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Novel fuzzy logic based coordinated control for multi-unit small modular reactor

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ABSTRACT

Multi-unit small modular reactor (M-SMR) is a nuclear power plant with multiple nuclear steam supply systems (NSSSs) connected to a single shared secondary loop system. Unlike single SMR, strong coupling characteristics of M-SMR will affect safe, smooth and steady operation under both fault and unbalanced load conditions. In order to improve fault-tolerant operation performance, an effective coordinated control strategy (CCS) is required. In this paper, a novel fuzzy logic based CCS with a M-SMR coordinating controller has been proposed, which utilizes two sets of local controllers for each subsystem. In order to meet the operation goal, the coordinating controller generates coordinated control actions using the fuzzy logic approach to coordinate the local controllers and to perform specific control actions. In this paper, we designed two different local controllers to ensure an excellent performance. The first is a back-propagation neural network (BPNN) based PID controller with capability for floating control and the second is a fuzzy controller with capability for quick regulatory control. The control strategy is designed to ensure operation safety of the reactors and to guarantee consistent and stable steam output of the secondary side under fault and unbalanced load conditions. To evaluate the fuzzy logic based CCS, we simulate faults in the 1# NSSS main coolant pumps (MCPs) which create considerable instability to the coordinated control. Simulation results show smoother and steadier operation performance, compared to the BPNN-based PID control strategy.

1. Introduction

According to IAEA (IAEA, 2004), SMRs are reactors with less than 300 MW electric power, having simplified system design and passive safety features. The existing SMRs like IRIS (Carelli et al., 2004) and NuScale (Ingersoll et al., 2014), have integral pressurized reactor vessel which contain multiple once-through steam generators (OTSGs). However, in order to ensure consistent and stable energy output of M-SMR under fault conditions, the operation goal between NSSSs will undergo tremendous changes. An effective CCS is needed to reach the operation goal quickly and smoothly, otherwise it will threaten safe, smooth and steady operation. A number of research work has digged into the ideal steady-state control strategy for SMRs (Hu et al., 2012; Du et al., 2015). These research works focus on keeping the average coolant temperature and pressure of the primary circuit and the steam pressure constant under load following conditions. In order to increase the stability of OTSG, Zhao (Zhao et al., 2015) proposed an integral pressurized water reactor (IPWR) control strategy which keeps the steam pressure constant, and changes the average coolant temperature along with reactor power. Additionally studies on the coordinated control of M-SMR have been conducted (Dong et al., 2016a, b). For multi-unit reactors, Perillo (Perillo et al., 2011) developed a CCS for a nuclear power plant which maintains both average coolant temperature and steam outlet pressure around their set points under load following condition and a series of perturbation cases in both two units of IRIS reactors. Yuan (Yuan and Coble, 2017) proposed a Takagi–Sugeno fuzzy logic-based power distribution system to maintaining key temperatures in the primary system or to meeting power demands during daily load-following operation under different levels of pump degradation. The above-mentioned studies show satisfactory transient performance in load following condition with considerable coordinated control. However, there are certain strategic limitations to the performance of these controllers under extended fault conditions, which threatens operation safety Highly automated coordinated control implies the detection of conditions and events, re-evaluation of operation goal, and immediate intervention for event management (Clayton and Wood, 2010). To overcome the limitations, coordinated control based on fuzzy logic approach has been studied in some industry applications, such as power-

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distribution control for a prototypical advanced reactor (Yuan and Coble, 2017), unmanned robot applied to automotive test (Chen and Zhang, 2016), large-scale photovoltaic farms to support grid frequency regulation (Thao and Uchida, 2017), grid-connected wind farms (Moger and Dhadbanjan, 2017), all resulting with satisfactory control performance. Motivated by this, we propose a hierarchical CCS in pursue of the operation goal. The proposed coordinating controller generates coordinated control actions using the fuzzy logic approach. The fuzzy inference method guides the local controllers to perform specific control actions. Currently, the most important goal for SMR autonomous control is to allow extended fault tolerance for anticipated events or degraded conditions (Wood et al., 2017). The proposed coordinated control system with the capability for extended fault tolerance reduces operator intervention and improves operation safety and economy, which makes a moderate progress in autonomous control.

2. Description and modeling of M-SMR

In order to study the M-SMR coordinated control strategy, a simplified two-unit SMR plant configuration is proposed. Fig. 1 shows two SMR coupled with a shared secondary system, where superheated steam from two NSSSs merges into the shared steam header. Feed-water mass flow rate to each NSSS is determined by corresponding feed-water valve and feed-water pump. In addition, an IPWR NSSS unit consists of a reactor core, four groups of OTSGs, four MCPs and a pressurizer which is incorporated into a single pressure vessel (each MCP sending coolant to a group of three OTSGs). The NSSS unit draws on the design of the IP200 integral pressurized water reactor (Khan et al., 2013; Sun et al., 2014; Sun et al., 2017; Wang et al., 2014), and major parameters of M-SMR under rated power conditions are shown in Table 1.

