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Nuclear Power Plant Instrumentation and Control

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1. Introduction

Installed throughout a nuclear power plant, instrumentation and control (I&C) is an essential element in the normal, abnormal and emergency operation of nuclear power plants (International Atomic Energy Agency [IAEA], n.d.). Through their equipment, modules, sensors, and transmitters, I&C systems measure thousands of variables and processes the data to activate pumps, valves, motors, and other electromechanical equipment that control the plant. The I&C system senses basic physical parameters, monitors performance, integrates information, and makes automatic adjustments to plant operations to keep process variables within the plant design limits. By reacting appropriately to failures and abnormal events, I&C ensures the plant's safety and efficient production of power (U.S. Nuclear Regulatory Commission [U.S. NRC], 2011).

All of these roles can be reduced to three basic functions (IAEA, 1999). First, as the plant's nervous system, I&C provides plant operators with accurate and relevant information so they can make the appropriate actions during normal as well as abnormal operation. Second, I&C provides plant operators with the capacity to exercise automatic control over the plant and its associated systems so they can take whatever actions are needed to maintain efficient and safe operation. Finally, I&C serves the critical function of protecting the plant from faults in the system or errors made by the operator as well as abnormal or extreme external events that threaten the plant's operation. More specifically, I&C should enable the plant to operate safely for an extended period without operator intervention following an accident (IAEA, 1999).

Nuclear plant I&C systems must be *accurate* to properly sense and communicate the process variables and reasonably *fast* to provide timely display, adjustment, and protection against upsets in both the main plant and its ancillary systems. For example, temperature sensors such as resistance temperature detectors (RTDs), which are key elements in the safety system instrumentation of nuclear power plants, may be expected to provide 0.1 percent accuracy and respond to a step change in temperature in less than 4 seconds.

Nuclear plant I&C is more complex and varied than the control instrumentation in other industrial applications because of the special nature of nuclear power. A nuclear plant's production must remain continuous because of its high capital costs, direct access to and control over the nuclear plant's reactor is impossible, and the potential risks of nuclear energy production require greater redundancy and reliability in plants' control infrastructure (IAEA, 1999). Although I&C is a relatively small component in a typical plant's maintenance and capital upgrade budget, its impact on the plant's safety, reliability, and performance is preeminent (Hurst 2007). For example, assuming that a 1000 MWe plant has a daily operating revenue of about $2 million per day, a loss in power production level of even 1 percent can quickly amount to millions of dollars in lost revenue.

Some 10,000 sensors and detectors and 5,000 kilometers of I&C cables—representing a total mass of 1,000 tons—comprise the I&C system of a typical nuclear plant unit, including up to 20 neutron detectors, 60 RTDs, as many as 100 thermocouples, and 500 to 2,500 pressure transmitters (IAEA, n.d.; Hashemian, forthcoming). Categorized by function, I&C components consist of:

- Sensors that interact with the plant's physical processes to measure process variables such as temperature, pressure and flow as well as control, regulation, and safety components that process the sensors' data.
- Communication infrastructure—wires and cables, fiber-optic and wireless networks, digital data protocols—that move sensor and control data through the I&C system.
- Human-system interfaces such as displays that enable human plant operators to monitor and respond to the continual flow of I&C data.
- Surveillance and diagnostic systems that monitor sensor signals for abnormalities.
- Actuators such as valves and motors that physically operate the plant's control and safety components to adjust physical processes so the plant's performance is optimized for efficiency and safety or, if needed, shut down.
- Actuator status indicators that visually reflect automatic or manual control actions, such as the switching on or off of a motor or the opening or closing of a valve (IAEA, n.d.).

2. Important I&C components

Nuclear plant instrumentation can generally be classified into the following four categories:

- *Nuclear:* instruments that measure nuclear processes or reactor power, such as neutron flux density.
- *Process:* instruments that measure non-nuclear processes such as reactor pressure, coolant or pressurizer level, steam flow, coolant temperature and flow, containment pressure, etc.
- *Radiation monitoring:* instruments that measure radiation, for example, in monitoring radiation in steam lines, gas effluents, and radiation at the plant site.
- *Special:* Instruments encompassing all other applications, such as for measuring vibration, hydrogen concentration, water conductivity and boric acid concentration or meteorological, seismic, or failed fuel detection applications (IAEA, 1999).

The variety of I&C components and applications notwithstanding, temperature, pressure, level, flow, and neutron flux remain the most important and safety-critical measurements for the control and safety protection of nuclear reactors. The heart of each of these measurements is the sensor itself--the most important component in an instrument channel and the one that usually resides in the harsh environment of the field (Hashemian, 2007). Despite the accelerating advances in I&C technology (to be discussed in the next section), the basic mechanism of measurement used by these sensors has not changed significantly since the earliest nuclear plants. Today, temperature, pressure, level, flow, and neutron flux are still primarily measured using conventional sensors such as resistance temperature detectors (RTDs), thermocouples, capacitance cells, bellows, force-balance sensors, and conventional neutron detectors although some advances have been made in developing new neutron detectors for nuclear power plants (Hashemian, 2009a).

The control and safety of nuclear power plants depend above all on temperature and pressure (including differential pressure to measure level and flow) instrumentation—the two most ubiquitous instrument types in a typical nuclear power plant process. In pressurized water reactor (PWR) plants, RTDs are the main sensors for primary system temperature measurement. RTDs are thermal devices that contain a resistance element referred to as the sensing element. Two groups of RTDs are typically used in nuclear power plants: direct immersion (or wet-type) and thermowell mounted (or well-type). The resistance of the sensing element changes with temperature, and therefore by measuring the resistance, one can indirectly determine the temperature. The number of RTDs in a nuclear power plant depends on the plant design and its thermal hydraulic requirements. For example, PWR plants have up to 60 safety-related RTDs while heavy water reactors such as Candu plants have several hundred RTDs.

