Proceedings of the 17th International Conference on Nuclear Engineering
ICONE17
July 12-16, 2009, Brussels, Belgium

ICONE17-76063

ADVANCED I&C SYSTEMS FOR NPPS BASED ON FPGA TECHNOLOGY: EUROPEAN EXPERIENCE

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ABSTRACT

The objective of this paper is to present features of I&C systems for NPPs based on Field Programmable Gate Arrays (FPGA) technology. It also presents the European experience of such systems in design, manufacturing, testing, production, commissioning and operation by giving the example of Engineering Safety Feature Actuation Systems (ESFAS) for Kozloduy NPP.

A large modernization project of ESFASs for Bulgarian NPP units Kozloduy-5, Kozloduy-6 includes replacement of six systems during 2008-2010 (three ESFASs for Kozloduy-5 unit and three ESFASs for Kozloduy-6 unit). The first part of the project was successful because a flexible FPGA-based platform “Radiy” was used, which permits the adaption of existing functional modules in a short time. The Kozloduy ESFAS project is an example of rapid development of nuclear applications for existing and prospective reactors on the base of platform “Radiy”.

INTRODUCTION

Today I&C systems play an important part in reactor unit control. The dependability of I&C systems directly affects the safety of NPPs.

The large volume of software in I&C systems is a source of potential common cause failures (CCFs). However, decreasing a program code would mean decreasing the volume of system functions. An effective solution to the decreasing effect on software system dependability is to use FPGAs as programmable components instead of programmable logic controllers (PLCs).

FPGA is a hybrid of software and hardware. FPGA use in I&C systems has some advantages such as closeness of the initial algorithms notation to final release..

The objective of this paper is to present features of I&C systems for NPPs based on FPGA technology, as well as European experience of such systems in design, manufacturing, testing, production, commissioning and operation by giving the example of ESFAS for Kozloduy NPP.

The following points are included in this paper:

– a brief description of FPGA technology

–advantages and abilities of advanced I&C systems for NPPs based on FPGA technology

– details of Kozloduy-5, Kozloduy-6 modernization project

– a brief description of VVER reactor and ESFAS

– analysis of digital safety I&C platform “Radiy”

– structure of ESFAS for Kozloduy-5, Kozloduy-6

– features of ESFAS function implementation on the basis of FPGAs

– results of ESFAS safety assessment including benefits for the general technical community.

FPGA TECHNOLOGY

Two lines exist in contemporary programmable logic arrays [1,2]: Complex Programmable Logic Devices (CPLD) and Field Programmable Gates Arrays (FPGA). CPLDs are a continuation of programmable matrix logic line, whereas FPGAs continue basic matrix crystal lines. The desire to combine the advantages of both lines led to the development of combined architecture VLSIs (see Figure 1).All contemporary FPGAs possess such architecture.

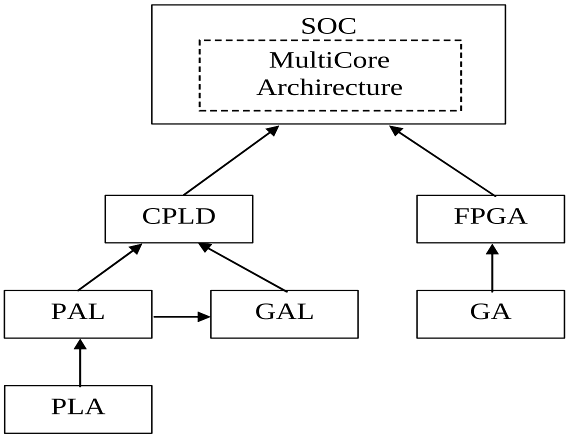

Figure 1. Architecture types of FPGA

CPLD architecture has its origins in Programmable Arrays Logic (PAL) preceded by Programmable Logic Arrays (PLA) and from Generic Arrays Logic (GAL). Its functional unit consists of microcells, each performing some combinatory and/or register functions. Functional logic within the block is a matrix of logic products (terms). A subset of terms may be accessed by each macrocell via a term distribution diagram. A switch matrix commutates the signals coming from outputs of the functional unit and I/O unit. As distinct from FPGA (segmented connections), CPLDs have a continuous system of connections, completely commuted.

