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FIELD PROGRAMMABLE GATE ARRAY BASED I & C SYSTEMS FOR NPPS: ENHANCING SAFETY AND EFFICIENCY

Introduction to NPPs

NPPs, or Nuclear Power Plants, are large facilities that use nuclear reactions to generate electricity. These reactions typically involve nuclear fission, which releases energy that is then used to heat water and produce steam. The steam powers a turbine, which drives a generator to create electricity. One of the main advantages of NPPs is their reliability. They can produce a large amount of electricity consistently for extended periods of time, and unlike fossil fuel power plants, they do not produce greenhouse gas emissions. However, NPPs also come with potential risks related to the management and storage of radioactive materials, requiring careful handling to ensure safety. There are various types of NPPs, such as pressurized water reactors (PWRs), boiling water reactors (BWRs), and advanced reactors. Each type has unique characteristics and designs, but all rely on nuclear reactions to produce electricity.

This paper serves as an overview of the uses of FPGAs in Nuclear Instrumentation and Control (I&C) systems and also seeks to discuss recent advances in, and implementations of, FPGAs for I&C systems in Nuclear Power Plants. It first introduces the basics associated with FPGAs, including FPGA background, FPGA technology and advantages, FPGA based I&C system in existing NPP, testing, validation and challenges for the use of FPGA in NPPs. It delves into various FPGA projects that have been completed, future projects as well as recent research on FPGA-based safety systems. The aim is to demonstrate the advantages of using FPGAs over other control technologies and provide a direction for future research in this area, specifically the development of FPGAs for safety and high reliability systems. By examining the successes and functionality of FPGAs in scientific literature and real-world implementations, this paper concludes that FPGAs are a valuable device for NPP I&C applications.

Overview of FPGAs

Most NPPs originally utilized analogue-based I&C systems, which were later replaced with computer-based, programmable systems in the 1980s and 1990s. While these newer systems offer advantages over their analogue counterparts, they are complex and time-consuming to verify and validate. Furthermore, computer-based applications utilizing microprocessors may quickly become obsolete. To overcome these issues, the industry is transitioning towards FPGAs based systems, which offer verifiable logic structures that can be interconnected to perform desired applications [1]. These systems have been used in NPPs since the 1990s, and have specific benefits in terms of both nuclear and cyber security [2, 3]. FPGA-based systems have a variety of applications, including replacing outdated analogue or digital systems in existing plants and implementing new builds [4].

FPGA based Technology

FPGAs are semiconductor chips which are exactly as the name suggests – gate arrays that be configured in the field by the designer based on their needs. It consists of many configurable logic blocks which can be programmed based on what functions the designer requires it to perform. In addition to the logic blocks, an FPGA consists of a programmable interconnect matrix that allows the designer to configure the FPGA internal wiring. The confirmable logic blocks and the interconnect matrix make the FPGA a very powerful and flexible technology [5]. They are design to be configured by the user, after manufacture, through the use of Hardware Description Language (HDLs) [6].

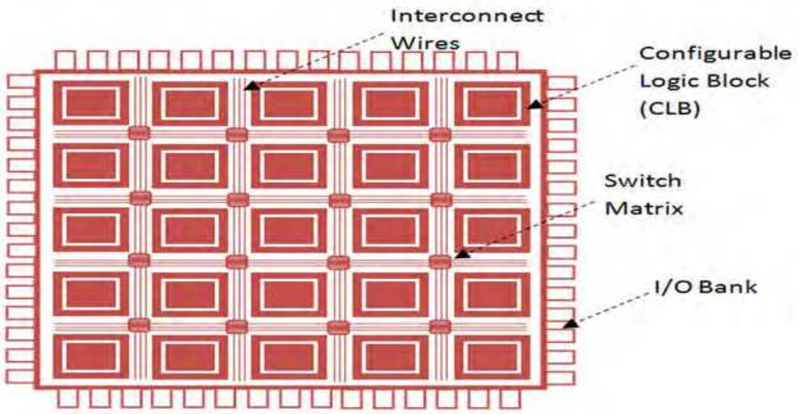

Fig. 1. FPGA Architecture

FPGA Architecture consist of the following features

- Configurable logic Block (CLB): Implements logic functions
- Input/Output Block: Connects with external components.
- Switching Matrix Interconnects: Implements routing.

