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Higher order sliding mode controller design for a research nuclear reactor considering the effect of xenon concentration during load following operation

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ABSTRACT

Reactor power control is one of the most important problems in a nuclear power plant. This paper presents the higher order sliding mode controller (H.O.S.M.C.) which is a robust nonlinear controller for a nuclear research reactor considering the effect of xenon concentration during load following operation. Sliding mode controllers for nuclear reactors were developed before. Traditional sliding mode technique has intrinsic problem of chattering. To cope with this problem higher order sliding mode (HOSM) is used. The nonlinear model of a research reactor (Pakistan Research Reactor-1) has been used for higher order sliding mode controller design and performance evaluation. The reactor core is simulated based on the point kinetics equations and three delayed neutron groups. The model assumes feedback from lumped fuel and coolant temperatures. The effect of xenon concentration is also included. The employed method is easy to implement in practical applications and moreover, the higher order sliding mode control exhibits the desired dynamic behavior during the entire output-tracking process. Simulation results show the effectiveness of the proposed controller in terms of performance, stability and robustness against disturbances.

1. Introduction

Nowadays, nuclear power plants have an important role in providing electricity power. In these kinds of power plants the primary energy is supplied by a nuclear reactor. One of the most important control aims in a nuclear power plant is the increasing power plant availability and improving the load following capability (Park and Cho, 1992). Reactor power control has been used in base-load operating conditions traditionally. But with the increasing share of nuclear power plants in electricity generation, it seems that the load-follow operation of nuclear reactors will be inevitable in the future. It is hard to get the satisfying performance with the classic control strategy to control the nuclear reactor power (Liu et al., 2009). Therefore, in order to establish good operation performance of nuclear power plants, many investigations have been proposed in the field of reactor power control. Edwards et al. (1990) demonstrated improved robustness characteristics of SFAC (state feedback assisted classical control) to cope with changes of reactor parameters over that of CSFC (conventional state feedback control) (Edwards et al., 1990). In another work Park and Cho introduced a model-based feedback linearization controller with adaptive PI gains (Park and Cho, 1992). They also designed a model-based two-stage controller (Park and Cho, 1993). These control systems mostly were designed based on an approximate linear core model and hold true in limited range, the performance of which will lapse if the range is gone beyond.

In recent years, various controllers including neural network method, fuzzy logic method (Akin and Altin, 1991; Khajavi et al., 2002), emotional learning based intelligent controller (Khorramabadi and Boroushaki, 2007) and robust optimal control systems have been used for controlling nuclear reactors power (Liu et al., 2009).

Since a nuclear reactor is a nonlinear and complex plant whose parameters vary with the power level, in spite of many advanced control methods proposed for controlling nuclear reactor core power, it seems that a simple and high performance control system is still needed. On the other hand, a successful strategy to control uncertain nonlinear systems is sliding mode control. The sliding mode controller is an attractive robust control algorithm because of its inherent insensitivity and robustness to plant uncertainties and external disturbances (Utkin, 1977).

In control theory, Sliding Mode Control, or SMC, is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a cross-section of the system's normal behavior.

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The state-feedback control law is not a continuous function of time. Instead, it can switch from one continuous structure to another based on the current position in the state space. Hence, sliding mode control is a variable structure control method. Sliding mode control has been widely applied in control applications. The main advantages of this method are: simple structure, its robustness against a large class of perturbations or model uncertainties, the need for a reduced amount of information in comparison to classical control techniques, the possibility of stabilizing some nonlinear systems which are not stabilizable by continuous state feedback laws, wide variety of operational modes such as regulation, trajectory control, model following and observation. Higher order sliding modes (HOSM) has recently been invented and applied in new applications to generalize the basic sliding mode idea acting on the higher order time derivatives of the system deviation from the constraint instead of influencing the first deviation derivative like it happens in standard sliding modes. In addition to keeping the main advantages of original approach, at the same time they totally remove the chattering effect and provide for even higher accuracy in realization.

Chattering effect is dangerous high-frequency vibrations of the controlled system (Utkin, 1977). This phenomenon is a drawback as, even if it is filtered at the output of the process, it may excite un modeled high frequency modes, which degrades the performance of the system and may even lead to instability. Chattering also leads to high wear of moving mechanical parts and high heat losses in electrical power circuits. That is why many procedures have been designed to reduce or eliminate this effect such as higher order sliding modes.

The second order sliding mode control algorithm has been applied for regulating output power of a research reactor PARR-1 which is a swimming pool type research reactor (Qaiser et al., 2008) based on the one delayed neutron group without effect of the xenon concentration. In this paper, the nonlinear controller is developed using reactivity and temperature and xenon feedbacks based on the three delayed neutron groups. The method used for controller synthesis is second order sliding mode based on the super twisting algorithm.

