Instrumentation and Control Program to Support Modernization of Safety and Control in NPPs.

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Abstract

Most nuclear power plants are operating with their original analog I&C equipment. This equipment requires increasing maintenance efforts to sustain system performance. Decreasing availability of replacement parts and support organizations for analog technology accentuate obsolescence problems and resultant O&M cost increases. Modern technology, especially digital systems, offers improved functionality, performance, and reliability; solutions to obsolescence of equipment; reduction in O&M costs; and the potential to enhance safety. Digital systems with their inherent advantages will be implemented only if reliable and cost-effective implementation and licensing acceptance is achieved and if the upgraded system supports reduced power production costs. EPRI and its member utilities are working together under the Integrated I&C Upgrade Initiative to address I&C issues. This paper will describe and give the status of EPRI's Integrated I&C Upgrade Initiative.

1. Introduction

Operating nuclear power plants in the United States were designed 20 to 40 years ago with analog instrumentation and control (I&C) technology. Today, most plants continue to operate with the original I&C equipment. This equipment is approaching or exceeding its life expectancy, resulting in increasing maintenance efforts to sustain system performance. Surveys of licensee event reports (LERs) show that a majority of the LERs are related to I&C issues. Decreasing availability of replacement parts and the accelerating deterioration of the infrastructure of manufacturers that support analog technology exacerbate obsolescence problems and resultant operation and maintenance (O&M) cost increases.

Instrumentation and control systems in nuclear power plants need to be upgraded in a reliable and cost-effective manner to replace obsolete equipment, to reduce operation and maintenance costs, to improve plant performance, and to enhance safety. The major drivers for the replacement of the safety, control, and information systems in nuclear power plants are the obsolescence of the existing hardware and the need for more cost-effective power production. The procurement of replacement modules and spares under current requirements, for hardware that was designed 20 to 40 years ago and is no longer fully supported by the original equipment manufacturer, is costly, time consuming and, in some cases, not even possible. In the US, and other countries, competition between power producers is dictating more cost-effective power production. The increasing operation and maintenance costs to maintain many of the analog systems is counter to the needs for more cost-effective power production and improved competitiveness.

Technological improvements, particularly the availability of digital systems, offer improved functionality, performance, and reliability; solutions to obsolescence of analog equipment; reduction in operation and maintenance costs; and the potential to enhance safety. Modern digital technology holds a significant potential to improve cost-effectiveness and productivity of nuclear power plants. Digital systems have the potential for solving the utilities' current problems of increasing analog equipment obsolescence; rapidly escalating operation and maintenance costs; lost generation due to system unavailability, spurious operation, and human error; and the inability to increase plant capacity due to equipment limitations. All of these problems contribute to reduced competitiveness with other power production sources and could lead to premature plant closures.

Reliance on proprietary system suppliers coupled with new licensing and design issues have resulted in high implementation costs when digital upgrades have been performed in nuclear power plants. There is a need for a systematic approach leading to the identification, prioritization, and implementation of I&C solutions in nuclear power plants. Viable alternatives range from extending the useful life of existing equipment to the complete replacement of systems in a cost-effective manner when vulnerability to obsolescence or the need for increased productivity so dictates.

Reliable, integrated information is a critical element for protecting the utility's capital investment and increasing availability and reliability. Integrated systems with integrated information can perform more effectively to increase productivity, to enhance safety, and to reduce O&M costs. A plant communications and computing architecture is the infrastructure needed to allow the implementation of I&C systems in an integrated manner. Current technology for distributed digital systems, plant process computers, and plant communications and computing networks support the integration of systems and information.

The test for future digital I&C system upgrades will be whether they are cost beneficial to the plant and if they can offer a payback to the utility in an acceptable time period. Digital systems with their inherent advantages will be implemented in nuclear power plants only if reliable and cost-effective implementation and licensing acceptance is achieved and if the upgraded system supports reduced power production costs.

