Digital Actuator Technology

Ken D. Thomas
Idaho National Laboratory
2525 Fremont Ave.
Idaho Falls, ID 83415
kenneth.thomas@inl.gov

Edward L. Quinn, Jerry L. Mauck, Richard M. Bockhorst
Technology Resources
23292 Pompeii Drive
Dana Point, CA 92629
tedquinn@cox.net, jerrymauck@verizon.net, r_bockhorst@hotmail.com

ABSTRACT

The nuclear industry has been slow to incorporate digital actuator technology into nuclear plant designs for several reasons, including:

- The high cost of design change modifications to implement them, versus simply replacing them with like-for-like technology when the components fail.
- Digital technology qualification issues, particularly in safety related applications that are susceptible to software common cause failure. This is a concern both for current operating plants as well as new builds.
- General familiarity and comfort with the existing analog technology on the part of the nuclear plant engineering staff, in spite of the superior performance and reduced maintenance costs of the digital replacements.

At the same time, the nuclear industry is under significant cost pressure in the electric marketplace due to the abundance of gas generation. The industry would benefit by investment in new technologies that could lower future operating costs while addressing current obsolescence and reliability issues of the current technologies. However, the industry has been unable to formulate the business cases to take advantage of these labor savings and production reliability improvements.

This paper presents the benefits digital actuator technology for four types of actuators that account for the vast majority of control applications in a nuclear power plant: pneumatic control, hydraulic control, motor control, and variable frequency drives. The paper describes the common failure modes of the analog actuators as confirmed by actual component failure records from an industry failure data base.

The paper discusses the benefits of digital actuators, which are generally found in two main areas. First, the digital technology offers superior operational performance over its analog counterparts, in terms of accuracy and reliability. Second, the cost of maintaining the digital actuators is lower due to simplicity of operation (circuit boards vs. mechanical parts) and on-board diagnostics that greatly improve troubleshooting and repair.

Notwithstanding the benefits of digital actuators, there are certain qualification and licensing challenges that are inherent with digital technology, and these are described in the report. One major qualification impediment for digital sensor implementation is software common cause failure (SCCF). A typical analysis for SCCF, in the form of a Nuclear Regulatory Commission

(NRC) regulatory submittal, is presented to demonstrate the difficulty in addressing SCCF for nuclear safety-related designs. It also addresses what options exist to mitigate the SCCF concerns.

The paper concludes with a summary of benefits to be gained and challenges to be addressed in pursuing the wide-scale application of digital actuator technology. In particular, it highlights the need for new approaches in digital technology qualification over the only currently-accepted approach of presenting a coping analysis for an assumed SCCF.

Key Words: digital, actuator, software common cause failure, nuclear power

1 INTRODUCTION

This paper presents the benefits of using digital actuators in nuclear power plants for component positioning and operation, and describes the challenges in digital technology qualification that are impeding their rate of adoption. This topic is more fully described in a related report entitled Digital Actuator Technology, produced under the Department of Energy's Nuclear Energy Enabling Technologies Research Program [1].

Too often today, nuclear plant designers implement a modern digital control system capable of high precision control, but then couple it with less-accurate analog sensors and actuators. This effectively negates the benefits of the digital control system in that the analog components tend to dominate the overall system accuracy and reliability.

The nuclear industry has been slow to incorporate digital actuator technology into nuclear plant designs for several reasons, including:

- The high cost of design change modifications to implement them, versus simply replacing them with like-for-like technology when the components fail.
- Digital technology qualification issues, particularly in safety related applications that are susceptible to software common cause failure. This is a concern both for current operating plants as well as new builds.
- General familiarity and comfort with the existing analog technology on the part of the nuclear plant engineering staff, in spite of the superior performance and reduced maintenance costs of the digital replacements.

Today, the nuclear industry is facing unprecedented cost pressure. Low-cost gas generation is setting market conditions that are challenging many unregulated nuclear power plants with financial viability. There is a pressing need to reduce operating costs so that the nuclear plants are positioned for long-term operation.

2 ACTUATOR TECHNOLOGIES

This section addresses the most common types of actuators used in nuclear power plants that account for the applications that can most benefit from digital technology. They are pneumatic valve and damper control, hydraulic valve control, motor control, and variable speed drives for pump control.

