Impact of Digital Control Systems on Nuclear Power Plants

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Abstract

Instrumentation and control is an integral component in nuclear power plant operation. It provides the operator with the means to understand the status of the plant, and the data needed to make the proper corrective actions when necessary. Instrumentation and control systems can also make automatic changes to the plants parameters when needed, and activate required safety systems to ensure that the plant always stays in a safe state even if the operator makes an error. I&C systems have generally been run on relay-based analog control, and were run as such successfully for several years. In the 1980s, after the emergence of the microprocessor, I&C systems in nuclear plants started to shift toward digital control. Digital control offered benefits over analog control, such as more flexibility, faster computational speed, networking of systems, increased data storage capability, and increased accuracy. However, the transition from analog to digital I&C technology is not simple. The regulations in existence at the time were all meant for analog control, and had to be completely redone for any digital components. More importantly, providing V&V (Verification and Validation) for digital systems was nearly impossible, since it could not be proven that they were indeed reliable. This is because they depend on software, whose reliability could not be predicted, whereas analog systems depended on hardware interlocks whose reliability could be proven more easily. Despite these disadvantages, digital control is shown to be superior to analog control, providing better plant performance and increased plant safety.

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Introduction to Instrumentation and Control in Nuclear Plants

Instrumentation and control (I&C) systems play a crucial role in the operation of Nuclear Power Plants (NPPs). Since the reactor itself is not readily accessible, the operator must rely on I&C systems to relay data on the status of the plant. The operator can then use the data presented to make informed decisions on a course of action, if necessary. Additionally, I&C systems can provide automatic control over the plant's systems. This relieves the operator of this duty, allowing the operator to instead monitor the responses of the plant and take any required corrective actions. If the operator should take an incorrect action and place the plant in an unwanted state, I&C safety systems will provide automatic actions to protect the plant and the environment.

I&C systems can be grouped as safety or non-safety related systems. Non-safety systems are responsible for monitoring and controlling the plant under normal operating conditions, and putting the plant in a safe state during any plant transients. The safety systems back up the non-safety ones. They will be automatically activated to stabilize the plant in case of operator or system error which results in an unsafe state of the plant. The safety and non-safety systems are part of the Defense-In-Depth strategy in keeping the plant safe.

This report will focus specifically on the safety systems in regard to an NPP's I&C systems. Although most safety systems are digitalized now, they were all on analog control before 1980. The analog control was as successful and (generally) as reliable as the current digital control. Therefore, the endeavor of this report shall be to establish whether or not the increase of digitalization of safety I&C systems has provided nuclear plants with an increase in overall plant safety and performance or not. A correlation between the trend towards digitalization and successful (and safe) performance of NPPs will attempt to be made by observing preventable accidents such as that at Three Mile Island and performance indicators of different facilities. Finally, a recommendation will be made on whether or not to fully digitalize all I&C safety systems.

The Movement from Analog to Digital Control

Analog control was extensively, and successfully, used in the nuclear industry for several years. The main problem with analog systems is their susceptibility to degradation from the conditions of their surroundings, and from their inevitable aging. Analog systems can be compromised by environmental degradation, mechanical failures, and simply becoming obsolete. Since analog control is slowly being phased out, it has become difficult to obtain spare parts to fix obsolete analog equipment. Due to the emergence of the microprocessor, there was a massive shift in nearly every industry to digital technology in the 1980's. Nuclear technology was no exception. Microprocessor based programmable logic controllers (PLCs) began to replace relay-based technology.

When digital technology was first implemented in nuclear plants, the frequency of unnecessary reactor trips decreased significantly [7] which increased the productivity of nuclear plants. Due to this success, digital technology started to become more involved in nuclear plants. The successful performance of digital control encouraged more support for it and helped build trust in it. Simultaneously, analog control started to phase out, as vendors of analog I&C equipment had begun to decrease their supplies and support [7]. However, the transition from analog to digital control was not necessarily easy. There were several challenges to be overcome. For example, since digital control systems function differently than analog ones, the regulations for several systems had to be changed by the regulatory body to account for that difference. Additionally, a certain amount of uncertainty existed in changing over to digital control, since it was, at that time, a new technology which did not have the benefit of having a long successful history to support its implementation. There was also a well established knowledge base in analog I&C systems, and so there was some difficulty present in terms of familiarizing the industry with the mechanics of digital I&C. These obstacles were all overcome in order to phase out analog control and replace it with digital I&C. The crucial question still remains: is all the effort to make the change to digital systems justified?

