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Linear active disturbance rejection control for pressurized water reactor power

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ABSTRACT

Since dynamic of pressurized water reactor (PWR) power is quite nonlinear, uncertain and time-varying, the reliable power-level control of PWR is necessary to guarantee high efficiency and safety of nuclear power plant. In this paper, a robust power-level regulation scheme based on linear active disturbance rejection control (LADRC) is presented for PWR. Its structure is simple and the Bandwidth-Parameterization based controller tuning is easy. First, the second order model with uncertainty is derived from a 18th order nonlinear model of PWR. And based on the derived model, two LADRC systems are designed for power control with and without model information respectively. Simulation results show the designed controllers both have satisfactory performance over the wide range of reactor operating conditions, while LADRC with model information has faster response, less overshoot, better disturbance rejection ability and robustness.

1. Introduction

PWR is a major component of a nuclear power plant. However, PWR is complex in nature nonlinear and the parameters vary with time as a function of power level. Reactor power control has been used in base-load operating conditions and it is also important from the standpoint of safety concerns. So the control system designed should not only satisfy the performance index, also be robust and can be adjusted easily. This classical control has advantages of simplicity to design and easy implementation, but the performance is often unsatisfactory. The conventional controller PID under the condition of large load change is being challenged. Therefore, in order to get good operation performance of nuclear power plant, various advanced control methods have appeared during the past few decades, for example, Ruan et al. introduced that a fuzzy logic theory for controlling the power level of a PWR was proposed in 1998 and Luan researched Load-following control of PWR based on Takagi-Sugeno fuzzy model (Luan et al., 2011). Na et al. designed an optimized fuzzy model predictive power controller for the PWR core (Na et al., 2006) and nonlinear fuzzy model predictive control was also used in literature (Liu and Wang, 2014), Liu et al. applied a fuzzy-PID control strategy to the PWR. The multi-step model predictive algorithmic was introduced to the power of PWR (Yao and Da-fa, 2010). Khajaviet employed robust optimal control self regulator for reactor power (Khajavi et al., 2002). Robust control of the PWR using quantitative feedback theory was used by TorabiK (Torabi et al., 2011) and robust nonlinear model predictive control for a PWR is also presented (Eliasi et al., 2012). An enhanced adaptation algorithm based on the normalized least square was employed to control reactor power (Alavi et al., 2009). Dong et al. presented an observer-based feedback dissipation controller and applied to PWRs (Dong et al., 2009). Park and Cho reported a model-based feedback linearization controller with adaptive PI gains.

Modern nuclear plants should meet the load demand on the power grid due to various kinds of constraints. Meanwhile, nuclear safety is very vital problem. Therefore, it is important to reach the economical and safe operation. Under the circumstance, ADRC shows the obvious advantages, since it does not heavily depend on the model. Han proposed ADRC in 1998 (Han, 1998) and this is a new method whose exciting performance is known to all. ADRC can deal with various processes, including large-scale of uncertainties, time varying, fractional order (Li et al., 2013), large dead time, non-minimum phase, unstable and distributed parameter systems and so on (Huang and Xue, 2014). ADRC has become very striking to engineer even though theoretical research was lagging behind for a long time. This is mainly due to the uniqueness in concepts,

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Nomenclature

n_r n/n_{r0}	neutron density relative to initial equilibrium density
n	neutron density (n/cm^3)
n_{r0}	initial equilibrium (steady-state) neutron density
C	(neutron) Precursor density (atom/cm^3)
C_0	equilibrium precursor density at rated power
C_r C/C_0	precursor density relative to density at rated condition
λ	effective precursor radioactive decay constant (s^{-1})
ρ	reactivity
ρ_r	reactivity due to the control rod
Λ	effective prompt neutron life time (s)
β	total delayed neutron fraction
T_f	average reactor fuel temperature (°C)
T_l	temperature of the water leaving the reactor (°C)
T_e	temperature of the water entering the reactor (°C)
f_f	fraction of reactor power deposited in the fuel
P_0	initial equilibrium power (MW)
μ_f	total heat capacity of the fuel = weight of fuel times its specific heat (MW·s/°C)
μ_c	total heat capacity of the reactor coolant = weight of coolant times its specific heat (MW·s/°C)
Ω	heat transfer coefficient between fuel and coolant (MW/°C)
M	mass flow rate multiplied by heat capacity of the coolant (MW/°C)
Z_r	control input, control rod speed in units of fraction of core length per second
G_r	total reactivity worth of control rod.
α_f	fuel temperature reactivity coefficient (δk/k/°C)
α_c	coolant temperature reactivity coefficient (δk/k/°C)
T_{f0}	initial equilibrium (steady-state) fuel temperature
H	core height
I	iodine concentration (atom/cm^3)
X	xenon concentration (atom/cm^3)
σ_x	microscopic absorption cross-section (cm^2)
Σ_f	macroscopic fission cross-section (cm^{-1})
λ_I	iodine decay constant (s^{-1})
λ_x	xenon decay constant (s^{-1})
γ_I	iodine yield
γ_I	xenon yield
ϕ	neutron flux (n/cm^2 s)
v	thermal neutron speed
D	diffusion coefficient
m	node number of core

