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Original Article

# Q1 Control of the pressurized water nuclear reactors power using Q8 optimized proportional–integral–derivative controller with particle swarm optimization algorithm

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ABSTRACT

Various controllers such as proportional–integral–derivative (PID) controllers have been designed and optimized for load-following issues in nuclear reactors. To achieve high performance, gain tuning is of great importance in PID controllers. In this work, gains of a PID controller are optimized for power-level control of a typical pressurized water reactor using particle swarm optimization (PSO) algorithm. The point kinetic is used as a reactor power model. In PSO, the objective (cost) function defined by decision variables including overshoot, settling time, and stabilization time (stability condition) must be minimized (optimized). Stability condition is guaranteed by Lyapunov synthesis. The simulation results demonstrated good stability and high performance of the closed-loop PSO–PID controller to response power demand.
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## Q4 1. Introduction

The development of load-following issues in nuclear reactors has always been of interest to researchers because of their nonlinear nature and the dependence of some dynamic parameters to the output power level. Accordingly, various controllers have been designed and optimized [1–4]. For example, Upadhyaya et al.[5] used a T-average controller on the primary side of integral pressurized water reactor (PWR) [5]. Proportional–integral–derivative (PID) controllers are widely used in various industries including nuclear facilities [6]. Therefore, various methods of PID gains tuning have been developed [7–9], and several methods have been used to optimize these gains for load-following in the nuclear power plants. Intelligent methods, such as fuzzy logic, have been at the forefront of these efforts. A comparative study of fuzzy, PID, and advanced fuzzy controls to simulate a nuclear reactor operation based on the experimental data was done by Li and Ruan [10]. Liu et al. [11] designed and optimized fuzzy-PID controller to control the nuclear reactor power and used the genetic algorithm to improve the "extending" precision. Their simulation results demonstrated good performance of the fuzzy-PID controller. Ye et al. [12] investigated water level control of a PWR based on radial basis function neural network and PID controller. The results showed remarkable robustness, adaptive ability, and higher control accuracy of this method. Dong [13] has Q5 used a physical approach to design PD power-level control for a PWR. The globally asymptotic stability was established for the reactor state variables. This method has been shown to be suitable for the cases in which the state-space model is used.

Particle swarm optimization (PSO) is a metaheuristic and real-coded algorithm. PSO is originally credited to Kennedy and Eberhart [14]. Primarily, it was intended by Shi and Eberhart [15] to simulate social behavior. de Moura Meneses et al. [16] have applied PSO to the nuclear reload problem of a PWR. Also, Pereira et al. [17] have used PSO for nonperiodic preventive maintenance scheduling programming for a high-pressure injection system of a typical 4-loop PWR. The power-level control is popular in comparison with other control methods such as coolant temperature. The numerous studies have been conducted on the reactor power-level control [18–20]. For example, Ansarifar and Akhavan [21] have employed sliding mode control design for a PWR during load-following

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operation. The present study is trying to optimize (tune) and schedule PID gains using the PSO algorithm. This controller is tuned to control a PWR-type nuclear reactor based on point kinetic model with any power demand (set point). The tuned PID is used to control relative power level changes which are equivalent to the relative neutron density/flux. It is shown that the coolant temperature is controlled along with the power level. The optimization is performed by minimizing an objective function of decision variables including overshoot, settling time, and stabilization time. Therefore, the tracking error between the output of the system and desired set point is minimized in each time interval.

## 2. Materials and methods

### 2.1. Nuclear reactor model

In this work, the point kinetic model of a nonlinear PWR core has been used with three groups of delayed neutrons (Skinner–Cohen's three groups model) and reactivity feedbacks due to changes in xenon concentration, lumped fuel, and coolant temperature (Eqs. (1)–(8)) [22]:

$$\frac{dn_r}{dt} = \frac{\rho_t - \beta}{\Lambda} n_r + \sum_{i=1}^{3} \frac{\beta_i}{\Lambda} c_{ri} \tag{1}$$

$$\frac{dc_{ri}}{dt} = \lambda_i n_r - \lambda_i c_{ri}, \quad i = 1, 2, 3 \tag{2}$$

$$\frac{dX}{dt} = \left(\gamma_X \Sigma_f - \sigma_X X\right) \frac{P_0}{G \Sigma_f V} n_r - \lambda_X X + \lambda_I I \tag{3}$$

$$\frac{dI}{dt} = \gamma_I \Sigma_f \frac{P_0}{G \Sigma_f V} n_r - \lambda_I I \tag{4}$$

$$\frac{dT_f}{dt} = \frac{f_f P_0}{\mu_f} n_r - \frac{\Omega}{\mu_f} T_f + \frac{\Omega}{2\mu_f} T_{in} + \frac{\Omega}{2\mu_f} T_{out} \tag{5}$$

$$\frac{dT_c}{dt} = \frac{\left(1 - f_f\right) P_0}{\mu_c} n_r - \frac{(2M + \Omega)}{2\mu_c} T_{out} + \frac{(2M - \Omega)}{2\mu_c} T_{in} \tag{6}$$

$$\frac{d\rho_{rod}}{dt} = G_r Z_r \tag{7}$$

$$\rho_t = \rho_{rod} + \rho_T + \rho_X = \rho_{rod} + \alpha_f \left(T_f - T_{f0}\right) + \alpha_c (T_c - T_{c0}) - \frac{\sigma_X}{\nu \Sigma_f} (X - X_0) \tag{8}$$

