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Original Article

A Takagi–Sugeno fuzzy power-distribution method for a prototypical advanced reactor considering pump degradation

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ABSTRACT

Advanced reactor designs often feature longer operating cycles between refueling and new concepts of operation beyond traditional baseload electricity production. Owing to this increased complexity, traditional proportional–integral control may not be sufficient across all potential operating regimes. The prototypical advanced reactor (PAR) design features two independent reactor modules, each connected to a single dedicated steam generator that feeds a common balance of plant for electricity generation and process heat applications. In the current research, the PAR is expected to operate in a load-following manner to produce electricity to meet grid demand over a 24-hour period. Over the operational lifetime of the PAR system, primary and intermediate sodium pumps are expected to degrade in performance. The independent operation of the two reactor modules in the PAR may allow the system to continue operating under degraded pump performance by shifting the power production between reactor modules in order to meet overall load demands. This paper proposes a Takagi–Sugeno (T–S) fuzzy logic-based power distribution system. Two T–S fuzzy power distribution controllers have been designed and tested. Simulation shows that the devised T–S fuzzy controllers provide improved performance over traditional controls during daily load-following operation under different levels of pump degradation.

1. Introduction

Advanced small modular reactors (AdvSMRs) can potentially complement the current fleet of large, baseload light water reactors and replace fossil fuel-based energy production to support safe, carbon-neutral energy. AdvSMRs support new concepts of operation, such as load following and power peaking, as renewable energy sources more deeply penetrate the energy grid. These new concepts of operation will precipitate new research in system dynamics and control. The control system, the function of which is to regulate the output power and temperatures of the reactor system during operation, is of great importance to the realization of the economic goals and the improvement of performance. Liquid metal reactors (LMRs) present additional control challenges not seen in the current fleet of baseload light water reactors, including additional feedback effects and large time delays due to thermal inertia of sodium coolant. Long-term control over planned operating cycles, some as long as 40 years [1], introduce further complications as the evolving condition of key components and systems may affect the plant's operation.

Primary and intermediate sodium pumps are key components in the reactor coolant system, which ensure that heat is removed from the core and transferred to the energy-producing balance of plant system. These pumps may degrade during long-term normal plant operation, which has a negative effect on the performance of the reactor power block. As pump degradation is detected and monitored, a plant could shut down for maintenance and repair; however, this will negatively impact the economics and availability of the system. Alternatively, the distribution of power production across independent reactor modules could be adjusted to compensate for degraded condition in one module, thereby extending the operating period of the overall system while meeting reactor power demands. In order to improve the economic competitiveness of advanced reactors, it is important to take pump degradation into consideration when designing control system for the reactor block.

The condition and performance of pumps is not directly measured during operation, and the available flow from pumps is

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usually unknown. Traditional control strategies may be challenged in controlling the system in the face of these uncertainties. Previous work has investigated the use of model predictive control for control of LMRs under normal conditions [2]. That work focused on a single large-scale reactor operating under normal load-following conditions with no equipment degradation. The proposed model predictive control approach could potentially be extended, but it would likely require models of the degradation of key equipment and systems as well as a model of the overall nuclear power system. Fuzzy control offers a straightforward strategy that does not require explicit modeling of the reactor system or the equipment condition. The Takagi–Sugeno (T–S) fuzzy control method studied in this work is a powerful tool in the control of complex systems, especially those with uncertainty [3].

Fuzzy theories have been studied for application in nuclear systems in many aspects, including the control of U-tube steam generators [4,5], the control of nuclear reactor power [6,7], and water level control of a steam generator [8]. Work by Na and Upadhyaya [9] investigated fuzzy control for power distribution across the core of a single pressurized water reactor. Luan et al. [10] demonstrated a T–S-based fuzzy controller for load following control of reactor. This paper goes beyond the prior work by applying fuzzy methods for high level power distribution control under uncertain equipment condition and performance.

