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Non linear Dynamic Inversion based controller design for load following operations in Pressurized Water Reactors with bounded Xenon oscillations

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A B S T R A C T

Nuclear Power Plants mostly act as base-load stations mainly because of constraints on rate of reactivity addition. In order that such plants operate as commercially viable entities, it is necessary that they are capable of operating as load following stations. The inherently self-regulating nature of a Pressurized Water Reactor (PWR) makes it a natural choice for load followers. However, this entails an associated problem of periodic variation in spatial concentrations of the burnable neutron poison Xenon which alters the spatial flux profile substantially within the reactor core, and this phenomenon is known as *Xenon oscillation*. This paper proposes a nonlinear controller design methodology based on Nonlinear Dynamic Inversion (NDI) which is coupled with constrained optimization to develop a tracking controller that achieves load following operation of a PWR over a wide range of reactor power with no Xenon oscillations and satisfies the operational constraints of the reactor imposed by reactivity worth of the control devices and allowable fuel and coolant temperatures.

1. Introduction

Nuclear reactors like a PWR used for power generation often have a neutronically large core and such a reactor core has a space-dependent thermal power generation profile, resulting from spatial and temporal variations in neutron flux which often leads to periodic variations in spatial Xenon concentration. It has been observed that such oscillations in spatial Xenon concentration often result in spatial variation in neutron flux and power, and due to this variation, temperature in one particular region can increase substantially causing local hot spots which may cause localized core damage. These oscillations may be axial, radial or azimuthal, resulting in corresponding variations in spatial power profile of core. Xenon oscillations are often triggered by a power variation, which is inevitable if a load following operation is envisaged.

Nuclear reactors generally work as base-load stations. With an increasing share of nuclear power in electricity generation, it is likely that Nuclear Power Plants (NPPs) need to operate in load following mode. Numerous control strategies for load following operation in nuclear reactors have been studied. With inherent self regulating characteristics, a PWR has mostly been the chosen candidate to achieve load following. A number of researchers (Edwards et al., 1990; Nair and Gopal, 1987; Torabi et al., 2011; Li and Zhao, 2014, 2013a,b) have proposed a number of methodologies for load following operation of a PWR. However, none of them have considered Xenon oscillation control within their scope and have mostly used linearized models corresponding to different regimes of operation of a reactor with switching from one regime to another (Li and Zhao, 2014, 2013a,b). Some other studies with different methodologies to control the power in a PWR during load following operations are presented in Li et al. (2014), Li (2014a,b), Sipush et al. (1976), Meyer et al. (1978) and Park and Cho (1992), some of these have also considered Xenon induced power oscillations during load following operations. Techniques using artificial intelligence e.g., Boroushaki (2004) have also been proposed by some for control of axial power offset in a PWR in the recent past. In a related domain, a recent work by Munje (2011) presents a survey of applicability of different control methodologies for a different genre of reactors viz. the Advanced Heavy Water Reactor (AHWR) which have a neurtonically large core and hence are susceptible to Xenon oscillations like the PWR, but the focus of this work is basically prevention of Xenon oscillation through flux-tilt correction across the zones and not a combined goal of load following without Xenon oscillations.

Approaches for designing load following control of a PWR with bounded Xenon oscillation use primarily (i) Model Predictive Control (MPC) and (ii) Sliding Mode Control (SMC). For example, Eliasi et al. (2011) uses MPC. Most MPC approaches are associated with a high

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computational burden, and accordingly it is often attempted to avoid a time consuming control cost optimization by assuming a restricted system and/or by imposing restrictions on predicted trajectories, which require uncertainty bounds to be known *a priori*.

SMC based approaches (Ansarifar and Saadatzi, 2015a,b; Ansarifar and Rafiei, 2015; Ansarifar and Akhavan, 2015) have gained popularity in the recent years. However, a problem with SMC approaches is chattering near the sliding surface which arises out of system uncertainties and discretization as well. Chattering in a nuclear reactor leads to wear out of control mechanisms and may lead to instability. Different approaches have been proposed by contemporary researchers e.g. sliding window algorithm which can be used with SMC approaches to control a PWR with bounded Xenon oscillations but most of these approaches depend heavily on bounds of parameter uncertainties which are difficult to ascertain in a nuclear reactor mainly due to its inherent time varying nature e.g. transition from a fresh to equilibrium core, in the simplest case. Another approach in reducing chattering (Ansarifar and Rafiei, 2015) proposes reduced chattering by considering higher order controllers.

In this paper a nonlinear control approach viz. NDI as explained in Yang et al. (2014) and Isidori (1995) has been proposed to achieve a load following of a PWR with bounded Xenon oscillations. Nowadays NDI is widely used in aircraft industry and has proved to be an easy and robust control technique for nonlinear systems. A very similar approach has been proposed for nonlinear control of a coal-fired thermal plant in Alamoodi and Daoutidis (2017). NDI is a nonlinear control technique that directs the system states to follow a desired trajectory which is defined by the user. NDI does not require linearization and again scheduled controller for operating points, as in the case of MPC based approaches, since it inverts the original dynamics to remove the system nonlinearities directly. Stability is always guaranteed by a simple control structure without having to consider higher order controllers or precise estimation of parametric uncertainties for suppression of chattering as in SMC based approaches. Therefore, NDI is conceptually simple and it has many similarities to classical control methods and the control scheme is *linear like*. In this paper, the NDI approach is coupled with constrained optimization to realize a simple control law that allows a PWR to be operated in a load following mode with no Xenon oscillations using a single controller over a wide range of power variation, while meeting operational constraints imposed by the limits of reactivity addition and maximum allowable temperatures of the fuel and coolant. This approach is new and has not been attempted by contemporary researchers working in this domain.

