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Roles of a Physical Simulator in I&C Development for Nuclear Power Plants

J. Jiang

Department of Electrical& Computer Engineering
The University of Western Ontario
London, Ontario, Canada
jjiang@eng.uwo.ca

Abstract

In this paper, advantages of a nuclear power simulator based on physical components to support I&C research and development are examined. From an I&C perspectives (low voltage, current and power), the simulator behaves as if the I&C system is connected to a real process. The simulator consists of 6 physical processes, and can be configured to form 15 different control loops to support various I&C testing situations. The simulator has been deliberately overly instrumented with 25 different industry-grade sensors and 30 industry-grade actuators so that it can be easily interconnected with external hardware control and instrumentation devices. This simulator allows researchers in the nuclear I&C field to test variety of instrumentation and control algorithms in a dynamic environment, similar to that encountered in a real nuclear power plant, in real-time. The biggest advantage of using physical simulator, as opposed to software based simulator, is that one does not have to deal with synchronous of timing between the simulator and the external control devices in the testing and validation process of control schemes. This simulator also facilitates development of new control and diagnostic schemes, e.g. smart sensors, applications of wireless sensor networks, in a dynamic environment. Our experience so far has indicated that such a simulator is a must-have item in research and development of I&C systems for nuclear power plants..

Keywords: Nuclear I&C, simulators, sensors, actuators, and safety shutdown systems

1. Introduction

This Simulation plays an important role in the development of instrumentation and control (I&C) systems for nuclear power plants and training of plant operators [1]. The main requirements for a simulation platform dedicated to I&C applications are very different from those of other simulators. They should be able to (1) create truthful dynamic environments in which the developed instrumentation or control schemes will eventually be deployed; and (2) establish realistic dynamic interactions among different system variables in which the developed instrumentation or control schemes are involved (often in a closed-loop form). Simulators for I&C applications are very different from those designed for thermal-hydraulic application. In the latter, realistic pressures and temperatures and other physical limiting conditions are of primarily importance. However, the main concern for an I&C simulator is whether it produces a replica of the true dynamic nature of the process it simulates, because I&C systems generally deal with low energy signals. The characteristics of the process are more important than actual magnitude of physical variables. Hence, the most important aspects here are the dynamic behaviors of the process, rather than actual magnitudes of the variables of interests, as long as the variables are scalable.

Currently, there are numerous software based environments for simulation of different processes found in a nuclear power plants, such as Matlab, 3Key-master from WSC, GPWR from GSE. Typically, I&C systems can interact with these software platforms to form a hardware-in-the-loop simulation environment for I&C research and development. However, hardware-in-the-loop simulations are not without problems of their own, most notable one is synchronization of timing between simulated processes and physical hardware based controller. Realizing the needs for a dynamic environment to test I&C systems, a new concept of a simulator based on scaled version of physical process has been developed recently. This paper describes its functionality and construction briefly.

In this paper, the development process of a physical simulator for a two-loop nuclear power plant (PWR or CANDU) has been described. It starts with identification of major physical processes in a nuclear power plant, and design of the simulator to mimic these processes, such as reactor dynamics, primary loop, steam generator, pressurizer, and safety shutdown systems. To meet the requirements for I&C research and development, the physical simulator is designed in such a way that one can easily access the sensor and actuator signals through standard industrial interface (4 to 20 mA or 0 – 5 Volt, or fieldbus signals). The dynamic behaviors from a specific actuator to a specific sensor represent a particular part of a process in a nuclear power plant.

The paper describes the design concept and selection of physical devices, and operational modes. The results of preliminary tests have been presented to valid the functionality of the simulator. As far as the control of the simulator is concerned, the simulator has its own control system based on ABB DCS so that it can operate on its own as a stand-alone unit. However, the simulator can also be controlled externally by any commercial industry-grade DCS. There are provisions for incorporating safety grade PLCs for implementing safety systems as well as rector protection systems.

