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Programmable Logic Controller of a Pressurized Water Reactor Core Protection Calculator

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INTRODUCTION

Digital instrumentation and control (I&C) systems offer high efficiency and performance in process control applications compared to analog systems, but at the risk of cybersecurity vulnerabilities. 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, to emulate digital I&C system architectures in Pressurized Water Reactor (PWR) plants for investigating potential cyber-vulnerabilities. This platform links emulated Programmable Logic Controllers (PLCs) to a physics-based power plant model for direct feedback.

The autonomous reactor protection and safety I&C system in a PWR plant presents a potential target for cyberattack. The digital protection systems in some PWRs use Core Protection Calculators (CPC) PLCs to perform the reactor trip protection safety function. The objective of this work is to develop a representative CPC PLC for integration into the NICSim platform. This CPC must perform the same tasks as its real counterparts, namely: (a) calculate the Critical Heat Flux Ratio (CHFR) and compare that to a minimum set point, (b) calculate the reactor coolant flow rate based on sensor readings and determine if it's adequate to remove the heat generated in the reactor core, (c) validate the margin of the coolant core exit temperature to saturation at system pressure. The CPC must also respond timely and similar to a real system.

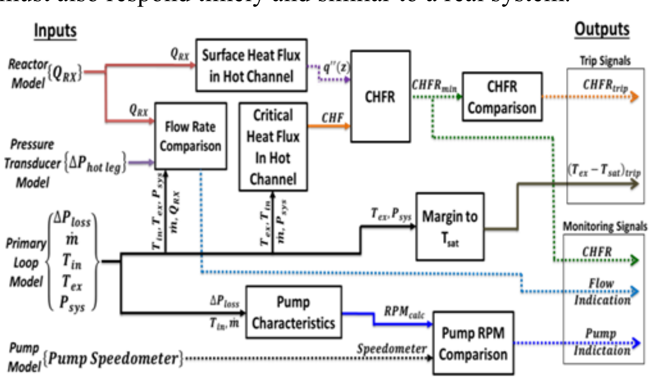

Fig. 1. CPC functional block diagram.

APPROACH

Industry digital I&C systems are based on PLCs running ladder logic programs. The developed emulated CPC employs an open-source methodology using the OpenPLC software[1]. The OpenPLC control program uses IEC 61131-3 standard PLC ladder logic programming. Ladder logic is a simplistic code that allows only basic computational functionality, requiring all calculations to be linear and preformed with basic logical operations. Fig. 1 presents a functional block diagram of the CPC PLC's functions and the inputs they receive from a connected Matlab Simulink physics-based PWR power plant model. A shared memory Data Interface Program transmits the state variables calculated by the Simulink plant models to the CPC using the Modbus communication protocol (Fig. 2)[3]. The developed CPC is also highly flexible and can be adjusted to fit different pressurized water reactor designs.

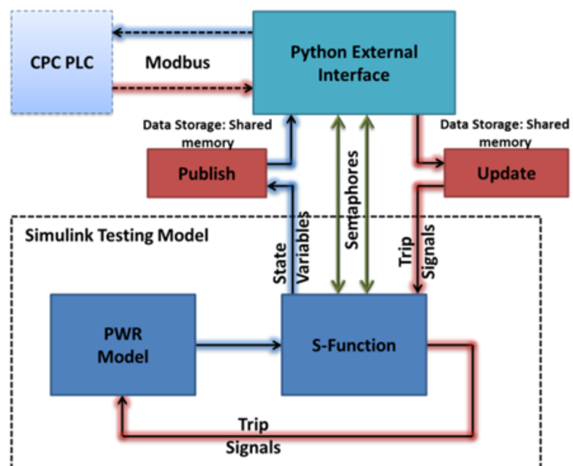

Fig. 2. Developed data transfer interface for linking Simulink to external PLCs.[3]

The developed data transfer interface uses a Simulink S-Function, which allows C code in a Simulink specific format to run and compiled. The S-Function takes state variables from Simulink model and writes them to a shared memory file that is read by an external Python script. The Python script reads the shared memory data and transmits it via the Modbus protocol to the CPC PLC. Trip signals are read from the CPC PLC and written to a separate shared memory file 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.