2. EPRI Nuclear Power Plant Instrumentation and Control Upgrade Program

Nuclear utilities are confronted by a growing equipment obsolescence problem which is a significant contributing factor to increasing costs for plant operation and maintenance. Plant age combined with the rapid pace of evolution of electronic technology is a significant factor in equipment obsolescence. The flexibility and performance of modern digital technology could be used as the basis for replacing obsolete modules or systems in a cost-effective manner in nuclear power plants. The realization of the benefits of digital technology is currently restrained by the relatively high cost of initial applications of new technology for the domestic nuclear power industry in a highly regulated environment. Work is needed to establish reliable and cost-effective methodologies for the design, qualification, and implementation of digital systems in nuclear power plants. This work should utilize, as much as possible, relevant information and experience from other process industries where digital systems are commonly used. Commercial-grade digital systems have proven reliable in other process industries for applications including safety related systems. Cost-effective approaches are needed to implement and qualify commercial-grade hardware and software for nuclear power plant applications. To address these issues and facilitate the upgrading of I&C systems in nuclear power plants, the Electric Power Research Institute (EPRI) has put together an industry-wide instrumentation and control program.

The Electric Power Research Institute and its member nuclear utilities(now including international members) are working together under the Integrated Instrumentation and Control Upgrade Program on a three pronged approach to address I&C issues. This program is documented in the Integrated Instrumentation and Control Upgrade Plan (1). This plan covers a wide range of I&C activities as demonstrated by the seven technical elements of the program. They are Instrumentation, Control and Protection, Man-Machine Support Systems, Verification and Validation, Communications, Maintenance, and Specifications and Standards.

The three prongs of the program consist of research and development activities, utility demonstration plant activities, and licensing stabilization activities. The research and development activities support the development and implementation of digital systems for cost and performance improvements, as well as providing a technical basis for qualification and licensing responses. It also provides part of the bases for the requirements and methodologies needed to design, develop, qualify, implement, operate, and maintain digital systems. The demonstration plant activities identify utility's needs, provide part of the bases for requirements and methodologies mentioned above, provide a test bed for and feedback on requirements and methodologies for upgrading systems, support the development of specifications for digital systems, and capture experience from implementing new digital systems. The licensing stabilization activities provide technical support, as requested, for the industry licensing positions with the United States Nuclear Regulatory Commission (USNRC) on digital systems which are being developed by utility working groups and facilitated by the Nuclear Energy Institute (NEI).

Part of the research and development activities, in conjunction with the demonstration plant activities, is to define and develop a set of generic methodologies and guidelines that will assist utilities in identifying, prioritizing, and implementing I&C solutions more effectively. These methodologies and guidelines will assist the utilities in performing integrated I&C upgrades in the most timely and cost-effective manner possible.

The EPRI Instrumentation and Control Upgrade Program has developed a life-cycle management program for I&C systems. Life-cycle management involves the optimization of maintenance, monitoring and capital resources to sustain safety and performance throughout the plant life. Life-cycle management for I&C systems and components additionally may require the use of digital technology, when analog equipment cannot be cost-effectively maintained or when an improvement in performance is desired. The main product of the life-cycle management program is a set of methodologies and guidelines that, as part of the utility's overall life-cycle management effort, will enable nuclear power plants to fully consider I&C cost and performance improvements, including the application of digital technology. Specific examples of system specification and designs will also be developed through the application of the upgrade implementation methodologies to safety-related and non safety-related systems and system prototypes.

3. Planning and Evaluation Methodologies

Four strategic planning and system evaluation methodologies were developed under the I&C Initiative. The first two methodologies enable the utility to prepare an I&C life-cycle management program plan (2) and a plant communications and computing architecture plan (3). The last two methodologies enable the utility to perform long-term maintenance planning (4) and detailed upgrade evaluation (5) for I&C systems or components.

