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White Paper

DCS Upgrades for Nuclear Power Plants:

Saving Money and Reducing Risk through Virtual-Stimulation Control System Checkout

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1. Abstract

Nuclear power plant control systems of 1970s vintage have reached the end of their life: reliability is poor and spare parts are hard to find. At FirstEnergy Perry Nuclear Power Station, two costly feedwater system trips caused by an ailing analog control system led to the decision to replace it with a modern Foxboro® I/A Series® Distributed Control System (DCS). The simulator was also upgraded using the Virtual-Stim simulation of I/A, called FSIM Plus™. Virtual-Stim simulation allows the configuration and graphics from the plant to be downloaded onto the simulator "as is," using the same tools and operator interface as the plant, without imprecise translations, conversions, or other emulation. Advances in simulation technology and market forces have led to an open architecture design, allowing FSIM Plus to be "bridged" to Perry Station's existing Opensim™ simulator process model. This appears to be an industry-wide trend as more control system vendors offer Virtual Stimulation solutions for connection to third-party simulation products. Taking a cue from FirstEnergy's Sammis Station FSIM Plus simulator projects, the Perry Station simulator was used for dedicated control verification and tuning. Preventing forced outages caused by control configuration errors can result in enormous savings and the simulator is now required to precede any plant modifications rather than just a training tool that lags the plant. This testing revealed several surprising results for a relatively straightforward control strategy, showing that simulator-based testing will be even more crucial in the future as the rest of the plant is migrated to digital control.

Figure 1. Perry Nuclear Power Station

2. Introduction

FirstEnergy Corp. Perry Nuclear Power Station was built starting in 1974, with 1253MW capacity (Figure 1). A Bailey analog control system was installed and remains the primary control system to this day. However, the system is showing its age. Recently, two feedwater control system trips attributed to faulty controller hardware caused a forced outage which resulted in loss of revenue in the hundreds of thousands of dollars. The feedwater control system made it to the number one position of a David Letterman-style "Top Ten List" of things that needed to be fixed in the Perry plant.

Of the 104 nuclear power plants in the United States, the Perry Station is not alone in needing control modernization. In order to qualify for NRC re-licensing, most of the plant's aging control systems will need to be replaced with modern Distributed Control Systems (DCS). By no means, however, is this transition a "no-brainer." DCS designs are now on the cusp of their third generation of evolution. Therefore, entirely new Instrumentation and Control, Controls Engineering and Operating skills are required. Before discussing strategies for dealing with this fundamental shift in technology, we first must look at the evolutionary stages of process control.

3. Digital vs. Analog Control Evolution: Coming Soon to a Nuclear Generating Station Near You

Analog control consisted of electronic circuitry, custom-designed, for individual control loops. Adjustable resistors and capacitors within amplifier circuits formed tunable gain controllers that were a step up from pneumatic controllers (bellows and springs) installed in 1950s generation fossil power plants.

Distributed Control Systems took advantage of the First Generation of microprocessors, making the formerly hard-wired control algorithms programmable. Furthermore, spreading the programming to run on multiple microprocessors gained increased computing power (hence, "distributed" control). The First Generation of digital control was modifiable, tunable and didn't suffer degradation.

The Second (and current) Generation of digital design increased processing power and data communication speed and began to migrate toward industry-standard operating systems (such as Microsoft Windows®). In the meantime, the control design tools and operator interface (Human Machine Interface) became increasingly powerful and easy to use. This generation now sees the first steps toward open connectivity (such as OPC - Object Linking and Embedding for Process Control) with "smart" instrumentation and other manufacturers of controllers (PLCs for instance).

The Third Generation of digital control now emerging seeks to drive hardware costs lower and to increase connectivity further. Open standard communication protocols such as Fieldbus, Profibus and Plant Ethernet allow control to be pushed further into the field, and wiring complexity is reduced. The Third Generation also increases vertical integration of the control system with the entire plant information systems; this so-called "sensor-to-boardroom" connectivity allows useful, detailed plant information to be rolled up into high-level Enterprise or Asset Management Software. In the DCS-to-come, an operator may not only just manipulate a control valve, he may call up its maintenance records, blueprints, wiring diagrams, design specifications, etc.

