ADVANCED DIGITAL TECHNOLOGY — IMPROVING NUCLEAR POWER PLANT PERFORMANCE THROUGH MAINTAINABILITY

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Abstract

In today's energy sector there is ever increasing pressure on utilities to operate power plants at high capacity factors. To ensure nuclear power is competitive into the next century, it is imperative that strategic design improvements be made to enhance the performance of nuclear power plants. There are a number of factors that affect a nuclear power plant's performance; lifetime maintenance is one of the major contributors. The maturing of digital technology has afforded ABB the opportunity to make significant design improvements in the area of maintainability. In keeping with ABB's evolutionary advanced nuclear plant design approach, digital technology has systematically been incorporated into the control and protection systems of the most recent Korean nuclear units in operation and under construction. One example of this was the multi-functional design team approach that was utilized for the development of ABB's Digital Plant Protection System (DPPS) The design team consisted of engineers, maintenance technicians, procurement specialists and manufacturing personnel in order to provide a complete perspective on all facets of the design. The governing design goals of increased reliability and safety, simplicity of design, use of off-the-shelf products and reduced need for periodic surveillance testing were met with the selection of proven ABB-Advant® Programmable Logic Controllers (PLCs) as the heart of the DPPS. The application of digital PLC technology allows operation for extended periods without requiring routine maintenance or re-calibration. A well documented commercial dedication program approved by the United States Nuclear Regulatory Commission (US NRC) as part of the System 80+™ Advanced Light Water Reactor Design Certification Program, allowed the use of off-the shelf products in the design of the safety protection system. In addition, a number of mechanical and electrical improvements were made which support maintainability. The result is a DPPS that has been re-designed to take full advantage of the many benefits associated with digital technology. The new design places emphasis on ease of maintenance in order to reduce operating and maintenance costs, allow greater plant availability and, ultimately, improve plant performance.

1. SYSTEM DESCRIPTION

The Plant Protection System is one of the most important systems in a nuclear power plant. Its job is to monitor the plant to ensure it is operating within safety limits. The DPPS does this by receiving inputs from critical plant sensors in the field. It monitors these inputs and compares them to the specified safety limits. If the DPPS detects that these limits are exceeded, it generates signals which initiate a plant trip and actuation of other safety features as required. Built into the DPPS is redundancy where four independent channels monitor each safety limit. Protection functions are initiated when two-out-of-four channels detect an unsafe plant condition.

The DPPS is comprised of bistable processors, local coincidence logic processors, initiation logic, and interface and test processors. Plant limits are compared by the bistable processors while the two-out-of-four trip limit coincidence logic is performed by the local coincidence logic processors. Initiation logic provides the interface to the actuated systems and accommodates hard wired manual initiation capability downstream of the programmable logic. Interface and test processors perform system monitoring and test functions.

2. DESIGN APPROACH

Historically, nuclear power plant protection systems have been designed with electro-mechanical relays and/or solid state electronics. Systems of this type, although highly reliable, typically require extensive periodic testing and maintenance. Spurious plant trips and extended outages due to the need for system maintenance can have an adverse effect on plant performance. In response, there has been an increased awareness in the nuclear industry of the need for improving the maintainability of power plants. ABB took advantage of the opportunity to design for improved reliability and maintainability when it initiated a program to digitize the existing analog Plant Protection System (PPS). The re-designed DPPS is significantly less susceptible to these maintenance issues and therefore contributes to improved plant performance.

2.1 Design Team

A multi-functional design team was assembled which consisted of design engineers, manufacturing engineers, startup engineers, maintenance technicians and procurement specialists. The diversity of the team was instrumental in identifying areas for improved maintenance based on actual operating experience with the previous PPS designs.The team was fully empowered to make design and product selection decisions.

The DPPS design was to remain functionally the same as the System 80® analog relay PPS design, but was to take full advantage of the benefits such as high reliability and system accuracy offered by the incorporation of modern digital technology. The governing design goals for the DPPS project embodied ease of maintenance and increased plant availability. The specific goals were:

- provide for increased reliability and safety over analog systems;
- strive for simplicity of design using proven, off-the-shelf products; and
- reduce the amount of periodic surveillance testing required.