The Life-Cycle Management Plan is a long term strategic plan for managing a power plant's I&C systems over the planning period selected by the utility. The Life-Cycle Management Plan Methodology (2) guides a designated team of utility personnel through a comparison of I&C life-cycle management strategies and through existing and planned life-cycle management program activities to identify interfaces and integration options. On the basis of this comparison, the I&C Life-Cycle Management Plan is prepared. This plan includes the identification of systems and components to be included in the program; the development of bases for upgrade or long term maintenance options; the initial cost and performance improvement estimates, prioritization for detailed upgrade evaluation, and deferred-upgrade maintenance planning; and the identification of related programs and organizational interfaces including key personnel and responsibilities. The methodology is accompanied by a workbook which contains various outlines, worksheets, and generic interview questions and topics that aid in the development of a Life-Cycle Management Plan. The document describing the methodology also explains the overall process for planning and implementing the various elements of I&C life-cycle management, and the relationship of the other EPRI planning methodologies and guidelines. A plant-specific version of the life-cycle management plan is given in reference 6.

The Plant Communications and Computing Architecture Plan Methodology (3) provides utilities with a detailed set of instructions for preparing a Plant Communications and Computing Architecture Plan that will allow them to upgrade their I&C systems in a logical, cost-effective, and non-disruptive fashion. The Plant Communications and Computing Architecture Plan Methodology provides all of the information necessary to allow utilities to develop their strategic architecture plans in the most cost-effective manner possible. It guides a designated team of utility personnel through an assessment of the existing plant data network architecture, corporate communications architecture life-cycle management plans, and I&C life-cycle management implementation guidelines with respect to the communications architecture. On the basis of the assessment results, a Plant Communications and Computing Architecture Plan is prepared to address a characterization of the existing network architecture; a characterization of the future network architecture in terms of a network model and communication standards for connectivity and interoperability of network elements; a set of network architecture requirements regarding the physical configuration, network access, network add-on provisions, network performance monitoring, and I&C equipment communications interfacing; and a set of consistent human-machine interface requirements for I&C systems. Some nuclear power utilities have used the need to upgrade their plant process computer (7) as an opportunity to develop a new plant communications and computing architecture. An example of a plant-specific architecture plan is given in reference 8.

The Systems Maintenance Plan Methodology (4) addresses long-term maintenance planning for systems or components where the initial screening in the Life-Cycle Management Plan indicates that detailed upgrade evaluation is not justified, over the planning period, by cost and performance improvement potential. The Systems Maintenance Plan Methodology contains a process for developing a comprehensive System Maintenance Plan for each identified system. The Systems Maintenance Plan will present the most efficient approach for maintaining the operational goals and life expectancy of the system. The Systems Maintenance Plan Methodology will describe how to develop long range maintenance objectives, to baseline and analyze the existing maintenance process, to analyze failure rates, inventory practices, and obsolescence issues, and to implement maintenance related problem solving techniques.

The Upgrade Evaluation Methodology (5) addresses a detailed evaluation of I&C system and components when upgrading is indicated by the cost and performance screening in the Life-Cycle Management Plan. The Upgrade Evaluation Methodology is used to analyze each candidate system upgrade to determine if the upgrade is justified from a cost benefit perspective. The Upgrade Evaluation Methodology is used to produce an Upgrade Evaluation Report for each candidate upgrade. The Upgrade Evaluation Report describes high level system functionality, upgrade alternatives and associated cost benefit evaluations, and the recommended alternative. The upgrade evaluation process includes detailed cost and performance analysis; conceptual design options analysis; cost/benefit analysis; and upgrade recommendations. Analysis of conceptual design options includes the consideration of digital design basis changes, associated technical specification changes, and equipment selection candidates. Where an upgrade is to proceed, the Upgrade Evaluation Report issued as input to the Functional Requirements Specification.

4. Integrated Plant Systems

While analog equipment is becoming obsolete and more costly to maintain, the requirements on nuclear power plant personnel to improve availability, reliability, and productivity and to reduce safety challenges to the plant have increased. These personnel are working with more complex systems, and responding to increasing operational, regulatory and productivity demands. As tasks become more complex, involving large numbers of subsystem interrelationships, the potential for human errors increases. Therefore, reliable, integrated information is a critical element for protecting the utility's capital investment and increasing availability and reliability. Integrated systems with integrated information access can perform more effectively to increase productivity and enhance safety.

