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Nonlinear PI output power regulation in a light water reactor

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ABSTRACT

Robust nonlinear control of the load following operation has been attempted for a nuclear facility with a pressurized water reactor. A multi-linear model of the plant has been employed to contrive an appropriate proportional-integral (PI) controller further applied to the original nonlinear system. PI parameters (k_P, k_I) are adopted within the largest intersecting stability regions for all local models. Plant uncertainties due to the variable model parameters are moreover characterized within a multiplicative layout and the largest bound for the local models is assigned as the overall system uncertainty. Nyquist stability criterion is accordingly investigated for the robust stability of the PI controller. The proposed strategy is finally applied in two realistic load following scenarios addressed as output trajectory tracking problems. Results confirm a successful robust control practice for the nonlinear plant with a feasible control rod drive current as the regulating input.

1. Introduction

The current tendency for sustainable development and its impact on the energy sector has brought nuclear based electricity production into reconsideration (Brook et al., 2014). Despite various controversial aspects, nuclear energy is still highly conceived as a sustainable platform to meet the clean and reliable energy paradigms (Dittmar, 2012). To this end, load following of the nuclear facilities as traditional base load providers is actively pursued to accommodate for the fluctuating electric grid demand (Nuclear Energy Agency, 2011). Several control strategies addressing a broad spectrum of objectives have been proposed in this respect (Li et al., 2016). However, the common practice is often characterized on the basis of a local linear model valid in the vicinity of the nominal operating point. Certain attempts which concurrently address robustness issues in nuclear facilities are as follows: The sensitivity of dominant poles for the closed loop plant of a nuclear reactor with regards to some postulated uncertainties have been employed in Edwards et al. (1992) as a measure to investigate robustness under state feedback control. Robust controller design deploying the mixed sensitivity analysis and the pertaining control synthesis schemes ($H\infty$ and μ synthesis) have likewise been investigated in Shaffer et al. (2005). Uncertainties due to model reduction of the high order nuclear plant have been incorporated. Similar strategy has been employed in Sun et al. (2017) wherein the nonlinear nature of the model has been moderately approached. To this effect, the discrepancies between the nominal model and multiple instances at different working levels thereof have been identified as the source of uncertainty.

The linear framework resorted in all the above cases is quite plausible for regulation processes wherein slight deviations from the quiescent operating point are taken into account. Often large departures as the load following operation may not be reasonably addressed likewise due to the sensible inherent nonlinearities (i.e. discrepancy between the locally linear model and the globally nonlinear plant) (Olanrewaju and Alafraj, 2005). Besides, model uncertainties are more pronounced throughout large power maneuvers and robustness issues need to be treated more elaborately in a nonlinear framework. Some attempts to undertake the problem of robust nonlinear control in nuclear reactors are cited herein. A PI control for the nonlinear reactor plant has been developed in Park and Cho (1992) applying the input-output linearization framework whose robustness is obtained through a feedback of the observed estimated uncertainty. Appropriate tuning of the intended dynamic observer to provide a fast and convergent transient error remains however as a challenge. On the same grounds, a similar work has been put forward recently wherein the authors have employed a Lyapunov based adaptively tuned PI controller for the primary circuit of a nuclear reactor (Dong et al., 2017). Though robustness issues have not been explicitly addressed the model-free nature of the control scheme helps provide a level of robustness through adaptation of the control law with regards to postulated disturbances. Sliding mode control has been employed in Qaiser et al. (2009) for output power regulation of a typical research reactor which requires careful treatment of the associated chattering phenomena. A nonlinear model predictive control has been proposed in Eliasi et al. (2012) with the need for a min-max optimization procedure successfully excluded. Certain restricted state constraints have been imposed on the predicted trajectory to account for robustness requirements. The approach calls

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for an excessive control practice on the other hand.

Multi-linear modeling constitutes a well-established method to extend the applicability of linear control synthesis schemes to the realm of complex nonlinear phenomena (Galan et al., 2000). The key idea in this approach is to perform local controller designs for a finite number of operating conditions and thereafter construct an appropriate gain scheduled controller to meet the desired objectives (Leith and Leithead, 2000). Multi-model control strategy has been employed in Tan (2011) to contrive a gain scheduled regulator for the steam generator of a nuclear power plant. Internal model control (IMC) strategy has been resorted as a simple scheme and tuning parameter assigned to characterize the controller. A single scheduled controller is shown to fulfill the intended robustness properties for the entire envelope of operation. Load following power control in a nuclear power plant has been addressed in Li et al. (2014) with the working region accordingly decomposed into several subdomains. Pertaining state space controllers are accordingly designed for each interval and the controller is switched across individual regions.

Despite several successful applications of the multi-model control strategy, certain open issues concerning the proper selection of local operating points yet remain unanswered. Often heuristic insight of the nonlinearity measure obtained through excessive simulations may be quite helpful in this regard. This work is an attempt to address the PI control of the output power in a nuclear reactor employing a multi-model framework to account for nonlinearities. Robustness is moreover investigated collectively for the set of obtained models. Proportional-integral-derivative (PID) regulators remain by far the most prevalent industrial control strategy owing to their simple and easily tunable structure (Astrom and Hagglund, 2001). The work is accordingly organized as follows: in the next section an overview of the open loop nonlinear reactor model is given with the control rod drive mechanism incorporated. Multi linear model at various operating points are thereafter outlined with the associated model uncertainties reflected through various parameters. A multiplicative uncertainty layout quite reasonably yields the upper bound for the associated uncertainties at each operating point. The section afterwards is dedicated to characterization of the stability region for PI controllers contrived for each local model. The ultimate (scheduled) PI controller parameters are adopted within the intersecting stability region for all local models whereas the largest uncertainty bound for uncertain models is employed for the robustness test. PI gains are selected so as to meet the Nyquist stability criterion as a measure of the robustness with respect to the pertaining uncertainty. In the last section, the proposed control strategy is employed on the original nonlinear plant for two realistic power regulation scenarios which demonstrate a quite successful robust output tracking practice. Simulation results are further discussed therein.