2.2 Maintainability Defined

Before addressing an issue such as maintainability, it was first necessary to define it in concrete terms that were understandable to the design team. Based on the types of activities performed during plant operation, plant outages, and the random occurrence of plant trips, the concept of maintainability was defined in two parts:

(1) the amount and frequency of required periodic maintenance, and

(2) the ease at which periodic maintenance can be performed.

By this definition, the ideal system would be one in which the need for periodic maintenance was minimal, and when necessary, was quickly performed with ease. This two part definition was the basis for the advanced design improvements made on the DPPS.

3. DIGITAL TECHNOLOGY ALLOWS A SIMPLER DESIGN WITH FEWER PARTS

An essential ingredient in anything that is designed for maintainability is simplicity. In striving for simplicity, fewer parts are better. Because the DPPS incorporates a modular design, component types were able to be standardized resulting in few unique parts.This attribute provides multiple benefits including:

- Equipment Familiarity - Personnel who work with and perform maintenance on the DPPS are more familiar with the makeup of the system. There are fewer parts that need unique maintenance procedures and less time is required to perform routine service and system checks.

- Reduced Spares Inventory - The need to stock numerous parts for use in the event of component failure is greatly reduced. The standardized design allows interchanging of hardware.

- Fewer Equipment Suppliers - Procurement is made easier by dealing with fewer equipment suppliers since there are fewer equipment supplier qualification and QA programs to review and fewer files to maintain.

3.1 Product Selection

Critical to achieving the goal of simplicity was the selection of the proper technology and products. Product selection was focused on finding a cost-effective replacement platform based on new technology which offered the added benefits of improved functionality, reliability and maintainability. After a comprehensive evaluation program was completed, the ABB-Advant® Programmable Logic Controller (PLC) was selected as the technology of choice for the "heart" of the DPPS. The ABB-Advant PLC was chosen in part due to its high reliability and use in nuclear applications worldwide. Versatility and ease of programming added to the long list of positives for the ABB-Advant PLC. In keeping with the design goal of off-the-shelf products, the ABB-Advant PLC was subject to an extensive verification phase prior to acceptance as a "Dedicated Commercial Grade Item" to be used in safety-related applications. Although the product selection process implemented by the design team was used for the selection of all components in the system, the PLC had the greatest impact on the simplicity of the design by replacing numerous electro-mechanical relays.

PLCs have an excellent reputation as being very reliable and simple to maintain which is supported by their extensive use in critical control and safety function applications in the petrochemical, pharmaceutical and fossil power industries. PLCs are capable of extended operation without the need for periodic maintenance or calibration. Use of PLC technology eliminates the custom made analog PC boards and the majority of the electro-mechanical relays associated with analog PPS systems. All of the relays associated with performing logic functions have been replaced by PLCs. Nine electro-mechanical relays still exist in the system. These nine remaining relays are off-the-shelf, commercially dedicated parts which are used as interposing devices. The elimination of the majority of electro-mechanical relays is a large contributor to reducing the overall number of parts in the DPPS by a factor of ten over the previous analog design. This reduction in parts means that fewer spares are required to be kept in inventory. Because all parts in the system are off-the-shelf, it is no longer necessary to be highly dependent on custom replacement parts and their associated long lead times. Off-the-shelf parts offer high availability as well as a reduced likelihood of equipment obsolescence.

Adding to the product selection decision is the ABB-Advant PLCs hardware and software upward compatibility. This means that as new hardware and/or software is developed, it will be compatible with the hardware and software that is utilized in the DPPS today. This is a major improvement to a situation that has historically rendered digital equipment platforms obsolete and has resulted in significant replacement costs.

3.2 Reduced Number of Power Supplies

It is typical for analog systems to require many different power types whereas digital systems can be configured to run on very few. ABB took advantage of the fact that digital systems are less power dependent than analog systems and used it to simplify the DPPS. All equipment in the DPPS is designed to operate at a common 24 VDC voltage. As a result, there are only two redundant power supply pairs in each channel of the DPPS; one pair of redundant Input/Output (I/O) external power and one pair of redundant internal equipment power. This improved configuration replaces the thirty power supplies with various voltages and currents in each channel of the older analog PPS system.

