et al. (1992) and Dong et al. (2011) designed the controllers under the state feedback assisted control structure to provide the tight control of nuclear reactors; Eliasi et al. (2012) proposed the robust nonlinear model predictive control for a PWR core; Ku et al. (1992) and Khajavi et al. (2002) designed neural network controllers to control a PWR core power and the core coolant exit temperature. However, the controllers in references (Edwards et al., 1990, 1991; Arab-Alibeik and Setayeshi, 2003; Ben-Abdennour et al., 1992; Dong et al., 2011; Eliasi et al., 2012) are all designed based on a linearized core model at a power level, and not always optimal or even ineffective for large or drastic load maneuvers; the controllers from references (Ku et al., 1992; Khajavi et al., 2002) are designed based on the neural network intelligent approach. The approach needs to obtain training samples which are usually given by either a linearized model or actual data of reactor cores, the sample based on a linearized model limits the working range of intelligent controllers and extracting or training actual data is inconvenient, time-consuming and expensive. Based on the considerations in the paper, new strategies including the linear multi-model modeling, the LQG/LTR control methodology and the principle of flexibility control proposed are utilized to devise a nonlinear PWR core load following control system.

PWRs are complex time-varying nonlinear systems and their parameters vary with time and the power level. The linear multi-model method is an effective modeling way of a nonlinear system (Johansen and Foss, 1999) and used to model the nonlinear PWR core in the paper. Linearized models of the core at five power levels are selected as local models of the core and the set of local models is used to substitute the nonlinear core model.

The LQG/LTR control strategy is utilized to design a controller with the robustness of every local model as a local controller of

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the nonlinear core. Major advantages of LQG/LTR controller are that it possesses the strong robustness and can be designed for single-variable or multi-variable plants including open loop unstable ones. The strategy has been developed from Linear Quadratic Gaussian (LQG). The LQG optimal control is a state feedback control with the optimal control theories and the optimal estimation theories (Athans, 1971; Balakrishnan, 1984). It is an integrated design way based on the linear quadratic regulator (LQR) and a state observer, and can handle the control problem of a linear system with some noises or immeasurable states. The application of LQG control to the nuclear science field has appeared (Berkan and Upadhyaya, 1989; Belyakov et al., 1999; Parikh et al., 2011). However, the introduction of a state observer in designing a LQG controller weakens the robustness of stability and performances of LQR that usually has an infinite gain margin and a phase margin from $[60°, \infty)$ (Safonov and Athans, 1977). To improve the robustness of a LQG control system, Athans (1986), Stein and Athans (1987) and Doyle and Stein (1981) have proposed and developed the LTR technology based on LQG. The method can recover the robustness of a LQG/LTR control system of a model in the light of a robustness of Target Feedback Loop (TFL) of the model. Therefore, the LQG/LTR method is suitable to design control systems of controlled plants with the model uncertainty characteristic such as the nonlinear core. Besides, based on the work in the references (Athans, 1986; Stein and Athans, 1987; Doyle and Stein, 1981), LTR principles are analyzed and proved theoretically by adopting the matrix inversion lemma in the paper.

Based on the local controllers, the principle of flexibility control is proposed to design a flexibility controller of the nonlinear core at a random power level. A nonlinear core model and a flexibility controller at a random power level compose a core load following control subsystem. The combination of core load following control subsystems at all power levels is the core load following control system.

Finally, the core load following control system is simulated and conclusions are drawn.

2. Model PWR core

2.1. Nonlinear model

According to the lumped parameter method, the nonlinear core model is established via using the point kinetics equations with six groups of delayed neutrons and reactivity feedbacks due to changes in fuel temperature and coolant temperature. The expressions of the nonlinear model (Schultz, 1961; Ash, 1979; Edwards et al., 1990; Khajavi et al., 2002) are as follows

$$\frac{dn_r}{dt} = \frac{\rho - \beta}{\Lambda} n_r + \sum_{i=1}^{g} \frac{\beta_i c_{ri}}{\Lambda} \tag{1}$$

$$\frac{dc_{ri}}{dt} = \lambda_i n_r - \lambda_i c_{ri}, \quad i = 1, 2, \ldots, g \tag{2}$$

$$\frac{dT_f}{dt} = \frac{f_f P}{\mu_f} n_r - \frac{\Omega}{\mu_f} T_f + \frac{\Omega}{2\mu_f} T_i + \frac{\Omega}{2\mu_f} T_e \tag{3}$$

