Digital Control and Safety System Modernization for the Penn State TRIGA Reactor

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INTRODUCTION

Penn State has historically been a leader in reactor control for the research reactor community. The current console, installed in 1991, continues in operation to this day with only minor updates of computer components. However, as is the case with all operating nuclear plants, obsolescence issues must eventually be addressed which require replacement of hardware and software. The original Equipment Manufacturer (OEM) no longer supports this product line - parts are difficult the find and upgrading the system software is very costly. The present system is a hybrid system - digital control and monitoring and an analog safety system. This instrumentation and control (I&C) replacement will replace the existing digital equipment (27+ year-old technology) with more versatile and supportable state-of-the-art technology. Additionally, the existing analog safety system will be incrementally phased-out, replaced with a 1E certified digital safety system used in the commercial nuclear power industry. PSU is partnering with Schneider-Electric subsidiaries Foxboro Controls and Triconex Automation to implement this first-of-a-kind safety and control system upgrade for a university research reactor.

As an initial phase in assessing the capabilities of the new system, Schneider-Electric donated a Foxboro Process Automation I/A System and a TRICON 1E digital safety system to the RSEC to develop a laboratory for the staff to become familiarized with the equipment and conduct preliminary control experiments. Many of the aspects of a full-scale control system are demonstrated on a small-scale with the laboratory equipment provided - from specification development through factory acceptance testing, to preliminary testing on the TRIGA using an Auxiliary Control Rod. This laboratory equipment would ultimately be used as a staging area for assessing future software and hardware changes on the upgraded console.

The obsolescence upgrade of this older control system will be undertaken using funding from a 2017 US Department of Energy infrastructure grant, using commercially-available, industrial-grade control equipment. The objective of the controls laboratory described is essentially phase one of the Penn State reactor digital control system modernization project - modelling, design and implementation of the new control system using the Foxboro I/A (Industrial Automation) state-of-the-art digital control system (DCS) and TRICON 1E-grade reactor protection system.

CONVERTION OF EXISTING SYSTEM INTO FOXBORO I/A SYSTEM

The PSU TRIGA control and safety system replacement would avert the possibility and negative impact of the existing, obsolete system failing prior to replacement, and provide continued support all of the personnel and activities currently performed at the RSEC. The proposed replacement will maintain the full-functionality of the present digital control system using modern digital technology. The Foxboro I/A control equipment will be the interface between reactor operators, the TRICON (during the assessment period) and the TRIGA, and will be housed in the existing control console enclosure to retain the same "feel" as the existing system (and to minimize costs). Similarly, the graphical user interface will retain the same form, fit, and function of the existing system to minimize impact to reactor operations. Figure 1 shows the existing AECL control console. Figure 2 shows the anticipated console upgrade.

Figure 1. Existing Penn State reactor control console.

The flexibility to easily update control code and incorporate new features, such automated nuclear instrument and control rod worth calibration, would be cost-effectively enhanced by use of the interactive software development environment and modular hardware architecture of the Foxboro I/A and TRICON systems (the present system is based on two 2003-vintage personal computers). The code and equipment architecture developed for the Penn State TRIGA control system upgrade would be "open source", in that all technical and regulatory content would be shared among the TRIGA Reactor User's Group, and potentially serve as an open-source model for power reactor control system upgrades.

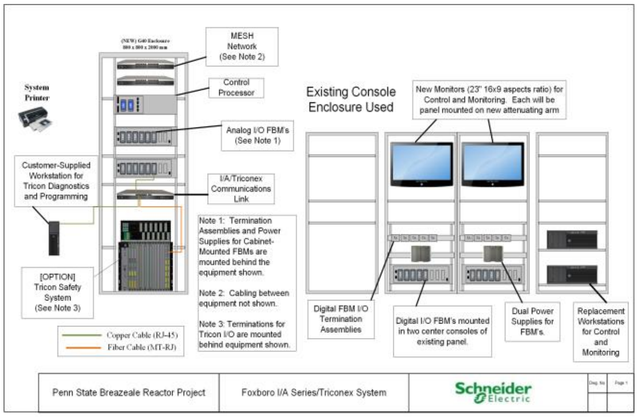

Figure 2. Penn State reactor control console upgrade.

Additionally, the console will be incorporated into the nuclear engineering curriculum at Penn State, demonstrating to senior-level and graduate engineering students state-of-the-art control engineering concepts and implementation. It is anticipated that the PSU RSEC will provide training opportunities in digital instrumentation and control to the Nuclear Regulatory Commission, Department of Energy, and nuclear utilities and service providers using the new control system as the focal point.

