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Design of a model predictive control method for load tracking in nuclear power plants

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ABSTRACT

Load tracking in pressurized water reactor (PWR) nuclear power plants has nowadays attracted comprehensive attention for the security concerns. In this paper, a novel state space model of the reactor core with multiple groups of delayed neutrons considered is developed, and a model predictive control (MPC) method is proposed for load tracking. In addition, Quadratic programming (QP) is introduced for system optimizing, and the stability analysis of the control system is also discussed. Compared with the currently used Proportional-Integral-Derivative (PID) control method, the effectiveness of the proposed QP-based MPC (QPMPC) method for load tracking is verified by numerical simulations.

1. Introduction

Nowadays, PID is still widely used in pressurized water reactors (PWRs) where load tracking is one of the most significant operations. Though PID has earned good reputation in the control fields and is of effectiveness in many cases for process control, manual control is currently used in low-load working condition (<15% nominal power) in PWRs, as PID cannot effectively control the core power to track the load changing in that situation. Therefore, a more accurate and effective controller is desperately needed to be developed for load tracking in PWRs. Being of the advantage of predictive effects, MPC can reflect faster than other control algorithms. The fine performance of MPC is guaranteed by the prediction model, continuously rolling optimization and feedback compensation for the model error. MPC that is an optimal control method, has been widely applied in both researches and industry because of its good performance in process control. For instance, an MPC controller was designed for superheater steam temperature control (Wu et al., 2014a). MPC was applied to an ultra-supercritical power plant (Kong et al., 2016). An MPC controller was developed for spatial control of a large pressurized heavy water reactor (Liu et al., 2016). MPC was applied to a boiler–turbine system (Liu and Kong, 2013). MPC was proposed for water level control of a U-tube steam generator (Liu et al., 2015).

There are a small amount of studies undertaken for load tracking in PWRs. For instance, a neural network controller was applied to load following operation in (Khajavi et al., 2001), in which a self-tuning regulator was introduced to determine the observer gains of the neural network controller. A fuzzy-PID controller for power control of a nuclear reactor was developed in (Liu et al., 2009), and a fuzzy logic controller was introduced for parameter self-tuning of the PID controller. A flexibility control scheme for load following control of PWRs was proposed in (Li and Zhao, 2013a), where the controller output was obtained by solving the Riccati equation. An improved load following strategy was presented in (Zhang et al., 2015). Based on multi-model, LQG, IAGA and flexibility idea, a load following control scheme was developed in (Li and Zhao, 2013b), and the controller output was found by solving the Riccati equation. There is no doubt that the researchers have achieved meritorious achievements. Nonetheless, most of the researches are only related to relatively high-load working condition, and few researches related to low-load working condition have been carried out.

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Nomenclature

n	Relative neutron density
n_0	Relative neutron density at initial equilibrium state
G_r	Reactivity worth of the control rod bank
P_0	Nominal core power (MW)
P	Actual core power (MW)
P_c	Heat quantity transferred from fuel to coolant (MW)
P_e	Heat quantity transferred from coolant to the secondary circuit (MW)
α_f	The reactivity coefficient of fuel temperature $(/^oC^{-1})$
λ_i	Decay constant of the i-th group of delayed neutron precursors $(/s^{-1})$
μ_c	Heat capacity of coolant $(MW{\cdot}s{\cdot}^oC^{-1})$
$\beta(\beta_i)$	The total fraction of effective (the i-th group of) delayed neutrons
Ω	The heat transfer coefficient between fuel and coolant $(MW{\cdot}^oC^{-1})$
f_f	The fraction of reactor power deposited in fuel
M	Heat capacity of mass flux of coolant $(MW{\cdot}s{\cdot}^oC^{-1})$
Λ	Mean neutron lifetime (s)
α_c	The reactivity coefficient of coolant temperature $(/^oC^{-1})$
μ_f	Heat capacity of fuel $(MW{\cdot}s{\cdot}^oC^{-1})$
$X\vert$	The concentration of xenon (cm^{-3})
X_0	The concentration of xenon at initial equilibrium state (cm^{-3})
I	The concentration of xenon iodine (cm^{-3})
γ_X	Xenon yield per fission
γ_I	Iodine yield per fission
λ_X	The decay constant of xenon (s^{-1})
λ_I	The decay constant of iodine (s^{-1})
ϕ	Neutron flux $(cm^{-2}{\cdot}s^{-1})$
Σ_f	Macroscopic fission cross section of fuel (cm^{-1})
σ_X	Microscopic absorption cross section of xenon (cm^2)
V	Mean velocity of thermal neutron $(cm{\cdot}s^{-1})$
c_i	The i-th group of normalized precursor concentration (m^{-3})
T_f	Average temperature of fuel $(^\circ C)$
T_{f0}	Average temperature of fuel at initial equilibrium state $(^\circ C)$
ρ	Total reactivity
$\delta\rho_r$	Reactivity produced by the movement of the control rod bank
T_l	Average outlet temperature of coolant $(^\circ C)$
T_c	Average temperature of coolant $(^\circ C)$
T_{c0}	Average temperature of coolant at initial equilibrium state $(^\circ C)$
T_e	Average inlet temperature of coolant $(^\circ C)$
Z_r	Velocity of the control rod bank $(m{\cdot}s^{-1})$