Traditionally systems have been implemented in a stand-alone manner which has resulted in increased operation and maintenance costs. Increased competition in the utility industry makes it essential that these operating and maintenance costs are minimized. Technology can be used to assist plant personnel and reduce the potential for human errors. At the same time, it can support improved productivity and the reduction of overall operating and maintenance costs. The modern technology available for distributed digital systems, plant process computers, and plant communications and computing networks is fully capable of supporting integration of systems and information. In fact, this capability has been proven in other process industries and in nuclear power plants in other countries.

Integration of the plant systems and information are essential to cost-effectively enhance cooperation between systems and to reduce unnecessary duplication of functions and information. The objectives of integrating plant systems and information are to improve plant availability and reliability, to reduce operations and maintenance costs, to reduce safety challenges, and to improve performance with existing and new equipment systems. The plant communications and computing architecture of the plant supplies the infrastructure which allows the integration of systems and information. This infrastructure supports integrated upgrades, provides access to all of the plant's information sources, and facilitates common interfaces between the human and the machine. This architecture will support the interoperability of systems and the interchangeability of equipment. It will also be designed to be easily expandable. This architecture is defined by a plan that includes a migration strategy to get from the current plant architecture to the final, desired architecture.

5. Productivity Enhancement Systems

Digital technology can support improved power output from nuclear power plants. The improved accuracy of digital systems and the associated reductions in uncertainties can allow the utility to increase its plant's power rating. Digital systems also have the potential to support faster startups for increased power output. They can also support the faster determination of the root causes of an unanticipated trip. At the same time, they can support the faster evaluation of the performance of the equipment and systems during the unanticipated trip. Both of these will allow a faster return to power after an unanticipated trip and; therefore, allow more power to be produced by the plant.

The abilities of digital systems offer many ways to reduce O&M costs. Besides improved reliability and availability, two examples of ways to reduce O&M costs are derived from the continuous monitoring, trending and reporting capabilities, as well as the archival capabilities, of digital systems. The first is the instrumentation calibration reduction program (9, 10) which can reduce the number of instruments to be calibrated and increase the interval between calibrations. Additional reports exist on instrumentation calibration, surveillance, and testing

(11-14). The second is a condition-based maintenance program which would allow maintenance to be performed when needed rather than on some predetermined interval. This is the next step in maintenance cost-effectiveness after preventive maintenance (15) and reliability centered maintenance (16).

The technological advances of the last few years have made it possible to develop sophisticated personnel support systems, which can not only process and present information, but can also give advice to the human. With appropriately implemented personnel support systems, humans can be augmented substantially in their capacity to monitor, process, interpret, and apply information; thus reducing errors and increasing reliability and availability. These personnel support systems can increase productivity by eliminating routine human-power-intensive efforts such as recording, collecting, integrating, and evaluating data; and by assisting in monitoring and control activities. These systems can improve the consistency and completeness of decision-making activities by performing the role of diagnostic and decision-support advisors. Personnel support systems can assist in reducing safety challenges to the plant by presenting more complete, integrated, and reliable information to plant staff to better cope with operating and emergency conditions. Reducing safety challenges leads directly to improved reliability and availability and hence productivity. It can also reduce the maintenance activities, which would have been required, for equipment that would have been unnecessarily challenged. Functional requirements for an environment that would support these capabilities is given in reference 17. A Reactor Water Cleanup prototype system using integrated information and soft controls is described in reference 18.

Advances in technological and human engineering offer the promise of helping nuclear power plant staff to reduce errors, improve productivity, and minimize the risk to plant and personnel. A plant-wide infrastructure for coordinated personnel support systems should be created to enhance these systems and to reduce their implementation costs. This infrastructure will include information communication capabilities, database and knowledge base managers, and a unified human-machine interface. This infrastructure, which is the plant communications and computing architecture discussed above, will permit incremental additions of personnel support systems in all domains.