Rest of the paper is organized as follows; Section 2 describes the reactor model, Reactor control problem is discussed in Section 3. Section 4 gives details about second order sliding mode controller design. Simulation results are given in Sections 5,6 concludes the paper.

2. Nuclear reactor core model

To simulate the nuclear reactor core, point kinetics equations with three groups of the delayed neutrons are used (Hetrick, 1993). The model assumes feedback from lumped fuel and coolant temperatures. The effect of xenon concentration is also included. The normalized model, with respect to an equilibrium condition, based on point kinetics equations with three delayed neutron groups are as follows:

$$\frac{dn_r}{dt} = \frac{\rho(t)-\beta}{\Lambda} n_r(t) + \frac{1}{\Lambda}\sum_{i=1}^{3}\beta_i c_{ri}(t) \tag{1}$$

$$\frac{dc_{ri}}{dt} = \lambda_i n_r(t) - \lambda_i c_{ri}(t), \quad i = 1,2,3 \tag{2}$$

$$\frac{dT_f}{dt} = \frac{1}{\mu_f}\left[f_f P_0 n_r(t) - \Omega(T_f - T_c)\right] \tag{3}$$

$$\frac{dT_l}{dt} = \frac{1}{\mu_c}\left[(1-f_f)P_0 n_r(t) + \Omega(T_f - T_c) - M(T_l - T_e)\right] \tag{4}$$

$$\frac{dx}{dt} = \gamma_x \Sigma_f B n_r + \lambda_I I - \sigma_x x B n_r - \lambda_x x \tag{5}$$

$$\frac{dI}{dt} = \gamma_I \Sigma_f B n_r - \lambda_I I \tag{6}$$

$$\rho = \rho_r + \alpha_f(T_f - T_{f0}) + \alpha_c(T_c - T_{c0}) - \left(\frac{\sigma_x}{\Sigma_f}\right)(x - x_0) \tag{7}$$

$$\frac{d\rho_r}{dt} = G_r Z_r \tag{8}$$

where

- n_r $\frac{n}{n_0}$, neutron density relative to initial equilibrium density.
- n Neutron density $\left(\frac{n}{\mathrm{cm}^3}\right)$.
- n_0 Initial equilibrium (steady-state) neutron density.
- c_{ri} $\frac{c_i}{c_{i0}}$, relative density of ith group precursor.
- c_i Core averaged ith group precursor density $\left(\frac{\mathrm{atom}}{\mathrm{cm}^3}\right)$.
- c_{i0} Initial equilibrium (steady-state)density of ith group precursor.
- ρ $\frac{(k-1)}{k}$, reactivity.
- k $k$eff, effective neutron multiplication factor.
- Λ Effective prompt neutron life time (s).
- λ_i Radioactive decay constant of ith group neutron precursor (s^{-1}).
- β Total delayed neutron fraction.
- β_i ith group delayed neutron fraction.
- T_f Average reactor fuel temperature (°C).
- T_l Temperature of the water leaving the reactor (°C).
- T_e Temperature of the water entering the reactor (°C).
- T_c $\frac{T_l + Te}{2}$, average reactor coolant temperature (°C).
- f_f Fraction of reactor power deposited in the fuel.
- P_0 Initial equilibrium power (MW).
- μ_f Total heat capacity of the fuel = weight of fuel times its specific heat $\left(\frac{\mathrm{MW.s}}{^\circ\mathrm{C}}\right)$.
- μ_c Total heat capacity of the reactor coolant = weight of coolant times its specific heat $\left(\frac{\mathrm{MW.s}}{^\circ\mathrm{C}}\right)$.
- Ω Heat transfer coefficient between fuel and coolant $\left(\frac{\mathrm{MW}}{^\circ\mathrm{C}}\right)$.
- M Mass flow rate multiplied by heat capacity of the coolant (MW/°C).
- ρ_r Reactivity due to control rod movement.
- Z_r control rod speed in units of fraction of core length per second.
- G_r Total reactivity worth of control rod.
- α_f Fuel temperature reactivity coefficient $\left(\frac{\Delta k}{k}/^\circ\mathrm{C}\right)$.
- α_c Coolant temperature reactivity coefficient $\left(\frac{\Delta k}{k}/^\circ\mathrm{C}\right)$.
- T_{f0} Initial equilibrium(steady-state)fuel temperature.
- T_{c0} Initial equilibrium(steady-state)coolant average temperature.
- σ_x Microscopic absorption cross-section of xenon(cm^2).
- λ_x Xenon decay constant (1/s).