The point of this discussion is that, in general, the nuclear industry is 10 to 15 years behind current control system technology. There are risks associated in making up this gap, but there is an avenue available to mitigate risk as discussed in Section 4.

Finally, the Third Generation introduces several flavors of loop self-tuning, neural nets or Advanced Process Control (APC). Multivariable APC has been proven in the oil and gas process industries for years and is now being incorporated into fossil power plant control for improved megawatt ramp rate, tighter steam temperature control and reducing emissions. It is not a leap to assume that these forms of advanced control will find their way into nuclear plant control.

4. The "Old Fossils" Point the Way

The nuclear generation industry has adopted a "walk before run" approach toward modernization. In contrast, their fossil-fired cousins are now mostly into Second Generation DCS and newly-constructed power plants will employ Third Generation designs. Notwithstanding the advantages of DCS over analog control, control configuration errors, untuned controls and operator unfamiliarity may lead to delays in coming back on-line after the control system change-out. Conservative estimates show that each day of lost generation revenue for a nuclear power plant amounts to between $500K and $1M.

Fossil power plants have increasingly justified the purchase of a brand new simulator based on reducing DCS upgrade outage time by wringing out "infant mortality" control errors. Using this "test before install" philosophy, savings of as little as two days out of a typical 30- day outage can completely pay for the entire high-fidelity simulator. The primary requirement for a simulator can almost be thought of as for Instrumentation and Controls checkout purposes alone; ending up with a valuable Operator Training Simulator afterward is a bonus. FirstEnergy W. H. Sammis Power Plant procured three simulators: one as a training-only tool, one as a checkout and training tool for a unit being upgraded, and one as a checkout tool for a planned unit upgrade.

Nuclear power plants have a built-in advantage over their fossil cousins: each of the 104 plants already has a high-fidelity simulator, well correlated to plant data. The existing plant simulator can be leveraged to become a highly valuable Instrumentation and Controls (I&C) engineering tool, equal in merit to its Operator Training function. However, the correct technology for simulating the control system must be used, as described in the next section.

5. DCS Simulation: The Virtual Stimulation Mandate

Simulating the plant control system has been relatively easy for analog, First and some Second Generation DCS. The control diagrams could be studied and converted to FORTRAN logic statements to be compiled and linked with the remainder of the process model source code. However, with the approach of Third Generation process control, this "Full Emulation" approach to simulating the control system will ultimately be inadequate. The control algorithms, advanced operator tools and controls engineering capabilities are becoming too complex to "reverse engineer." What alternative exists?

The answer is Virtual Stimulation: taking the underlying controller source code and porting it to run on a low cost computer platform. Virtual Stimulation supports required basic simulation functions (freeze, run, snapshot, etc.) and has the added advantage of allowing multiple controllers to run on a single processor (thus minimizing total hardware required for the simulator).

For the Virtual Stimulation approach to work, it must be able to integrate with any simulation software. SimSci-Esscor's solution employs distributed simulation with a "bridge" architecture, whereby simulator commands come from the parent simulator and are routed to one or more Virtual Stimulation "Engines." See Section 5 for details.

The resulting Virtual Controller communicates with real Operator and Engineering workstations and their associated applications. These applications include I&C, Control Engineering and Operator Interface tools with the look, form, fit and operation identical to those in the real control room.

Finally, increased competition among DCS suppliers has meant that new software versions, with enhanced features, are released more frequently than they used to be. In order that the plant not fall behind the times, most DCS suppliers offer some form of maintenance agreement that provides for regular software upgrades. It is easy for the Virtual Stimulation approach to keep pace with the DCS software releases, since they share the same source code. On the other hand, emulations may force the whole development process to start over for each new DCS software release. The "mandate" for the Virtual Stimulation approach to modeling the control system is illustrated in the workflow diagram of Figure 2.