This paper presents the results of applying a T–S-based fuzzy power distribution controller to the prototypical advanced reactor (PAR) model. The following section introduces the PAR design and the proposed concept of operation. Traditional proportional–integral–derivative (PID)-based control of the PAR under normal conditions, as developed by Liu [11], is also described. The performance of this control strategy is demonstrated under normal and degraded conditions. Section 3 introduces the proposed T–S controller for power distribution across the two reactor modules in the PAR and presents the results of two proposed T–S controllers, one giving preference to maintaining key temperatures in the primary system and the other giving preference to meeting power demands. Finally, Section 4 draws conclusions from the current work and suggests approaches for the integration of the power distribution controller in a larger supervisory control strategy.

2. PAR design

The PAR is a generic reactor concept developed to support test and evaluation of online monitoring, enhanced risk assessment, and operations and maintenance planning for the general class of AdvSMRs. The PAR design includes many features of AdvSMRs, such as nonlight water coolant, multimodular operation, deliberately small power output, and advanced concepts of operation. The PAR design is intended to support load following, cogeneration and process heat applications, and so-called passive safety features. The PAR is not intended to represent any specific AdvSMR design currently being developed; instead, it is a platform for testing online monitoring and controls strategies that may be necessary to support the future development and deployment of any in the class of AdvSMRs.

2.1. Description of the PAR design

A schematic diagram of PAR is shown in Fig. 1 [12]. The PAR power block includes two independent, pool-type LMR cores, each with an integral intermediate heat exchanger and a dedicated steam generator located outside the primary containment. Steam from the two modules is mixed in a steam header and sent to a common balance of plant. A simulation model of the PAR design was previously developed in MATLAB-Simulink [11]. The two LMRs are based on Experimental Breeder Reactor-II [13], each providing 20 MWe power for a total reactor block output of 40 MWe. The intermediate heat exchangers and steam generators are also based on those at Experimental Breeder Reactor-II [13], whereas the balance of plant model is adapted from [14].

The PAR design adopts the multimodular concept, which means that each unit can be operated independently with different power output as desired. The multimodular operation supports greater availability of the overall system by providing some level of redundancy in heat production. Smaller reactor cores are expected to be more responsive to fast changes in demand as expected with power-peaking modules to accommodate intermittent renewable production, although this is not the focus of the current work. Of particular interest in the current work is the possibility of using the flexibility of multimodular plants to compensate for potentially degrading equipment in one module. The overall control strategy of the PAR is described in the following subsection, including both local control in each module and global control (e.g., power distribution) in the full power block.

2.2. Control targets of the control system

For multimodular power blocks, power distribution between the modules needs to be considered in the design of control strategy, on the condition that the total output power of the modules matches the demanded load profile.

Moreover, to provide a steady environment to the reactor cores, it is reasonable to choose keeping the inlet and outlet sodium temperatures constant during daily operation as a control target for the control system [15].

For the proposed concept of operation, the control targets of the control system can be summarized as follows:

1. The total power of the reactor power block meets the demanded load
2. The temperature of the inlet sodium in each reactor core is constant (371.5 °C)
3. The temperature of the outlet sodium in each reactor core is constant (472.7 °C)

The available actuators to meet these control targets include external reactivity (control rod motion) in each reactor module, primary sodium flow rate in each reactor module, and secondary sodium flow rate in each reactor module. In this control scheme, demand is evenly divided across the two power modules to provide the total load. For speed of simulation, the feedwater temperature and flow rate to the steam generators follow a program set by the overall power block power and the power produced by each reactor module, respectively.

2.3. Control strategy under normal conditions

One means of operating the PAR power block would be to evenly split production of the demanded load between the two modules. This strategy is reasonable when the two modules both operate under normal conditions. Traditional PID controllers can then be used in the control of power-level and temperatures of each module. This approach to system control was studied by Liu [11]; a full discussion of the proposed control scheme is given there, along with the relevant PID gains. Using primary and intermediate sodium pumps to control the outlet and inlet sodium temperatures, respectively, and external reactivity to control the power production, the control strategy for a single module is shown in Fig. 2. Under normal conditions, when no equipment degradation is affecting module performance, the two reactor modules are operated independently, but their operation is identical.