The current PSBR control system was developed by Atomic Energy of Canada Limited (AECL), using the PROTROL block diagram language. This system needed to be thoroughly reviewed prior to recreating the new reactor control system with the Foxboro DCS. The Foxboro Integrated Control Configurator (ICC) software provides a means to program the system control processor, and assign necessary input/output (I/O) connections to the hardware. All possible control functions are resident in the processor, and the processor is configured, via the ICC, to accommodate the specific application [1].

Typically, the engineer creates a block diagram with the intended functionality and configuration information and uses the ICC to implement. As an example, a PID (proportional + integral + derivative) controller block may be used to automatically control each control rod to maintain the desired power level. The control rod PID controllers automatically reposition 3 of the 4 TRIGA reactor control rods to follow/maintain the desired setpoint power level of reactor (AKA, the setpoint). The controller monitors that setpoint, compares it to a power measurement, and performs mathematical and logical operations to adjust the control rod velocity demand signal to the rod motor drives.

The Foxboro ICC system, while visually similar to the PROTROL system, is more extensive and has greater functionality. Both the PROTROL and Foxboro ICC utilize a text-based configuration tool programming environment, which allows the user to set parameters from a predefined list of functions. For example, Analog input, Analog output, PIDA, and CalcA blocks are typically used to create a closed-loop control system. Blocks can be created, edited and linked together with the ICC through assignment of signal variables. The ICC is the legacy Foxboro programming tool, dating back to the late 1980's.

Preliminary studies focused on assessing the capabilities of the Foxboro system and the ICC were used to partially replicate the control functionality of the existing system. For deployment on the actual TRIGA reactor, a more modern graphical programming environment will be employed, which has algorithm development via block diagram creation (example presented in Figure3). Once the algorithm block diagrams are developed, they are automatically converted into the equivalent control code for execution on the Foxboro control processors. This process not only facilitates control code development and deployment, but automatically generates the corresponding documentation and data tables for permanent record.

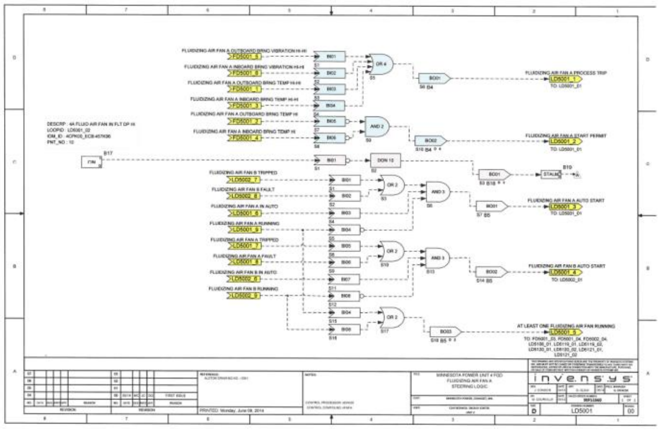

Figure 3. Example of Foxboro graphical control code generation tool

FoxDraw™ is used for creating user graphical user interfaces (GUI). Foxdraw™ allows the engineer to create faceplates with data and signals from the system which can allow the user to see reactor input and output variables, such as reactor power, control rod heights and velocity demand, and fuel temperature. Proper design of the GUI is essential because it is the primary interface between the operator and the reactor control system. The GUI should be easy to use and similar to the existing control interface so that existing operators can adapt quickly to the new system with minimal re-training.

FoxView™ is used to run the GUI and interface to the I/O modules and control processor. The GUI has, for example, manual/auto control mode change buttons, SCRAM button, and various indications (Figure 4). In manual mode, the operator can move control rods manually with directional push buttons. In automatic mode, the control rods follow the desired set point value and adjust the power level by driving the control rods. Once again, one of the goals of the TRIGA control console replacement is to provide a new system with the same form, fit, and function as the existing system – thus the similarity between figures 1 and 4.