The rest of the paper is organized as follows. Section 2 presents a model of a PWR incorporating neutronics and thermal-hydraulics. A two-zone model of a PWR has been proposed in this section. Section 3 develops the relevant concepts related to NDI and Xenon oscillation which are necessary for understanding the controller design presented in Section 4 that follows. Section 4 also includes a description of the reduced order observer used for estimation of delayed neutron precursors and Xenon concentration in the core. Finally, the effectiveness of the control methodology is demonstrated with credible simulation in Section 5. The results establish that the control scheme proposed in this paper is capable of achieving load following control in a PWR with no Xenon oscillation.

2. Modeling of PWR reactor

A two-zone model of a PWR (2500 MW) core is developed using the methodology and data presented in Ansarifar et al. (2015), Esteki et al. (2015) and Ansarifar and Saadatzi (2015a). For the purpose of modeling, the core is assumed divided into two axial halves-*top* (*upper*) and *bottom* (*lower*) by a horizontal plane called the *central plane* and for each zone a lumped model is considered incorporating the reactor point kinetics with feedback due to thermal hydraulics and Xenon build up. The model for the top zone may be represented as follows:

$$\frac{dN_T}{dt} = \frac{\rho_T-\beta}{l}N_T + \frac{\beta}{l}C_T + \frac{\alpha}{l}(N_B-N_T) + w_{NT} \tag{1}$$

$$\frac{dC_T}{dt} = \lambda N_T-\lambda C_T + w_{CT} \tag{2}$$

$$\frac{dI_T}{dt} = \gamma_I\sum_f \phi_T-\lambda_I I_T + w_{IT} \tag{3}$$

$$\frac{dX_T}{dt} = \gamma_x\sum_f \phi_T + \lambda_I I_T-(\lambda_x + \sigma_x\phi_T)X_T + w_{XT} \tag{4}$$

$$\frac{dT_{fT}}{dt} = \frac{1}{\mu_{fT}}[f_F P_0 N_T-\Omega_T(T_{fT}-T_{cT})] \tag{5}$$

$$\frac{dT_{cT}}{dt} = \frac{1}{\mu_{cT}}[(1-f_F)P_0N_T + \Omega_T(T_{fT}-T_{cT})-M_T(T_{lT}-T_{eT})] \tag{6}$$

$$\rho_T = \rho_{rT} + \alpha_{fT}(T_{fT}-T_{fT_0}) + \alpha_{cT}(T_{cT}-T_{cT_0})-\frac{\sigma_a^x(X_T-X_{T_0})}{\Sigma_f} \tag{7}$$

$$\rho_{rT} = \frac{2G_T}{H}Z_{rT} \tag{8}$$

Eqs. (1)–(8) can be used interchangeably to represent the top or bottom zone by suitable choice of T or B as a subscript of variables and this convention is followed throughout the rest of the paper. The subscript 0 used with a variable indicates its equilibrium value while the subscript *fp* denotes its value corresponding to 100% FP and the subscript *ref* denotes the reference value of a variable. Thus, $N_{T,B}$ represents the normalized neutron concentration, $C_{T,B}$ represents the normalized precursor densities, $\phi_{T,B}$ is the neutron flux in (n/cm^2 s), $X_{T,B}$ and $I_{T,B}$ are Xenon and Iodine concentrations in top, bottom zone of the core- all normalized with respect to their values for an equilibrium condition corresponding to 100% Full-Power (FP) or P_{fp}. The variable $\rho_{T,B}$ represents the total reactivity in top, bottom zone and $\rho_{rT,B}$ is the component of $\rho_{T,B}$ introduced by the relevant bank of control rods.

As in Ansarifar and Saadatzi (2015a), two banks of control rod are considered with uniform differential worth. Half of the first control rod bank is assumed to be remain parked at the top of the reactor and the second control rod bank is assumed not to exceed beyond the central plane. Eq. (8) shows the relation between control rod reactivity in top zone with control rod displacement (cm) where $G_{T,B}$ is the total control rod worth for the top, bottom zone of the core, H is the height of core (cm) and $Z_{rT,B}$ represents the length of the core (cm) covered by the control rods in the top, bottom zone. The instantaneous velocity of the control rods $\dot{Z}_{rT,B}$ (cm/s) is assumed to be positive for a withdrawal and negative for an insertion.

Further, for representing the Thermal hydraulics, a nodal approach is adopted as in Nejad and Ansarifar (2017). In Eqs. (5) and (6), the subscript e,l associated with the coolant temperature correspond to *inlet* and *outlet*. It is further assumed that the coolant temperature at the outlet of the bottom zone is equal to the coolant temperature at the inlet of the top zone even though no physical outlet exists at the boundary of the two zones. The variable $T_{cT,B}$ represents the mean coolant temperature in the top, bottom zone of the core. Similarly, the variable $T_{fT,B}$ represents the nodal fuel temperature in the top, bottom zone of the core.

Now, with the reactor operating at any equilibrium power $P_0 \leqslant P_{fp}$, it is assumed that the parameters $\mu_{cT,B}$,$\Omega_{T,B}$,$M_{T,B}$,$\alpha_{fT,B}$ and $\alpha_{cT,B}$ are the functions of the equilibrium normalized zonal neutron density N_{T,B_0} corresponding to P_0 at $t = 0$ and the following equations show how these variables depend on N_{T,B_0} (Esteki et al., 2015; Nejad and Ansarifar, 2017)

$$\mu_{cT,B} = \left(\frac{160}{9}N_{T,B_0} + 54.022\right)\text{MW}\cdot\frac{\text{s}}{^\circ\text{C}} \tag{9}$$