3.3 Reduced Cabling

Digital design is conducive to the usage of fiber optics. The DPPS utilizes fiber optics for transmission and isolation of signals that are required to pass between safety channels. Fiber optic isolation replaces the complex relays and multiple fuse isolation of the older analog PPS design. Fiber optics improve the isolation protection of the DPPS while reducing the quantity of equipment that is needed to perform this function. Additionally, the use of fiber optic isolation cables results in an overall reduction in the required amount of internal cabinet cabling from more than 1000 hard wires to approximately twenty four fiber optic cables.

4.0 DIGITAL TECHNOLOGY INCREASES THE TIME BETWEEN REQUIRED MAINTENANCE

ABB's first definition of maintainability; the amount and frequency of required periodic maintenance, is directly impacted by how reliable the system is. The design improvements discussed in this section all contribute to the reliability of the DPPS.

4.1 Software Development

ABB has a long and successful history developing high quality software for the nuclear industry. In 1978, ABB delivered the world's first safety grade software to the Arkansas Nuclear One Generating Station Unit 2, and since then has been involved in numerous software development projects. It is this extensive experience which provides the basis for the software development program on the DPPS.

Because PLCs are software based, they are capable of extended operation without the need for periodic maintenance or calibration. Trip setpoint limits on the DPPS are no longer set mechanically, but are now accomplished by digital software code. Built in automatic tests and diagnostics are also performed by software. Well-designed software can be expected to run indefinitely without the likelihood of failure. In order to assure that the DPPS software is designed with a high degree of quality and reliability, an extensive verification and validation program exists.

ABB has made significant progress defining the codes, standards and regulatory guides required to address the software design and qualification process. The software design, development, verification and validation process for the DPPS was performed in accordance with ABB's Quality Program Instructions [1] and Software Program Manual for ABB's Advanced Control Complex, Nuplex 80+ [2]. This software program approach was developed by ABB in accordance with industry standards and approved by the USNRC during the licensing of System 80+™. The program includes phases for requirements, design, implementation, testing and installation and checkout, operations and maintenance, and retirement.

4.2 Digital Setpoints

One of the major differences between analog systems and digital systems is how setpoints are programmed. Analog systems rely on mechanical potentiometers which convert a particular setting into corresponding voltage values. These voltage values are prone to "drift" which must be compensated for in order not to exceed regulatory safety limits. Digital systems allow the operator to program in a value which does not change. No longer is it necessary to routinely verify and re-calibrate setpoints monthly as was the case with analog systems. The elimination of these operations increases plant availability due to unnecessary, spurious trips resulting from human error. Digitally programmed setpoints also increase system accuracy and improve the margin to trip. The ABB Advant PLC analog-to-digital (A/D) conversion is self-checking, thus the calibration verification interval is extended from every month in the old analog PPS design to once every refueling outage (i.e., 12 - 24 months).

4.3 On-Line Diagnostics and Test

The DPPS design includes a comprehensive on-line diagnostics and test program which automatically provides health status monitoring on a system as well as component level. At the system level, the automatic testing programs test both the hardware and the software greatly reducing the time needed to perform NRC required surveillance testing of the DPPS. This on-line testing also identifies random hardware failures which previously went undetected between normally scheduled outages and tests. The diagnostics program can identify failures at a module level. If a failure were detected and the system was brought off-line for maintenance, an extensive diagnostic search would not be necessary because the problem would already be categorized. This process improvement results in a typical Mean Time To Repair (MTTR) of less than 30 minutes. Reducing the amount of manual troubleshooting performed reduces the potential for human error which can be the cause of spurious trips.

4.4 Redundant Power Supplies

The fully redundant 24VDC power supplies also add to the DPPS's reliability in that any single power failure will not result in the loss of the DPPS operation. "Hot Swap" capability, the ability to change out components without the need to take the system off-line, was provided for the power supplies further increasing channel availability. The decision to use the 24VDC power supplies also supported the DPPS's total design against Electro-Mechanical Interference and Radio Frequency Interference (EMI/RFI).

4.5 Early Warning Features

Other design features that contribute to the reliability of the DPPS are built in cabinet temperature and smoke detectors. The cabinet temperature detectors monitor the environment inside the cabinet and provide alarms to the operators. The setpoint for these temperature detectors is such that a high temperature alarm is provided before equipment availability would be affected. Each channel of the DPPS is outfitted with its own smoke detector that provides input to the fire protection system in the plant. Both of these design features add to the maintainability of the system by providing early warning of potentially serious problems.

