Review of the Conventional Regulations Guideline for Digital Instrumentation and Control of Nuclear Power Plants focusing on Small Modular Reactors

Sujeong Lim[a], Jiyoung Song[b], Sejin Jung[c], Yoona Heo[d], Junbeom Yoo[d], Eunkyoung Jee[a]*
[a] *Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea,*
[b] *Hannam University, 70 Hannamro, Daedeok-Gu, Daejeon, Republic of Korea,*
[c] *Chinju National University of Education, Republic of Korea,*
[d] *Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul, Republic of Korea.*
[*] *Corresponding author: ekjee@se.kaist.ac.kr*

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1. Introduction

Small Modular Reactors (SMRs) are being actively developed worldwide, including in South Korea, where iSMR and SMART [1] SMR projects are underway. As a result, the need for regulatory standards for reviewing SMRs has emerged, and South Korea should also establish its own regulatory framework for SMR safety reviews.

Unlike large-scale nuclear power plants, SMRs may face challenges in meeting existing regulatory requirements related to instrumentation and control (I&C) diversity and design. Due to differences in instrumentation environments and design modifications, appropriate review guidelines must be developed to ensure safety specifically for SMR [2].

This paper aims to identify the necessary modifications or additions to the existing review guidelines for digital I&C systems of large nuclear power plants when applied to SMR digital I&C. In particular, since Field-Programmable Gate Array (FPGA) is being introduced to replace traditional Programmable Logic Controller (PLC) in SMR digital I&C, the focus has been on considering the unique characteristics of FPGA.

Based on the content of NUREG/CR-7006 [2], which provides review guidelines for FPGAs in the NUREG review framework, this study proposes necessary modifications and discussions for domestic review guidelines, which is the Safety Review Guidelines for Light Water Reactors (KINS/GE-N001).

2. FPGA Development Process

FPGA-based digital I&Cs also should be developed under appropriate life cycles described in the international standard and regulatory guidelines (IEC 62566 [3]). Unlike software development in PLC-based digital systems, FPGA-based systems have specific features that develop software with hardware description language (HDL) through FPGA-specific steps such as translation and downloading to a chip. The software aspect follows the typical development life cycle. After that the register transfer level (RTL) design, written by HDLs, is transformed into the gate-level design (i.e. netlist) by synthesizing tools and netlist design is placed and mapped physically for preparing a downloadable file sequentially. The synthesis and Place and Route (P&R) steps are automatically performed by the tools provided by FPGA vendors. These steps are hardware aspects steps which translate RTL design to gate-level design and place and map all netlist elements to a downloadable file to board. Therefore, FPGA software development includes both software and hardware aspects such as requirements analysis, design, implementation, synthesis and P&R. Software requirement specifications for FPGA are often specified in the form of hardware aspects like modules in the FPGA board.

3. Key Considerations Suggested by CR-7006

NUREG/CR-7006 was developed to address the limitations of existing regulatory guidelines related to software used in I&C for conventional Nuclear Power Plant (NPP) in dealing with safety issues. Specifically, these existing guidelines fail to fully reflect the characteristics of FPGA, which encompass both hardware and software, as well as its complexity. Therefore, NUREG/CR-7006 aims to supplement the existing regulatory guidelines by providing FPGA-specific review guidelines related to safety assessment, FPGA design life cycle, verification and validation (V&V), configuration management, and documentation requirements, etc.

This document mainly covers FPGA hardware design practices, FPGA design entry methods, and FPGA design methodologies, following the framework of NUREG/CR-6463 [4]. Particularly, Chapter 4 presents the FPGA-specific design life cycle and FPGA design flow, including the V&V process.

Since this document was developed with the goal of establishing review guidelines that consider FPGA for use in safety-related nuclear applications—specifically, in I&C systems—it includes essential content that must be considered when developing regulatory guidelines and review methodologies tailored to the characteristics of FPGA in SMR digital I&C. Based on this content, this work conducts a review of domestic regulatory guidelines, and proposes necessary additions or modifications related to FPGA.

4. Review of the Conventional Review Guidelines

4.1 Hardware and Software Characteristics of FPGA

Since FPGA possesses characteristics of both hardware and software, its adoption necessitates explicit clarification in existing digital I&C guidelines that the term "software" encompasses programmable complex logic devices such as FPGA.

