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Multi-objective optimization of control parameters for a pressurized water reactor pressurizer using a genetic algorithm

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ABSTRACT

This paper presents the multi-objective optimization of control parameters for a pressurized water reactor (PWR) pressurizer using a genetic algorithm. Firstly, a widely-used nonequilibrium three-region pressurizer model is adopted to describe dynamic behavior of the pressurizer during transient operations. Then, a pressure and water level control strategy of the pressurizer employing proportional-integral-derivative (PID) controllers is introduced and analyzed, which uses a spray valve and two electric heaters for pressure control and regulates charging flowrate with letdown flowrate keeping constant for water level control. With implementation of the pressurizer model and control strategy, a control simulation platform of the pressurizer is developed in MATLAB/Simulink environment. Based on the simulation platform, the non-dominated sorting genetic algorithm II (NSGA-II) is applied for the multi-objective optimization of the PID controllers' parameters in the pressure and water level control systems of the pressurizer, respectively, with multi-objective functions defined as the control performance obtained and the control cost required. Fitness values of the multi-objective functions are generated based on simulation results of the pressurizer during a 100% of full power (FP) to 25% FP load rejection transient in each iteration step of the optimization. Two Pareto fronts consisting of non-dominated optimal solutions are obtained for two multi-objective optimization problems for the pressure and water level control systems. Five typical points on each Pareto front are chosen for the corresponding multi-objective optimization problem. Dynamic responses of the pressurizer employing the optimal control parameters at these points are compared with those using original design control parameters, under a 100% FP to 90% FP step load decrease transient, a 90% FP to 100% FP step load increase transient and the above load rejection transient. Based on the comparison results, optimum parameters are chosen for the pressure and water level control systems. It has been demonstrated that the control systems with these optimum parameters can keep good balance between maximizing control performance and minimizing control cost of the pressurizer, which contributes to the improvement of system responses with reduced mechanical wear and fatigue risk of corresponding actuators.

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1. Introduction

A pressurizer is a key equipment to maintain the pressure of reactor coolant system (RCS) in a pressurized water reactor (PWR) at its setpoint value during steady-state operations and to regulate its variation within allowed tolerances during transient operations. Moreover, it is usually connected to a hot leg of RCS to maintain the coolant quantity during transient operations by absorbing (discharging) coolant from (to) the RCS during the swell (shrink) of coolant caused by its temperature increase (decrease). In view of the two reasons, the pressurizer pressure and water level control systems are very import to ensure the safe and stable operation of PWRs. At present, the pressure of a PWR pressurizer is usually controlled by adjusting electric heater power or spray flowrate according to a control signal generating program with proportional-integral-derivative (PID) compensated pressure error as input, where the PID controller is called the pressure error controller. While the water level of the pressurizer is usually maintained by regulating charging flowrate with letdown flowrate keeping constant by a cascade control system consisting of two proportional-integral (PI) controllers called the level error controller and the flowrate error controller, respectively. Considering the PID or PI controller in a process control system determines the system response largely, the parameters of the pressure error controller as well as those of the level error and flowrate error controllers should be well turned to obtain satisfactory control performance of the pressurizer.

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For control parameter optimizations, the establishment of reasonable objective function(s) is a key process. However, for many practical problems, mathematical equations that could describe the interconnections among the parameters to be optimized and their coupling effects on the targets to be achieved cannot be obtained. This makes the determination of a reliable objective function to be challenging. For many complex systems, the objective function for optimization is just too complex to be analytical. In this case, the simulation-based optimization is a useful technique for the tuning of system parameters, which evaluates the objective function by computer simulations and requires no prior knowledge of the structure of the objective function for estimating statistical measures of the system. According to different ways in searching optimal parameters, the technique can be generally classified into manual search methods and automatic search methods. The simulation-based manual trial and error method is a widely used optimization method, which determines optimal parameters one by one through comparing the simulation results obtained by assigning one parameter with different values and fixing the others. This method has been used by many researchers to optimize control parameters of nuclear reactors. Wang et al. (2014a) applied this method for the optimization of power control parameters of the CPR1000 reactor during daily load follow operations. Wang et al. (2014b) used this method to study the impacts of key parameters on the Mechanical Shim (MSHIM) control system performance of the AP1000 reactor and to obtain the optimum numerical ranges for these parameters. Since it is difficult for the method to search two or more parameters simultaneously, it is inefficient, and its application to complex problems with many parameters to be optimized is very time consuming. Moreover, due to the unavoidable coupling effects between different parameters on system responses, the method may not provide good optimization results for nonlinear complex systems, and the parameters after tuning may be far from their optimum. The automatic search method mentioned here can be generally defined as a simulation-based optimization that could find optimal or satisfactory solutions according to a presetting update algorithm instead of searching them manually or subjectively.