The developed simulator has been used to support several research projects to validate design and test novel I&C concepts. Brief description as how the simulators are being used is also included. Advantages of a physical simulator over software based simulators are discussed. It is concluded that a physical simulator is an indispensable tool to carry out research and development activities for instrumentation and control research.

2. Overview of the physical simulator

To test different hardware control, monitoring and diagnostic systems in a real-time environment effectively; it becomes awkward to reply on software-based simulators. The main reason is that the software-based simulator is not strictly running in real-time. However, by definition, all hardware control systems do run in real-time. Since most of the control systems are operating in a closed-loop environment, any mis-match in timing will essentially deem the result completely incorrect. In such situations, a physical hardware-based simulator, (which runs in real-time by definition), will be extremely useful and effective in mimic the behaviors of the control system in a realistic environment. Furthermore, for high-speed applications, such as reactor protection systems, the effect of time delays contributed by the interface hardware is also a crucial factor to consider. This cannot be easily studied on a software-based simulator.

2.1 Design philosophy

The essential philosophies for design of such a hardware-based simulator are:

1. Resembling major physical processes found in a typical two-loop nuclear power plant;
2. Focusing on dynamic behaviors of the process and interactions among different process variables;
3. Relying on industry-grade overly instrumented physical sensors and actuators;
4. Providing multi-type and redundant user interface functionalities, including 4 – 20 mA, 0 – 5 Volt, fieldbus signals, and wireless connectivity;
5. Incorporating redundancies and defense-in-depth concepts in the design with multiple and diversified sensors, actuators and redundant shutdown systems;
6. Operating either as a self-contained unit or can be controlled externally via other distributed control systems; and
7. Allowing easy insertion of faults and malfunctions for testing different control, monitoring, and diagnostic schemes.

2.2 System Overview

A picture of the designed simulator is shown in Figure 1. All the process components are located on the left section of the system. A pair of redundant shutdown systems is located in the middle section. The overall built-in unit control is located on the right side.

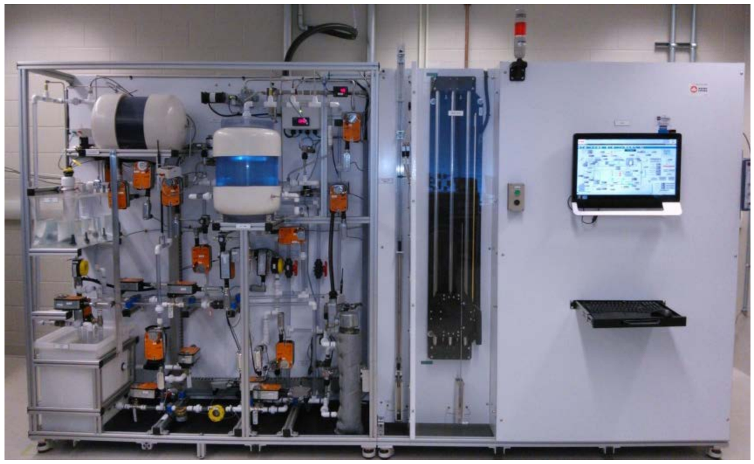

Figure 1 Physical nuclear power plant simulator for I&C applications

The detailed processes of this simulator are summarized in Figure 2. It forms the design basis