Pressure transmitters are the next most common I&C component. A pressure transmitter may be viewed as a combination of two systems: a mechanical system and an electronic system. The pressure transmitter’s mechanical system contains an elastic sensing element (diaphragm, bellows, Bourdon tube, etc.) that flexes in response to pressure applied. The movement of this sensing element is detected using a displacement sensor and converted into an electrical signal that is proportional to the pressure. Typically, two types of pressure transmitters are used in most nuclear power plants for safety-related pressure measurements. These are referred to as motion-balance and force-balance, depending on how the movement of the sensing element is converted into an electrical signal.

A nuclear power plant generally contains about 400 to 1200 pressure and differential pressure transmitters to measure the process pressure, level, and flow in its primary and secondary cooling systems. The specific number of transmitters used in a plant usually depends on the type and design of the plant. For example, the number of transmitters used in PWRs depends on the number of reactor coolant loops. Figure 1 illustrates a typical process instrumentation channel in a nuclear power plant.

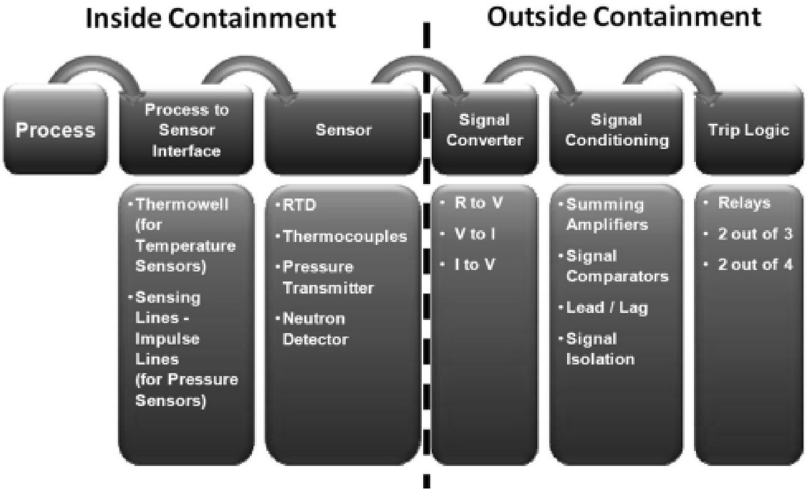

Fig. 1. Typical Instrumentation Channel in Nuclear Power Plant (R = resistance; V = voltage; I = current).

3. Evolution of I&C

The evolution of I&C has been marked by three generational shifts. In the first, analog technology was used for instrumentation, and mechanical relay-based equipment was used for control of discrete processes. The second generation of I&C was marked by the use of discrete or integrated solid-state equipment for both instrumentation and control. The emergence of the microprocessor in the late 1970s made possible the replacement of mechanical relays by programmable logic controllers (PLCs). PLCs were initially used in non-nuclear applications in nuclear plants, but their evolving ability to handle large volumes of data, perform mathematical calculations, execute continuous process control, and communicate with computers brought them into plants' nuclear applications. The third generation of I&C is digital, to be discussed in the next section.

One of the key forces driving the evolution of I&C has been the obsolescence of analog equipment. A second driver has been technological: new information, electronic, display, and digital technologies seem tailor made for the NPP I&C environment, where complexity rules, automation is essential, and high initial infrastructure cost can be rationalized (IAEA, 1999). Though sensor technology itself has not changed significantly, other I&C systems have—perhaps more so than any other area of nuclear power plant science, offering quantum functionality and performance improvements.

A third driver has been accidents, like Three Mile Island, Chernobyl, and Fukushima, which force I&C system designers to reevaluate operating principles, system robustness and safety margins, and accident probability assumptions. For example, both Three Mile Island and Fukushima underscored the critical role of I&C signals in enabling operators to understand the nature of the accident they are facing. On a general level, Three Mile Island helped stimulate new research and development into signal validation, ultimately spawning the discipline of on-line monitoring (to be discussed later in this chapter). Specifically, Three Mile Island led directly to the adoption of safety parameter display systems. Both Chernobyl and Fukushima forced I&C designers to focus more on analyzing the potential occurrence of very rare events that would once have been considered non-'design basis events' so their consequences might be mitigated.

A fourth driver of changes in I&C has been economic. Enhanced I&C means greater knowledge of and control over plant conditions and therefore greater leeway in pushing plant operating limits and extending uptime. More in-core instrumentation, redundant and diverse instrumentation providing deeper comparative operational databases, and enhanced qualification, calibration and maintenance have enabled plants to uprate their power profiles without sacrificing safety margins (IAEA, 1999).

Because the cost of building new plants is so high, regulatory hurdles are so substantial, and political resistance to nuclear power so significant, few new plants have been built. Instead, existing plants are relicensed for extended lives far beyond their original design assumptions. Nuclear power plants that operate for 60 years, for example, live through three generations of I&C evolution (the qualified life of most nuclear plant pressure transmitters and RTDs is typically about 20 years, although most properly maintained pressure transmitters last longer than 20 years) (IAEA, n.d.). In the mid-1980s, the nuclear industry began to talk about aging and obsolescence in analog I&C equipment (Hashemian, 2009a). In this plant-life extension climate, enhanced, digital I&C became a way to offset the plant's age by giving operators new eyes and ears for staying on top of the continuing aginginduced degradation of the plant. New fatigue monitoring and 'condition limitation' systems have made it possible to minimize disturbances and smooth out transients (IAEA, 1999). Typically, plants will replace I&C in steps or modularly, swapping out a discrete analog control system with a digital one, but retaining the existing field cabling, sensors, and actuators (IAEA, 1999).

I&C system advances as a result of these drivers have produced a significant improvement in plant capacity factor, outage time duration, personnel radiation exposure, power uprates, and operational efficiency (Hashemian 2009b). However, it remains the case today that the bulk of I&C systems used to monitor and control existing NPPs use analog process technology developed in the 1950s and 1960s (IAEA, 1999).