2.1 Digital Pneumatic Positioners

In pneumatic control, compressed air is used to provide motive force for various types of displacement mechanisms. A series of devices are used to take air from a regulated supply and then provide the correct amount of air pressure to move the device to the desired position. Pneumatic actuators are susceptible to a number of operational problems and failure modes. Accuracy is affected by hysteresis in the mechanical parts.

For a digital valve positioner, a microprocessor accepts the control signal and adjusts the signal to the I/P based on the output pressure, the supply pressure and the valve position. The I/P provides a pressure signal to a pneumatic relay that amplifies the signal and provides the pressure to the valve actuator.

Digital positioners offer a number of advantages in four fundamental areas.

- High reliability
- Improved operational performance
- Increased productivity and reduce maintenance costs
- On-board diagnostics for early warning of pending failure modes

Operational performance is enhanced through improved accuracy of the digital positioner, achieved by enabling consideration of a number of factors digitally to adjust the positioner output pressure. Self-tuning features improve the dynamic response of the associated control valve resulting in better process control. The digital nature of the positioners permit remote diagnostics to be performed routinely or whenever deemed appropriate. These diagnostics have the capability to detect a variety of issues related to the control valve functionality such as the following potential problems.

- air leakage
- valve assembly friction and dead band
- instrument air quality
- loose connections
- supply pressure restriction
- valve assembly calibration

The availability of diagnostics permits early identification of degradation allowing corrective action to be taken and avoiding an upset condition. The diagnostic capability also facilitates characterization of the valve performance following maintenance on the valve to increase the assurance that the valve will function properly when returned to service.

Implementing digital positioners on critical control valves also enables online partial stroke testing of the control valve without upsetting the normal process control. This testing provides assurance that the control valve will actually move on demand.

The ability to remotely configure, calibrate, and diagnose the health of the controls greatly simplifies maintenance. Digital positioners have the ability to self-calibrate, potentially eliminating the need to access the valve locally. If the valve is located in a radiological controlled area, personnel radiation exposure may be reduced. Depending on the specific valve location, implementing personnel safety measures such as scaffolding may be avoided if the maintenance can be conducted remotely. If maintenance on a digital valve positioner is required, the modular design of the positioner simplifies the repair.

2.2 Electro-Servo Actuators

Large nuclear plant valves that require precise control often use electro-hydraulic actuators. These actuators have an electric motor-pump set to create the hydraulic pressure, which is then applied to a piston in a cylinder to deliver the actuating force. Often this force is applied against a spring so that any intermediate position of the valve or damper can be obtained by providing the amount of hydraulic force needed to compress the spring to the desired point. The spring also serves to provide a fail-safe mechanism in which the spring returns the valve to a desired position (either open or closed) on loss of hydraulic pressure.

A viable replacement for analog hydraulic actuators is a digitally-controlled electro-servo actuator, also known as an electro-mechanical linear actuator. An electro-servo actuator is a high-speed electric motor that typically uses a roller screw to achieve fast, accurate linear motion. Due to a number of design features, they are faster than conventional electric actuators that rely on reduction gears to translate motor speed to valve movement. They are more accurate than hydraulic actuators, being able to resolve position within a fraction of a turn of the roller screw using advanced positioning feedback. In addition, the accuracy and repeatability are exceptionally good due to very low hysteresis in the roller screw drive system.

With a digital interface, the electro-servo actuator is able to directly translate a position demand for the plant control system into an actuation signal with no degradation due to loop drift or other types of signal fidelity loss. It is able to self-calibrate by articulating the entire range of motion when first initialized. By contrast, the calibration of a hydraulic actuator is far more complex and time consuming.

In addition to the operational benefits, there is considerably less maintenance with an electro-servo actuator. Foremost is the amount of maintenance on the oil system itself, which requires filter changes, periodic oil cleaning or replacement, and repair of leaks around fittings and moving parts. There is also significant maintenance required to keep the hydraulic system in good working order, including the hydraulic oil pump, oil cylinder or piston, porting valves, and over-pressure protection devices. [2]

There are a number of operational benefits with electro servo actuators:

- The elimination of hydraulic actuators also removes a significant fire hazard. The high-pressure oil is also a personnel safety concern, requiring protective clothing and special precaution when working around these energized systems.
- They are much easier to install, requiring only the connection of electrical cables rather than hydraulic fluid fittings.
- The footprint of the installation is much smaller. Typically, the entire electro servo actuator fits into the same space as the hydraulic cylinder and does not require the additional space needed for a hydraulic pump, filter, and oil reservoir tank.
- The electro servo actuator is more energy efficient, drawing power only when it is repositioning as opposed to a hydraulic pump, which runs continuously.
- The operation of an electro servo actuator is much quieter than the hydraulic system.