Considering the strong nonlinearity and high complexity of the PWR pressurizer and the involvement of numerous control parameters to be optimized which are also called decision variables, the artificial intelligence (AI) based automatic search methods seem to be practicable alternatives. These AI-based methods like the neural network, genetic algorithm (GA) and particle swarm optimization (PSO) have been widely used and shown good results in different fields (Mohammadi et al., 2018; Ganjehkaviri et al, 2017; Bendu et al., 2017). Many researchers have also used these methods for control parameter optimization of nuclear reactors. Wang et al. (2016) applied a PSO for parameter optimization of the MSHIM control system of the AP1000 reactor with system requirements including power control performance, control bank movement and AO control constraint synthetized in one objective function. Analysis results demonstrate that the optimized MSHIM control system can improve the power control performance and reduce the control rod movement without compromising the AO control. Mousakazemi et al. (2018a,b) used the real-coded GA and PSO, respectively, to optimize the gains of a PID controller for a PWR power control system by minimizing an objective function with integration of different performance indexes including overshoot, setting time and stabilization time. The results show good stability of the method and high performance of the optimized PID gains for load follow operations of the PWR. In the above three articles, the authors used one objective function with weighted sum of different performance indexes like the integral time absolute error (ITAE), overshoot, settling time of system responses during parameter optimizations. Although better control performances can be obtained after optimization, the impacts of the control parameters on different performance indexes cannot be described and explained straightforwardly. And the selection of suitable weighting factors to keep good balance between different performance indexes is not easy and always lacks of effective objective criteria.

In view of the drawbacks of the above single-objective optimization methods, many other researchers applied the AI-based multi-objective simulation optimization methods for the seeking of feasible compromising combinations of control parameters to satisfy requirements on different types of performance indexes. Wan and Zhao (2017a) optimized four AP1000 power control parameters using the non-dominated sorting genetic algorithm II (NSGA-II) with the overshoot in reactor power and the maximum absolute deviation of coolant average temperature (T_{avg}) from its reference value defined as two objective functions. Simulation results have shown satisfactory responses of both the reactor power and the T_{avg} during typical load change transients with optimized parameters. Wan et al (2017b) designed conventional power and temperature controllers for an advanced small PWR using the analytical solution of lead compensator through trial and error first and then optimized the controllers' parameters using the NSGA-II with the ITAEs of reactor power and T_{avg} as two objective functions. Results have also shown improved reactor power and T_{avg} responses with the optimized control parameters. The above multi-objective optimizations of control parameters have demonstrated to be able to improve multi-objective control performance, but the control cost needed was not taken into consideration. In this case, control actions of corresponding actuators may be more frequent than those before optimization in order to obtain better control performance, which increases their mechanical wear and fatigue risk.

Given the above, this paper presents the multi-objective optimization of control parameters with consideration of both the control performance obtained and the control cost required for a small PWR pressurizer using the NSGA-II. The remaining part of the paper is organized as follows. Section 2 presents a nonequilibrium three-region pressurizer model, a pressure and water level control strategy and a simulation platform with implementation of the pressurizer model and control strategy, for the small PWR pressurizer. Based on the platform, key parameters of the pressurizer pressure and water level control systems were optimized using the NSGA-II in Section 3. After that, three typical load change transients have been simulated employing the optimized and original design control parameters, respectively, to show the effectiveness of the multi-objective optimization in Section 4. Conclusions are drawn in the last section.

2. Development of the pressurizer simulation platform

In the present study, the pressurizer of a small PWR is chosen for the control parameter optimization study. Structure and operating parameters of this pressurizer are tabulated in Table 1. At steady-state condition, the volumes of water and steam in the pressurizer are 8.907 m^3 and 5.853 m^3, respectively. In the rest of this section, the nonequilibrium three-region model, pressure and water level control systems and simulation platform in MATLAB/Simulink for the small PWR pressurizer will be introduced, respectively.

2.1. Pressurizer model

Due to the complicated thermodynamic processes in a pressurizer during transient operations, it has always been a challenge to develop high-fidelity, dynamic mathematical models for PWR pressurizers. Since 1960s, various types of pressurizer models have been developed, which can be generally classified as equilibrium and nonequilibrium models. The equilibrium pressurizer model only suits for the steady-state condition or very slow transients due to

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