The above question can best be explored by examining the advantages of digital control systems, specifically their advantages over analog systems. First of all, digital systems are not vulnerable to the “drift” that occurs with analog systems. This drift can cause problems with calibration for analog systems. Digital systems are also more efficient and quick with performing calculations, and can have a high level of accuracy. They can perform complex computations that may be outside of the capabilities of analog systems. Part of their efficiency with computations stems from the fact that they are capable of storing and handling large amounts of data. Digital systems also have the possibility of special capabilities impossible to analog systems, such as fault tolerance, self-testing, signal validation, and process system diagnostics [7]. For these reasons, digital systems are generally thought to be superior to analog ones. However, to really see if the trade of analog for digital was an improvement for nuclear technology, the effects of digital I&C systems must be explored.

Three Mile Island

The Three Mile Island accident occurred near Middletown, Pennsylvania in 1979. This was the most serious nuclear accident in US history, and as expected in 1979 the TMI plant was under entirely analog control, as digital control was relatively far from being phased in, especially in the United States. Several factors contributed to a partial core meltdown. These included design problems and equipment malfunctions, but most importantly, human error was a large contributing factor. The initiating event to the TMI accident was a relief valve on the top of the pressurizer which got stuck open and could not close when it should have. This resulted in a loss of coolant accident, as cooling water poured out of the core and into the pressurizer, which prevented the decay heat from the reactor to be removed by the coolant. The instrumentation connected to the relief valve also failed, and did not tell the operator that the valve was opened. This failure is excellent proof of how valuable properly functioning reactor instrumentation is to the safety of the NPP. The coolant continued to empty out of the pressurizer, and once again I&C systems failed to provide the operators with accurate information. There was no data being provided on the level of coolant in the core (which was quickly declining). The operators decided to use the level of coolant in the pressurizer to judge how much coolant was in the reactor. Since the pressurizer was full of coolant, it was assumed that the core was too, which was an incorrect and dangerous assumption. Alarms began to go off, and since the operators were acting under the assumption that the core was full of coolant, they took actions which only made the situation worse by removing more of the small amount of coolant in the core. This caused the core to overheat, and the fuel began to meltdown. The NRC (Nuclear Regulatory Commission) was notified, and although they did not know a meltdown was occurring they shut down the core and ensuring cooling to it. A complete meltdown was avoided, however in the end about half of the core was discovered to have melted. This caused serious ramifications for the nuclear industry, particularly with building distrust with the public. One of the most important lessons learned from this accident is the importance of proper information getting to the operator quickly and efficiently. If the I&C control systems were all functioning adequately and providing the right data, it is unlikely that this accident would have occurred. Digital control systems that are currently in use in reactors provide monitoring of plant status, automatic correction of plant abnormalities, and self-testing. If a digital system was in use at TMI, the accident may have not occurred because the operators would be receiving concise information, and even if they did not take proper corrective actions to cool the core the plant protective and safety systems could have automatically been activated to mitigate the problem. TMI is a testament to the potential danger of using only analog control for plant monitoring systems.

Although the TMI accident occurred in a time when digital control was not readily available, many plants in the US are still partly run on analog I&C. As mentioned earlier, Canadian plants were quicker to adopt digital control. The following section explores digital I&C systems in CANDU plants.

Digital Control in CANDU Plants

Each CANDU plant has been built incorporating more digital technology than its predecessors. The following graph displays the percentage of digital technology in use in various CANDU plants.

