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Steam Generator Model and Controller for Cybersecurity Analyses of Digital I&C Systems in PWR Plants

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INTRODUCTION

Digital Industrial Control Systems (ICS) raise cybersecurity concerns in critical energy infrastructure, including nuclear power plants. A Nuclear Instrumentation & Control Simulation (NICSim) platform is currently being developed at the University of New Mexico's Institute for Space and Nuclear Power Studies in collaboration with Sandia National Laboratories. It aims to emulate the digital Instrumentation and Control (I&C) architectures in PWR plants for investigating potential cyber-vulnerabilities. This platform links emulated Programmable Logic Controllers (PLCs) to physics-based models of the power plant and various components, such as the Steam Generator (SG).

This paper presents a simplified, fast-running transient model of a PWR steam generator with a Feedwater Control PLC, for implementation in the NICSim platform (Fig. 1). The PLC maintains the water inventory in the SG by adjusting the flow rate to the feedwater injection ring[1].

The developed steam generator transient model uses the versatile Matlab Simulink[2] and it is linked to the emulated PLC using a developed and validated shared memory Data Transfer Interface[3]. This interface keeps the Simulink simulation timing in synch with a real-time clock. This research investigates the effects of the PLC's response time, cycle frequency, and the simulation timestep on the dynamic response of the coupled PLC and steam generator model. The PLC's response is compared to that of an ideal controller consisting of internal control logic built within the Simulink model. This ideal controller uses the same control logic but runs within the SG Simulink model with no control signal response delay.

APPROACH

The developed steam generator model solves the mass, energy, and momentum balance equations for the primary coolant on the tube side. It also solves the mass and energy balance equations for the secondary coolant on the shell side (Fig. 1a). The model calculates the total pressure losses in the primary loop and the mass flow rate and the inlet and exit enthalpy for the primary coolant flow through the steam generator U-tube bundle. The steam/water flow on the shell side is modeled using a separate flow approach. The feedwater mixes with the recirculated saturated water in the downcomer, before flowing up on the shell side of the steam generator.

The steam generator model calculates the non-boiling and boiling heights, the steam exit quality and flow rate to the turbine in the secondary loop. It also determines the water level in the SG annular downcomer as well as the exit enthalpy of the water flowing in the primary loop to the reactor. The water level in the annular downcomer is calculated from equating the weight of the water column to that of the water and steam column within the central section of the SG. The SG model does not account for the thermal inertia in the energy balance.

The thermodynamic state points (1-5 in Fig. 1a) are specified as model inputs. The steam generator exit pressure (3) is taken constant (5.76 MPa), and so is the condenser exit pressure (5) (0.01 MPa). The SG model also assumes constant turbine and feedwater pump efficiencies of 95%. The pressure head of the feedwater pump is kept constant while varying the shaft speed commensurate with the desired feedwater rate.

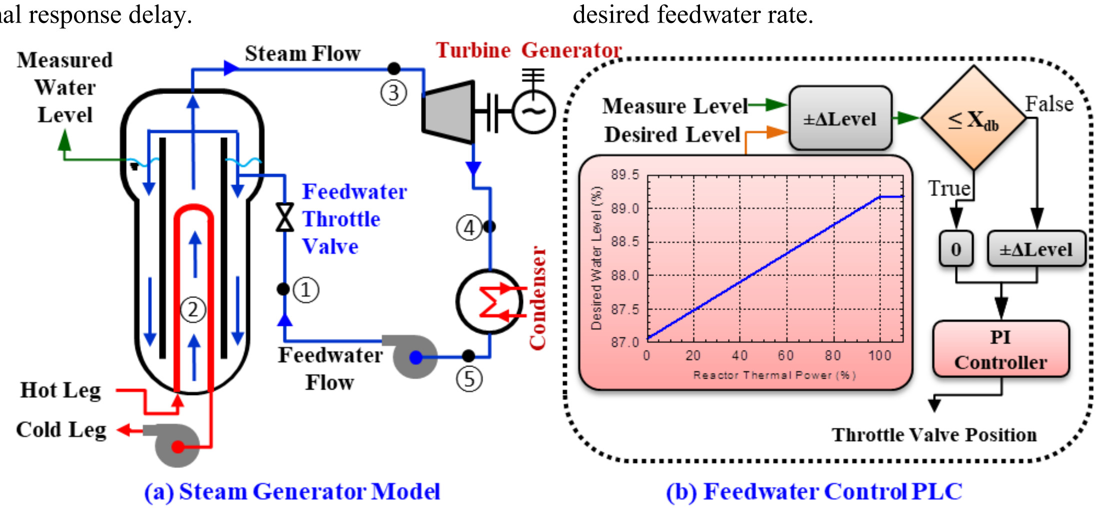

Fig. 1. Block Diagram of (a) Steam Generator Model and (b) Feedwater Controller PLC

The developed emulated Feedwater Control PLC employs an open-source methodology using the OpenPLC software with IEC 61131-3 standard PLC programming.[3] The OpenPLC runtime runs within a virtual machine using the Raspian operating system. The shared memory Data Interface links the Simulink physics-based model of the SG with the virtual PLC, communicating with OpenPLC using Modbus over a TCP/IP connection[3].The determined water level in the downcomer of the SG is transmitted to the Feedwater Control PLC and compared to desired set points. The difference is passed through an optional deadband filter to a Proportional-Integral (PI) controller. It adjusts the feedwater rate by changing the opening of the feedwater throttle valve (Fig. 1b).