$$\frac{dT_e}{dt} = \frac{(1 - f_f)P}{\mu_c} n_r + \frac{\Omega}{\mu_c} T_f + \frac{2M - \Omega}{2\mu_c} T_i - \frac{2M + \Omega}{2\mu_c} T_e \tag{4}$$

$$\rho = \rho_{rod} + \alpha_f (T_f - T_{f0}) + \frac{\alpha_c}{2}(T_i - T_{i0}) + \frac{\alpha_c}{2}(T_e - T_{e0}) \tag{5}$$

where n_r – normalized relative neutron density; Λ – neutron generation time, s; ρ – total reactivity; β – effective delayed neutron fraction; c_{ri} – ith group normalized precursor concentration; g – delayed neutron group number, $g = 6$; λ_i – ith delayed neutron group decay constant, s^{-1}; T_f – fuel average temperature, °C; T_{f0} – fuel average temperature at the initial point, °C; f_f – fuel power coefficient; P – reactor power, W; μ_f – fuel total heat capacity, J/°C; Ω – coefficient of heat transfer between fuel and coolant, W/°C; T_i – coolant inlet temperature, °C; T_{i0} – coolant inlet temperature at the initial point,°C; T_e – coolant outlet temperature, °C; T_{e0} – coolant outlet temperature at the initial point, °C; μ_c – total heat capacity of coolant, J/°C; M – mass flow heat capacity, W/°C; ρ_{rod} – reactivity due to control rod movement; α_f – fuel temperature coefficient of reactivity, °C^{-1}; α_c – coolant temperature coefficient of reactivity, °C^{-1}.

2.2. Linearized model

The small perturbation linearization methodology is utilized to linearize the nonlinear core model and then the linearized core model is calculated.

Eqs. (1)–(5) are linearized and the linearized equations are the followings

$$\frac{d\delta n_r}{dt} = -\frac{\beta}{\Lambda}\delta n_r + \sum_{i=1}^{g} \frac{\beta_i}{\Lambda}\delta c_{r_i} + \frac{n_{r0}}{\Lambda}\delta\rho \tag{6}$$

$$\frac{d\delta c_{ri}}{dt} = \lambda_i \delta n_r - \lambda_i \delta c_{ri}, \quad i = 1, \ldots, g \tag{7}$$

$$\frac{d\delta T_f}{dt} = \frac{f_f P}{\mu_f}\delta n_r - \frac{\Omega}{\mu_f}\delta T_f + \frac{\Omega}{2\mu_f}\delta T_i + \frac{\Omega}{2\mu_f}\delta T_e \tag{8}$$

$$\frac{d\delta T_e}{dt} = \frac{(1 - f_f)P}{\mu_c}\delta n_r + \frac{\Omega}{\mu_c}\delta T_f + \frac{2M - \Omega}{2\mu_c}\delta T_i - \frac{2M + \Omega}{2\mu_c}\delta T_e \tag{9}$$

$$\delta\rho = \delta\rho_{rod} + \alpha_f \delta T_f + \frac{\alpha_c}{2}\delta T_i + \frac{\alpha_c}{2}\delta T_e \tag{10}$$

and

$$\frac{d\delta\rho_{rod}}{dt} = G_r z_r \tag{11}$$

where δ – the deviation of a parameter from initial steady-state value; n_{r0} – normalized relative neutron density at the initial point; G_r – the total reactivity worth of the control rod in the core; z_r – the control rod speed (fraction of core length per second).

One-group delayed neutron model is adopted and the coolant inlet temperature is treated as a constant (Ben-Abdennour et al., 1992). According to Eqs. (6)–(11), the transfer function and the state equation of the core are respectively calculated and represented by

$$G = \frac{\delta n_r}{z_r} = \frac{\sum_{i=0}^{3} a_i s^i}{s\left(\sum_{i=0}^{4} b_i s^i\right)} \tag{12}$$

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{13}$$

where $u = z_r$ – the input; $y = \delta n_r$ – the output; $a_i (i = 0, 1, 2, 3)$ – numerator coefficients; $b_i (i = 0, 1, 2, 3, 4)$ – denominator coefficients; $x = [x_1, x_2, x_3, x_4, x_5]^T = [\delta n_r, \delta c_r, \delta T_f, \delta T_e, \delta\rho_{rod}]^T$ – the state matrix; A – the 5×5 system matrix; B – the 5×1 input matrix; C – the 1×5 output matrix; D – the zero matrix.

2.3. Selection of local models

Transfer functions of the core at power levels 10%, 30%, 50%, 70% and 90% are denoted by G_1, G_2, G_3, G_4 and G_5 in turn. The transfer functions are calculated by using parameters from the reference