Pressurizer Model and PLCs for Investigation of Cybersecurity of PWR Plants

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INTRODUCTION

Nuclear power plants, like other critical infrastructure, need to be protected against potential cyber-attacks. The use of digital Instrumentation and Control (I&C) systems in nuclear power plants raises concerns about cybersecurity vulnerabilities. A nuclear power plant employs a number of digital Programmable Logic Controllers (PLCs), which could be targeted by cyber-attacks.

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 would emulate the digital I&C system architecture in a typical Pressurized Water Reactor (PWR) plant and investigate potential cyber-vulnerabilities[1]. This platform would link emulated PLCs to physics-based models of the fully integrated power plant and various plant components such as the steam generator and the pressurizer.

The pressurizer is an important component in the PWR plant for controlling and maintaining the pressure in the primary loop. The pressurizer functions are controlled by PLCs that maintain the system pressure within safe set points. This work develops a physics-based pressurizer model and the emulated PLCs for maintaining the system pressure and the water level in the pressurizer. The performance of the pressurizer model and the emulated PLCs are tested to ensure compliance and fidelity.

APPROACH

In order to investigate cybersecurity risks for the pressurizer PLCs, the developed model simulates the real physical behavior of the pressurizer at steady state and during operation transients. The pressurizer model is built using the Matlab/Simulink platform. The pressurizer PLCs are developed using open-source OpenPLC software[2]. The Matlab/Simulink model of the pressurizer is linked to the PLCs using a recently developed and verified data transfer interface program[1]. The developed pressurizer model is also highly flexible and can be adjusted to fit different pressurized water reactor designs. Fig. 1 presents a sketch of a typical PWR pressurizer and indicates the different physical process associated with the functionality and operation of the pressurizer during operation transients of surge in and surge out of the coolant from and to the hot leg and both over and under pressurization.

The fast-running and transient non-equilibrium model divides the pressurizer volume intro three regions. These are a saturated vapor region at the top, a saturated liquid region in the middle, and a subcooled liquid region at the bottom (Fig. 1). The later exists following a surge-in of the coolant from the hot leg. The model, which assumes the same pressure in the three regions of the pressurizer, solves the coupled mass and energy conservation equations in these regions. The model accounts for the different processes that affect the mass and energy balance in the various regions, such as heat addition, liquid spray, and evaporation and condensation[3] (Fig. 1). In the vapor region, the model accounts for the condensation on the inner surface of the wall. The released latent heat of condensation is transferred completely to the pressurizer walls. The produced condensate flows from the vapor region to the saturated liquid (Fig. 1).

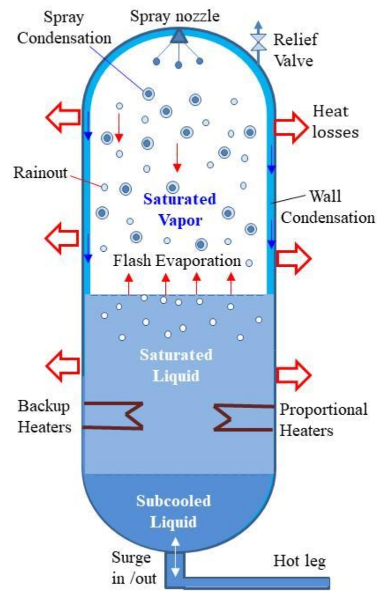

Fig. 1. A sketch of a PWR pressurizer.

The model accounts for the pressurizer spray system which activates after the system pressure increases above a defined set point. The controller adjusts the rate of spray droplets proportional to the system pressure (Fig. 2). The released latent heat from the condensing vapor is transferred to the spray water droplets (Fig. 1). The calculated rate of condensation on the outer surface of the falling spray droplets in the vapor region assumes that the droplets reach saturation temperature during flight and before entering the saturated liquid region.

The present pressurizer model also accounts for rainout, or bulk condensation in the vapor region (Fig. 1). The calculated rate of rainout condensation assumes that latent heat of condensation is supplied by the vapor region to maintain saturation conditions.