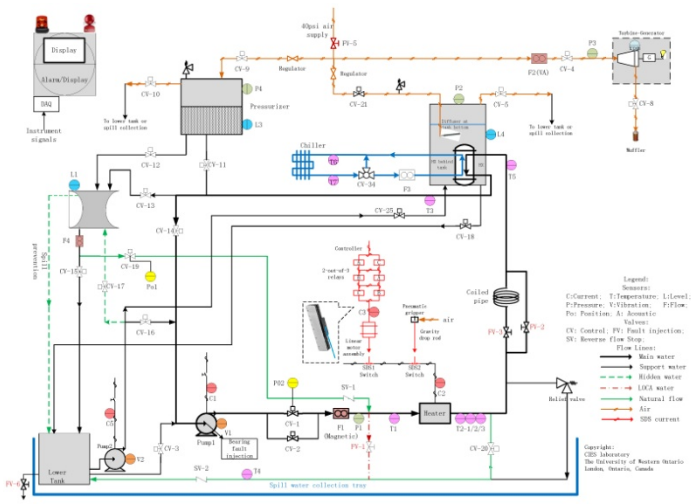

Figure 2 Overview of the process of the simulator

2.3 Physical processes in the simulator

The simulator uses water as the operating fluid to simulate thermal processes in a two-loop nuclear power plant. No neutronic dynamics are considered. As shown in Figure 3, the water in the inventory storage tank is pumped through a 7 kWatt heater which simulates a fission reactor. The heat is removed from a chiller located at the back of the unit (see insertion). The steam generator loop is regulated by a pressurizer and a level control mechanism. The water is directed back into the upper holding tank. Once the reactor is shutdown, the water can flow from this upper holding tank through the heater to simulate a gravity-driven emergency core cooling system.

On the simulator, there are two separate and diversified shutdown systems based on different working principles. Furthermore, there is also a turbine and generator set to complete the electrical power generation part of a nuclear power plant. Even though it is not highlighted in Figure 3, the system contains 25 sensor and 30 actuators.

It comes with its own built-in control system as well as interface panels to connect with any industry-grade commercial distributed control systems and safety PLCs.

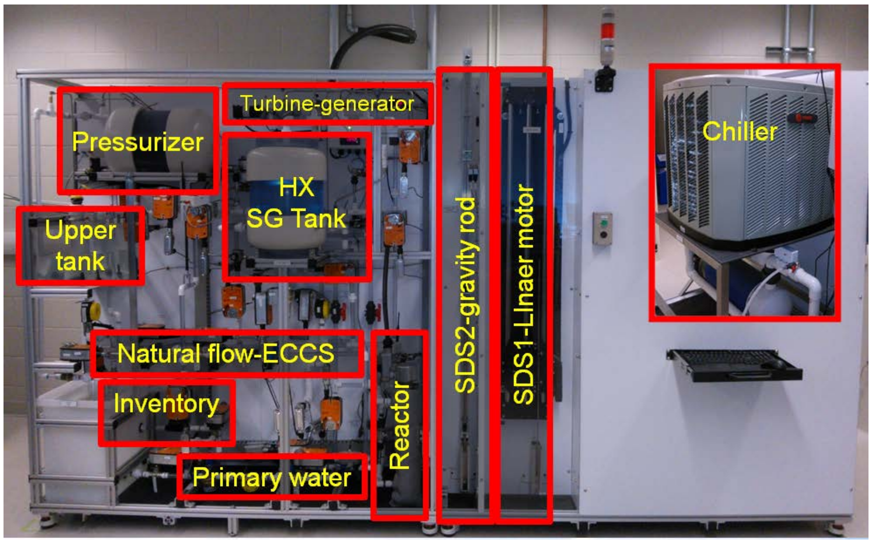

Figure 3 Physical processes in the simulator

3. Functionalities of the simulator

Since this simulator is designed specifically to support research and development of I&C activities, efforts have been made to facilitate data acquisition and process modifications. As an example, this simulator can support I&C research and development through the following control loops:

1. Reactor power control
2. Steam generator level and pressure control
3. Pressurizer pressure and level control
4. Turbine flow and pressure control
5. Heat Transport System (HTS) pressure control by feed-bleed mechanism
6. Emergency core cooling control
7. Diversified shutdown systems

Based on the needs of the research projects, the simulator can be configured to operate in the following modes:

1. Closed water loop with pressurizer (normal mode)
2. Closed water loop without pressurizer (solid mode)
3. Open water loop (open) to charge to or discharge from tanks
4. Residual heat removal mode (SDS) after reactor shutdown
5. Gravity-driven natural flow (ECCS)
6. Start-up and shutdown transients

The simulator can be controlled either manually by physically adjusting the setting through opening or closing of valves, or through a touch-screen user interface located on the simulator (see Figure 1 screen on the right). It can also be operated remotely from a main control room through a software user interface as shown in Figure 4.