Relevant parts in Safety Review Guidelines for Light Water Reactors (KINS/GE-N001) that should reflect this consideration include:

- Section 7.7 (Control Systems): Review procedures for control systems
- Section 7.9 (Data Communication Systems): Review procedures and evaluation plans for data communication systems
- Appendix 7.1-4 (Evaluation Guidelines for Compliance with KEPIC ENB-6370 “Safety System Digital Computers”) may consider the hardware aspect of FPGAs in addition to the software aspects.
- Appendix 7-13 (Software Review Guidelines for Digital Computer-Based Instrumentation and Control Systems): Evaluation guidelines for I&C systems based on digital computers are stated in Appendix 7-13. This appendix deals with the software development life cycle. However, FPGA follows the development life cycle stated in NUREG/CR-7006 and IEC 62566, which considers both the software aspect and the hardware aspect. Also, this appendix only mentions the NUREG/CR-6463 standard for the implementation of digital computers. However, FPGA is developed with Verilog of VHSIC Hardware Description Language (VHDL), a hardware description language (HDL), which is not dealt with in NUREG/CR-6463.
- Appendix 7-17 (Evaluation Guidelines for Real-Time Performance of Digital Computers): The list of related guidelines in the background section of evaluation guidelines for the real-time performance of digital computers should be revised to incorporate FPGA-specific guidelines such as those presented in CR-7006. Furthermore, in the regulatory acceptance criteria, the software requirements specification referenced in digital computer timing requirements should be updated to include corresponding specifications for FPGA.

Additionally, to incorporate hardware-specific characteristics of FPGA, it may be required to include DO-254 [5], which is a certification standard for airborne electronic hardware, ensures design assurance and safety in aviation systems, specifically for the hardware design life cycle.

4.2 Consideration of FPGA-specific Design Flow

Appendix 7-13 serves as a regulatory guideline for software used in safety systems, specifying the regulatory requirements necessary for approval and providing guidance for evaluating the software lifecycle process. However, if FPGA replaces the traditional software role, it becomes necessary to establish FPGA-specific guidelines that reflect FPGA-specific design flow outlined in CR-7006 to incorporate the integrated hardware and software design process.

Since the main content of Appendix 7-13 provides regulatory guidelines for the design artifacts produced at each stage of the software lifecycle, rather than modifying its content, it would be more appropriate to introduce a separate appendix that mirrors Appendix 7-13 but specifically outlines regulatory guidelines for each stage of the FPGA design flow.

Moreover, NUREG/CR-7006 specifies that the regulatory guidelines for documentation are based on IEEE 1012-2004 [6] and DO-254. Also, IEC 62566, the standard for HDL-Programmed Devices (HPD) to be used in safety I&C systems of nuclear power plants, mentions that HPD such as FPGA should follow IEC 60880 in software level and IEC 60987 in hardware level. Given that IEEE 1012-2004 pertains to software and is already covered in Appendix 7-13, it is necessary to expand regulatory guidelines to also incorporate DO-254, which addresses hardware-specific requirements. This would ensure comprehensive regulatory coverage for FPGA implementation.

4.3 Need for FPGA-Specific Review Guidelines Corresponding to Existing PLC Usage Guidelines

Similar to Appendix 7-15, which provides review guidelines for the use of PLCs, the adoption of FPGA necessitates corresponding regulatory guidelines addressing its use. Therefore, a dedicated appendix should be established to define regulatory requirements for FPGA implementation.

This appendix should incorporate FPGA-specific information, including relevant regulatory guidelines, definitions, characteristics, programming languages, and the key documentation subject to regulatory review. By doing so, it would ensure that FPGA usage in safety-related applications is appropriately regulated, aligning with the framework already established for PLCs.

5. Conclusions

Unlike existing reactors, SMRs may have difficulty meeting existing regulatory requirements in I&C systems, and in particular, the use of FPGAs is increasing, requiring guidelines for them. NUREG/CR-7006 was developed to supplement the fact that existing software-centric regulatory guidelines for nuclear power plants do not sufficiently reflect the characteristics of FPGAs. This document ensures their applicability to SMR digital I&C systems.

As a result of reviewing Korea's existing regulatory guidelines (KINS/GE-N001), it is recommended to revise the existing software-centric regulatory guidelines or add FPGA-specific guidelines to reflect the hardware and software characteristics of FPGAs. Specifically, similar to the existing PLC usage guidelines (Appendix 7-15), a separate appendix should be provided for FPGA use, clearly defining its characteristics, programming language, and documentation requirements.

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