2.3 Motor Control Centers

A motor control center (MCC) is an assembly of one or more enclosed vertical metal cabinet sections having a common power bus and principally containing motor control units. Motor control centers are usually used for low voltage three-phase alternating current motors from 208 V to 600 V.

Motor control centers that utilize various digital devices are available from a number of suppliers. Digital motor control centers typically incorporate a digital communication interface and have a number of options available that can improve performance. The current and voltage is continuously digitized and capable of transmission. The benefits are increased reliability, reduced maintenance, remote diagnostics, sequence of events recording, improved electrical protection of the loads, and reduced personnel hazard.

Increased reliability can result from several different available features of digital motor control centers, primarily from the ability to easily perform diagnostics. Since the current and voltage can be monitored for each load trending of these parameters for each load is facilitated. Changes in these parameters may be indicative of a serious problem that can be corrected prior to failure. Motor current signature analysis may also be possible that can broaden the spectrum of problems that may be detected in advance of a failure.

A second feature of digital motor control centers is the ability to perform soft starts of the connected motors. Soft starts reduce the motor inrush current by ramping up the applied voltage on a start avoiding the more severe application of full voltage with the motor at rest.

A third available feature is that solid state overload relays may be used to replace conventional thermal overloads. These relays provide a more accurate assessment of the thermal condition of the motor potentially avoiding unnecessary thermal trips. Additional protection of the load is available through detection of a phase loss, current imbalance, a ground, a stall of the associated motor, or a significant underload condition. Remote operation of the thermal overload relay is an available feature as well as automatic reset of the relay following a thermal overload trip.

Arc flash detection and protection is available with digital motor control centers. Flash detection within the MCC is coupled with incoming current monitoring to determine if a trip of the incoming circuit breaker is appropriate. This may serve to significantly limit the energy of the arc flash assisting in protection of personnel.

2.4 Variable Frequency Drives

Variable frequency drives (VFD) are equipment used to control the speed of machinery, ranging from small appliances to the largest of mine mill drives and compressors. Many industrial processes such as assembly lines must operate at different speeds for different products. When process conditions demand adjustment of flow from a pump or fan, varying the speed of the drive may save energy compared with other techniques for flow control.

The advantages of VFD’s in the nuclear industry are many as discussed in a paper published in IEEE PEDS 2011 [3]. Nuclear plants, especially BWR’s are including VFD’s in their AC power systems in many cases now to improve the reliability, efficiency and enhanced compliance with the Clean Water Act.

The benefits of VFD’s can be categorized in the following:

- Higher efficiency and improved power consumption.
- Higher reliability and availability
- Reduced maintenance
- Improved flow control in condenser applications
- Soft start
- Elimination of portions of the fire detection and suppression system
- Improvements in fill and vent activities.
- Reduced water hammer

3 ACTUATOR RELIABILITY

The reliability of actuators in a nuclear power plant is highly-important to safe operations in that they initiate the required control and protection actions. Unreliable plant actuators also result in excessive maintenance, which is both expensive and can result in maintenance-induced faults. In other words, frequent maintenance on troublesome components can induce further problems as these components are excessively handled, manipulated, and tested. A good example of this is disconnecting instrument tubing over and over, which leads to fitting wear and future tubing leaks. Therefore, unreliable actuators result in more frequent maintenance, which becomes a vicious cycle by providing more opportunity for maintenance-induced faults, due either to component wear or human error.

The reliability of a specific actuator design can be quantitatively determined in accordance with IEC 61508 [4] using a Markov Model, including the reliability data for individual components combined in the manner in which they support performance of the safety function. This analysis is based on the proof or surveillance test intervals, repair rates of components, and the plant specific configuration that is performing the safety function.