For the Virtual Stimulation approach to work, it must be able to integrate with any simulation software. SimSci-Esscor®'s solution employs distributed simulation with a "bridge" architecture, whereby simulator commands come from the parent simulator and are routed to one or more Virtual Stimulation "Engines." In this manner, only the bridge adapter software need be written, one time, to connect any simulator offering to an array of Virtual Stimulation engines (see Figure 3). The bridge and Virtual Stimulation engines start and connect in real time, as the simulator main executable is started. The bridge and engines may run on the same platform as the executable or may be distributed to additional machines as needed.

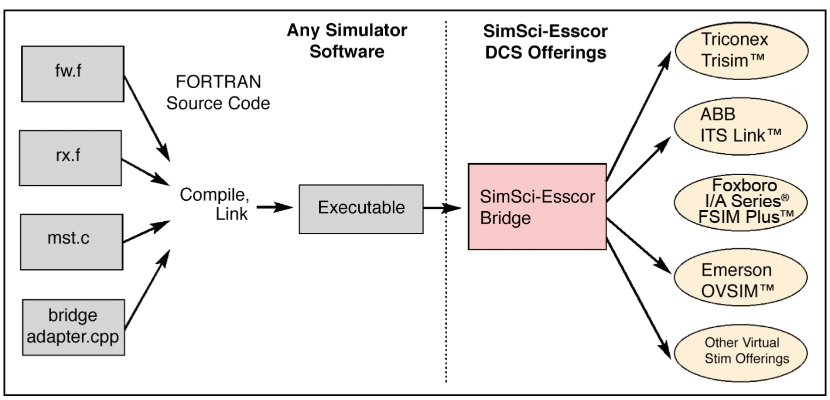

Figure 3: Integration of Virtual Stimulation with Opensim or other Simulator

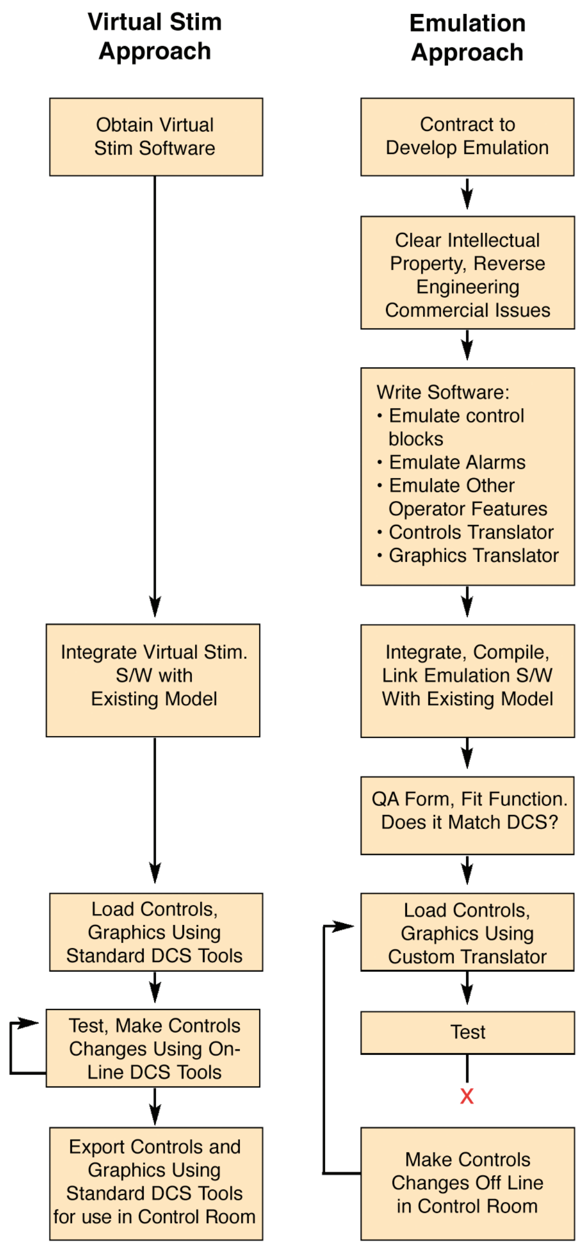

Figure 2. Development workflow diagram for simulation of DCS: Virtual Stim vs. Emulation