FPGAs are integrated circuits within the broader family of HDL programmable devices, and are designed to be configured by the user, after manufacture, through the use of HDLs. FPGAs differ in their detail design among different vendors and product lines; however, they share a common basic architecture [7].

Advantages of FPGA based technology

FPGA-based technology offers several advantages, including superior performance, programmability, cost efficiency, parallel task performance, prototyping, faster time-to-market, simpler design cycles, adaptability, real-time application, and the ability to function as a system on chip. FPGAs outperform general CPUs by performing parallel processing, allowing them to process and calculate data simultaneously and faster. FPGAs are also reprogrammable, allowing for modifications, updates, and complete functionality changes, reducing maintenance costs. While FPGAs may have a higher unit cost, their reprogrammability makes them more cost-effective in the long run. FPGAs can also be designed to include multiple blocks processing data in parallel, making them ideal for time-critical data processing and offering greater scalability than other processors. FPGAs are perfect for prototyping purposes, especially for Application Specific Integrated Circuits (ASICs) validation. Compared to ASICs, FPGAs have simpler design cycles and take care of placement, routing, and timing in reference to specifications. FPGAs' adaptability allows modifications at the customer level, reducing the need to recreate products for updates. Due to their more efficient processing architecture, FPGAs are ideal for real-time applications, where they can perform more processing in a shorter time than alternatives. Since the 90s, FPGA gate counts have increased, making it possible to include CPU cores inside the FPGA, allowing them to function as a system on a chip. [5]

In addition to the current typical FPGA applications, such as providing computer emulation, interfaces between systems, replacement of obsolete modules and diversity against CCFs, the technology is expected to be applicable to large scale replacement of I&C systems in modernization projects, as well as providing complete I&C systems (safety and non-safety) in new nuclear power plant designs.

FPGA-based digital control systems and existing applications in NPPs

FPGAs have been widely installed in NPPs around the world, with many more projects expected to start in the future. For instance, in Argentina, RPC Radiy is developing the signal processing units of the new safety shutdown system No. 2 for the Embalse NPP using FPGA-based technology. Meanwhile, in Bulgaria, RPC Radiy has already installed six FPGA-based Category A Engineered Safety Feature Actuation Systems (ESFASs) of the Kozloduy NPP units 5 and 6, with each unit having three ESFASs [8]. In Canada, an FPGA-based emulator has been implemented for the obsolete PDP-11 computers used in several non-safety systems in CANDU plants, and the FPGA-based replacement of the display system controller circuit card is also underway.

FPGAs are also utilized in Non-Programmable Logic (NPL) parts of the instrumentation and control (I&C) systems of the Temelin NPP Units 1 and 2 in the Czech Republic. In France, EDF has initiated the FPGA-based replacement of obsolete electronic modules comprising the Rod Control System (RCS) and the reactor in-core measurement system in its 900 MW series of plants, while Toshiba has supplied various FPGA-based safety and non-safety systems to operating Japanese nuclear power plants.

In Sweden, FPGAs are used in the Component Interface Module (CIM) of the replacement safety system in Unit 2 of the Ringhals NPP. Finally, in the Republic of Korea, FPGAs are used for performing self-diagnostic functions and are expected to perform component control functions for the engineered safety features in new APR-1400 plants that are currently under construction. [9]

Testing and validation of FPGA-based systems in NPPs

Simulation techniques can be utilized in the course of development and Verification & Validation (V&V) to assess the performance of the FPGA design and the changes in internal signals and states under varying functional conditions. These techniques can yield reasonably accurate results. On the other hand, online observation of internal signals and states can facilitate monitoring and diagnostics. Offline observation can be used for testing or troubleshooting during application development. Furthermore, offline observation can ensure that the produced and configured chip adheres to the validated and verified design, specifically that all designated logic blocks are present, connected, and functioning appropriately.