4. Emergence of digital I&C

Digital I&C evolved from microprocessor-based PLCs and plant process-monitoring computers (IAEA, 1999). Because they can be programmed to perform complex tasks, microprocessors quickly replaced analog relays and spawned new applications in plant monitoring and control systems, including graphical display interfaces so human operators could observe and interact with the I&C system (IAEA, 1999). The first protection systems using digital technology, known as "core protection calculators," were implemented on combustion engineering designed reactors in the late 1970s (Bickel, 2009). In the 1980s, digital technology was integrated into control systems for NPPs' auxiliary subsystems. Digital relays and recorders, smart transmitters, and distributed control systems (DCSs) were implemented primarily in non-safety systems such as feedwater control, main turbine control, and recirculation control (U.S. NRC, 2011; IAEA, 1999).

By the 1990s, microprocessors were being used for data logging, control, and display for many nonsafety-related functions (U.S. NRC, 2011). In 1996, the first fully digitalized I&C system was integrated into Japan's Kashiwazaki-Kariwa Unit 6 advanced boiling-water reactor (ABWR), followed by Kashiwazaki-Kariwa Unit 7 in Japan (U.S. NRC, 2011; Hashemian 2009a). In the 2000s, all-digital I&C systems for both safety-related systems and safety-critical systems were implemented worldwide (IAEA, 1999). For example, France, the United Kingdom, Korea, and Sweden, among other countries, implemented digital I&C systems in their nuclear power plants (U.S. NRC, 2011; Hashemian 2009a). Today, about 40% of the world's operating power reactors in almost all of the thirty nations with operating NPPs have been upgraded to some level of digital I&C. Ten percent of such installations have occurred at new reactors, with the rest involving upgrades at existing reactors (IAEA, n.d.). Since 1990, all of the reactors under construction worldwide have some digital I&C components in their control and safety systems (IAEA, n.d.).

Today, control panel instruments such as controllers, display meters, and recorders are mostly digital. Most diagnostic and measuring equipment is digital, and increasingly common digital transducer transmitters now offer so-called smart features like automatic zeroing and calibration (IAEA, 1999). Similarly, digital I&C systems like Westinghouse's Eagle 21, Common Q, and Ovation systems, Areva Nuclear Power's Teleperm XS, the Triconix Company's TRICON system and Rolls Royce's Spinline are available for retrofitting implementation on existing plants' safety-related applications or in new all-digital plants (U.S. NRC, 2011; Hashemian 2009a; IAEA, 2008). The advanced boiling water reactor (ABWR) plants built in Japan for more than a decade all use fully integrated digital I&C systems for both safety-related and nonsafety-related plant control and protection (Hurst 2007). Finally, the new reactor designs that have already won certification (including the AP1000, System 80+, and ABWR) will make extensive use of digital I&C (Oak Ridge National Laboratory [ORNL], 2007). To satisfy the demanding operational environments of new designs, ranging from high temperatures to high neutron flux (not to mention the post-Fukushima demands for I&C that can survive “beyond design basis” conditions), advanced and in many cases digital sensors, detectors, transmitters, and data transmission lines will continue to be needed (IAEA, n.d.).

4.1 Benefits of digital

The attractions of digital I&C are many. First, by minimizing the number of analog circuits required to perform an I&C measurement, digital processing reduces the potential interference (noise) and drift that result from using multiple analog circuits. This makes possible more accurate or precise measurements, which can be further refined through digital data processing programs (IAEA, 1999; ORNL, 2007; Lipták, 2006). Second, measurement parameters can be much more easily modified with digital systems than with analog systems. In contrast to the physical reconfiguration of an analog device, modifying digital I&C merely requires loading a different program, which greatly enhances versatility. Shifting functionality from hardware to software in this way means quicker installation of I&C components (IAEA, 1999; ORNL, 2007; Lipták, 2006). Third, the increasingly miniaturized integrated circuits in digital I&C offer substantial processing power relative to device size, greatly reducing the space required for I&C equipment. Fewer and smaller devices capable of transmitting higher concentrations of data using multiplexing also translates into minimized cabling needs. Both the number and quality of I&C links in a plant can be increased (IAEA, 1999; ORNL, 2007). Fourth, digital technology’s processing power means more complex functional capabilities for I&C, from on-line power density limit computation and dead-time and temperature measurement correction to highly specifiable and versatile signal filtering (IAEA, 1999). Fifth, by offering greater automation possibilities, digital I&C minimizes the need for human intervention, thus minimizing the possibility of human error. Sixth, because digital I&C systems can perform automatic self-testing much more easily than analog systems, they reduce maintenance costs and improve reliability through continuous monitoring capability. Such self-testing functionality greatly aids in analyzing system faults (IAEA, 1999).

4.2 Emerging sensors for digital I&C

Although the core technology of nuclear plant sensors has remained largely unchanged since the inception of the industry, since the 1990s several new sensor technologies have been conceived, and some prototyped, that may find adoption in the next-generation nuclear power plants. The extreme high temperatures of next-generation reactors are probably the most significant driver of and technical challenge facing new sensor development today. While the current generation of industrial RTDs can accurately measure processes up to about 400ºC, some Gen IV reactors are expected to operate at coolant temperatures three or four times higher than light water reactors—that is, up to about 1,000ºC (Hashemian, forthcoming).

Emerging sensors fall into three main categories: (1) so-called next-generation sensors, (2) fiberoptic sensors; and (3) wireless sensors (Hashemian 2009a; Hashemian 1999).

4.3 Next-generation sensors

Next-generation sensors encompass advanced sensor designs that will only find application in the longer term, 20-30 years from the present (Hashemian, forthcoming). Solid-state and Silicon Carbide (SiC) neutron flux monitors, magnetic flow meters, hydrogen sensors, virtual sensors, Nanotriodes, gamma ray tomographic spectrometers, fuel mimic power monitors, and Quantum Cascade Laser infrared sensors that sniff emissions and detect overheating, odor, burning, and fumes are among the designs currently in the R&D stage at Oak Ridge National Laboratory (ORNL), Ohio State University, Idaho National Laboratory (INL) and other facilities (Hashemian 2008). One advanced sensor that is closer to actual implementation in nuclear power plants is the Johnson noise thermometer, which consists of an RTD whose open-circuit voltage is measured and related to temperature. This essentially drift-free sensor measures absolute temperature, and its reading is independent of RTD characteristics (Hashemian 2009a). The sensor was developed at ORNL and is ready for commercialization.