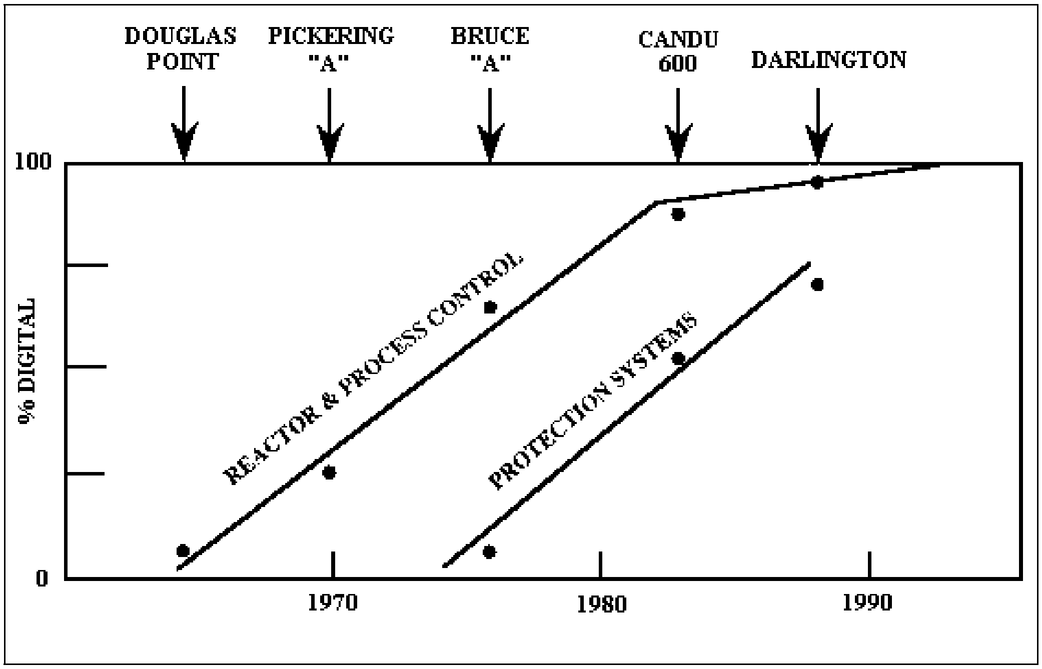

Fig. 1 - Trends toward digitalization in different CANDU plants (AECL)

As visible from Figure 1, the trend in CANDU plants is to increase the percent of digital technology in reactor and process control, and protection systems. This is because success with digital I&C in CANDU plants has motivated new plant designs to incorporate increasingly more digital control. Darlington, which represents recent CANDU technology, has nearly 100% digitally controlled I&C systems for reactor and process control, and about 70% for its plant protection system. Unfortunately, the CNSC (then the AECB) delayed Darlington's operation because a strict review indicated that the software engineering of the shutdown system may be inadequate. Darlington is now in operation, providing about 20% of Ontario's electricity supply [1], and has an excellent record of safety with no major incidents to report. In 8.3 million hours worked, there has been only 1 lost time accident [3]. The performance indicators for each of the Darlington units of 2005 were excellent and surpassed the older, analog I&C NPPs.

Success of Digital Control

The power of digital control can be noted by observing individual implementations at NPPs. At Calvert Cliffs NPP in Maryland USA, the feedwater and steam generator feedwater pump control systems were both run on analog control. The systems presented some problems over time, such as instability, unreliability, and control problems. In an attempt to eliminate these problems, a digital control system was used to replace the analog one for both systems. Due to the new digital systems, feedwater control is automatic from 2-100 percent power, whereas with the analog systems the operators had to control the feedwater system. Touch screens are used as operator interfaces, which facilitates inputting and reading data. Since their installation, the digital systems have proven their reliability and performance [4]. This has resulted in less unnecessary plant outages, and therefore better plant performance in terms of annual power output.

At Cook NPP in Michigan analog control was used extensively throughout the plant, as it was built in the 1970s. Most of the analog systems presented little problems, however the signal processing portions of the safety and control systems was prone to failure due to analog drift. It was difficult to fix and replace the components of these systems, since vendors of analog equipment were becoming increasingly rare. Therefore, the decision was made to replace the analog system with a digital one, and the implementation was an irrefutable success. The digital system has eliminated the concern of drift, and provided an increase in reliability and processing speed.

Korea's NPP's Turbine Control System (TCS) was run on analog control for several years. The TCS is a crucial component, as it controls the speed of the turbine-generator, and the quality on power directly depends on it. There was a great demand to digitalize the TCS in Korea's NPP, due to maintenance difficulties and a shortage of spare parts [6]. In 2003, the TCS was retrofitted with a digital system, and results were a success. The digital system has provided increased reliability, easier control and maintenance, and improved monitoring and storage of data.

As seen from the above three examples, digital technology has been implemented successfully in I&C for completely different systems. This proves that digital control can be used in a variety of systems, and often provides an increase in reliability and performance.