6. FirstEnergy Nuclear Operating Company (FENOC), Perry Nuclear Power Plant I/A Series System Controls Checkout Case Study

Employing the philosophy discussed in previous sections, Perry Station used SimSci-Esscor Bridge and FSIM Plus software and integrated it with their existing RNI Technologies Opensim simulator. The goal: thoroughly test the Foxboro I/A Series digital feedwater control replacement for the faulty analog system. Adopting the philosophy of test before install, the controls checkout was required to be completed prior to the simulator being released for training and before the upcoming outage.

Figure 4: Installed Foxboro I/A Series System on simulator (upper), old feedwater hard panel control (lower)

Far from being experimental technology, FSIM Plus Virtual Stimulation has been in existence for over 10 years and has seen continuous upgrades from Version 4.0 up to the current Version 8.0. The Opensim Master Simulation Task program (mst.c) was modified to insert a call to the bridge Application Programming Interface (API) software, supplied with the FSIM Plus software. This software, along with additional utilities to cross-reference I/O points to model database variables, were combined to form the bridge adapter software. Figure 5 shows the installed I/A Series engineering and operator stations and FSIM Plus installed on the simulator.

A series of eight severe events were tested to validate feedwater response. The following tests were run:

- Reactor Feed Pump Turbine (RAPT) trip
- Reactor recirculation pump trip to off (single)
- Reactor recirculation pumps trip (double)
- Inadvertent HP Core Spray (HPCS) initiation
- Inadvertent 1 Safety Relief Valve (SRV) open
- Loss of one HP feedwater heater
- Reactor recirculation pump start
- Reactor SCRAM

Of these tests, the reactor level response to a reactor feedwater pump trip was deemed unsatisfactory, since peak level on trip was four to six inches above what the simulator predicted with the old Bailey controls emulation (see Figure 5). Tuning the three element cascaded control could not get satisfactory response, no matter how tightly the gain was set. This indicated some rate limiting element, either in the controls or in the model (for instance, valve stroke time).

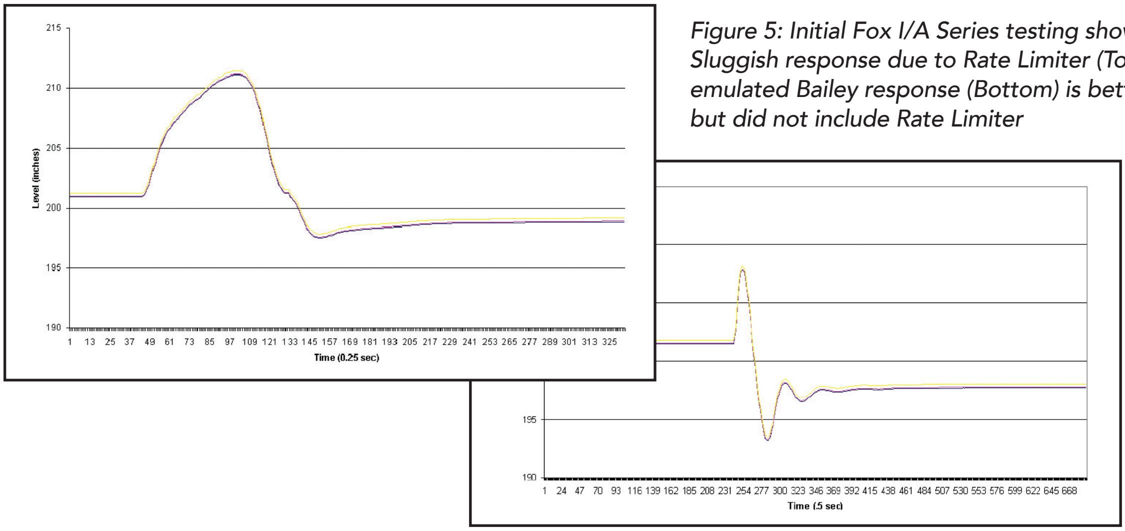

Figure 5: Initial Fox I/A Series testing showing Sluggish response due to Rate Limiter (Top); emulated Bailey response (Bottom) is better, but did not include Rate Limiter

