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Development of an engineering simulator for a physical component based nuclear process control test facility

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ABSTRACT

To support research in instrumentation and control (I&C) of a nuclear power plant (NPP), a physical simulator based on scaled version of real plant processes using physical components has been developed, known as a NPP process control test facility (NPCTF). Even though this facility has proved to be a must-have system for any nuclear I&C system research activities, it is not without limitations of its own. Because this facility is made up with physical components, many variables are bounded by their safe operating ranges. This fundamentally limits the applicability of the facility in studying NPP under accident conditions, where excursions of the physical variables, such as pressure, temperature, may suppress the safe limits of the physical components. Furthermore, the facility can only be used for one experiment at a time. Henceforth, an engineering simulator (ES) based on software model, which extends functionalities of the NPCTF to examine accident scenarios and to allow multiple users to run different experiments, ought to be developed. This paper details the development of such a simulator by describing the models for thermal-hydraulic systems in the NPCTF as well as the corresponding NPP processes. The simulator is then implemented in Matlab Simulink environment with the help of Simscape toolbox. The performance of the ES has been validated by comparing the simulation results against those from the experiments on the NPCTF. Some operational scenarios that are not permitted to conduct safely on the NPCTF can now be conveniently carried out in the ES. The paper has demonstrated that the ES indeed plays a complementary role to the NPCTF in the support of I&C research and development for nuclear power plants.

1. Introduction

Instrumentation and control (I&C) systems are the central nervous system for safe, reliable and efficient power generation in nuclear power plants (NPPs). Due to their complex and safety-critical nature, it is not practical to test and tune I&C systems on-line during on-power operation. Instead, simulators are extensively used for this purpose [1,2]. Furthermore, since nuclear energy conversion processes and associated thermal-hydraulic systems are complex, it is very difficult to predict the behaviours of a plant under all perceivable operating conditions. This is especially true under accident conditions. Simulators play an important role to assist I&C engineers in control system design and instrumentation selection/calibration. Plant-specific simulators are also used to produce nearly identical responses as the plant does for operator training purpose.

In practice, simulators in the field of nuclear power generation can be classified into physical simulators and software simulators. Physical simulator is a facility made up with physical components, which supports experiments under specific

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Nomenclature

Notation Description (Unit) (Conversion)

t	calculation step size or time (s)
p	pressure ($Pa(Pascal)$ ($1\ Pa = 1.450377 \times 10^{-4}\ PSI$)
g	gravity acceleration (N/kg *or* m/s^2)
Cp	specific heat at constant pressure ($J/(kg.K)$
T	temperature (K)
F	mass flow rate (kg/s)
G	volumetric flow rate (m^3/s)
Q	total heat (J)
P	power (W)
U	voltage ($V(Volt)$)
I	current ($A(Ampere)$)
V	volume (m^3)
m	mass (kg)
D	hydraulic diameter (m)
A	area (m^2)
J_ω	moment of inertia ($kg.m^2$)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number

Greek symbols

ρ	density (kg/m^3)
α	convective heater transfer coefficient ($W/(m^2.K)$
λ	thermal conductivity ($W/(m.K)$
ω	angular velocity (rad/s)

Subscripts

w	water
m	metal
a	air
e	electricity
i	inlet
o	outlet
l	lost
0	initial

Abbreviation

amb	ambient

conditions similar to what encountered in a nuclear power plant. Software simulator, on the other hand, consists of software models of the processes, which produces similar responses as the plant does when presented with the same scenarios, but in a digital form inside a computer. For operator training, software simulators are undoubtedly an effective and economical approach. However, their usefulness is hampered for I&C system studies, because an I&C system is much more than just a sequential execution of program codes. I&C system often deals with parallel injection of different control signals based on real-time measurements, real-time decision-making in the controller which affects the responses of the entire process through feedbacks, not to mention about calibration, measurement noise, and degradation of physical components, etc. Hence, a simulator made up of physical components, and can physically simulate processes in NPP is ideal to support research and development for I&C systems.

To meet such a need, a physical simulator, referred to as NPP Process Control Test Facility (NPCTF), has been constructed at the Control, Instrumentation, and Electrical Systems (CIES) Research Laboratory at The University of Western Ontario (UWO). Industrial grade sensors, actuators, and controllers are used to build this simulator. The dynamic processes are simulated physically using water and air as working fluids. Since the simulator is to support I&C activities, the magnitudes of thermal, hydraulic, and electrical variables are all reduced within safe levels in a laboratory environment. Even though a specific variable in NPCTF has a corresponding equivalence in an actual nuclear power plant, the magnitudes of these variables can be vastly different. As long as the output of the sensor for a variable in actual plant matches well with the output of the corresponding sensor on the NPCTF, the physical component simulation is considered to be successful. The reason that one can do it is because of different sensor scaling factors for the variable in the actual plant and that on the NPCTF. Since the NPCTF is designed to support I&C activities, the dynamic characteristics of particular variables of interests