In traditional analog actuator designs, failures of actuators could go undetected until the next scheduled testing at the end of the current surveillance interval. Therefore, the device would be in a latent failure state and it would not operate correctly if called upon for its design basis function. Since the failure might have happened at any time during the surveillance interval, the predicted reliability of the actuation system would have to take this into account.

A key measure of reliability used by the nuclear industry is the Average Probability of Failure on Demand or PFDavg. The PFDavg is a function of Mean-Time-Between-Failure (MTBF) and the Proof Test (or Surveillance) Interval. Surveillance intervals for many safety-critical actuators are often 18 or 24 months, corresponding to a refueling cycle, and therefore the time period over which a failure could go undetected could be quite long.

A key consideration in the crediting of monitoring is the treatment of what is termed dangerous detected and dangerous undetected failure fractions, which are established to provide input to the Markov reliability model for the device and the associated system. IEC-61508 defines these as follows:

> Dangerous Detected Failure - A detected failure which has the potential to put the safety actuation system in a hazardous or fail-to-function state. Dangerous detected failures do not include hardware failures and software faults identified during proof testing, represented by the plant's surveillance testing.
>
> Dangerous Undetected Failure - An undetected failure which has the potential to put the safety actuation system in a hazardous or fail-to-function state. Dangerous undetected failures do not include hardware failures and software faults identified during proof testing.

A failure fraction refers to the relative proportion of both the detected and undetected failures, expressed as a fraction of one. Thus, dangerous detected failure fraction of 0.93 means that 93 out of 100 dangerous failures are detected by the monitoring capability. The role of the monitoring capability is to detect as many of the total possible dangerous failures of the system and related devices as possible, with the monitoring credit being proportional to the fraction. Note that there are other failures that are designated as safe, meaning they do not threaten the reliability of the system.

Obviously, if the sensor health could be confirmed on a more frequent basis, the PFDavg of the instrument design would be reduced (improved). Digital systems are able to do this by performing continuous monitoring of the sensor health.

4 DIGITAL TECHNOLOGY QUALIFICATION

An important barrier that must be overcome is the issue of digital technology qualification. Because digital involves electronic components and software, there are qualification requirements that go beyond those for their analog predecessors. Some of these are based on the plant physical environment, such as seismic, environmental (temperature, pressure, high energy spray impingement, radiation), and electromagnetic interference. Electronic components tend to be more sensitive to these phenomena compared to their analog (electro-mechanical) counterparts. In addition, software-based components are susceptible to other types of hazards, including software faults, cyber-attacks, and software common cause failure (SCCF).

The concern for SCCF is the most difficult barrier to address, in that a group of safety-related actuators could simultaneously fail in such a fashion that the acceptance criteria for the transient and accident analyses would not be met. Because of this, a plant could choose to provide diverse actuators on a per train/division basis where feasible or only use software for the non-safety functions of the actuator. However, this detracts from economies in spare parts, training, procedures, etc.

To address SCCF from a regulatory requirements standpoint, a Diversity and Defense-in-Depth (D3) [5] evaluation must be performed that demonstrates that there is sufficient defense-in-depth and diversity to cope with a postulated SCCF to the safety-related digital based actuators in the reactor protection and engineered safeguards systems. This requires the assumption that a SCCF occurs within the digital technology and then the proof that the nuclear plant can cope with the failure, considering all applicable events and accidents of the plant safety analysis. A pro forma D3 evaluation [1] of the actuators for the safety injection system injection vales in a reference nuclear plant confirmed that the acceptance criteria could not be met when all trains used the same digital actuators and therefore diverse actuators would be required. This study analyzed a large break loss-of-coolant accident (LBLOCA) and determined that the required response time would be much too short to rely on operator manual actions.

So, the challenge for the industry and the regulator is to find a way to use this superior technology where it would do the most good by resolving the qualification barriers to safety-related usage. The current regulatory framework for SCCF does not provide a means for determining how much diversity in a design is sufficient. It is possible that within given manufacturer's make and model, there could be sufficient diversity to minimize the probability of a SCCF due to other factors, including diverse software development. The manufacturers do not offer these options today because there are no objective criteria for determining how much diversity is enough, and therefore no objective way to credit this diversity in the analysis (as sufficient to preclude a SCCF).

Oak Ridge National Laboratory is addressing the impediments to qualification of digital technology for nuclear power application [6] The project is developing an objective, scientific basis for determining necessary and sufficient mitigation of software common cause failure vulnerabilities.