The parameters in Eqs. (1)–(8) are shown in Table 1. Also, the parameter values of a typical PWR at the beginning of fuel cycle in 100% of nominal power are displayed in Table 2.

In addition, $\mu_c$, $M$, $\Omega$, $\alpha_f$, and $\alpha_c$ are not constant but rather a function of the initial equilibrium power level ($n_{r0}$) as follows [23]:

$$\mu_c = \left(\frac{16}{9}\right) n_{r0} + 54.022 \tag{9}$$

$$M = 28 n_{r0} + 74 \tag{10}$$

$$\Omega = \left(\frac{5}{3}\right) n_{r0} + 4.93333 \tag{11}$$

$$\alpha_f = (n_{r0} - 4.24) \times 10^{-5} \tag{12}$$

$$\alpha_c = \left(-4 n_{r0} - 17.3\right) \times 10^{-5} \tag{13}$$

### 2.2. PID controller

The PID controller is the simplest controller to design and use in about 90% of industries as real-time controllers. It alone indicates the importance of this controller [9]. The PI controller can also be used as regards it is less responsive to real and relatively rapid changes in state, and the system will be slower to meet the desired signal. This can be important in controlling of accidents and highly rapid changes in power. In addition, PID controller has less overshoot and settling time compared to PI controller [24]. PID equation specifies as follows: Q6

$$C(t) = K_P + \frac{1}{s} K_I + \frac{s}{1 + \tau s} K_D, \tag{14}$$

**Table 1**
Model parameters.

| | | | |
|---|---|---|---|
| $P_0$ | Full core power, MW | $\Lambda$ | Neutron generation time, s |
| $n_r$ | Normalized neutron density (relative to neutron density at rated power—$P_0$) | $\lambda_i$ | $i$th Delayed neutron group decay constant, $s^{-1}$ |
| $c_{ri}$ | $i$th Group normalized precursor density (relative to density at rated power) | $\gamma_X$ | Xenon yield per fission |
| $X$ | Xenon concentration, $cm^{-3}$ | $\lambda_X$ | Xenon decay constant, $s^{-1}$ |
| $I$ | Iodine concentration, $cm^{-3}$ | $\gamma_I$ | Iodine yield per fission |
| $T_f$ | Fuel average temperature, °C | $\lambda_I$ | Iodine decay constant, $s^{-1}$ |
| $T_{f0}$ | Fuel average temperature at the initial condition, °C | $\Sigma_f$ | Macroscopic thermal neutron fission cross-section, $cm^{-1}$ |
| $T_c$ | Coolant average temperature, °C | $\nu$ | Average number of neutrons produced per fission of $^{235}U$ |
| $T_{c0}$ | Coolant average temperature at the initial condition, °C | $\sigma_X$ | Microscopic thermal neutron absorption cross-section of xenon, $cm^{-2}$ |
| $T_{in}$ | Coolant inlet temperature, °C | $G$ | Useful thermal energy liberated per fission of $^{235}U$, MW·s |
| $T_{out}$ | Coolant outlet temperature, °C | $V$ | Core volume, $cm^3$ |
| $\rho_t$ | Total reactivity, δK/K | $f_f$ | Fraction of reactor power deposited in the fuel |
| $\rho_{rod}$ | Reactivity due to control rod movement, δK/K | $\mu_f$ | Fuel total heat capacity, MW·s/°C |
| $\rho_T$ | Temperature reactivity feedback, δK/K | $\mu_c$ | Coolant total heat capacity, MW·s/°C |
| $\rho_X$ | Xenon reactivity feedback, δK/K | $M$ | Mass flow rate time heat capacity of water, MW/°C . |
| $Z_r$ | Control rod speed, fraction of core length/s | Ω | Coefficient of heat transfer between fuel and coolant,MW/°C |
| $G_r$ | Control rod total reactivity, δK/K | $\alpha_f$ | Fuel temperature coefficient, (δK/K)/°C |
| $\beta$ | Effective delayed neutron fraction, $\beta = \sum_{i=1}^{3} \beta_i$ | $\alpha_c$ | Coolant temperature coefficient, (δK/K)/°C |
| $\beta_i$ | $i$th Group effective delayed neutron fraction | | |

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