The desired water level in the steam generator and targeted by the PLC increases with the reactor thermal power. In an operation transient associated with a change in electrical load demand, the response of the PI controller to adjust the feedwater rate will also depend on the change in reactor power. The load-following change in reactor power affects the magnitude of $\pm\Delta$ Level (Fig. 1b). The resulting change in the feedwater rate ensures that the water level in SG remains within specified setpoints.

RESULTS

The developed steam generator model and Feedwater Control PLC are tested over a range of transient conditions, including a 10% increase in the load demand (Fig. 2). The simulation results of the transient using the emulated PLC are compared to those obtained from the Simulink model with internal controller logic. The SG is initially at nominal conditions. The steam generator in this example is not coupled to the primary loop model. The primary coolant inlet temperature to the SG, at the nominal reactor power of 3400 MW_{th}, is held constant at 594 K, at a constant flow rate of 7585 kg/s. The PLC has proportional and integral constants of 4.196 and 0.0119, respectively, and no deadband filter ($X_{db} = 0$).

At the start of the transient (point 1 on Figs. 2a-c) the load demand increases by 10% over a period of 30 min (Fig. 2a). The increase steam flow exiting the SG in response to the increase in load demand increases the exit quality and decreases the temperature, T_{ex}, of the primary coolant exiting the SG (Figs. 2b,c). This, in turn, increases the reactor thermal power due to temperature reactivity feedback (Fig. 2c). The increased steam flow decreases the steam generator water inventory, and hence the water level.

The Feedwater Control PLC responds to the decrease in water level in the SG by adjusting the throttle valve to increase the feedwater flow rate. After 21 minutes into the transient, the increased feedwater flow rate restores the water level in SG to the desired level of 89.18% (Fig. 2b). The controller limits the change in the total water level to < 1%, and brings the system back to steady state operation within 50 minutes from the start of the transient (point 3). The response of the PLC's PI controller to adjust the feedwater flow rate is affected by the PLC's internal cycle frequency and the timestep size in Simulink simulation.

The simulation with internal Simulink controller, in contrast, is insensitive to the timestep size. With a timestep and sample frequency of 75 ms the steam generator transient simulation results with the external PLC control are nearly the same as with internal Simulink controller logic (Fig. 2). The developed SG model and the feedwater PLC controller will be coupled to the PWR primary loop model along with other safety and operation PLCs in the I&C system in the NICSim platform. Once integrated and validated, it could be used to investigate potential cyberattacks and help in developing next generation digital I&C security measures.

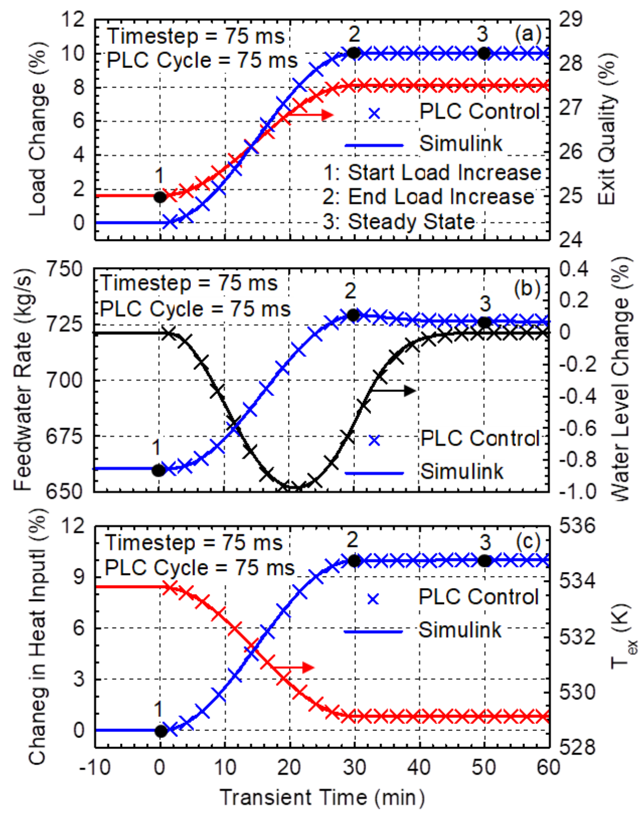

Fig. 2. Transient simulation for 10% increase in demand

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REFERENCES

1. USNRC, "Westinghouse Technology Systems Manual Section 11.1: Steam Generator Water Level Control System Rev 0706," ML11223A293, US NRC (2006)

2. THE MATHWORKS, Simulink 9.3 (R2019a) (2019)

3. M. S. EL-GENK, T. M. SCHRIENER, C. C. LAMB, "Nuclear Instrumentation and Control Simulation (NICSim) Platform for Investigating Cybersecurity Risks." Trans. ANS 2020, Phoenix, AZ, June 7-11, 2020.