Because flow is an inherently difficult parameter to measure and most industrial flow measurement techniques have large uncertainties, flow measurement is another area where advanced sensor types may find application in the longer term (Hashemian 1999). For example, one conventional method, measuring differential pressure across venturi flow elements, is susceptible to fouling, which causes erroneous flow indication. Ultrasonic flow meters address this because they do not depend on venturi elements or other constrictions in the pipes. Rather, they measure flow by sending an ultrasonic signal through the fluid and measuring the time that it takes for the signal to travel through the fluid from the signal source to a downstream signal receiver and back again. Referred to as “transit time,” the signal travel time depends on the fluid flow rate (Hashemian 1999).

Despite the long-term promise of advanced sensor types, in the short term--the next 10-15 years--advances in sensors and transmitters are expected to center primarily on fiber-optic and wireless sensors (Hashemian, forthcoming).

4.4 Fiber optic sensors

Fiber optic technologies are emerging as a potential near-term sensor class for future nuclear power plants (Hashemian 1999). Fiber-optic sensors offer driftless accuracy and high sensitivity, light weight and small size, ease of installation, low power requirements, immunity to electromagnetic interference (EMI), potential for multiplexing (several sensors can be used with a single transmission cable), large bandwidth, and reliability and environmental ruggedness. Moreover, since some fiber-optic sensing modulation techniques are digital in nature, fiber-optic sensing can easily be made compatible with digital control systems (Hashemian, forthcoming).

Fiber-optic sensors operate on the principle that environmental effects or displacements can be converted into measureable optical signals. Fiber-optic sensors can be divided into two broad categories based on the way in which the process measurement is applied to the fiber: extrinsic (or hybrid) and intrinsic (or all-fiber). In extrinsic or hybrid sensors, the sensing element itself is often similar to those in conventional sensors, but fiber optics are used to sense the movement of the sensing element (as with a strain gage) and then convert it into an electrical signal.

In contrast, in intrinsic or all-fiber sensors, the fiber itself senses the environmental effect and itself transmits the affected light beam to a device that converts it into a measurement. The three most advanced fiber-optic sensor technologies—those most likely to replace the functionality of conventional non-fiber-optic sensors now installed in nuclear power plants—are single-point interferometry, distributed fiber Bragg grating, and optical counter and encoder techniques.

Fiber-optic temperature sensors are the most mature fiber-optic sensor types, with some commercially available types able to withstand operational temperatures of up to about 450°C (Hashemian, forthcoming). Longer term, new sensor principles based on the transmission modes of fiber optic devices may also emerge (IAEA, 1999).

4.5 Wireless sensors

While sensor technologies change slowly, rapid advances have been made in networking technology to wirelessly transmit sensor data to a monitoring system (IAEA, 2008). So-called wireless sensors usually consist of a conventional sensing device such as a thermocouple, resistance temperature detector (RTD), or strain gauge as well as circuitry to convert the sensor output into an electrical signal (voltage or current), filter the signal, digitize it, and transmit it to a receiver. If fast data acquisition is required, the data is sometimes processed at the sensor, and the results are then transmitted. For example, averaging and fast Fourier transform (FFT) can be performed at the sensor. Faster data rates consume more battery power, and data processing at the sensor places additional demands on any battery (Hashemian 2008).

In nuclear plants, equipment is typically spread over a large footprint, and data is gathered through wires that are drawn through conduits buried in trenches. Moreover, much of the cost of adding new instrumentation to existing equipment in a nuclear plant lies in the cabling. Wireline networks usually impose high cabling and installation costs, which can exceed $1000 per linear foot in typical nuclear power plants. A recent project funded in part by the Electric Power Research Institute (EPRI) concluded that adding cabling in existing nuclear plants costs approximately $2000 per foot (Hashemian 2009b). In addition to cost, over time rust, corrosion, steam, dirt, dust, and water degrade the wires and cause maintenance issues (IAEA, 2008). The extension of older plants' licenses necessitates more instrumentation to monitor age, but installing wired sensors on all the equipment of an aging plant that needs monitoring would be prohibitively expensive (AMS, 2010b). Fortunately, the cost of wireless systems can be less than 1% of the cost of wired systems in a nuclear plant environment. These cabling costs alone represent a substantial incentive for plants to explore wireless systems. Moreover, the wireless industry is aiming to reduce wireless costs from $20/foot to $2/foot over the next few years (AMS, 2010b).

Wireless sensors facilitate difficult measurements in processes where wiring is a weak link, in hazardous environments, and in applications where space for wiring installation is limited. Wireless sensors can also be added as needed, without laying more cabling, and they can be moved from one location to another without having to move wires. Wireless sensors can usually be installed and operational very quickly and offers immediate off/on availability, minimizing communication complexity, promoting system modularity, and facilitating the interconnection of devices within an I&C system. Wirelessly networked devices can be monitored for anomalies and quickly reconfigured (via software) much more easily than wirelined or cabled devices (IAEA, 2008).

Furthermore, with wireless sensors, data can be collected from anywhere and routed on to the Internet where it can be easily accessed and analyzed (Hashemian 2008). The return on investment of wireless systems is often only several months, versus the years that wired/cabled systems require (IAEA, 2008). Wireless technologies do not suffer from a number of critical weaknesses to which wired technologies are susceptible. For example, one intrinsic benefit to using wireless sensors is that the communication link between the sensor and destination is largely unaffected by moisture. For instance, in a loss-of-coolant accident (LOCA) the containment building of a nuclear reactor can be inundated with water, which can damage sensitive equipment cabling. On the other hand, a wireless sensor would likely be unaffected by this connection issue and continue to provide reliable and important reactor health information throughout the accident and subsequent investigations (AMS, 2010b).

Though wireless technologies do not completely eliminate all wiring needs, they reduce it by one to two orders of magnitude. For example, at Comanche Peak Nuclear Power Station--currently, the largest installation of wireless sensors in the world--more than 10,000 feet of cable were used to develop the foundation for implementing wireless technologies. The wireless infrastructure put in place there provides 100% communications coverage throughout the site and gives the plant the ability to add wireless sensors to monitor and analyze various plant processes and equipment (Hashemian 2009b). This installation has demonstrated that wireless sensor networks can be cost efficient, reliable and secure (IAEA, 2008).