Disadvantages of Digital I&C Systems

Several advantages to using digital systems have been mentioned, but with all advantages come disadvantages. Before making a choice on whether a complete shift to digital control is merited, the negative side must be explored as well. As already mentioned previously, digital systems pose a problem for regulatory requirements. This is because an analog and digital system that performs the same function can do it completely differently. This means that digital systems have to be tested for their safety criteria and new regulatory guidelines must be set out for them. A bigger, and probably the most threatening disadvantage is the difficulty of proving reliability. There are no methods in existence to prove software reliability as concretely as hardware reliability. This gives the software associated with digital system an element of uncertainty and unpredictability which is not wanted at a nuclear power station. Therefore, the Verification and Validation (V&V) of digital-based technology is exceptionally difficult to do, and a plant cannot be brought online without it. Also, as mentioned previously, it is difficult to escape the paradigm of analog technology which has existed for so long, and replace it with digital systems.

Concluding Remarks

This report has explored the responsibilities of instrumentation and control systems in a nuclear reactor. In particular, the transition between analog and digital systems was discussed. Canada is one of the most progressive countries in using digital I&C systems in its CANDU plants. It uses an increased percentage of digital control for each successive NPP. The accident at Three Mile Island in the US was explored, and it was reasonably argued that digital control could have helped prevent the accident from occurring. Three examples of the implementation of digital I&C were discussed, and it was noted that each of the three examples focused on very different plant systems.

The most important advantage of digital systems is that they help prevent human error. They are nearly free of the drift that occurs with analog systems which throws off calibration. Digital systems can present critical plant variables to a high degree of accuracy to the operator in a neat and concise manner. Since the operators make decisions on corrective actions, it is crucial for them to get correct plant data quickly and in an organized manner. Digital systems can store and transfer large amounts of data to various systems quickly, and provide excellent opportunities for networking between systems. Most of the disadvantages of digital systems are regulation related, but once new regulations and V&V are set, then digital systems will be the clear choice over analog ones. It is therefore concluded that the effort and funds required to incorporate more digital I&C systems wherever reasonable is not only merited, but inevitable. As analog systems get replaced by digital ones, less support and supplies are available for analog control. Over the next few years, analog systems will be phased out nearly entirely, as they have been at Darlington. The microprocessor will revolutionize the nuclear industry further, just as it did the personal computer. Digital systems will make plant safety and protection systems even more reliable, providing more good reason to choose nuclear energy as a dependent, safe, and reliable energy source.

References

[1] Canadian Nuclear Association. “CANDU Nuclear Reactor Performance in 2005.” Nuclear Canada. Volume VII (2006): 1-3.

[2] Carruth, Robert et al. “Design Concepts for the Reactor Protection and Control Process Instrumentation Digital Upgrade Project at Cook NPP”. IEEE Industrial Electronics Society. Volume 43 (1996): 1899-1902

[3] Charlebois, Pierre. Presentation to the Winter Seminar, Canadian Nuclear Association. 2004. Ontario Power Generation. Accessed March 20, 2006 <http://www.cna.ca/english/seminar2004/files/charlebois_CNA_Feb.pdf>

[4] Doran, Patrick et al. “Improving Secondary Plant Performance and Reliability Using Digital Control Systems at Calvert Cliffs NPP”. IEEE Industrial Electronics Society. Volume III (1994): 1111-1114

[5] International Atomic Energy Agency. Modern Instrumentation and Control for Nuclear Power Plants: A Guidebook. 1999. Vienna. Technical Report Series 387.

[6] Kim, Jong-an et al. “Digital Control System Development for Turbine Control of Nuclear Power Plant”. IEEE Industrial Electronics Society. Volume III (2004): 2573-2576

[7] National Academies Press. Digital Instrumentation and Control Systems in Nuclear Power Plants. Washington: National Academy of Sciences, 1997.

[8] Uhrig, Robert E. et al. Instrumentation, Control, and Safety Systems of Canadian Nuclear Facilities. 1993. Oak Ridge National Laboratory. Accessed March 15 2006 <http://www.wtec.org/loyola/ar93_94/icss.htm>

[9] U.S. Nuclear Regulatory Commission. Fact Sheet on the Accident at Three Mile Island. 2006. NRC. Accessed March 20 2006. <http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html>

[10] White, James D. Comparative Assessments of Nuclear Instrumentation. 1994. Oak Ridge National Laboratory. Accessed March 15 2006 <http://www.wtec.org/loyola/ar93_94/canic.htm>