2. Nuclear reactor model

A coupled dynamic model for the nuclear reactor will be resorted hereafter to investigate the load following operation. The model consists in several interacting phenomena which basically reflect the overall fission induced chain reaction and the consequent heat produced within the core both governed by the pertaining conservation laws. The open loop plant is controlled through movement of control rods made up of neutron absorbing material which modulate the neutron flux level and the output heat power of the core. The control rod movement itself is regulated by means of a drive mechanism often being a permanent magnet DC motor. Fig. 1 displays a schematic of the reactor core with lumped fuel and coolant zones and the control rod mechanism. The heat generated inside the core is transferred by the coolant to a steam generator where it further produces the required steam as the turbine prime mover. This work is however solely dedicated the reactor output power regulation as the main component in a nuclear facility.

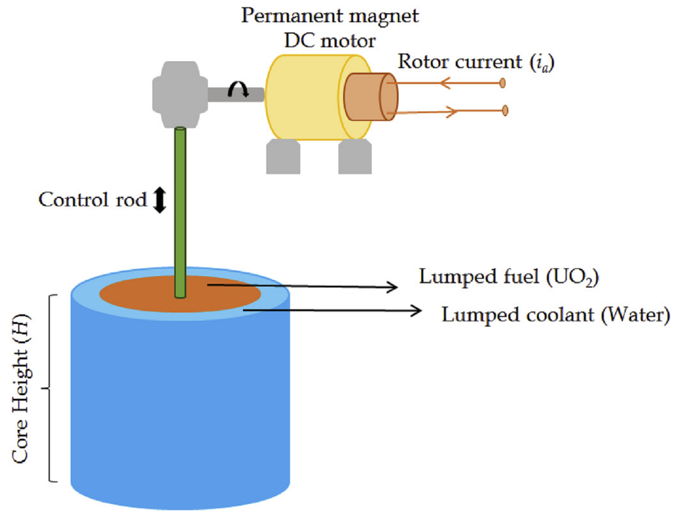

Fig. 1. Nuclear reactor core (lumped model) and the control rod drive mechanism.

The thermal power generated through fission within the reactor core is satisfactorily characterized by the point kinetics equations implying the conservation balances of the neutron population (Schultz, 1955). This model comprises one effective group of delayed neutron precursor ($C(t)$) which represents the power released due to unspontaneous fission reactions. The corresponding equations with power and precursor concentrations normalized to their initial values (P_0 and $C_0 = \beta_{eff} P_0/(\lambda_{eff}\Lambda)$) are given in Eqs. (1) and (2) respectively. Required design data and parameters definitions for all the forthcoming equations are moreover given in Table 1 (Edwards et al., 1992).

$$\frac{dP}{dt} = \frac{\rho_{net} - \beta_{eff}}{\Lambda}P + \frac{\beta_{eff}}{\Lambda}C \tag{1}$$

$$\frac{dC}{dt} = \lambda_{eff}P - \lambda_{eff}C \tag{2}$$

Table 1
Nuclear reactor model nominal parameters and definitions (Edwards et al., 1992).

$P(t)$	Reactor power	$P_{nom} = 3000\ MW$
β_{eff}	Effective delayed neutron fraction	700×10^{-5}
λ_{eff}	Effective precursor decay constant	$7.84 \times 10^{-2}s^{-1}$
Σ_f	Effective fission cross section of the core	$0.3358cm^{-1}$
γ_I	Iodine fission yield	6.386×10^{-2}
λ_I	Iodine decay constant	$2.875 \times 10^{-5}s^{-1}$
γ_X	Xenon fission yield	0.228×10^{-2}
λ_X	Xenon decay constant	$2.092 \times 10^{-5}s^{-1}$
σ_X	Neutron absorption cross section of Xenon	$2.7 \times 10^{-18}cm^2$
Λ	Neutron mean generation time	$32.0 \times 10^{-6}s$
E_f	Energy release per fission	$3.2 \times 10^{-11}J$
G_r	Worth of control rods	$8.0 \times 10^{-3}(\delta k/k)$
D	Reactor core diameter	$3.11m$
H	Active core height	3.55 m
τ_m	Electric motor time constant	$0.5s$
K_m	Electric motor constant	$10\ A^{-1}cm/s^2$
μ_f	Heat capacity of the fuel	$26.3\ MW.\ s/°C$
Ω	Fuel to coolant heat transfer coefficient	$6.6\ MW.\ s/°C$
μ_c	Heat capacity of the coolant	$71.8\ MW.\ s/°C$
M	Mass flow rate times heat capacity of the coolant	$102.\ MW/°C$
α_f	Fuel temperature coefficient of reactivity	$-3.24 \times 10^{-5}(\delta k/k)$
α_c	Coolant temperature coefficient of reactivity	$-2.13 \times 10^{-4}(\delta k/k)$
T_{in}	Core inlet coolant temperature	290°C
$v_{r,\max}$	Maximum rod withdrawal speed	$2(cm/s)$