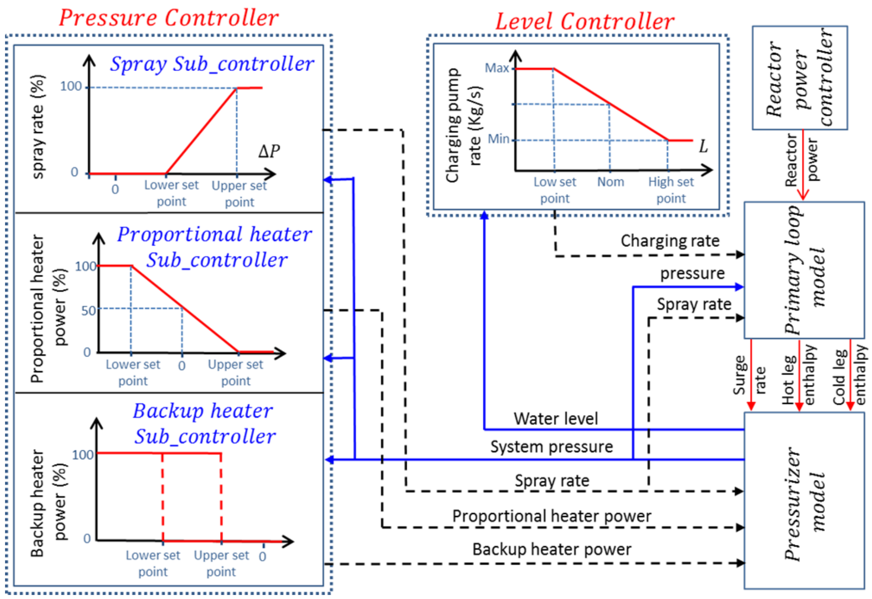

Fig. 2. A flow diagram of the pressurizer controllers' logics and communications with other power plant components.

In the saturated liquid region, the pressurizer model accounts for flash evaporation into the saturated vapor region (Fig. 1). The calculated rate of flash evaporation assumes that latent heat of evaporation is supplied by the saturation liquid region to maintain saturation conditions.

The pressurizer model also accounts for the thermal energy provided by the proportional heaters to compensate for the heat losses through the walls. The controller maintains the heater's power inversely proportional to the system pressure during normal operation (Fig. 2). The model also accounts for power generated by the backup heaters in the saturated liquid region. These heaters play a critical role in preventing the system pressure from decreasing below the set point during operation transients by evaporating saturated liquid into the vapor region to increase the system pressure.

The subcooled liquid region accommodates the surge water from the reactor primary loop. In the event that surge water reaches the electric heaters, the model accounts for the mass transfer from the surge region to the saturated water region as the subcooled water heats up to saturation.

The pressurizer model accounts for the mass loss in the saturated vapor region due to opening of the relief valve. It accounts for mass gain from the pressurizer spray and the water surge from the cold leg and the hot leg of the primary loop, respectively. The developed model also accounts for the surge out of water from the pressurizer into the primary loop as the system pressure approaches nominal value and the water level in the pressurizer approaches set points.

The pressurizer employs two PLCs; the system pressure control PLC, and the water level control PLC[4]. Fig 2 shows a flow diagram of the pressurizer controller's logic, with inputs from the nuclear reactor power plant. The pressure control PLC maintains or restores the system pressure to a preset target value during steady-state and following an operation transient. The pressure control is accomplished using the electric heaters in the liquid regions, and by adjusting the valve for liquid spray and the relief value in the saturated vapor region. The water level control PLC maintains or restores the water level in pressurizer to within set-points. It controls the water inventory in the primary loop by adjusting the charging and letdown rates of the coolant in response to changes in the water volume in the pressurizer.

Data transfer interface

A shared memory Data Interface Program transmits the state variables calculated by the Simulink plant models to the pressurizer model using Modbus communication protocol (Fig. 3). The developed data transfer interface works uses a Simulink S-Function, which allows C code in a Simulink specific format to run and be compiled. The S-Function takes state variables from the Simulink model and writes them to a shared memory location named 'publish' that is read by an external Python script. The Python script reads the shared memory data and transmits it by Modbus over TCP/IP to the Pressurizer PLCs. Data are read from the Pressurizer PLCs and written to a separate shared memory location named 'update' that is read and exported to the Simulink model by the S-Function. Data integrity is ensured with semaphores that enforce synchronicity between the external interface and the S-Function.

RESULTS

The performance of the pressurizer model is validated using reported experimental data[5], with good agreement.