In nuclear power plants, wireless sensors can provide a simple, cost-effective path to improved redundancy without compromising safety. Wired sensors would continue to be designated as the primary element and wireless sensors as a substitute if the wired sensor fails, such as during a LOCA, in which cables become wet or damaged and provide compromised signals (AMS, 2010b).

Many sensor manufacturers have partnered with companies that make wireless transmitters, receivers, and network equipment to produce an integrated network of wireless sensors that can measure process temperature, pressure, vibration, humidity, and other parameters (Hashemian 2008). In addition, wireless community leaders, users, and producers are working on common terminology, a unified platform, and a new standard to facilitate the use of wireless sensors. For example, in 2009 the Instrumentation, Systems, and Automation Society (ISA) approved and released a new standard, referred to as ISA100, to harmonize the use of wireless technologies in industrial applications such as nuclear plants (Hashemian 2008). Including wireless communication capabilities based on a standard protocol such as ISA 100 or IEEE 802.11 in the design plans of the next generation of nuclear power plants can not only provide the necessary means to transmit much-needed sensor data; it can also provide an infrastructure for plant-wide communications (Hashemian 2009b).

Wireless sensors are gaining popularity in plant monitoring in non-nuclear plants and radio frequency identification (RFID)–based sensors, coupled with small-scale, distributed, device-specific “energy harvesting” systems (Hashemian, forthcoming). Though wireless sensors may eventually find their way into nuclear plant process measurement and control, today, they are mainly useful for condition-monitoring applications (Hashemian, 2008). Indeed, on-line condition monitoring (to be discussed later in this chapter) is emerging as the first opportunity for wireless technology to prove itself in the industry (IAEA, 2008).

Because of the potential offered by wireless networking, sensors are rapidly evolving from information devices to communication devices, with substantial implications for the management of security and configuration control in nuclear plants (IAEA, 2008). New wireless sensors from Eaton, Honeywell, General Electric, and others are expected to offer improved reliability and security in monitoring process conditions in real-time or near-real-time. Not only will they likely find application in nuclear condition monitoring applications; they may even one day be used in nuclear control applications.

Future applications of wireless technologies will include distributing intelligence along the I&C network (which IAEA calls "the convergence of sensing, computation and communication"), thereby reducing the need for high data rates along wireless links, and reductions in sensor size and power requirements (IAEA, 2008). Already, the author is working with the Department of Energy on a project to extend wireless sensors and networks inside the reactor containment for equipment condition monitoring, auxiliary measurements during plant outages, and improved capability for post accident monitoring of the plant. Phase III of this project, which started in the fall of 2010, is designing and qualifying a wireless sensor network for use in the reactor containment building of nuclear power plants, where wiring costs can be as high as $50,000 per foot (Analysis and Measurement Services Corp. [AMS], 2010b).

5. Challenges of digital I&C

Although digital I&C technology has been successfully applied outside the U.S., the U.S. nuclear power industry has been slow to adopt digital I&C, and even then mostly for only non-safety-related applications, such as feedwater control systems, recirculation control systems, demineralizer control systems, main turbine controls, etc. (U.S. NRC, 2011; IAEA, 1999; Hashemian, 2009a). This is largely the result of regulatory concerns over the unique question marks raised by digital I&C technology (Hashemian 2009a).

One critical concern—and the primary reason why digital instrumentation is subject to stringent licensing requirements for use in process safety systems (Lipták, 2006)--is digital I&C's dependency on software. Although analog I&C may have higher overall failure rates, its failure mechanisms and modes are perceived as better understood and more easily reproducible (ORNL, 2007). Repeatability gives confidence that periodic testing can minimize future failures. In contrast, software programs' high number of discrete logic steps and inputs and algorithmic complexity means that I&C programs could potentially generate a unique, potentially infinite range of operating characteristics. To verify the reliability of such systems would require testing each line of code for every conceivable combination of inputs and at all possible rates of change—a monumental task (IAEA, n.d.; European Nuclear Agency [ENA], 2008). As a concrete example, in 2009 the UK Nuclear Installations Inspectorate reviewed the European Pressurized Reactor I&C architecture developed by AREVA and EDF and concluded that it "appears overly complex" and contains too many connections with less safety-critical systems (Hirsch, 2009).

Common mode failure—failures resulting from errors or 'bugs' shared by identical software programs running on multiple I&C systems--is a second concern stemming from digital I&C's dependence on software (Lipták, 2006). Specifically, calibration errors, errors in generating setpoints, and hardware and sensor failures are the types of common mode failure most feared from shared flaws in I&C software (Bickel, 2009). According to the U.S. Nuclear Regulatory Commission, in the past twenty years, 38 of about 100 operating plants have reported "potential and actual" common-mode failures, some affecting single plants, but others affecting multiple plants using the same digital system (U.S. NRC, 2011). The more software is integrated into every layer of I&C—from large platform computer systems and microprocessor-driven control systems to software embedded in primary instrumentation and controllers—the greater the potential challenge posed by common mode failure (IAEA, 1999).

A second challenge posed by digital I&C is cyber security--the protection of data and systems in a network, both wired and wireless, from unauthorized access or attack, whether from business espionage, technology theft, or disgruntled employee interference or from recreational hacking, cyber activism, or the probing of a foreign state or terrorist organization. Wireless is the least secure of the physical layers (IAEA, 2008). Wireless transmissions are inherently open, meaning that access can potentially be obtained anywhere within the transmission zone, so they are more vulnerable to such intrusions and threats as non-directed, damaging attacks by software viruses and worms; data network nonperformance from denial-of-service attacks and network spoofing; loss of data privacy and confidentiality from eavesdropping and network packet sniffing; and directed threats involving network packet modification, mimicking, and data tampering (Hashemian, 2009b; AMS, 2010b). These threats can generally be grouped into four categories: loss of confidentiality (unauthorized access to data), loss of integrity (data or software/hardware changed by the intrusion), loss of availability (data transmissions interrupted or systems shut down), and loss of reliability (potential changes made to I&C data systems or computers) (IAEA, n.d.).