6. Application of Three Diverse Modern I&C Technologies

The majority of control and protection systems in nuclear power plants are based on analog and electromechanical technologies. However, utilities face a growing unavailability of replacement parts for such systems. Three diverse modern forms of I&C technologies are being studied and prototyped for application to safety systems in nuclear power plants. The first is programmable logic controllers (PLCs). PLCs with appropriate qualification programs appear to be ideally suited for a large number of nuclear power plant applications. PLCs have proven highly reliable in many industrial applications and can be used to replace aging analog and electromechanical equipment to solve the obsolescence problem, improve operation and productivity, and reduce operation and maintenance costs. Areas that must receive careful attention when adopting commercially available PLCs include software verification and validation, hardware qualification, and regulatory acceptance. Standardized designs of PLC-based systems for safety system applications offer the opportunity for increased cost-effectiveness in implementations.

Work is underway to apply modern PLC technology to design, develop, test, and demonstrate a safety-grade control system. It will study various alternative PLC designs for safety systems to develop a cost-effective standardized design. This effort will develop, in conjunction with the commercial-grade dedication working group's activities, a reviewable process for hardware qualification and software verification and validation of commercially available PLCs for safety-grade applications in nuclear power plants. It will demonstrate the applicability of the generically-developed commercial-grade dedication process for digital systems to commercial PLCs.

Due to the stringent and, from past history, costly requirements for licensing digital systems for reactor protection systems, application specific integrated circuit (ASIC) technology is being considered as one solution for reactor protection system upgrades. Cost and regulatory risk are major concerns with licensing a digital reactor protection system. To satisfactorily insure that a microprocessor-based reactor protection system will perform as desired, be highly reliable, and not have unintended functions is very costly. A potentially cost-effective alternative is to develop an ASIC-based reactor protection system. In this case, the ASIC is designed to perform only the needed functionality of the reactor protection system. This reduces the effort required to assure the reactor protection system's performance in protecting the plant and public.

The reactor protection systems at most plants are based on obsolete relay systems. The cost of maintaining these systems to an acceptable safety level is increasing. In addition, the effort to test these systems is substantial. Also, spare parts are hard to find and very costly. The increasing procurement, maintenance, and testing costs are contributing to the decreased competitiveness of nuclear plants. ASIC-based systems could reduce the costs in each of these areas. If designed properly, they would be readily available, highly reliable, require much less test and maintenance time, and allow testing the reactor protection system with the channel for testing in bypass mode rather than out-of-service mode. This last can be very effective in reducing inadvertent trips while testing is underway.

The feasibility of implementing reactor protection system functionality in an ASIC has been demonstrated. ASICs are being designed and tested that will perform most of the typical functions in the reactor protection system. Several EPRI-member utilities are working with EPRI to demonstrate replacement RPS components using the ASIC technology.

The third technology being studied is the Dynamic Safety System (DSS) technology. Compared to existing static safety systems' technology, DSS offers the advantages of decreased costs and increased reliability. The on-going work includes design, interfacing, and testing an emulator of a BWR reactor protection system using DSS technology at a BWR plant simulator to determine feasibility for use of DSS technology in BWR's. A project is underway with an EPRI-member utility to evaluate the complete RPS replacement with DSS technology.

7. Areas of Concern about Digital Systems

Design and licensing issues have inhibited access to cost and performance improvements possible with digital technology. Examples of the areas of concern for digital systems in nuclear power plants are licensing, software verification and validation (V&V), hardware qualification including electromagnetic interference compatibility and seismic, reliability, performance, separation, redundancy, fault-tolerance, common-mode failures, diversity, human-machine interfaces, and integration of systems and information through communications networks. Commercial-grade dedication of digital systems is an approach for more cost-effective implementations that is of considerable interest to the nuclear utilities. As part of the EPRI Instrumentation and Control Upgrade Program and other EPRI activities, approaches to address many of these concerns have been developed and the results are given in recent EPRI reports (19-35).

The Guideline on Licensing Digital Upgrades (19) was developed to be consistent with the established 10 CFR 50.59 process. It helps utilities design and implement digital upgrades, perform 10 CFR 50.59 safety evaluations, and develop information to support licensing submittals. It suggests a failure analysis-based approach that encompasses digital-specific issues and other possible failure causes, addressing both according to their potential effects at the system level. Abnormal conditions and Events (ACES) (20), as described in ANSI/IEEE ANS 7-4.3.2-1993 "Application Criteria for Programmable Digital Computer Systems in Safety Systems of Nuclear Power Generating Stations", play an integral role in this approach.