Using the Fox Select tool on the operator workstation, a control block-by-block investigation revealed that a velocity limiting block limited controller output rate-of-change to 5% per second.

Here was the first surprise. The emulated Bailey response in Figure 5 didn't show this rate limiting. The controller output traveled as fast as 12% per second. This led to a line-by-line examination of the FORTRAN source code for the Bailey emulation, whereupon it was discovered that, contrary to belief, the rate limiting was not included in the simulation.

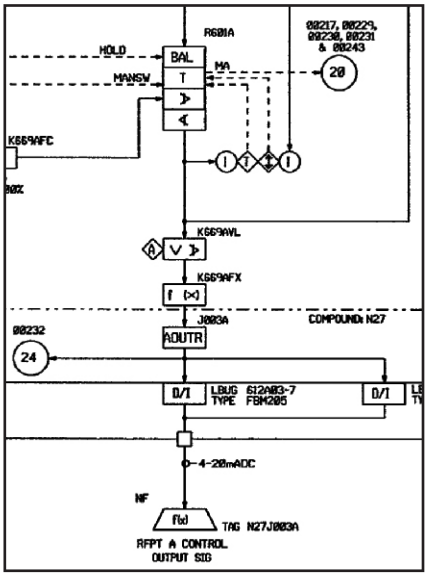

Figure 6: Fox I/A Series showing Rate Limiter before Characterizer. Bailey Controls had rate limiter after characterizer.

The reason was that a load-following control scheme was being tested in the plant whereby the reactor recirculation pump flow rate was regulated to regulate load. Interactions with the level control resulted in unstable response, resulting in the insertion of a velocity-limiting block on the feedwater controller output. Because, at the time, the simulator always followed and was secondary to plant developments, the simulator got out of sync.

The rate limiter investigation revealed a second surprise: the Bailey control diagrams show the velocity-limiter after the output characterizer, while the Foxboro controls configuration has the limiter block before the controls characterizer (see Figure 6).

The output characterizer corrects for non-linear feed pump response from zero to 100% demand. The Foxboro I/A Series control design is probably most correct, since rate limiting should be done on the 0 - 100% signal, not the output signal. However, was there a peculiar reason why the Bailey design had it after? Only simulator testing could find, ask and answer the question.

Furthermore, is the velocity limiting block even necessary? Until the investigation, no one on the simulator team knew why the block was required. On-line reactor testing showed that the load following scheme did not work and was abandoned, but the rate limiter block remained behind. Is it a vestige, or is it still needed? When the 5% per second constraint was removed from the simulator I/A controls, level response improved beyond the original Bailey controls, resulting in increased margin before trip on high reactor level.

7. Conclusions

The conclusions from this section are:

- The simulator should be used as a test before the install tool
- The simulator asks and answers questions
- The simulator must lead the plant, instead of following behind it
- Originally-installed nuclear plant control system technology is 10 to 15 years behind Second and Third Generation DCS design. Leveraging simulation beyond a "training-only" tool will be required to close this gap.
- Increasingly, fossil power plants require simulator-based controls checkout prior to upgrading and justify the return on investment through shortened outage time. Nuclear plants should adopt this same paradigm.
- DCS controls emulation is an inadequate representation of leading-edge DCS designs, whereas Virtual Stimulation packages (being offered by most DCS vendors) are an exact representation. "Bridge" software ensures that any Virtual Stimulation offering can work with any simulator vendor.

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