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Control of xenon oscillations in Advanced Heavy Water Reactor via two-stage decomposition

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ABSTRACT

Xenon induced spatial oscillations developed in large nuclear reactors, like Advanced Heavy Water Reactor (AHWR) need to be controlled for safe operation. Otherwise, a serious situation may arise in which different regions of the core may undergo variations in neutron flux in opposite phase. If these oscillations are left uncontrolled, the power density and rate of change of power at some locations in the reactor core may exceed their respective thermal limits, resulting in fuel failure. In this paper, a state feedback based control strategy is investigated for spatial control of AHWR. The nonlinear model of AHWR including xenon and iodine dynamics is characterized by 90 states, 5 inputs and 18 outputs. The linear model of AHWR, obtained by linearizing the nonlinear equations is found to be highly ill-conditioned. This higher order model of AHWR is first decomposed into two comparatively lower order subsystems, namely, 73rd order 'slow' subsystem and 17th order 'fast' subsystem using two-stage decomposition. Composite control law is then derived from individual subsystem feedback controls and applied to the vectorized nonlinear model of AHWR. Through the dynamic simulations it is observed that the controller is able to suppress xenon induced spatial oscillations developed in AHWR and the overall performance is found to be satisfactory.

1. Introduction

The analysis and control of large scale systems has always been a complicated task due to high order nature and interacting dynamic phenomena of widely different speeds, which gives rise to time-scales. Such systems are extensively studied in control theory by singular perturbations and time-scale methods. Excellent survey of control theory applications of singular perturbations is given by Kokotovic et al. (1976). Another survey on singular perturbation in modeling, analysis and design of nonlinear, stochastic and large scale decentralized system is presented by Saksena et al. (1984). Singular perturbation methods have successfully been used in control application to deal with large scale system, by which the system is decoupled into 'slow' and 'fast' subsystems (Kokotovic et al., 1976). These methods work by decoupling the slow and fast varying phenomena, which leads to model order reduction. This decoupling is achieved either by quasi-steady-state method (Gajic and Lim, 2001) or direct block diagonalization (Naidu, 1988; Ladde and Siljak, 1983). The quasi-steady-state method is an effective method for decoupling a large order system into slow and fast subsystems for sufficiently small perturbation parameter ϵ. However, for real systems, like nuclear reactor the perturbation parameter is not zero. As a result, when using quasi-steady-state method the eigenvalues of the slow and fast subsystems are no longer in the same position as the eigenvalues of the full order system. To overcome this, block-diagonalization procedure (Phillips, 1980; Naidu, 1988) can be employed. In this method, exact decoupling is achieved. Feedback control designs for such systems may then proceed for each subsystem and the results are combined to yield a "composite" feedback control for the original system. The cases of state feedback control are treated in Chow and Kokotovic (1984), Phillips (1980), Saberi and Khalil (1985), and Suzuki (1981). Chow and Kokotovic (Chow and Kokotovic, 1984) have developed the procedure for linear systems and applied it to linear quadratic optimal designs. A cost functional, extracted from the cost functional for the full system, is associated with each subsystem. They have also shown that the composite state feedback control is stabilizing and near-optimal with the optimal cost. Suzuki (1981) has shown that controllability and stabilizability properties of the slow subsystem are invariant with respect to the feedback from fast state variables. This property is further explored by Saberi and Khalil (1985). They showed that the closed

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Nomenclature

Notations

C	precursor concentration
α	coupling coefficient
E_{eff}	thermal energy liberated/fission, J
β	delayed neutron fraction
$\mathbf{E}_n$	identity matrix of dimension n
γ	fraction fission yield
H	position of regulating rod, % in
λ	Decay constant
I	iodine concentration
ℓ	the prompt neutron life-time, s
P	fission power, W
ρ	reactivity, k
V	volume, m^3
σ_a	microscopic absorption cross-section, cm^2
X	xenon concentration
Σ_a	macroscopic absorption cross-section, cm^{-1}
h	enthalpy, kJ/kg
Σ_f	macroscopic fission cross-section, cm^{-1}
q	mass flow rate, kg/s
κ	constant of regulating rod position
v	voltage signal to RR drive, V
δ	deviation parameter
x	exit mass quality
φ	eigenvalue

Subscripts

C	precursor
f	fast, feed water, fission
H	position of regulating rod
i, j	node number
I	iodine
k	regulating rod number
P	power
s	slow, steam
X	xenon
w	water
c	vaporization
gp	global power
d	downcomer
sp	spatial power

loop slow subsystem is invariant with respect to any feedback function which preserves the equilibrium of the fast subsystem as an isolated equilibrium of fast subsystem obtained with $\epsilon = 0$. Further, two-stage eigenvalue placement via explicitly invertible transformation is suggested by Phillips (1980).