The CPC program calculates the reactor trip functions and sends warnings to the operator if values exceed specified setpoints. The primary trip function of the CPC is to calculate the Critical Heat Flux Ratio (CHFR) and compare it to the minimum allowable setpoint. This setpoint is determined considering the response time of the PLC to trip the reactor before the CHFR drops below 1.0 and boiling ensues in the hot channel. The minimum CHFR setpoint must allow a margin significant enough that the CPC has enough time to respond before reactor conditions become unsafe. The Critical Heat Flux (CHF) is determined using the ANL CHF correlation[2]. The CPC calculates the axial distribution of the surface heat flux at 10 discrete locations in the hot channel and compares the lowest CHFR to the specified minimum setpoint. If the minimum calculated value of CHFR reaches the lowest set point the CPC will send a trip vote to a logic coincidence counter PLC. The logic coincidence counter PLC counts the reactor trip votes from independent CPCs. A trip is initiated if at least 2/4 of the CPCs vote to trip.

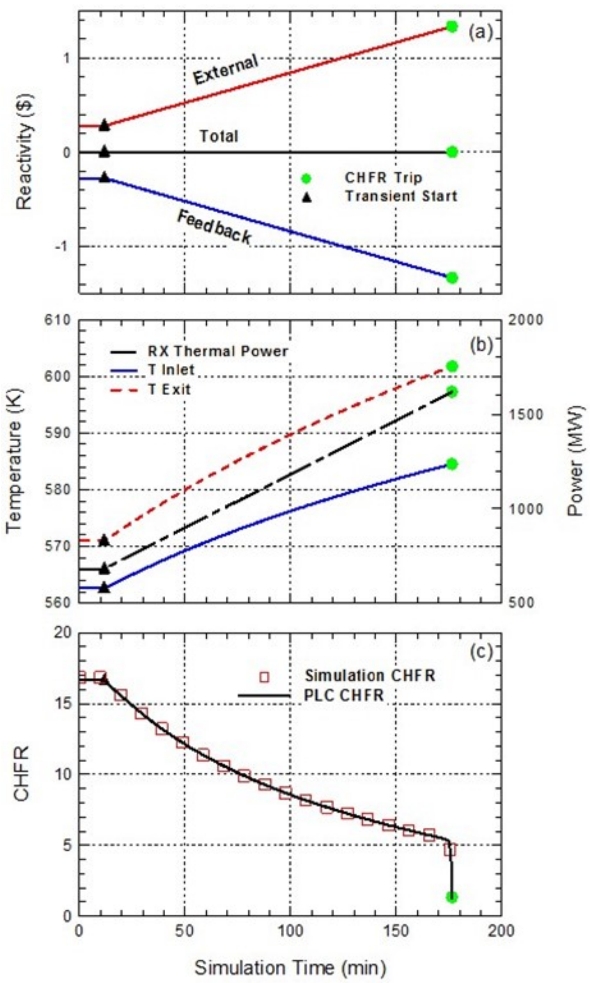

Fig. 3. Comparison of CPC CHFR trip simulation data to those of the Simulink based model.

RESULTS

To evaluate the performance and timing response of the CPC, results are compared to a mirror CPC implemented within a Simulink platform[4]. The developed reactor model using this mirror CPC represents the ideal response expected from the core protection PLC, with no response delay. The testing scenario begins with the reactor model at nominal steady state 50% power conditions. Positive reactivity is then inserted at a rate of 0.01 cents/sec until the PLC sends a trip signal. (Fig. 3a)

Figures 3b and 3c show the data from the CHFR trip test and compare the response of the emulated PLC and to that of the ideal simulation. Fig. 3a shows the inserted external reactivity, the feedback reactivity and the total reactivity. The reactor power and inlet and exit coolant temperatures are displayed in Fig. 3b. In Fig. 3c the calculated CHFR by the PLC is compared to that of the ideal internal CPC. The inserted external reactivity (Fig. 3a) increases the reactor thermal power and subsequently the reactor core inlet and exit coolant temperatures (Fig. 3b). This CHFR within the hot channel is calculated until the PLC signals for a trip 176 min into the start of the transient. The PLC response is identical to that of the ideal model. It sends a trip signal within 150 ms of the ideal internal CPC.

The developed Core Protection Calculator PLC has been successfully validated by comparing results to those of an idealized Simulink model. Results show identical responses with a 150 ms time lag, which is within industry accepted range for CHFR calculators[5]. This PLC emulation will be integrated into the NICSim platform alongside other safety and operation PLCs in the I&C system to investigate cybersecurity risks in the nuclear plant digital I&C systems.

ACKNOWLEDGEMENT

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