There are two major cybersecurity concerns related to the use of wireless technologies in nuclear power plants: being able to satisfy regulatory requirements and employing sufficiently robust methodologies to protect data transmissions across wireless networks (e.g., encryption, authentication, intrusion prevention) (AMS, 2010b).

A final challenge posed to digital I&C is electromagnetic and/or radio frequency interference (EMI/RFI). For wireless devices to be safely used in nuclear power plants, they must first be deemed electromagnetically compatible with the surrounding environment. A device is said to have electromagnetic compatibility (EMC) if it does not interfere with surrounding electronics and is not itself susceptible to interference from the other devices (AMS, 2010b). Aside from the EMI/RFI effects of wireless devices on surrounding plant equipment and vice versa, EMI/RFI issues can also exist between wireless devices.

In industrial applications, most interference results from intermittent bursts of narrow-band signals, random electromagnetic interference (e.g., background noise) and deterministic EMI (e.g., radio stations; AMS, 2010b). The sources of EMI are many and varied, ranging from welders to managers with radio sets (IAEA, 1999). The range and fidelity of wireless signals can also be influenced by implementation issues such as multipath and signal attenuation resulting from proximity to metallic structures, which can limit deployment (IAEA, 2008; AMS, 2010a). Although, EMI/RFI issues have largely been addressed with respect to implementing wireless sensors and networks for equipment condition monitoring in nuclear plants, using wireless for equipment or process control is another matter. Much more secure EMI/RFI safeguards are required for wireless to find use in safety or control applications, which is why NRC standards specifically prohibit the use of wireless technology on “critical digital assets” (AMS, 2010b; Hashemian, 2008).

5.1 Addressing the challenges posed by digital I&C

The challenges posed by the application of digital and wireless I&C in nuclear power plants can partly be addressed by continued application of the nuclear power community’s longstanding “defense-in-depth” strategy. This strategy’s basic principle is that safety risks can be met by designing in multiple, distributed barriers and layers in I&C systems so that no abnormal event, error, or failure—external, electronic or mechanical, or human--can completely interrupt the system’s functioning (IAEA, 1999).

Broadly speaking, defense in depth takes three different forms: diversity of components, redundancy of components, and independence of components. Diversity can involve design diversity (the use of different technologies such as digital versus analog or different architectures, etc.), equipment diversity (the use of different equipment manufacturers, different equipment versions, etc.), functional diversity (applying different mechanisms such as rod insertion versus boron injection or different response times), human diversity (the use of different designers, engineers, programmers, testers), signal diversity (relying on different process parameters sensed by different physical effects or sensor types), and software diversity (different algorithms, logic, programming languages) (U.S. NRC, 2011; Hashemian 2009a). Such diversity diminishes the likelihood that an error or failure in one I&C element will be duplicated in another. As such, diversity is a specific form of protection against common mode failure in I&C software and systems (IAEA, 1999).

The redundancy aspect of defense in depth complements the diversity aspect: not only are diverse systems available to perform functions should one system fail, but multiple components of the same systems are also available. If one component fails, an identical component is available to take its place (IAEA, n.d.; IAEA, 1999).

The third aspect of defense in depth, independence or separation, minimizes the risk of I&C failure by ensuring that each element in an I&C system is truly independent of the others, through, for example, electrical isolation, physical separation (e.g., barriers, distance), and/or independence of system intercommunication (IAEA, n.d.; IAEA, 1999; Hirsch, 2009).

The Fukushima Daiichi emergency of 2011 illustrates the principle and limits of the defense-in-depth strategy. The Tokyo Electric Power Co. (TEPCO), the plant's operator, believed it had sufficient *diversity* of electrical supply to provide the plant with ongoing electrical power during an emergency: it had primary electrical supply from TEPCO's regional grid, it had backup generators in case grid power failed, and it had 8-hour emergency batteries in case the generators failed. However, in one stroke the earthquake and tsunami knocked out the primary grid power and rendered the generators unusable. The backup batteries worked but not long enough to enable TEPCO to reinstitute continuous power to prevent a LOCA. In other words, the plant's electrical plan lacked true *independence* (both grid and backup generators were knocked out by the same factor, the tsunami) and true *redundancy* (no second-line generators or batteries were available to replace the first-line-of-defense generators and batteries).

Of course, adding diversity, redundancy, and independence also increases a system's complexity, expanding, in other words, the range of possible error or failure scenarios that plants must track. The nuclear power community has attempted to address the complexity issue through stringent regulation of proposed new I&C, by requiring the use of hardware and software I&C components that have been thoroughly verified and validated for nuclear plant environments (IAEA, n.d.), and by requiring that the complexity of I&C components be graded such that a safety-essential I&C component may have only limited, specific functionality to ensure that it will more reliably perform its design task. (Thus, I&C elements controlling non-safety tasks are allowed to have more complexity since less is at stake should that complexity produce unanticipated errors or failures) (IAEA, 1999).

For example, field-programmable gate array (FPGA) technology has emerged as an answer to the risks posed by overly complex I&C software. An FPGA is a device made up of thousands or millions of logic gates on integrated circuit chips that can be programmed after manufacture by the customer to perform various tasks, ranging from simple logic operations to complex mathematical functions (U.S. NRC, 2011; Hashemian, 2009a). Because, once programmed, an FPGA executes only that program repetitively and link only the functions needed for a given I&C application, they are substantially simpler than microprocessors, minimizing the risk posed by complexity (U.S. NRC, 2011).

The cybersecurity concerns posed by the use of wireless in nuclear plant I&C are being addressed by the application of experience gained in military, national security, banking, and air-traffic sectors (IAEA, n.d.). On a technological level, intrusion detection, virus scanning, and encryption tools can identify and block cyber threats. In technical terms, security in wireless is no different from security in wired infrastructure. Wireless can be made more secure than wired by including security in the physical layer, thus providing no access to record or tap into the bit stream (AMS, 2010b). On an administrative level, security zones, security management systems, passwords and biometric identification can limit cybersecurity concerns (IAEA, n.d.). At least four sets of standards are relevant to cybersecurity in nuclear applications: IEC Security Standards ISO/IEC 27000 series, IEEE P1711 and IEEE P1689 for Cyber Security of Serial SCADA Links, ISA99 Security for Industrial Automation and Control Systems, and North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) standards CIP-002 through CIP-009 (Hashemian, 2009b).