The two-unit SMR model is established with the best-estimate code RELAP5, whose main steam system and feed-water system are modeled as system boundary, which is shown in Fig. 2.

3. The coordinated control strategy of M-SMR

3.1. The framework of the coordinated controller

We propose a fuzzy logic based CCS which considers hierarchical coordinated control, comprising of a fuzzy logic based coordinating controller and two local controllers, as shown in Fig. 3. With situational awareness from sensors and diagnostic informa-

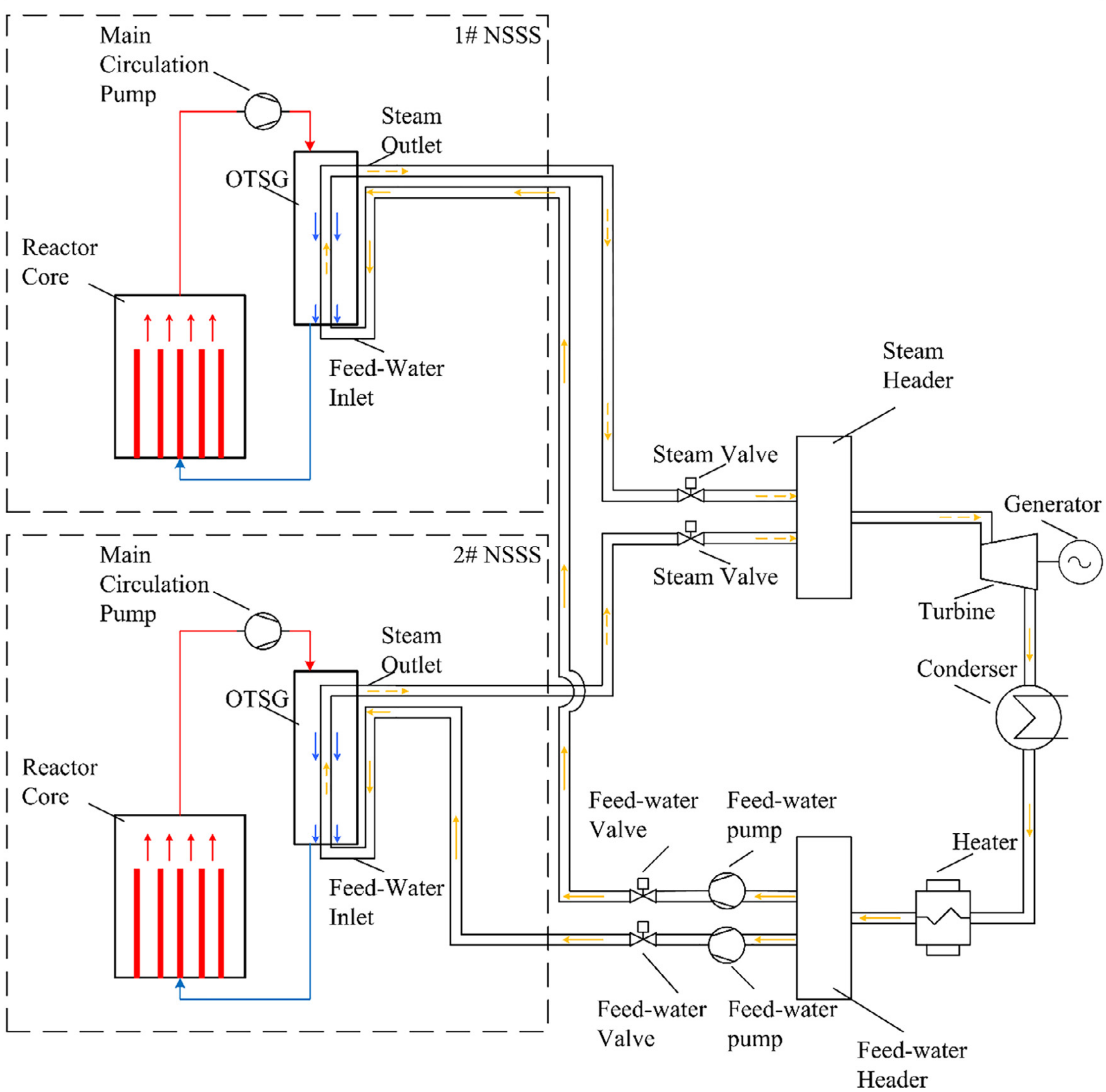

Fig. 1. Simplified flow diagram of M-SMR.