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Original Article

# ROBUST FEEDBACK-LINEARIZATION CONTROL FOR AXIAL POWER DISTRIBUTION IN PRESSURIZED WATER REACTORS DURING LOAD-FOLLOWING OPERATION

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ABSTRACT

Improved load-following capability is one of the most important technical tasks of a pressurized water reactor. Controlling the nuclear reactor core during load-following operation leads to some difficulties. These difficulties mainly arise from nuclear reactor core limitations in local power peaking: the core is subjected to sharp and large variation of local power density during transients. Axial offset (AO) is the parameter usually used to represent the core power peaking. One of the important local power peaking components in nuclear reactors is axial power peaking, which continuously changes. The main challenge of nuclear reactor control during load-following operation is to maintain the AO within acceptable limits, at a certain reference target value.

This article proposes a new robust approach to AO control of pressurized water reactors during load-following operation. This method uses robust feedback-linearization control based on the multipoint kinetics reactor model (neutronic and thermal-hydraulic). In this model, the reactor core is divided into four nodes along the reactor axis. Simulation results show that this method improves the reactor load-following capability in the presence of parameter uncertainty and disturbances and can use optimum control rod groups to maneuver with variable overlapping.



## 1. Introduction

Controlling the nuclear reactor core during load-following operation is an important area in nuclear engineering, particularly in pressurized water reactors (PWRs) [5].

A nuclear reactor core has a multivariable nature and is a complex nonlinear system. Any power level change can induce unintended time–space xenon oscillations, resulting in large local power peaking. Such complexity cannot be duly represented by point kinetics models [12]. Therefore, a multipoint kinetics model, which is based on the nodal neutronic and thermal-hydraulic method, is a suitable choice for modeling the power axial oscillations. In the case of nodal methods, the reactor core is considered to be divided into a number of regions in which the neutron flux and material composition are treated as uniform. The regions are treated as smaller cores coupled through neutron flux [7]. Avery [4] and Komata [11] described the basic idea of the multipoint kinetic model. Kobayashi [10] has used unperturbed flux to calculate kinetics parameters for multipoint kinetics equations.

Furthermore, central to the method are the values of the coupling coefficients. In load-following mode, the reactor should track the demand load changes while considering the core limitations in safety margins and local power peaking.

Axial offset (AO) is the parameter usually used to represent the core power peaking, this is a practical parameter that is defined as the actual axial power distribution in the core, which varies significantly. In previous classical control systems, usually crisp logics have been used to control the thermal power and AO. However, in the constant AO strategy the reactor AO is maintained within predetermined limits via suitable maneuvering of the control rods. Thus, using robust control based on the multipoint kinetics model is more suited to this type of problem and may improve the load-following capability. Modern intelligent techniques, using sliding mode control, allow us to satisfactory handle such a problem [3], but only at the expense of high gains [21]. Indeed, the main obstacles for application of sliding mode control are two interconnected phenomena: chattering and high activity of control action. It is well known that the amplitude of chattering is proportional to the magnitude of any discontinuous control. Especially, to achieve perfect tracking and stability in the presence of parameter uncertainty, external disturbance, and measurement noise, the magnitude of the sliding mode control should be increased,

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which leads to high chattering phenomena. Besides this, boundary layer thickness expansion to decrease the chattering phenomena leads to large steady output tracking error. These two problems can be handled simultaneously if the magnitude of the control is reduced. In this article, a new robust approach based on feedback-linearization control is used to obtain the minimum possible value of control and to decrease both the chattering phenomena and the boundary layer thickness expansion, which exhibits large steady output tracking error, leading to external disturbances and parameters uncertainty.

This article, for the first time, presents a robust feedback-linearization controller using the Lyapunov approach based on the multipoint kinetics reactor model. Indeed, the purpose of this article is to present a robust feedback-linearization control system for the load-following operations of nuclear reactors such that oscillations of axial power distribution are bounded within acceptable limits, which will improve the performance of the conventional feedback-linearization and nonlinear sliding mode control techniques. The motivation of modeling the robust feedback-linearization controller for power offset is its simplicity, ease of implementation in practical applications, and improvement of the performance and robustness of conventional feedback-linearization in the face of external disturbances and parameter uncertainty; another motivation is improvement of the nonlinear sliding mode control techniques while obtaining a minimum possible value of control and decreasing both chattering phenomena and boundary layer thickness expansion in the face of external disturbances and parameter uncertainty. One of the important advantages of the presented robust feedback linearization technique is its simplicity. Indeed, contributions of the proposed approach in this article are (1) improvement of the performance and robustness of the conventional feedback-linearization technique in the face of external disturbances and parameter uncertainty by combining dynamic sliding mode control and conventional feedback-linearization, (2) improvement of the nonlinear sliding mode control technique while obtaining the minimum possible value of control and decreasing both chattering phenomena and boundary layer thickness expansion in the face of external disturbances and parameter uncertainty. Indeed, in this article, chattering phenomena, which are the main obstacles for application of sliding mode control in the face of external disturbances and parameter uncertainty, are removed by combining dynamic sliding mode control and conventional feedback-linearization.