In this work, an MPC method is applied to track the load changing in PWRs. And a novel state space model of the reactor core is presented with point-reactor kinetic equations of six-group delayed neutrons, reactivity equations, temperature feedback, and xenon concentration feedback considered. In addition, in the controller designing stage the constraints on the mechanical limits of the control rod bank are considered, thus QP is employed for system optimizing. The MPC controller that is designed based on the state space model of the reactor core, can continuously calculate the future tracking error. And the optimal controller output is found to minimize the future tracking error. The good performance and effectiveness of the proposed QPMPC control method is proved by numerical simulations.

The rest of this paper is comprised of: the modeling of the reactor core is presented in Section 2; Section 3 presents the MPC model; simulation results are given in Section 4; and conclusions are drawn in Section 5.

2. Modeling of the reactor core

In this section, the reactor core model is presented based on point-reactor kinetic equations where six groups of delayed neutrons are considered, reactivity equations, temperature feedback, and xenon concentration feedback.

2.1. Equations in PWRs

In this paper, six groups of delayed neutrons are considered for point-reactor kinetic equations. The reactor core model is modeled based on point-reactor kinetic equations, reactivity equations, temperature feedback, and xenon concentration feedback (Khajavi et al., 2001; Li and Zhao, 2013b; Edwards et al., 1992; Edwards, 1990; Ben-Abdennour et al., 1992; Arab-Alibeik and Setayeshi, 2003; Khoshahval and Ahdavi, 2016; Wang et al., 2014; Levent Akin and Altin, 1991; Park and Cho, 1993; Hatami et al., 2016).

The point-reactor kinetic equations of six groups of delayed neutrons can be described as (Edwards et al., 1992; Edwards, 1990):

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{6} \lambda_i c_i \tag{1}$$

$$\frac{dc_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i c_i \quad (i = 1, 2, 3, 4, 5, 6) \tag{2}$$

The reactivity equations can be described as (Arab-Alibeik and Setayeshi, 2003; Khoshahval and Ahdavi, 2016):

$$\delta\rho = \delta\rho_r + \alpha_f\left(T_f - T_{f0}\right) + \frac{\alpha_c(T_l - T_{l0})}{2} + \frac{\alpha_c(T_e - T_{e0})}{2} + \sigma_X(X - X_0) \tag{3}$$

$$\frac{d\delta\rho_r}{dt} = G_r Z_r \tag{4}$$

where δ is the deviation value of the reactivity relative to the equilibrium point.

The temperature feedback can be expressed as (Khoshahval and Ahdavi, 2016; Wang et al., 2014; Levent Akin and Altin, 1991):

$$f_f P = \mu_f \frac{dT_f}{dt} + P_c \tag{5}$$

$$\left(1 - f_f\right)P + P_c = \mu_c \frac{dT_l}{dt} + P_e \tag{6}$$

The xenon concentration feedback can be described as: