STUDY OF ADVANCED DIGITAL FIELDBUS TECHNOLOGY APPLICATION AND ITS LICENSING IMPLICATIONS FOR THE NUCLEAR POWER INDUSTRY

Jack Y. Zhao
U.S. Nuclear Regulatory Commission
Instrumentation, Controls, and Electrical Engineering Branch No. 2
11555 Rockville Pike
Rockville, MD 20852
jack.zhao@nrc.gov

ABSTRACT

Advanced digital fieldbus technology has been successfully used in oil and gas, petrochemical, pulp and paper, and other industries. This technology has also been implemented increasingly in the fossil fuel power industry. However, the application of the advanced digital fieldbus technology to nonsafety-related systems in the nuclear industry has been limited to date, and there has been only one proposal to apply this technology to safety-related nuclear systems.

This paper presents an overview of the advanced digital fieldbus technology application and its benefits to both the fossil fuel and nuclear power industries. In addition, it reviews and compares various functional features for the two leading digital fieldbus technologies. This paper also provides a detailed case study of a typical power plant system to demonstrate some benefits and advantages of using digital fieldbus technology during the lifecycle of a nuclear power plant. Finally, the possible licensing implications and issues involved in applying digital fieldbus technology to safety-related nuclear systems are investigated and analyzed.

Keywords: digital fieldbus technology, Foundation fieldbus, Profibus, digital control system, safety- and nonsafety-related systems, and nuclear power plant.

1.0 INTRODUCTION

The advanced digital fieldbus technology is an all-digital, multidrop, bidirectional serial communication bus that connects microprocessor-based control and field devices. This technology also serves as a local area network for the instrumentation and control used within power plants and other industrial facilities that have the built-in capability to monitor and distribute control applications across a network. This technology therefore offers an open architecture for control and information integration. Advanced digital fieldbus technology has already gained wide acceptance in other industries, including the oil and gas, petrochemical, and pulp and paper industries.[1] This technology

Distributed with permission of author(s) by ISA 2009
Presented at the 2009 ISA POWID/EPRI Conference; http://www.isa.org

has also been applied increasingly to the fossil fuel power industry.[2,3] The benefits achieved with this technology include lower installation costs, easier troubleshooting, improved maintenance, and extensive diagnostics. Some advanced digital fieldbus technology applications have been implemented for nonsafety-related systems to retrofit the analog-based control systems in existing nuclear power plants. For example, Oconee Nuclear Station, located in Seneca, SC, installed a Foundation fieldbus (FF) network and related field devices to replace obsolete pneumatic and electrical control and monitoring loops for its balance-of-plant systems. The application of advanced digital fieldbus technology has also been proposed for nonsafety-related systems in new reactor systems[4,5] currently under U.S. Nuclear Regulatory Commission (NRC) review. Another application has been proposed for use in safety-related systems in the U.S. nuclear power industry.[5] Moreover, digital fieldbus technology has been tested internationally for use in nuclear plant safety applications.[6]

For years, the industry has investigated methods to use digital fieldbus communications with field devices without the need for a separate cable for each. Many types of digital fieldbus technologies[7] exist; however, two digital fieldbus platforms have ultimately emerged as leaders for process control systems (CS): (1) FF and (2) Profibus. The discussion and analyses in this paper focus on these two leading fieldbus technologies. In addition, the FF technology will be used as an example in the detailed case study of a typical nonsafety-related system in a nuclear power plant to illustrate the benefits of using digital fieldbus technology.

As demonstrated in the case study below and in other applications, there are many benefits and advantages to using digital fieldbus technology over discrete, point-to-point hardwired conventional control systems (CCSs); however, use of this technology in the nuclear industry has been limited. This paper explores the reasons why this technology has not been widely used in the nuclear industry, especially for safety-related nuclear systems. The potential licensing implications and deployment issues are also discussed for its application to safety-related nuclear systems.

2.0 DIGITAL FIELDBUS TECHNOLOGIES AND THEIR BENEFITS

Digital fieldbus technology can be defined as a communication protocol that allows two-way digital communications among various control devices such as those used in control room equipment. Many types of fieldbus architectures are available for use, including FF, Profibus, ControlNet, DeviceNet, AS-i, World-FIP, and Interbus.[7,8] Among the available fieldbus technologies, FF and Profibus have been widely acknowledged, accepted, and used because of their simplicity, flexibility, and international and interoperable standards. Therefore, the discussion and analysis in this paper focus on these two leading digital field technologies. The benefits of using digital fieldbus technology are presented with a concise comparison between FF and Profibus protocols.

2.1 BENEFITS OF USING DIGITAL FIELDBUS TECHNOLOGY

Compared with CCSs that use point-to-point hardwired technology, a fully digital control system (DCS) using FF or Profibus offers the following lifecycle benefits:

- **Reduced hardware and related costs.** The following five reasons illustrate why digital fieldbus technology reduces costs significantly although the required terminators, connectors, and power conditioners may offset the savings to some extent:

  (1) Because digital fieldbus technology allows multiple devices to use a single wire pair, less wire, conduit, fewer cable trays and control cabinets are needed.
  (2) Standard function blocks, which are used in digital fieldbus technology to implement control strategies, reduce the amount of system hardware needed, including input/output (I/O) converters, power supplies, and cabinets.
  (3) Multivariable digital fieldbus transmitters with close-coupled mounting eliminate the need for temperature transmitters.
  (4) Power loads on control room equipment and the size of control cabinets are reduced because of the reduction in the number of I/O cards required.
  (5) Reduced hardware simplifies startup and parameterization operations and reduces installation, commissioning time, and construction costs.

- **Improved system operation.** Digital fieldbus technology allows multiple variables from each device to be brought into the control system for remote diagnostics, archival activities, trend analysis, process optimization studies, report generation, predictive maintenance, remote configuration, and asset management. Moreover, the high resolution and distortion-free characteristics of digital communications increases the accuracy of measurement and enables improved control capability.

- **Decreased risks of system failure and increased operating reliability.** The self-test and communication capabilities of microprocessor-based digital fieldbus devices help reduce downtime and improve plant safety. Plant operations and maintenance personnel can be notified upon detection of abnormal conditions or the need for preventive maintenance, allowing them to initiate corrective action quickly and safely.

- **Enhanced plant performance and asset management.** Digital fieldbus technology enables asset management functions such as diagnostics, calibration, identification, and other maintenance management operations to "mine" massive amounts of information from field devices in real time. Asset management allows users to move to proactive maintenance, thus allowing resources to be allocated where they are needed.

- **Increased flexibility and interoperability.** Because digital fieldbus technology has an open protocol, different subsystems from different suppliers in a nuclear power plant can be easily integrated, and information can be accessed without the need for custom programming. Furthermore, the consistent function block design increases flexibility in the selection of suppliers.

2.2 COMPARISONS BETWEEN FOUNDATION FIELDBUS AND PROFIBUS

The digital FF- and Profibus-based control systems have much in common. Both technologies can provide the following features:

- fully digital, serial, two-way, and multidrop communication
- remote access to status and diagnostic information from smart field devices
- a method to communicate to field instruments over fieldbus
- bus power and intrinsic safety features
- faster verification and validation of control loop configurations

However, for the FF technology, which is a single communication protocol, field equipment, such as sensors, actuators, controllers, and I/O devices, is first interconnected with a single cable to form a segment known as an H1. Then various H1 subsystems and other devices such as high-speed controllers, data servers, and workstations are connected to form a high-speed Ethernet (HSE) network, which can run at 100 megabits per second. The FF H1, which is usually used for process control with limited discrete applications, is a deterministic network running at a speed of 31.25 kilobits per second. This communication speed is appropriate for the majority of process conditions in nuclear power plants, but it is not fast enough for some safety-critical discrete applications. The FF HSE can provide peer-to-peer communication capability. The HSE technology is designed to support fault-tolerant networks and devices in safety-critical monitoring and control applications. All or part of the HSE network and devices can be made redundant to achieve the level of fault tolerance required for a particular application. Because FF devices can communicate with each other directly without having to go through a central computer, advanced control strategies that involve variables throughout the plant can be implemented without the risk of a central computer failure, thus further reducing risk. In addition, control and I/O functions can be distributed to field FF devices, which can further improve the operating safety and reliability of systems.

In contrast, Profibus is not a single-communication protocol; it has a family of protocols. The two main Profibus protocols are Profibus-DP and Profibus-PA. The digital Profibus-DP running at 500 kilobits per second is a better candidate for discrete and safety-critical control, whereas Profibus-PA has a speed of 31.25 kilobits per second similar to that of the FF and is more suited for process control. Unlike the Profibus-DP, the Profibus-PA can be fieldbus-powered. In Profibus-based control systems, the I/O functions are moved to the field instruments; however, no control functions are moved to the field instruments. All control in the Profibus system is still done by the central controller.

The FF and Profibus technologies share many similar design features, but each technology has its own specific functions and limitations. In nuclear power plants, there are areas with different levels of automation and control system hierarchy that have different communication needs. It may be necessary to use a mix of different fieldbus technologies to take advantage of each individual digital fieldbus characteristic to achieve more benefits, higher reliability, and adequate safety.

3.0 DETAILED CASE STUDY

This section presents a detailed case study for a typical circulating water system that uses cooling towers in a nuclear power plant in order to demonstrate the benefits derived from using the digital fieldbus technology in terms of installation and required hardware costs. For the purpose of simplicity, this study uses only the FF; however, as discussed in Section 2.0, a mixed system that incorporates both leading digital fieldbus technologies may be a better solution for some applications. This study focuses on comparisons between a CCS and a DCS using the FF technology.

Table 1 lists 166 candidate field devices and 311 related I/O points for this typical circulating water system. The discrete I/O points associated with the pump and fan controls used in the circulating water system are not included because they are more appropriately controlled by using Profibus technology. In addition, the study does not include the monitoring of the vibrations caused by the pumps and fans because these devices are usually wired to a packaged vibration monitoring system. If the study also included discrete control and vibration monitoring using a diverse fieldbus-based system, more benefits could be achieved.

Table 1. Field Devices and Related I/O Points of the Circulating Water System

		Number of I/O Points**			
Device*	**Quantity**	**AI**	**AO**	**DI**	**DO**
MOV (ZT)	5	5	0	10	15
MOV (without ZT)	30	0	0	60	90
AT	4	4	0	0	0
CT	4	4	0	0	0
FT	2	2	0	0	0
LT	9	9	0	0	0
PT	4	4	0	0	0
TT	108	108	0	0	0
Total	166	136	0	70	105

*Motor-operated valve (MOV), valve-position feedback (ZT), analyzer (AT), conductivity transmitter (CT), flow transmitter (FT), level transmitter (LT), pressure transmitter (PT), and temperature transmitter (TT).
**Analog input (AI), analog output (AO), digital input (DI), and digital output (DO).

The following assumptions were made for this comparison case study:

- Transmitters and valves are connected to I/O cards through junction boxes.
- A maximum of 16 wires, each of which has 3 terminations (a twisted pair with shielding), can be connected to each junction box.
- A maximum of eight devices can be attached to one H1 segment.
- Each AI card can accommodate 10 channels, and each DI card can accommodate 24 channels in a CCS. Each field-powered DO card selected to provide DO signals can accommodate 12 channels.
- Each FF I/O card can accommodate 64 channels.

- Each double-wide control cabinet, 1,600 by 800 millimeters (mm) in size, can accommodate about 30 conventional I/O cards and the related power supplies, communication devices, and other necessary equipment.

3.1 REDUCTION IN INPUT/OUTPUT TERMINATIONS

With a CCS, 311 I/O points require 3 sets of 933 ((311 x 3) x 3 = 2,799) terminations:

- 311 wires from 311 I/O points to 933 terminations into junction boxes
- 933 terminations from junction boxes into I/O cards

In a DCS using the FF technology, 166 devices can be divided into at least 21 H1 segments, requiring 540 (498 + 21 x 2 = 540) terminations as follows:

- 166 wires from 166 candidate devices to 498 terminations (166 x 3 = 498) into junction boxes
- 21 terminations from 21 H1 segments into I/O cards

According to the analysis above, the FF technology can lead to an 81 percent reduction in the number of terminations (see Table 2). This reduction in the number of terminations decreases the installation costs given in Table 3.

Table 2. Savings in Terminations

Task	CCS	DCS with the FF	Percent Decrease
Terminations	2,799	540	81%

Table 3. Termination Installation Costs of a CCS versus a DCS with FF Technology

Unit Installation Cost	CCS with 2,799 Terminations	FF-Based DCS with 540 Terminations	Savings
Assumes $15 per termination installation	$41,985	$8,100	$33,885

3.2 REDUCTION IN THE NUMBER OF INPUT/OUTPUT CARDS AND CONTROL CABINETS

The candidate field devices using FF technology in a typical circulating water system that uses cooling towers require 136 AIs, 70 DIs, and 105 DOs (see Table 1 above). A total of 61 I/O cards are needed for a CCS to operate under conditions of double redundancy for DI cards and triple redundancy for DO cards (see Table 4). However, if the FF technology is used, only 10 I/O cards are needed to achieve double redundancy. FF technology thus decreases the number of I/O cards required by 84 percent and decreases hardware costs by 74 percent as shown in Table 4.

In addition to simplified cabling and reduced power requirements, the reduction in I/O cards leads to a significant reduction in the size of the control cabinet. Sixty-one I/O cards with remote-multiplexing unit communications and the associated power supplies for a CCS would require about two double-door 1,600 by 800 mm cabinets, which cost about $108,000. In contrast, 10 FF I/O cards with their related communication cards and power supplies can be contained in one single-door 800 by 800 mm cabinet, which costs about $27,000. In addition to the reduction in required building space; civil design; and heating, ventilation, and air conditioning, the use of FF technology can reduce the cost of control cabinets by 75 percent.

Table 4. Savings in I/O Cards and Control Cabinets*

Card Type (Unit Price)	CCS		DCS with FF		Percent Decrease	
	Quantity	Cost	Quantity	Cost	Quantity	Cost
AI ($800/card)	14	$11,200	N/A	N/A	N/A	N/A
DI ($500/card)	3	$1,500	N/A	N/A	N/A	N/A
DO ($500/card)	9	$4,500	N/A	N/A	N/A	N/A
FF I/O ($1,000/card)	N/A	N/A	5	$5,000	N/A	N/A
Subtotal	26	$17,200	5	$5,000	81%	71%
Total (with redundancy)	61	$38,900	10	$10,000	84%	74%
Number of control cabinets ($27,000/single-door cabinet)	2 double-door	$108,000	1 single-door	$27,000	75%	75%

*Note that the cost information in the table is used for comparison only in this study.
**N/A means "not applicable."

3.3 REDUCTION IN HOME-RUN WIRING

With a CCS, a total of 311 home-run wires are needed to connect junction boxes to I/O terminations. If the FF technology is used, only 21 wires are required to connect H1 segments to I/O terminations, leading to a 93 percent reduction (see Table 5).

Table 5. Savings Using Home-Run Wires

Task	CCS	FF Based DCS	Percent Decrease
Home-Run Wires	311	21	93%

The data listed in the tables above illustrate significant savings in hardware and installation costs achieved by using FF technology, and they also show the engineering and maintenance advantages of a DCS with FF technology over those of a conventional CCS.

4.0 POTENTIAL LICENSING IMPLICATIONS AND ISSUES FOR SAFETY-RELATED NUCLEAR SYSTEMS

The application of digital fieldbus technology has a successful track record in other industries. An increased use of these applications has also been found in fossil fuel power and nonsafety-related nuclear systems. However, digital fieldbus technology has not yet been applied to safety-related systems in the nuclear power industry. There are a number of reasons why the nuclear industry has been slow to adopt this technology despite its promising features and benefits. First, because of the safety critical nature of the nuclear power generation process, the nuclear power industry has historically been slow to adopt new technologies that have a perceived risk to safety, availability, and reliability. Secondly, the digital-fieldbus-based approach can directly impact many aspects of a nuclear power plant, including the regulatory and licensing process, design specifications and equipment procurement, construction, startup, and operation. Other issues that limit the quick adoption of digital fieldbus technology include a lack of workforce knowledge, regulatory uncertainty, and lack of management and employee acceptance. In addition, this technology is unproven in safety-critical applications.

Considering that other industries have successfully implemented digital fieldbus technology in their operations and that its use has many benefits as demonstrated in the above case study and in many other publications, the nuclear power industry should not preclude the application of this technology from its safety-related nuclear systems. However, specific regulations or guidelines do not currently exist to address the application of the digital fieldbus technology to safety-related nuclear systems. This section explores and discusses some potential licensing implications and deployment issues for applying digital fieldbus technology to safety-related nuclear systems from a regulatory point of view.

First-of-a-kind engineering: Both FF safety-instrumented-functions technology and Profibus PROFIsafe communication protocols have been approved up to International Electrotechnical Commission (IEC) 61508 Safety Integrity Level 3 for their use in safety-related applications. However, these two platforms have not yet been approved and used for safety-related nuclear systems. All the issues related to first-of-a-kind engineering need to be addressed before the technologies can be used in safety-related nuclear systems.

Cyber and physical security: Because FF technology control functions are executed in the field devices, physical security must be addressed to prevent tampering with the fieldbus field devices. More importantly, an FF-based DCS may have more severe vulnerability issues involving cyber security than that of a CCS because of the communication features of fieldbus technology, including remote configuration and diagnostics, field execution of control functions, and multiple device connections in the same control loop.

Diversity and defense-in-depth issues and common-cause failure: Although the FF-based DCS can be designed to be redundant, common-cause failure from both hardware and software design features will need to be addressed to meet the separation and independence requirements. If different fieldbus technologies are used to address diversity and defense-in-depth issues, the interoperability of the device within the integrated control system needs to be carefully reviewed. Testability guidance provided in Institute of Electrical and Electronics Engineers (IEEE) Standard 7-4.3.2-2003[9] and in NRC Digital Instrumentation and Control Interim Staff Guidance (DI&C-ISG)-02[10] needs to be addressed to meet the full combination testing requirements.

Safety analyses: The nuclear power industry needs to analyze selected fast processes to ensure that the communication speed of digital fieldbus devices, especially the FF and Profibus-PA, is fast enough to meet plant conformance to safety analyses (e.g., accident and transient analyses).

Environmental qualifications: Ideally, fieldbus technology would be effective in Class 1E mild and harsh environments from a maintenance and diagnostics perspective; however, for Class 1E harsh environments inside the containment structure where there are high levels of radiation, the microprocessor-based fieldbus devices usually do not fare well. In addition, if the fieldbus devices are to be used in the Class 1E environments, they must be qualified to environmental standards such as IEEE Standards 323 and 344, which include testing for seismic effects, thermal aging, radiation aging and hardening, vibration, and loss-of-coolant accidents.

