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Non-linear simulation and control of xenon induced oscillations in Advanced Heavy Water Reactor

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ABSTRACT

The physical dimensions and the reactivity feedbacks of Advanced Heavy Water Reactor (AHWR) are such that, it is susceptible to xenon induced spatial oscillations. If these oscillations are not controlled, the power density and the rate of change of power at some locations in the reactor core may exceed their respective thermal limits, resulting into increased chances of fuel failure. Hence, it is essential to suppress xenon oscillations and achieve spatial stabilization of AHWR. Reactor core of AHWR is divided into 17 non-overlapping nodes. Non-linear model of AHWR is characterized by 90 first order differential equations. Total reactor power and 17 nodal powers are output variables. Four voltage signals to the Regulating Rods (RRs) and a feed flow rate are input variables. Applying a highly developed simulation is necessary for analysis and control of spatial oscillations developed in AHWR for safe operation. In this paper, after carrying out stability analysis, a control strategy based on feedback of total power and nodal powers in which RRs are placed is presented for spatial control of AHWR. For the same, a vectorized non-linear model of AHWR is developed and is implemented in the MatLab/Simulink environment which helps to understand the relationship between different variables of the system in a better way. With the proposed controller, non-linear model of AHWR is simulated and results are generated for different transient conditions. The behavior of delayed neutron precursor and xenon concentrations is also analyzed for each transient. From the simulation results, performance of the proposed controller is found to be satisfactory.

1. Introduction

Design of the robust controller for spatial power control of nuclear reactor depends very heavily on how well we know the dynamics of the nuclear reactor. Dynamics refer to interactions among different system variables. To investigate the dynamics and to explore modern control system techniques for nuclear reactor control system design, it is important to have a reactor model that not only captures the essential features but also is moderate in its complexity for applying control system design and simulation technique (Javidnia et al., 2009). Nuclear reactors of small and medium size are generally described by the point-kinetic model which characterizes every point in the reactor by an amplitude factor and a time independent spatial shape function. This model is, however, not valid in case of large reactors, like Pressurized Heavy Water Reactor (PHWR) and Advanced Heavy Water Reactor (AHWR), because the flux shape undergoes appreciable variation with time and space (Shimjith et al., 2011). For explicit consideration of the variation of the flux shape it is necessary to have suitable model of nuclear reactor. Further, because of the potential for accidents or sabotage at nuclear power plants, the operation and control of these plants represents a complex problem. Several safety and control features are engineered at the design stage and operational policies are incorporated to avoid accidental release of radioactivity to the general population. The problems are further complicated in case of large nuclear reactor (Tiwari, 1999). Because of safety critical nature of the nuclear reactor, wide variety of computer codes have been developed and implemented in the form of off-line computer programs to study the behavior of plant in various postulated accident conditions (Javidnia et al., 2009; Seyed, 2012; Tiwari, 1999). In this paper, vectorized non-linear model of AHWR is developed and implemented by Simulink tool kit of MatLab software to explore dynamic behavior for control system studies. Also, the existence of spatial oscillations in AHWR is studied for control purposes, since, such oscillations are highly detrimental for safe operation of large nuclear reactor. In (Shimjith et al., 2011) it is shown that, the feedback of total power and all the nodal power distribution signals are required to suppress xenon induced oscillations. However, in this paper it is demonstrated that, to suppress xenon oscillations, feedback of total power and

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Nomenclature

Notations

C	precursor concentration
x	exit mass quality
E_{eff}	thermal energy liberated/fission, J
α	coupling coefficient
E_n	identity matrix of dimension n
β	delayed neutron fraction
H	position of regulating rod, % in
γ	fraction fission yield
I	iodine concentration
λ	decay constant
P	steam drum pressure, Mpa
ℓ	the prompt neutron life-time, s
V	volume, m^3
ρ	reactivity, k
W	fission power, MW
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

Subscripts

C	precursor
d	downcomer
H	position of regulating rod
f	feed water, fission
I	iodine
i, j	node number
P	power
k	regulating rod number
R	regulating rod
r	riser
T	total power
s	steam
X	xenon
w	water
c	vaporization
x	exit quality

only nodal power distribution signals where RRs are placed would be sufficient. The effectiveness of proposed control strategy is established through non-linear simulation results.