Guidance for electromagnetic interference susceptibility testing of digital equipment (21) and a handbook for electromagnetic compatibility of digital equipment (22) have been developed. These reports integrate the current knowledge and understanding of the electromagnetic issues concerning the installation of digital equipment in power plants. They direct the utility toward practical and economical solutions for dealing with electromagnetic interference. The handbook also helps eliminate some misconceptions that questioned the reliability of digital equipment subjected to the electromagnetic environment of nuclear power plants.

Guidelines and a handbook for software V&V have been developed (23-25). These products describe approaches to categorize the software systems in terms of criticality and consequences of failure. They then identify levels of V&V commiserate with these categorizations. The guidelines for V&V in reference 23 developed a set of 16 V&V guideline packages based on the system category, development phase, and software system component which is being tested. For V&V methods in the guidelines that do not have a good description elsewhere in literature on how to use them, 11 sets of procedures have also been developed. The report identifies 153 V&V methods for software systems which can be used on the 52 identified software defect types. The guidelines developed were based on the attempt to identify the methods which were most successful in finding various types of defects, on the attempt to assure that the different guidelines catered to the different needs of different systems, and on the attempt to emphasize the practicality and cost-effectiveness of the methods recommended.

A process for the commercial-grade dedication of hardware has been developed (26, 27) and proven very successful. The basic concepts of this process are being used as the starting point for proposed commercial-grade dedication processes for digital systems. The use of commercial-grade programmable logic controllers (PLCs) for safety related systems is described in reference 28. Guidelines for evaluating and dedicating commercial-grade PLCs have been developed (29, 30). Considerable concern has been raised about annunciator systems and the magnitude of alarms that an operator must be aware of during a transient. The large number of alarms and the presentation of them make the operator's job more difficult and can potentially contribute to human errors. Work has been done on more intelligent alarm systems and the methods for presenting them (31-33). Additional areas that have been addressed are pressure transmitters (34), radiation monitoring systems (35), and wireless monitoring systems (36).

8. Demonstration Plant Projects

The utility demonstration plants essentially are the laboratories where I&C cost and improvement options are being researched and developed. There are five utility demonstration plant projects in progress which are providing the primary inputs, as well as testing, validation and refinement activities for the methodology and guideline development under the I&C Initiative.

Activities at each of the five demonstration plants include the preparation of I&C life-cycle management plans and plant computing and control architecture plans; system screening, deferred-upgrade maintenance planning, and detailed upgrade evaluations; testing, validation, and refinement of various plant-specific methodologies and guidelines; and development of options and plans for integration of I&C cost and performance improvement activities with related life-cycle management efforts.

Demonstration project activities were completed at the Tennessee Valley Authority's Browns Ferry Unit 2, Baltimore Gas and Electric Company's Calvert Cliffs Units 1 and 2, Northern States Power Company's Prairie Island Units 1 and 2, Entergy Company's Arkansas Nuclear One Units 1 and 2, and Omaha Public Power District's Fort Calhoun. An example of a plant-specific plan developed under the demonstration program is the architecture plan for the plant data network at Browns Ferry (8). Additional I&C project activities using EPRI I&C methodologies are underway at Korea Electric Power Company and Nuclear Electric (UK).

Conclusions

The implementation and integration of digital I&C systems enhances the ability to achieve the goals of improved availability and reliability, enhanced safety, reduced operations and maintenance costs, and improved productivity in nuclear power plants. The plant communications and computing architecture provides the infrastructure which allows the integration of systems and information. The modern technology of distributed digital systems, plant process computers (both monolithic and distributed), and plant communications and computing networks have proven their ability to achieve these goals in other industries and in nuclear power plants in other countries. The use of this modern, proven technology is a key contributor to improved competitiveness in nuclear power plants. EPRI has established an Integrated Instrumentation and Control Upgrade Initiative to support its member nuclear utilities in developing strategic plans and taking advantage of this modern technology to improve nuclear power plant competitiveness, while enhancing plant safety. The EPRI developed technology can be used for all types of nuclear power plants.

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