In the context of power distribution control in large nuclear reactors, like Advanced Heavy Water Reactor (AHWR) and Pressurized Heavy Water Reactor (PHWR), it is worth mentioning that the models of these reactors belong to singularly perturbed systems. These reactors exhibit slow as well as fast varying dynamical modes, which causes ill-conditioning of the problem. Moreover, the physical dimensions of these reactors are large compared to neutron migration length. Hence, they are susceptible to xenon induced spatial oscillations. Spatial oscillations in neutron flux distribution resulting from xenon reactivity feedback are a matter of concern in large nuclear reactors. If the spatial oscillations in power distribution are not controlled, power density and rate of change of power at some locations in the reactor core may exceed limits of fuel failure (Duderstadt and Hamilton, 1975). Spatial control means to suppress xenon oscillations from growing. Control of xenon oscillations developed in AHWR has been attempted by Shimjith et al. (2011a), Munje et al. (2014a) using static output feedback technique. However, static output feedback does not guarantee stability of closed loop system. As an extension to this, a state feedback based two-time-scale approach for PHWR is given by Tiwari et al. (1996) and three-time-scale approach for AHWR is presented by Shimjith et al. (2011b). In these, quasi-steady-state method is used to decouple the higher order system into lower order subsystems. Nevertheless, the practical implementation of such a state feedback based controller demands a state observer of large order. Hence, a linear observer has been suggested for PHWR in Tiwari and Bandyopadhyay (1998). Further, the observer based design increases the implementation cost and reduces the reliability of the control system. To overcome this, a three-time-scale based Fast Output Sampling (FOS) controller is investigated in Shimjith et al. (2011c). A similar kind of approach for two-time-scale system is also suggested by Munje et al. (2013a) for AHWR system. In FOS, control signal is generated as a linear combination of a number of output samples collected in one sampling interval, where input sampling time is larger compared to output. For example in Shimjith et al. (2011c), sampling time for spatial control component of input is taken as 60 s and in Munje et al. (2013a) it is taken as 54 s. However, for practical reactor control to work with larger sampling time is not desirable, because in small time, reactor system can undergo a considerable change. Hence, Periodic Output Feedback (POF) based controller for three-time-scale system of AHWR is presented in Munje et al. (2014b) with sampling period of 2 s. A two-time-scale decomposition approach using POF is documented in Patre et al. (1997), Tiwari et al. (2000). These multirate output feedback based controllers (i.e. FOS and POF) have their own advantages, but they lack robustness. Moreover, these methods may not work satisfactorily in the presence of disturbance, parameter variations and perturbations in the operating conditions. Recently, Munje et al. (2013b) have explored state feedback based robust Sliding Mode Control (SMC) technique to AHWR and it is shown that, better results are obtained compared to other control techniques. Furthermore, a single-input fuzzy logic controller (Londhe et al., 2014) is also proposed for spatial control of AHWR.

In this paper, singularly perturbed structure of Advanced Heavy Water Reactor is exploited, to decouple it into a slow subsystem of 73rd order and fast subsystem of 17th order, using the method of Phillips (1980) and a composite controller is designed for suppressing xenon induced spatial oscillations. In contrast to the earlier work of Shimjith et al. (2011b), where quasi-steady-state method was used to obtain three subsystems, this two-stage decomposition method provides higher degree of accuracy. Moreover, the comparison of results, helps to understand the effect of different model order reduction methods. Organization of the paper is as follows. In Section 2 brief overview of AHWR system is given. Control design is proposed in Section 3. In Section 4 application to AHWR system is presented followed by conclusion in Section 5.

2. Overview of AHWR

2.1. Introduction

In India, Advanced Heavy Water Reactor, a 920 MW (thermal), vertical pressure tube type reactor has been designed. It is moderated by heavy water, cooled by boiling light water and