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Original Article

INSTRUMENTATION AND CONTROL STRATEGIES FOR AN INTEGRAL PRESSURIZED WATER REACTOR

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ABSTRACT

Several vendors have recently been actively pursuing the development of integral pressurized water reactors (iPWRs) that range in power levels from small to large reactors. Integral reactors have the features of minimum vessel penetrations, passive heat removal after reactor shutdown, and modular construction that allow fast plant integration and a secure fuel cycle. The features of an integral reactor limit the options for placing control and safety system instruments. The development of instrumentation and control (I&C) strategies for a large 1,000 MWe iPWR is described. Reactor system modeling—which includes reactor core dynamics, primary heat exchanger, and the steam flashing drum—is an important part of I&C development and validation, and thereby consolidates the overall implementation for a large iPWR. The results of simulation models, control development, and instrumentation features illustrate the systematic approach that is applicable to integral light water reactors.

1. Introduction

The University of Tennessee (Knoxville, TN, USA) is engaged in research and development projects related to instrumentation and controls (I&C) for small modular reactors (SMRs) and integral pressurized water reactors (iPWRs). The technical approach incorporates the development of physics-based models for the control design, the development of nonintrusive sensors for flow monitoring, and placement of sensors to maximize fault detection and isolation. The results of research and development are illustrated with application to an integral inherently safe light water reactor (I2S-LWR) that is being developed under a United States (U.S.) Department of Energy-funded research and development project.

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Integral reactors have in-vessel space constraints and limited vessel penetrations [1]. Because of this, traditional instruments installed in the primary loop piping need to be placed elsewhere and necessitate the development of new approaches for measuring safety and nonsafety parameters. The overall objective of the work presented in this context is to identify and overcome I&C challenges posed by large scale integral platforms, and to demonstrate the applicability of monitoring and diagnostic strategies that should be incorporated in all future nuclear plant designs.

The I2S-LWR is a 1,000 megawatt-electric (MWe) iPWR, and incorporates some features of an earlier iPWR [2]. The complete plant is being designed and developed as part of the U.S. Department of Energy Integrated Research Project (IRP). The Georgia Institute of Technology (Atlanta, GA, USA) is the project lead with partners from universities, national laboratories, industry, and international organizations as collaborating institutions.

The I2S-LWR consists of a reactor core with a maximum uranium-235 (U^{235}) enrichment of 5%. The steam generator system is divided into a primary heat exchanger and a flashing drum. The reactor vessel has eight microchannel heat exchangers that provide efficient primary coolant to secondary water liquid phase heat transfer [3]. The high-pressure secondary water is converted to steam in a flashing drum outside the primary vessel. In case of a structural breach, this design provides additional safety by minimizing steam water interaction inside the reactor pressure vessel (RPV). The compact design of the heat exchangers provides sufficient space for the installation of eight passive decay heat removal loops inside the vessel. The approximate overall vessel height is 21 meters and an overall vessel diameter of 5.25 meters.

The following control systems have been developed as part of the overall simulation model: (1) T-average controller on the primary side that changes reactor power using control rod reactivity; (2) flashing drum water level controller using feed flow manipulation; and (3) flashing drum pressure controller by turbine control valve actuation.

Simulation models describing the physics of various components are central to the development of I&C strategies and for testing the feasibility of these technical approaches.

One issue in the operation of integral reactors is the ability to measure key process parameters, especially when they are safety-related. The direct measurement of process variables such as the primary coolant flow rate is restricted because of the limited space and the penetrations of the RPV, thus making it difficult to install flow meters for direct measurement. Experimental studies and theoretical analysis [4] indicate a direct relationship between the flow rate and electrical power of the motor driving the pumps. The pump hydraulic power is a function of the pump head and flow rate; hence, pump discharge is a function of motor power.

An alternative approach for measuring the primary flow rate has been proposed for when there is access to the secondary (i.e., steam) side dynamics [5]. Some integral light water reactor designs have part of the steam generator system outside the primary vessel [6]. This provides access to the steam generator (SG) feed flow rate, and allows measurement of the SG inlet and outlet conditions. This information is used to make an enthalpy balance on the primary and the secondary sides, and is used to infer the primary coolant flow rate. This inferential technique can be implemented online.

A second issue is the placement of in-vessel instrumentation. Because of space limitation in integral reactors, it is necessary to manage the placement of process and neutron sensors, cable routing, and data transmission. The necessary in-vessel instrumentation includes core upper and lower plena temperatures, in- and ex-core neutron detectors, and primary coolant flow rate. Ex-vessel ultrasonic transit time flow meters are being developed, and are especially useful when the primary pumps are shut down during a severe accident condition. Studies are underway to determine the optimum locations and the types of transmitters needed for these measurements. In-core detector strings are being used in some current designs [7].

The following sections provide the development and results of I&C approaches through dynamic simulation of an integral, inherently safe light water reactor (I2S-LWR) system being developed under a U.S. Department of Energy research project, which is led by the Georgia Institute of Technology (Atlanta, GA, USA). General instrumentation strategy and sensor locations are outlined in Section 2. A new approach for primary flow measurement, which measures the ultrasonic reflection transit time, is described in Section 3. The dynamic modeling of key system components such as reactor core dynamics, microchannel heat exchanger, and flashing drum (i.e., SG system) is presented in Section 4. Concluding remarks and continuing future work are explained in Section 5.

2. In-vessel instrumentation for I2S-LWR

2.1. *System configuration and instrumentation*

In the integral design of the I2S-LWR, the primary coolant is restricted to the RPV, and thereby eliminates the possibility of a large pipe break loss of coolant accident occurring via coolant piping. To accomplish this, the secondary coolant must enter the RPV for heat transfer to occur. In small reactor designs, this is typically accomplished with a once-through SG that produces superheated or saturated steam. This type of SG is entirely contained within the RPV. To achieve this within the I2S-LWR, the pressure vessel would have to be unreasonably tall because of the high power rating of the reactor at 2,850 megawatts-thermal (MWth). One approach to resolve this issue is to use a liquid-to-liquid microchannel heat exchanger contained within the RPV, and a steam flashing drum outside the RPV to produce saturated steam from the high-pressure, high-temperature liquid secondary flow, which exits the heat exchanger and enters the flashing drum.

Fig. 1 illustrates the secondary fluid flow and its interface with the primary coolant, and its relative configuration with respect to the reactor vessel.

The numbers at various points in the fluid flow pathway in Fig. 1 are the locations of instrumentation placement. The measurements at these locations in the secondary heat transport system are listed in Table 1.