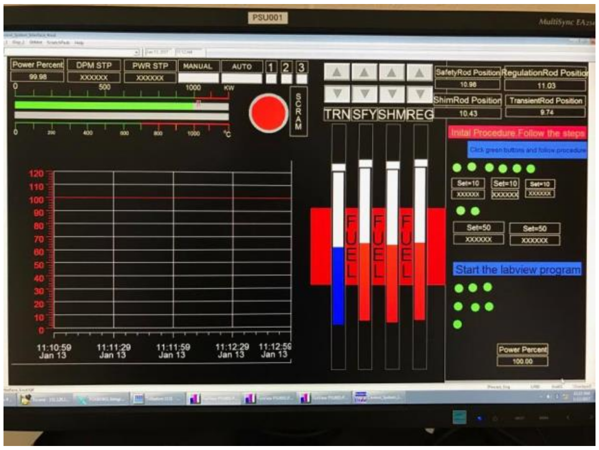
Power Percent 99.98
DPM STP XXXXXX
PWR STP XXXXXX
SafetyRod Position 10.98
RegulationRod Position 11.03
ShimRod Position 10.43
TransientRod Position 9.74
Initial Procedure Follow the steps
Click green buttons and follow procedure
Start the labview program
Power Percent 100.00

Figure 4. Foxboro Control System User Interface

HARDWARE-IN-THE-LOOP (HIL) TESTING OF THE FOXBORO TRIGA CONTROL SYSTEM

Initial work used a National Instruments LabView™ simulation system to perform hardware-in-the-loop (HIL) testing of the Foxboro system. LabView™ provides a block diagram-based visual programing language and can be interfaced with hardware to provide signals for testing control systems. For testing the Foxboro control system, a TRIGA model was developed that responded similarly to PSBR. The reactor was modeled by using the point kinetic equations and core-averaged thermal-hydraulics.

Model parameters were derived from PSBR test data. A National Instruments compact real-time input-output (cRIO) controller has a 40 MHz real-time processor, for running the TRIGA model, and a high-speed Field Programmable Gate Array (FPGA) for input/output signal operations. The real-time processor simulates neutron population, fuel temperature, coolant temperature, and control rod dynamics. Temperature feedback coefficient, heat transfer correlations and thermal-hydraulic constants are derived from the PSU TRIGA`s operating data.

The model is monitored from a LabView™ front panel which allows the user to view indicators and graphs displaying model output. For real-time performance, the LabView™ reactor model uses Euler`s numerical integration method implemented in a formula node to numerically integrate 6 delayed neutron group Point Kinetic equations, thermal hydraulics and control rod dynamics. During each calculational cycle of the model, LabView™ transfers the resulting reactor power, fuel temperature, and control rod position to cRIO's FPGA hardware, which is the interface to the Foxboro equipment. The cRIO outputs voltage and current for use by the Foxboro (Figure 5). Essentially the cRIO (and LabView™) *is the reactor* for the Foxboro controller.

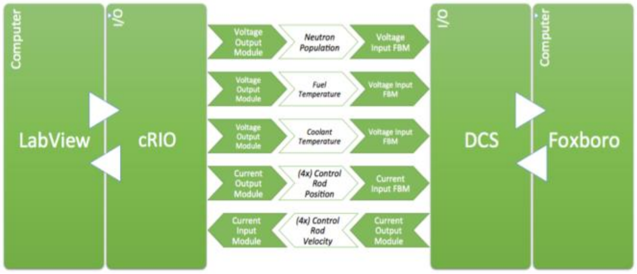

Fig. 5. Communication between cRIO and Foxboro I/A

EQUATIONS USED IN THE LABVIEW TRIGA MODEL

Neutron (Power) Dynamics:

$$\frac{dn(t)}{dt}=\frac{(\rho(t)_{net}-\beta)}{\Lambda}\times n(t)+\frac{\sum_{1}^{6}\beta_i C_i(t)}{\Lambda} \tag{1}$$

Delayed Neutron Precursor Dynamics (i=1 to 6):

$$\frac{dC_i(t)}{dt}=\lambda_i(n(t)-C_i(t)) \tag{2}$$

Fuel Temperature Dynamics:

$$\frac{dT_f(t)}{dt}=\frac{1}{M_f C_f}[Q_f-U_f A_f(T_f-T_c)] \tag{3}$$

Coolant Temperature Dynamics:

$$\frac{dT_c(t)}{dt}=\frac{1}{M_c C_c}[U_f A_f(T_f-T_c)-2\dot{m}_c C_c(T_c-T_0)] \tag{4}$$