5. DIGITAL TECHNOLOGY MAKES MAINTENANCE EASIER

ABB's second definition of maintainability - the ease at which periodic maintenance can be performed, is a more tangible subject. There are a number of design improvements in the DPPS which decrease the mean time to repair and reduce the amount of down time for the system.

5.1 PLC Rack Design

Digital technology has allowed the DPPS to accommodate future expansion of system capabilities if the need arises. The racks (backplanes) which mount the required PLC modules have spare capacity beyond that which is necessary to operate the system. Until the empty PLC slots are used, a full complement of "dummy" modules are incorporated into the design as place holders. Having the entire rack full provides additional structural strength and also prevents replacement of a module in the wrong location after performing maintenance. In the event an incorrect type PLC module were inadvertently installed in a rack during maintenance, the built in software diagnostics would provide automatic error notification.

Further adding to the structural integrity of the PLC rack is a patented seismic support bracket designed to hold the PLC modules in place. For ease of maintenance, the seismic support bracket requires no tools to remove. Additionally, all loose parts are attached to lanyards to prevent loss within the cabinet.

The ABB-Advant® PLC module and rack design are perfectly suited to "hot swapping" in that the modules are back plane hinged into the rack so that they can be "hot-swapped" without power spiking of the modules. This is made possible by the fact that power is not introduced to the module until it is screwed in. In addition, the module design allows the replacement of failed modules without the removal of terminated wires. The edge connector is able to be disconnected from the PLC module in one piece. This process helps avoid any potential rewiring errors.

5.2 Four Channel Methodology

ABB has always incorporated a four channel methodology into the design of all plant protection systems. The DPPS is no different in this respect. All four channels monitor the plant for operation within specified safety limits. A two-out-of-four coincidence logic is employed to send actuation signals to the safety features systems. The decision to incorporate four channels was made with maintainability in mind. US NRC regulations require that nuclear plant safety systems be single failure proof. ABB's two-out-of-four logic not only allows one channel to fail but additionally allows one channel to be bypassed during plant operation for testing or replacement and still satisfy regulatory requirements.

5.3 Cabinet Arrangement

Some simple design improvements have been made to the cabinet arrangement of the DPPS. Power distribution terminal block strips on the DPPS are all located next to their respective PLC I/O racks for ease of maintenance and operator familiarity. These terminal blocks have also been color coded for quick identification of the power circuit's polarity.

The DPPS cabinet has been designed to be immune from the effects of the EMI/RFI present in a nuclear power plant application. The doors have been gasketed, there are no sharp edges, the flanges on the cabinet are outwardly curving, and EMI filters have been installed.

5.4 Blown Fuse Indication

Sometimes even the simplest design improvements are the most effective. The time spent attempting to diagnose a system problem has often taken hours with prior systems when it may have been as simple as a blown fuse. ABB has incorporated L.E.D. blown fuse indicators on all the fuses in the DPPS. With this feature, any blown fuse can be identified by a red light which is located in plain sight on the inside of the cabinet. This may allow the operator to quickly and easily correct the problem or at least will have led him to the problem circuit.

5.5 Reduced Risk of Electrical Shock

The move to digital technology allowed the use of 24VDC for all components and wiring in the cabinet. The result is a greatly reduced threat of electrical shock to personnel while performing maintenance activities on the DPPS. This is a human factors engineering improvement which makes maintenance safer and more efficient

6. CONCLUSION

The advanced design features made possible by the migration to digital technology in the DPPS have resulted in a number of improvements in the area of maintainability. The DPPS is proof positive that with proper planning, simple maintainable designs are possible. The nuclear industry can benefit from the lessons learned in ABB's digitization of the plant protection system. The DPPS has been designed to:

- Provide high reliability
- Require less periodic surveillance testing
- Reduce the incidence of random, undetected failures
- Reduce the spares inventory
- Simplify maintenance
- Increase personnel safety
- Attain higher system accuracy
- Improve the margin to trip
- Improve plant performance

The DPPS will be first deployed to an operating nuclear power plant as part of the Oskershamm 1 modernization in Sweden. This application will be followed shortly thereafter by the initial startups of Ulchin Units 5 and 6 in the Republic of Korea.

REFERENCES

[1] ABB's Quality Program Instructions, QPM-1.1

[2] Software Program Manual for ABB's Advanced Control Complex, Nuplex 80+, NPX80-SQP-0101.0