The simulation results demonstrate the effectiveness of the proposed control system in diverse operating conditions. Also, the article shows that this controller may improve the responses, compared to conventional proportional integral derivative (PID) controller, conventional feedback-linearization and nonlinear sliding mode control techniques.

## 2. Nuclear reactor model

As discussed above, the point kinetics model is not valid in the case of PWRs because the neutron flux shape undergoes appreciable variation with time, and this model cannot analyze the power axial oscillations [9]. Besides this, control of the axial power distribution is essential during load-following operation in nuclear reactors. Therefore, the multipoint kinetics model, which is based on the nodal method, is a good choice for modeling power axial oscillations [4]. To use the multipoint method, the reactor core is considered to be divided into a number of nodes along the reactor axis, in which the material composition and neutron flux are treated as uniform. Furthermore, the nodes are treated as small cores coupled through neutron diffusion; central to the method are the values of the coupling coefficients.

To simulate the nuclear reactor core, a multipoint kinetics model with four nodes is selected as the validated multipoint kinetics model [21]. Therefore, the PWR core is considered to be divided into four nodes along the reactor axis, as shown in Fig. 1.

To simulate the nuclear reactor core, with respect to an equilibrium condition, the normalized model, based on the four points kinetics equations with three delayed neutron groups, based on the Skinner–Cohen model, which has been validated and benchmarked [9], is used. The utilized normalized neutron kinetics model is as follows [21]:

$$\frac{dn_{ri}}{dt} = \frac{\rho_i - \beta}{l_i} n_{ri} + \sum_{k=1}^{3} \frac{\beta_k}{l_i} C_{ri,k} - \alpha_{ii} \frac{n_{ri}}{l_i} + \sum_{\substack{j=1 \\ j \neq i}}^{\boldsymbol{N}} \frac{\alpha_{ji}}{l_i} n_{rj}, i = 1, \ldots, 4 \tag{1}$$

$$\frac{dC_{ri,1}}{dt} = \lambda_1 n_{ri} - \lambda_1 C_{ri,1}, \tag{2}$$

$$\frac{dC_{ri,2}}{dt} = \lambda_2 n_{ri} - \lambda_2 C_{ri,2}, \tag{3}$$

$$\frac{dC_{ri,3}}{dt} = \lambda_3 n_{ri} - \lambda_3 C_{ri,3}, \tag{4}$$

$$\frac{d\rho_{r1}}{dt} = \frac{G_r Z_{r1}}{2} \left(1 - sign\left(h_1 - \frac{h_0}{4}\right)\right) \tag{5}$$

$$\frac{d\rho_{r2}}{dt} = \frac{G_r Z_{r1}}{2} \left(1 + sign\left(h_1 - \frac{h_0}{4}\right)\right) \tag{6}$$

$$\frac{d\rho_{r3}}{dt} = \frac{G_r Z_{r2}}{2} \left(1 - sign\left(h_2 - \frac{3h_0}{4}\right)\right) \tag{7}$$

$$\frac{d\rho_{r4}}{dt} = \frac{G_r Z_{r2}}{2} \left(1 + sign\left(h_2 - \frac{3h_0}{4}\right)\right) \tag{8}$$

$$\frac{dh_1}{dt} = h_0 Z_{r1} \tag{9}$$

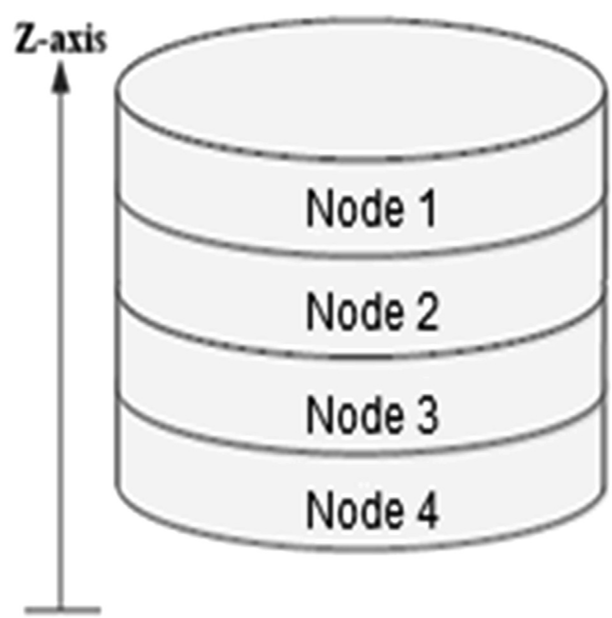


**Fig. 1.** Nodalization of the PWR reactor core in the axial direction. PWR, pressurized water reactor.