Simulation is the primary V&V technique for FPGA design, used to replicate the behavior of the hardware circuit with varying degrees of accuracy and detail at different stages of development. RTL simulation is useful for detecting logical errors during the logical design phase, while timing errors are generally detected during the implementation phase. FPGA circuit vendors provide electronic design environments with advanced simulation capabilities and timing information, which are crucial complements to their products

Challenges and potential future application of FPGA-based control systems in NPPs

FPGAs used in the nuclear power industry are relatively new, and they are not yet widely used in this field. Although FPGAs are already used in digital I&C systems in some NPPs, they are not as prominent as microprocessors and their software in a PLC-based system. This poses challenges for safety analyses and licensing efforts. There is currently only one standard that provides guidance and requirements for FPGA-based solutions for the nuclear power industry, but it has not been adopted by most regulatory bodies [9].

Furthermore, the availability of FPGA-based platforms and products is limited, with few products designed specifically for NPP applications. Development tools for FPGAs are not as user-friendly or widely accepted as those for microprocessor-based solutions such as Programmable Logic Circuits (PLCs). Additionally, FPGAs may provide less observability and access to signals than conventional electronics or microprocessor-based solutions, reducing their usefulness for monitoring, testing, and troubleshooting. Design teams must possess specialized expertise in both software and hardware to design FPGA-based solutions, as FPGA designs are represented as code written in an HDL, which requires software tools for synthesis and design implementation. Finally, FPGAs may struggle to accommodate complex graphical human system interface functions, and soft core Central Processing Unit (CPU) emulation may be necessary for these functions.

CANDU Energy and RPC Radiy are collaborating to develop FPGA applications for safety-critical functions for the new enhanced CANDU-6 reactor in Canada. In China, both China Nuclear Power Engineering Company and China Techenergy Company are evaluating and developing FPGA-based safety systems for their new reactor designs. The former is considering FPGA-based solutions for RPSs, DASs, ESFASs, and post-accident monitoring [10], while the latter is developing FitRel, an FPGA-based platform for the DAS of Yangjiang NPP Units 5 and 6 [11].

Conclusion

The article discusses the current use of FPGAs in NPP I&C and their adaptation to safety and non-safety electronic systems in European and Asian NPPs. In summary, NPP face various challenges over their operational lifetime, and new plants should be designed to accommodate future adaptations. FPGAs offer potential solutions to I&C system needs, with advantages over other control technologies, although there are inherent challenges. FPGAs are expected to become more prevalent in the industry as operators and regulators become more familiar with them, and future research should focus on designing and qualifying safety-critical FPGA systems to meet regulatory safety requirements for enhancing the operational performance and safety. Several countries are conducting research and implementation projects on FPGA safety systems, demonstrating their effectiveness in practical applications.

To summarize, this paper has shed light on the current and future FPGA implementation projects, as well as the latest research in FPGA-based systems, particularly safety systems. While most of the implemented systems have been for non-safety critical I&C systems and monitors, new research and development in Canada, Bulgaria, Sweden, and China show promising results for FPGA safety systems.The benefits of FPGAs over other control technologies, such as speed, reliability, resistance to obsolescence, and fewer licensing issues, have been demonstrated in various implementation programs. The successful use of FPGAs in real-world scenarios, with no known issues and replacing obsolete systems, indicates the effectiveness of the technology.

However, there is still a need for future research to design and qualify safety-critical FPGA systems, such as the SDS and RPS, to meet safety regulations. This paper can serve as a valuable resource for past and present FPGA projects, providing insight for the development of new FPGA-based safety systems in power plants' upgraded and new builds.

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