Net Reactivity with Temperature Feedback:

$$\rho_{net}=\rho_{CR}+\rho_{SD}+\alpha_f(T_f-T_{reference}) \tag{5}$$

Power Generated in the Fuel (driven by the PKE):

$$Q_f=P_{avg.f}\times n(t) \tag{6}$$

Equations (1) and (2) are the Point kinetic equations which provide the relative neutron population. The six delayed neutron group dynamics are represented by equation (2). Equations (3) and (4) are the core-averaged temperatures of the fuel and coolant respectively. Equation (5) calculates net reactivity based on control rod, shutdown reactivity and temperature feedback. Equation (6) is the power generated in the fuel and is driven by the PKE [2]. A comparison between the TRIGA model implemented in LabView™ and the PSBR was performed, and the results showed a good comparison between the two, and provide a model that is acceptable for control system development and HIL testing. Future HIL testing of the actual console will use a 3D RELAP coupled neutronic/thermal-hydraulic model for assessing the performance of the new control system on a spatially-distributed core.

RESULTS

Figure 6 shows a series of transients where the Foxboro control system is controlling the PSU TRIGA reactor simulation. Two controller set point changes were implemented (1MW to 700 kW and 700 kW to 900 kW) - showing that the Foxboro could effectively follow operator commands - then the controller set point remained at 900 kW and the Transient control rod was manually removed and inserted - showing that the Foxboro controller could effectively reject disturbances and remain at a desired power.

Given the present differences between the programming of the Foxboro system and the AECL console, the results meet expectations and are consistent with the performance of the existing AECL console controlling the actual reactor, and suggest that the Foxboro would be an excellent candidate for a replacement system. Reactor SCRAM, power increases and decreases, automatic mode and manual mode changes as well as power set point tracking are successfully accomplished by the Foxboro and TRICON systems.

CONCLUSIONS AND FUTURE WORK

The Foxboro I/A control system and TRICON safety system have successfully demonstrated the essential features of reactor control e.g., power setpoint tracking, reactor period tracking, and protective functions (high fuel temperature and high power SCRAM). Data taken from the Foxboro and TRIGA reactor output were closely aligned in every scenario, such as manual transient rod insertion and removal and SCRAM. Additionally, the graphical user interface of the Foxboro control system was intentionally designed to look and behave like the current AECL TRIGA control console. This interface will be upgraded in the future by incorporating more details of the current console and adding new indicators via Foxdraw™. Control rod height alignment (in automatic mode) has also been incorporated. A TRICON 1E protection system, donated to Penn State by Schneider Electric Inc., has been implemented as an addition to the current laboratory system. Future HIL testing of the actual console will use a 3D RELAP coupled neutronic/thermal-hydraulic model for assessing the performance of the new control system on a spatially-distributed core.

ACKNOWLEDGEMENT

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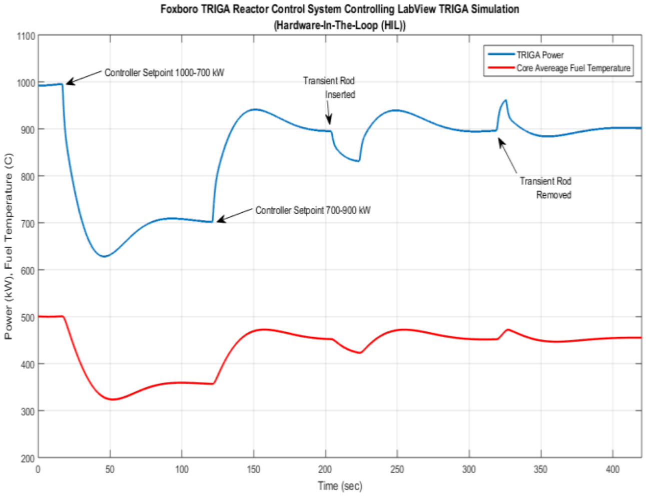

Figure 6. LabView Model being controlled by the Foxboro control system

NOMENCLATURE

n(t):	Neutron Population
$C_i(t)$:	Neutron Precursor Concentration for Group i
λ_i :	Effective delayed neutron precursor decay constant
β :	Beta Fraction
Λ :	Neutron Generation Time
$\rho(t)_{net}$:	Net reactivity insertion at time t
T_f :	Temperature of Fuel
M_f :	Mass of Fuel
C_f :	Specific Heat of Fuel
Q_f :	Power Generated in Fuel
$U_f A_f$:	Heat Transfer Constant in Fuel
T_c :	Temperature of Coolant
M_c :	Mass of Coolant
C_c :	Specific Heat of Coolant
$\dot{m}_c$:	Mass flow of Coolant
T_0 :	Temperature of Coolant Entering Core
$P_{avg.f}$:	Average Power in fuel