Because there is no existing standard or guidance specifically created to address the application of digital fieldbus technology to safety-related nuclear systems, digital fieldbus-based safety control systems shall be developed and validated in the same manner as other existing digital safety control systems according to current regulations and guidelines, such as Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic Licensing of Production and Utilization Facilities”; 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants”; IEEE Standard 603-1991; IEEE Standard 7-4.3.2; and NRC NUREG-0800.[9–12] However, in the future, specific guidelines or standards will need to be established to address the application of digital fieldbus technology to safety-related nuclear systems.

5.0 CONCLUSIONS

This brief overview of digital fieldbus technology shows that applications of this technology can be found in the fossil fuel power industry and in other industries. Many benefits can be achieved by using digital fieldbus technology, as demonstrated by the case study presented in this paper. The comparison of a CCS with a FF-based DCS for a typical circulating water system of a nuclear power plant in terms of installation and hardware costs shows that significant savings could be achieved by using digital fieldbus technology.

With the remarkable technological advancements in digital fieldbus technology, the use of this technology could significantly increase nuclear power plant performance and could decrease the lifecycle costs involved in the ownership of power plants. However, many specific issues need to be addressed before the technology can be applied to safety-related nuclear systems. From a regulatory perspective, this paper discussed several potential licensing issues. The most likely path forward for the use of digital fieldbus technology in the nuclear power industry will be in applying it to nonsafety-related systems. Although the use of digital fieldbus technology in the safety-related systems should not be precluded, all potential licensing and deployment issues need to be fully addressed before this technology could be widely accepted for use in safety-related nuclear systems.

6.0 DISCLAIMER

This paper represents the personal opinions and viewpoints of the author. Although the author is an employee of the NRC, the NRC expresses no opinion whatsoever either in support of, or in opposition to, the contents of this paper. The NRC supports the efforts of the author in the preparation and publication of this paper in the interest of fostering discussion and broadly promulgating ideas, but it does not endorse the ideas themselves. Reference to this paper is not a sufficient basis for establishing the acceptability of any proposed system and idea, and it will not be accepted as an adequate justification or technical explanation in any licensing application. The NRC has not reviewed or approved the contents of this paper. Applicants and licensees who wish to adopt any of the ideas presented herein will need to provide their own justifications and demonstrations of suitability.

7.0 REFERENCES

1. P. Welander, "Fieldbus: Growing Globally," *Control Engineering*, March 2008.
2. J. Blaney, J. Murray, and G. Tingley, "Digital Power," ISA *InTech*, March 2008.
3. J. Blaney and J. Murray, "Digital Bus Technology in New Coal-Fired Plants," *Power Engineering*, October 2007.
4. South Texas Project Nuclear Operating Company, "COL Application for STP Units 3 and 4," Rev. 2, September 2008.
5. Areva, "U.S.-EPR Design Certification Application," Rev. 0, May 2008.
6. J. Montague, "Foundation Fieldbus Tested for Nuclear Plant Safety Applications," *Control Engineering*, June 2002.
7. International Electrotechnical Commission, "Digital Data Communications for Measurement and Control—Fieldbus for Use in Industrial Control Systems," IEC Standard 61158, Geneva, Switzerland.
8. International Society of Automation, "Fieldbus Standard for Use in Industrial Control Systems," ISA Standard 50-02, Research Triangle Park, NC.
9. Institute of Electrical and Electronics Engineers, "IEEE Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations," IEEE Standard 7-4.3.2-2003, Piscataway, NJ.
10. U.S. Nuclear Regulatory Commission, "Digital Instrumentation and Controls—Diversity and Defense-in-Depth Issues," ISG DI&C-ISG-02, Task Working Group No. 2, September 2007.
11. Institute of Electrical and Electronics Engineers, "IEEE Standard Criteria for Safety Systems for Nuclear Power Generating Stations," IEEE Standard 603-1991, Piscataway, NJ.
12. U.S. Nuclear Regulatory Commission, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, Chapter 7, Rev. 5, May 2007.