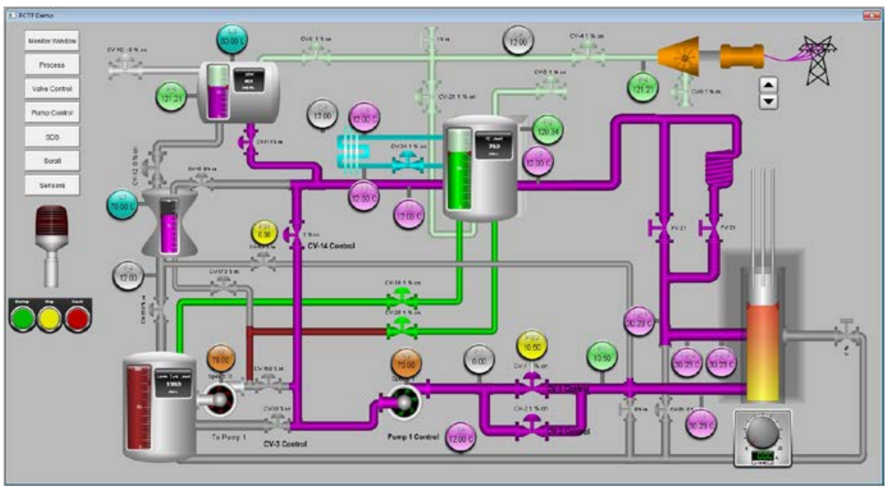

Figure 4 Graphic user interface for the simulator

4. Research supported by the simulator

Since commissioning of this simulator over a year ago, several research projects have been initiated to take advantage of this unique facility. One feature of this simulator is its re-configurability. Multiple projects can be executed on this simulator with minimal re-configuration efforts in the transition process. Furthermore, one does not have to run the entire simulator at all time. Depending on specific needs of a particular research project, only some physical loops of the simulator can be used to simulate intended dynamics.

With this physical simulator, one can easily inject 'faults' in the system physically and examine their effects to develop effective fault detection and diagnostic and fault-tolerant control schemes. Since this simulator makes it possible to physically change parameter settings on the sensors and actuators, another interesting application of this simulator is for development of smart sensors which can calibrate themselves and detect any bias in the measurement quantities. Wireless sensor network nodes have also been installed to provide real-time data access for process diagnosis applications.

There are endless examples that this simulator can be used in I&C research and development activities. A list of sample projects carried out on this simulator so far is summarized in Table I.

Table I. Research projects supported by the simulator

Project titles	References
Development of mathematical models for the simulator	[2]
Demonstration of wireless based diagnostic systems	[3]
Safety shutdown systems using HFC6000	[4]
Identification of safe operating boundaries	[5]
Development analytical redundancies for safety systems	[6]
Fault-tree analysis of safety systems	[7]
Time-frequency based fault diagnosis systems	[8]
Semi-learning schedule for fault diagnosis	[9]
Distributed control system evaluation using DeltaV DCS	[10]

5. Summary and conclusions

To support research, development, and training of engineers in the area of instrumentation and control for nuclear power plants, a physical simulator has been developed at the University of Western Ontario. The simulator mimics major dynamic processes in a two-loop nuclear power plant by using physical components and industry-grade sensors and actuators. This physical simulator has also facilitated experimentations with industry-grade hardware control systems (such as DCS, or safety PLC) by observing the control system behaviors when different operating scenarios are implemented in real time. This becomes critical in evaluating the performance of newly developed control schemes and hardware devices.

One important conclusion is that, to support research and development of I&C systems, the dynamic relationships between different variables are more significant than actual physical values of the system variables, because I&C system deals with low voltage, small current and low power signals anyway.

Our experience has indicated that such a physical component based simulator offers some unique features that software simulators are unable to provide, such a simulator is a must-have item for any organization involving research and development of nuclear I&C systems. Work is still in progress to improve the simulator system and to make it more versatile to meet diverse requirements demanded by different R&D scenarios.

Acknowledgments

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