The rest of the paper is organized as follows. In Section 2 brief overview of AHWR is given. Mathematical model of AHWR is discussed in Section 3. In Section 4 vectorized model of AHWR is developed and is implemented in Simulink environment. Section 5 presents proposed control strategy. Non-linear simulation results are discussed in Section 6 and finally paper is concluded in Section 7.

2. Brief overview of AHWR

In India, Advanced Heavy Water Reactor, a 920 MW (thermal), vertical pressure tube type reactor, moderated by heavy water, cooled by boiling light water under natural circulation is designed using thorium-based technology as a third step of Indian nuclear power program. The AHWR is fueled with (Th–^{233}U) O_2 and (Th–Pu) O_2 pins (Sinha and Kakodkar, 2006). The 3.5 m long active core of AHWR has 513 lattice locations. Out of these, fuel assemblies occupy 452 locations and remaining 24 locations are reserved for reactivity control devices consisting of 8 Absorber Rods (ARs), normally fully inside the core, 8 Shim Rods (SRs), normally fully out of the core, and 8 Regulating Rods (RRs). RRs are used for fine adjustments in reactor power and they remain partially inside the reactor core under normal operating conditions. Out of the eight RRs, four are available for automatic control whereas, the remaining four are under manual operation. The remaining lattice locations are occupied by the shutdown system-1 consisting of 37 Shut-Off Rods (SORs). The neutron flux is measured using out-of-core ion chambers as well as in-core detectors. The total power of the reactor is inferred from ion chambers in low power range and from in-core detectors in power range. In-core detectors, however, are provided primarily for monitoring of spatial flux distribution in the core (Shimjith et al., 2008; Shimjith et al., 2010; Sinha and Kakodkar, 2006). The Main Heat Transport (MHT) system of AHWR consists of 452 coolant channels in reactor core, equal number of tail pipes, 4 horizontal cylindrical steam drums, 16 downcomers, an inlet header and 452 inlet feeders as shown in Fig. 1. Coolant starts boiling in the reactor core by absorbing the fission heat. Coolant channels belonging to each quadrant of the reactor core are connected to separate steam drums through individual tail pipes. The coolant circulation is driven by natural convection through tail pipes to steam drum at 7 MPa. Steam–water phase separation and feed water mixing takes place inside the steam drums. The steam is fed to the turbine whereas, the sub-cooled water flows back to the coolant channels through the 4 downcomer pipes to a common inlet header. Individual coolant channels of the core are fed from this common header through individual feeder pipes (Sinha and Kakodkar, 2006; Shimjith et al., 2008; Gaikwad et al., 2009; Shimjith et al., 2011). AHWR has a significant degree of coupling between the neutronics and the two-phase thermal hydraulics. The physical dimensions of AHWR are large compared to the neutron migration length in the core, making it susceptible to xenon induced spatial oscillations (Duderstadt and Hamilton, 1975). Further, situations such as on-line refueling might cause transient variations in flux-shape from the nominal flux-shape. Analysis of such situations can be done by developing a suitable vectorized model of AHWR in Simulink environment.

3. Mathematical model of AHWR

Mathematical model of AHWR is developed in Shimjith et al. (2008); Shimjith et al. (2010) using separate models for core neutronics and for thermal hydraulics of MHT system.

3.1. Core neutronics model

The simplified core neutronics model is obtained by nodal approach, based on finite difference approximation of the two group diffusion equations and the associated equation for an effective single group of delayed neutron precursor's concentration. Seventeen fictitiously divided nodes, as given in Fig. 2, are considered as seventeen small cores, each of which is coupled to its