Finally, concerns over EMI/RFI arose partly because many nuclear plants discovered their security personnel's 'walkie-talkie' radios inadvertently affected plant systems. As a result, they established exclusion zones for such wireless devices around sensitive or critical equipment. However, the radios typically used by plant security personnel transmit at a much higher power level (several watts) than do wireless sensor technologies and in the megahertz (MHz) region. Wireless systems' operate at the 100 milliwatts (mW) power level and in the gigahertz (GHz) range of frequencies. In general, modern wireless devices' lower power and higher frequency levels significantly decrease the chances of interference with nuclear power reactor equipment (AMS, 2010a). Moreover in new plants, the plant EMI/RFI design should allow for other wireless sensor networks to be deployed side-by-side for various applications. This will enable the wireless sensors from various manufacturers to be used in the plant without interference (Hashemian, 2009b).

Recent R&D work performed by the author under a Department of Energy Small Business Innovation Research grant has demonstrated that concerns such as cyber security, EMI, and wireless signal impact on plant equipment can be easily managed. Wireless technology can be implemented successfully and practically in industrial nuclear power plants for condition monitoring of safety-related equipment (AMS, 2010b). However, although wireless sensors and networks are well suited for equipment condition monitoring in nuclear power plants, they are not yet ready for control applications nor is it yet safe to attempt to use wireless sensors for equipment or process control. A hacker cannot cause much damage through wireless technologies used for condition monitoring, but he/she can cause problems in control (AMS, 2010b). The full application of digital I&C to safety-essential control will depend on further advances in nuclear plant I&C design, technology, and regulation.

6. On-line monitoring

The evolution of digital I&C is making possible the development of holistic, integrated systems for automatically verifying the performance of I&C sensors and assessing the health of nuclear power plant equipment and processes while the plant is operating. These so-called online condition monitoring (OLM) systems can be used for on-line I&C maintenance, predictive maintenance, and troubleshooting of reactor components, aging equipment, and to support life extension objectives (EPRI 2008). OLM can be used in PWRs, BWRs, and other reactor types. The system can be built into the design of new plants or deployed as an add-on feature to the existing generation of plants (Hashemian, 2009b).

Applications that can be performed using OLM include in-situ response-time testing of process instrumentation; instrument calibration monitoring; cross-correlation flow measurement; online detection of venturi fouling; online detection of sensing-line blockages, voids, and leaks; fluid and gas leak detection; equipment and process condition monitoring; core barrel vibration measurement; online measurement of temperature coefficient of reactivity; aging management of neutron detectors and core exit thermocouples; and measurement of vibration of in-core flux monitors, core flow monitoring, or N-16 flow measurement.

One of the important applications of OLM is in monitoring the performance of pressure, level, and flow transmitters (AMS, 2010b). In the simplest implementation, redundant channels are monitored by comparing the indicated measurement of each individual channel to a calculated best estimate of the actual process value. Each channel's calibration status can be made by monitoring each channel's deviation from the calculated best estimate (IAEA, 2008). Figure 2 shows the data acquisition signal path for an OLM system.

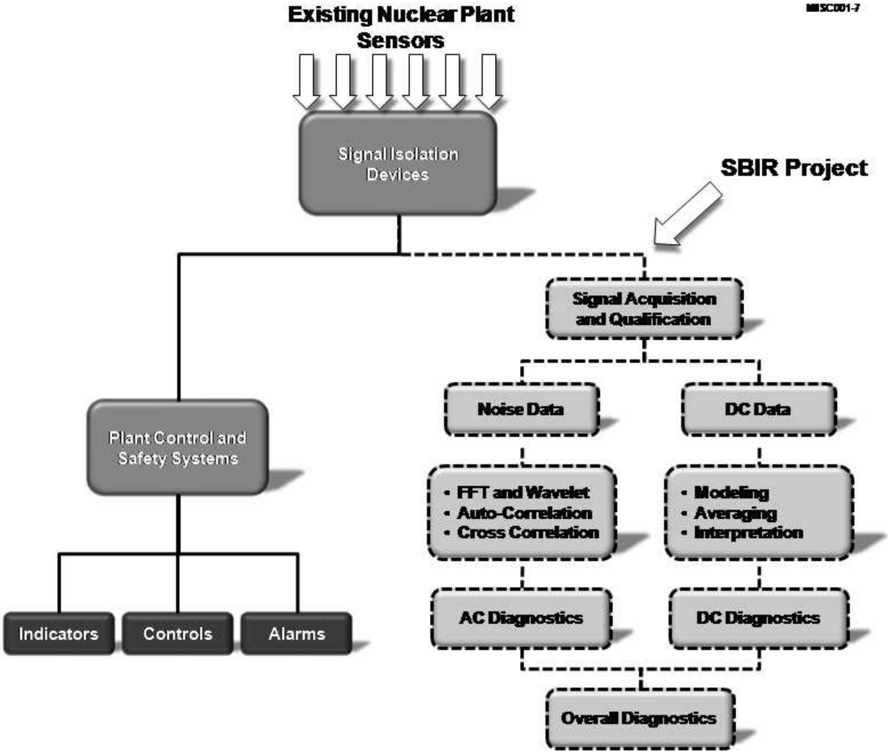

Fig. 2. Data Acquisition Signal Path for OLM

An OLM system is made up of a data acquisition module involving hardware and software and a data processing module involving software implemented on a fast computer. The data acquisition module includes signal isolation devices as well as fast sampling capabilities (e.g., 1000 Hz). If the data is sampled fast, it can be used for both calibration verification by DC signal analysis using averaging and modeling techniques, and response- time testing by AC signal analysis using the noise analysis technique (Hashemian, 2009b). Dynamic analysis of nuclear plant sensors and equipment uses AC signal analysis to determine how sensors and equipment react to fast-changing events such as temperature or pressure steps, ramps, spikes, etc. (Hashemian, 2009b).