The performance of the developed PLCs for the pressurizer is also compared to that of an ideal controller response during a simulated operation transient to evaluate their fidelity and time response. The ideal controller is made up of the same control logic as the external PLC's control program, but is implemented within the Simulink model of the pressurizer. This ideal Simulink controller represents a PLC with instantaneous response or a zero response time delay, as it does not require signal communication to and from the emulated PLC.

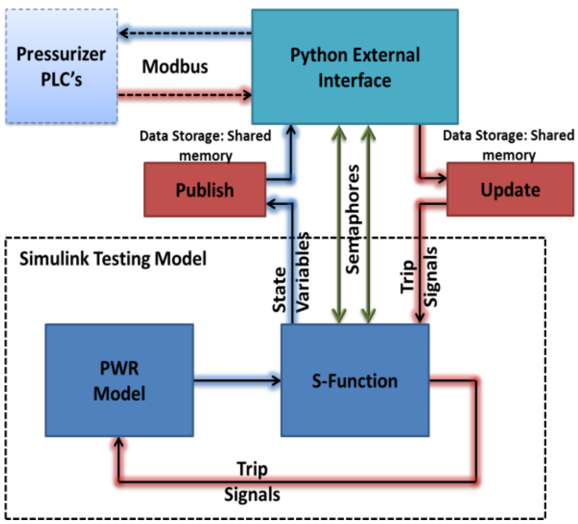

Fig. 3. Developed data transfer interface for linking Simulink to external PLCs.

Figure 4 compares the performance results of the pressurizer's PLCs and the ideal controller in the Simulink model during a simulated operation transient. The transient begins by surging water at a specific rate from the hot leg of the reactor primary loop into the pressurizer for 200 seconds (Fig. 4a). The water surge from the primary loop raises the internal water level in the pressurizer and increasing the system pressure.

When the increase in pressure reaches the upper limit for the proportional heaters (Fig. 4b), the controller turns off the heaters to stop further water evaporation from the saturated liquid region into the saturated vapor region of the pressurizer. However, as the water surge continues, the pressure continues to increase until reaching the set point for opening the valve for spraying water from the cold leg of the reactor primary loop into the saturated vapor region. The water spray stimulates vapor condensation, limiting the increase in pressure. When the surge phase of the simulated transient ends, the pressure remains steady until the subsequent surge out phase of the transient begins (Fig. 4b).

The surge out continues for 200 seconds, causing both the pressure and water level in the pressurizer to decrease. The spray valve closes after the pressure drops below its set point. In addition, the proportional heaters turn back on and generate thermal power proportional to the decrease in the system pressure. When the surge out phase ends, the system pressure and the water level in the pressurizer reach steady state, but their values are higher and lower, respectively, than those at the start of the simulated transient (Figs. 4b,c). The comparisons in Fig. 4 shows excellent agreement between the pressurizer's PLCs and the ideal controller within Simulink model of the pressurizer.

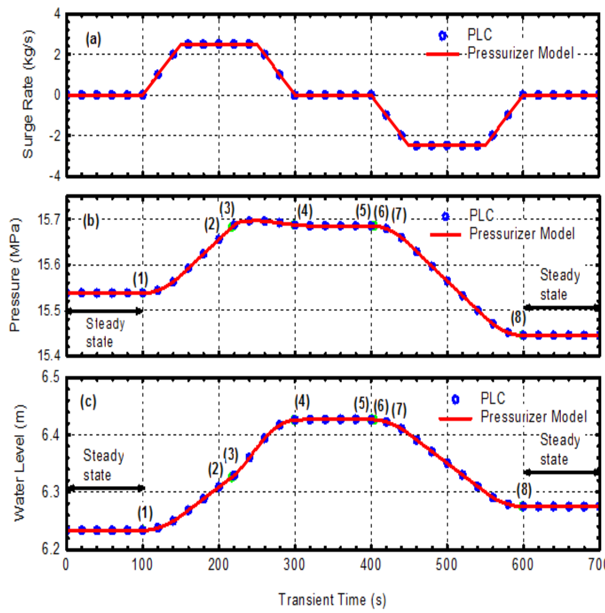

Fig. 4. Performance comparisons of the pressurizer's PLCs and the ideal controller in the Simulink model of the pressurizer during a simulated transient: (a) surge rate, (b) system pressure, (c) water level; (1) surge in starts, (2) heaters turn off, (3) spray starts, (4) surge in ends, (5) spray ends, (6) surge out starts, (7) heaters turn on, and (8) surge out ends.

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