simplicity in engineering implementation, and good quality. The range of applications (Zheng and Gao, 2010) is very wide, including almost all fields, such as motion control (Gao et al., 2001), chemical processes, robotic system, flight control (Huang et al., 2001), the boiler–turbine–generator control system (Yu et al., 2010) and so on. For example, in USA, ADRC has been used at a Parker Hannifin Extrusion Plant in North America, and the outcome is more than 50% energy saving per line across ten production lines (Gao, 2015). And Texas Instrument has licensed ADRC technology and ADRC algorithms will be embedded in control chips (Schoenberger, 2011).

ADRC is developed mainly based on Han's two important concepts: (1) canonical form that breaks through the limit of linear and nonlinear systems; and (2) extended state observer (ESO) which can estimate disturbance and do real-time compensation, and total disturbance that including the uncertainties of model and external unknown disturbance (Huang and Xue, 2014).

ADRC inherits the advantage of PID and has better robustness performance. To tune the parameters easily, Gao Z Q proposed a parameterized LADRC (Gao, 2003), where linear gains replace nonlinear ones and the adjusted variable is only one, the band-width, which is familiar to engineers. Gao's approach makes control design and tune in the direction of science. The Characteristics and frequency response analysis of LADRC have been researched by Tian G and Gao Z (Tian and Gao, 2007). LADRC has already used in many areas of control engineering, but it is infrequent that LADRC based on bandwidth adjustment is applied to the PWR power control. In this paper, we also give full consideration to the model information. A new powerful systematic method to design a controller using LADRC theory is used. The designed controller is fairly simple and can be implemented easily. Simulation results show the effectiveness of the proposed method.

The rest of this paper is organized as follows: In Section 2, the models for the reactor are given. We introduce LADRC in Section 3. Section 4 presents the design of controller for PWR, simulation results in various operating conditions are discussed. Finally, some concluding remarks are drawn in Section 5.

2. Models of PWR

2.1. The reactor power plant model

The model used in this paper is typical for a TMI-type PWR at the middle of the fuel cycle rated at 2500 MW (Edwards et al., 1990; Ku et al., 1992). Two models are constructed. The first one is composed of the two nodes for neutron kinetic and heat transfer, and thermal feedback mechanisms from lumped fuel and coolant temperature and Xeon poison effect. This model is 18th order and it is used for controller design and control performance test. The second model is quite similar in equations to the first one, but composed of 10 nodes instead.

The models are represented with the following equations (Ben Abdennour et al., 1992; Edwards, 1991; Edwards et al., 1992; Arab-Alibeik and Setayeshi, 2003; Schultz, 1961; Ansarifar and Saadatzi, 2015a, 2015b; Wang et al., 2016; Wei et al., 2016; Wan et al., 2015; Wang et al., 2014, 2013):

$$\frac{dn_{ri}}{dt} = \frac{\rho_i - \beta}{\Lambda} n_{ri} + \frac{1}{\Lambda}\sum_{j=1}^{3}\beta_j C_{ri,j} + \Delta_i \tag{1}$$

$$\frac{dC_{ri,j}}{dt} = \lambda_j n_{ri,j} - \lambda_j C_{ri,j}, j = 1,2,3 \tag{2a}$$

$$\frac{dC_{ri,k}}{dt} = \lambda_k n_{ri,k} - \lambda_k C_{ri,k}, k = 1,2,\cdots,6 \tag{2b}$$

$$\frac{dT_{fi}}{dt} = \frac{f_f P_{i0}}{\mu_f} n_{ri} - \frac{\Omega_i}{\mu_f} T_{fi} + \frac{\Omega_i}{2\mu_f} T_{li} + \frac{\Omega_i}{2\mu_f} T_{ei} \tag{3}$$

$$\frac{dT_{li}}{dt} = \frac{(1-f_f)P_{i0}}{\mu_{ci}} n_{ri} + \frac{\Omega_i}{\mu_{ci}} T_{fi} - \frac{2M + \Omega_i}{2\mu_{ci}} T_{li} + \frac{2M - \Omega_i}{2\mu_{ci}} T_{ei} \tag{4}$$

$$\frac{dI_{ri}}{dt} = \lambda_I n_{ri} - \lambda_I I_{ri} \tag{5}$$