OLM originated from reviews of equipment performance data from a variety of industries. These reviews showed that a majority of process equipment performs well for long periods of time and that frequent hands-on maintenance is not needed and is sometimes counterproductive. For example, research performed by Emerson Company's Rosemount Division--which manufactures process sensors such as pressure, level, and flow transmitters for a variety of industries--has shown that these sensors perform well for periods of ten to twenty years and need little hands-on maintenance (Hashemian, 2008). Based on such research, it is now known that over 70% of maintenance work on pressure transmitters in industrial processes does not reveal problems, and maintenance intervals can therefore be extended (AMS, 2010b).

Building on such findings, over the past twenty years, the nuclear power community has made substantial strides to establish OLM technologies in the industry. Numerous academic, government, and industry institutions (as well as private companies) have sponsored R&D efforts in this area. As a result, the feasibility of OLM technologies has been successfully demonstrated for implementation in the existing nuclear fleet (AMS, 2010b).

Moreover, the NRC has approved the OLM concept for in-situ determination of the calibration status of pressure, level, and flow transmitters in nuclear power plants. That is, nuclear power plants can use OLM to establish when a pressure, level, or flow transmitter must be calibrated.

Although OLM provides substantial benefits to the safety and economy of nuclear power plants and has been approved by the NRC, OLM use in nuclear power plants is fragmented and sporadic (Hashemian, 2009b; Electric Power Research Institute [EPRI], 2008; AMS, 2010b). For example, the Sizewell B plant in the United Kingdom was able to extend the calibration intervals of 70% of the transmitters that were eligible for calibration extension using OLM techniques. Similarly, as noted, TXU Comanche Peak nuclear power plant currently has the largest installation of wireless sensors in the world in its $14 million wireless network. Most of existing nuclear power plants have the capabilities and equipment needed for implementing many of the OLM technologies. However, for most plants, these capabilities are not used to their fullest extent for OLM applications (Hashemian, 2009b).

One reason is that the implementation of OLM techniques depends on the availability of data from a large network of sensors deployed on equipment such as motors, fans, pumps, etc. While many nuclear power plants have an OLM or predictive maintenance program for equipment outside of their containments, none have OLM programs for equipment inside the containments due to the sensor wiring costs and penetration space limitations (AMS, 2010b). Today, a majority of industrial equipment does not benefit from OLM technologies partly because no sensors exist to provide the necessary data, and installing wired sensors is often cost prohibitive and impractical.

Wireless sensors will help fill this gap, enabling condition-monitoring technologies to flourish (Hashemian, 2008). As a result, wireless sensors promise to experience explosive growth over the next decade in OLM. Incorporating a wireless infrastructure will help new plants to provide the necessary means of communicating OLM data to plant engineers at low cost, and provide a means for the future expansion of OLM capabilities (Hashemian, 2009b). Inevitably, research in OLM methods will continue, and there will be a need to measure and analyze parameters that are not being considered now.

The application of wireless sensors for equipment condition monitoring in industrial processes has left open a critical gap in the handling of data from wireless sensors, in the guidelines that define which parameters must be measured, in the type and number of sensors to be deployed for measuring these parameters, and in the methods for ensuring that optimum data is gathered to monitor the health and condition of various equipment.

Furthermore, over the next few years, the use of wireless sensors will generate an enormous amount of data from industrial processes. Although much thought has been focused on developing wireless sensors, little or no effort has been expended on data qualification and data processing techniques for these sensors. Moreover, little effort has been spent in determining the type of parameters that should be measured and what the correlation should be between these parameters and the actual condition of the equipment being monitored (Hashemian, 2008).

In the next generation of reactors OLM systems should be built into the design so as to provide automated measurements, condition monitoring, and diagnostics to contribute to optimized maintenance of the plant (Hashemian, 2009b). Reactor designs for next-generation plants will typically incorporate an integrated digital infrastructure including highly integrated control rooms, fault-tolerant control systems, and monitoring systems with large amounts of available information and data. Most of these digital systems will be designed to monitor their own performance continuously, self-correct for identified changes, and function more reliably than previous designs (Hashemian, 2009b).

To develop OLM for future needs, considerations will be needed for increased availability of process sensor data in the plant computer, higher sampling frequency and resolution data acquisition capabilities, increased redundancy for critical process sensors, and more flexible infrastructure to accommodate future data acquisition needs. Utilities will have to adapt to continuous 24-hour monitoring of instrumentation (AMS, 2010b).

7. Conclusion

Today, OLM technologies and techniques have evolved to the point where in many cases equipment failures and/or maintenance needs can be adequately predicted days, weeks, or even months in advance of a system or equipment failure (AMS, 2010b). In general, a wireless system provides the lowest overall cost for large-scale OLM applications (IAEA, 2008). In the years ahead, future I&C will be fully digital (software based), distributed, bus connected, amenable to OLM, and qualified to industrial standards (IAEA, 1999).

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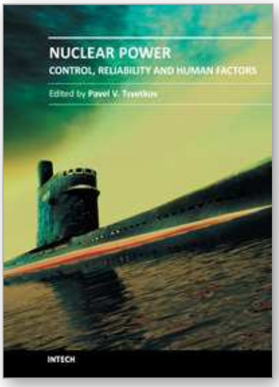

Nuclear Power - Control, Reliability and Human Factors
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Advances in reactor designs, materials and human-machine interfaces guarantee safety and reliability of emerging reactor technologies, eliminating possibilities for high-consequence human errors as those which have occurred in the past. New instrumentation and control technologies based in digital systems, novel sensors and measurement approaches facilitate safety, reliability and economic competitiveness of nuclear power options. Autonomous operation scenarios are becoming increasingly popular to consider for small modular systems. This book belongs to a series of books on nuclear power published by InTech. It consists of four major sections and contains twenty-one chapters on topics from key subject areas pertinent to instrumentation and control, operation reliability, system aging and human-machine interfaces. The book targets a broad potential readership group - students, researchers and specialists in the field - who are interested in learning about nuclear power.

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