5 CONCLUSIONS

Digital actuator technologies are available to the nuclear power industry to improve operating performance, improve safety margins, and to reduce costs. These technologies have been proven in other industries and amply demonstrated the performance advantages over the legacy analog counterparts.

The U.S. nuclear power industry is currently under significant cost pressure due to the abundance of low-cost gas generation. The only practical solution to this is to reduce operating and maintenance costs. Therefore, the nuclear industry should take advantage actuator replacement opportunities when they present themselves. These technologies provide benefits in many different aspects of plant operations and support, and they represent an attractive option to contribute to the competitiveness of the nuclear plants.

For new nuclear facilities, including small modular reactors, it would be advantageous for the initial design of the plant systems to use digital actuators, avoiding the cost of later back-fits and ensuring the long-term cost advantages of lower maintenance are realized from the very beginning of commercial operation.

It is evident that there are substantial barriers in implementing digital actuators that must be overcome if the industry is to obtain the long-term operational benefits of digital actuators. So far, these factors in various combinations have been a significant impediment to the use of digital actuators in both operating plants and new reactor designs, especially for safety-related applications. Non-safety related digital actuators are also impacted, but to a lesser degree.

Therefore, further work is needed in several areas to promote the widespread use of digital actuator technology.

- A reasonable solution to the SCCF must be found such that all actuators of the same manufacturer and model number do not have to be assumed to fail, and that diverse actuation capability must be provided.

- Actuator suppliers need to qualify, and harden if necessary, the digital sensor alternatives, so that they can be used in safety-related applications located in harsh environments.
- The industry would benefit by the development of a formal business case related to widespread use of digital actuator technology. This study would capture the plant-wide performance improvement and cost savings related to accuracy and reliability, and thereby help overcome the "nuclear designer comfort factor" in the continued use of the legacy analog actuator technologies.

6 ACKNOWLEDGMENTS

The U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) established the Advanced Sensors and Instrumentation (ASI) technology area under the Nuclear Energy Enabling Technologies (NEET) Program to coordinate the instrumentation and controls (I&C) research across DOE-NE and to identify and lead efforts to address common needs. As part of the NEET ASI research program, the Digital Technology Qualification project was establish based on collaboration between Oak Ridge National Laboratory (ORNL) and Idaho National Laboratory (INL). This paper has been developed with the funding provided for the Digital Technology Qualification project, and is derived from a related project report entitled Digital Actuator Technology (INL/EXT-14-33132). The authors would like to thank Ms. Suibel Schuppner of the U.S. Department of Energy, Program Manager for the NEET ASI research program, and Dr. Bruce Hallbert of the Idaho National Laboratory, Technical Director for the NEET ASI research program.

The authors also would like to thank the following individuals for providing valuable industry reference information on digital actuator technology:

- Richard Little and Joel Molito, General Electric
- Steve Hagen and Mike Hagen, Emerson Process
- Bill Matthews and Curtis Fields, AREVA
- Ron Jarrett, Tennessee Valley Authority

7 REFERENCES

1. Quinn, E., Mauck, J., Bockhorst, R., & Thomas, K., Digital Actuator Technology (INL/EXT-14-33132), Idaho National Laboratory, September 2014
2. Steam Turbine Hydraulic Control System Maintenance Guide, EPRI Technical Report 107069, December 1996
3. IEEE PEDS 2011, Singapore, 5-8 December, 2011, "Variable Speed Pumping in Thermal and Nuclear Power Plants: Frequency Converter versus Hydrodynamic Coupling," Page 228-234.
4. International Electrotechnical Commission, IEC 61508 - 2009, Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems, Parts 1 through 6
5. U. S. Nuclear Regulatory Commission, Standard Review Plan, NUREG-0800, Chapter 7, Branch Technical Position (BTP) – 19 Revision 6, Guidance for Evaluation of Diversity and Defense-in-Depth in Digital Computer-Based Instrumentation and Control Systems, Washington, DC, July 2012
6. Wood, R., Pullam, L., Smith, C., Holcomb, D., Korsah, K., Muhlheim, M., Common Cause Failure Mitigation Practices and Knowledge Gaps, NEET/ASI/ORNL/TR-2012/01, Oak Ridge, TN: Oak Ridge National Laboratory