FPGA architecture topologically originates from channeled Gates Arrays (GA). In an FPGA internal area, a set of configurable logic units is disposed in a regular order with routing channels between them with I/O units at the periphery. Transistor couples, logic gates NAND, NOR (Simple Logic Cell), multiplexer-based logic modules, and logic modules based on programmable Look-Up Tables (LUT) are used as configurable logic blocks. All these have segmented architecture of internal connections.

System-On-Chip (SOC) architecture appears due to two factors: a high level of integration permitting the arrangement of a very complicated circuit on a single crystal, and the introduction of specialized hardcores into FPGA. Additional hardcores may be:

− additional Random Access Memory (RAM) units

− JTAG interface for testing and configurating

− Phase-Locked Loop (PLL) – frequency control system to correct timing relations of clock pulses, as well as for generation of additional frequencies, or

− processor cores enabling creation of devices with a control processor and a peripheral.

FPGA resources and additional RAM are disposed at the processor address space. Examples of such solutions are the families of Altera Excalibur (Embedded Processor Programmable Solution), and Atmel FPSLIC AT94 (Field Programmable System Level Integration Chip).

ADVANTAGES AND ABILITIES OF ADVANCED I&C SYSTEMS FOR NPPS BASED ON FPGA TECHNOLOGY

Application of FPGA technology permits:

– control and other safety-critical functions in the form of “hard” logic (FPGA with implemented project with its own hardware for each algorithm), without software

– use of software only for diagnostics, archiving, signal processing, data reception and transfer between I&C systems components, provision of man-machine interface. Failures of those functions do not affect execution of basic I&C systems control functions - an operation system is not applied at I&C systems lower levels

– a reduction in the time necessary for software verification

– parallel processing of all process control algorithms within one cycle, thus ensuring high performance of the system (for instance, RTS within 20 ms) and proven determined temporal characteristics due to parallel operation of control algorithms

– development of the software-hardware platform in such a way that it becomes a universal interface to create I&C systems for any type of reactors;

– high reliability due to the application of industrial components as well as using the principles of redundancy, single failure and diversity

– resistance to failures and external effects

– modification in quite a simple manner, including algorithm alterations, without any interference in I&C systems hardware structure

– application of an FPGA-based platform to monitor and control circuits of any kind of actuators (gates, engines, pumps, valves, etc.) in industries where very high action speed and reliability are required (hydrocarbons, metallurgy, chemicals, etc.)

– reduction by more than 10 times the number of contact and terminal joints, which cause many operational failures of equipment on account of the wide use of integrated solutions and optic fiber communication lines

– deep diagnostics of I&C systems equipment permitting quick and unambiguous detection of place, time, character of a failure and hazard degree of equipment operability violation, and

– small energy consumption and heat radiation.

DETAILS OF KOZLODUY-5, KOZLODUY-6 MODERNIZATION PROJECT

In February 2008 the Research and Production Corporation (RPC) “Radiy” won a tender for delivery of six Engineering Safety Feature Actuation Systems (ESFAS) to Bulgarian NPP units Kozloduy-5 and Kozloduy-6. The type of these units is VVER-1000. This modernization project is characterized by a very short time for ESFAS design, production, acquisition and commissioning, as well as by very strong management requirements.

The project to modernize Kozloduy's ESFASs includes replacement of six systems during 2008-10 (three ESFASs for Kozloduy-5 unit and three ESFASs for Kozloduy-6 unit). The NPP site mounting and commissioning schedule is as follows:

– August – September 2008 – ESFAS-2 for Kozloduy-6

– April – May 2009 – ESFAS-2 for Kozloduy-5

– August – September 2009 – ESFAS-1 and ESFAS-3 for Kozloduy-6

April – May 2010 – ESFAS-1 for Kozloduy-5

– August – September 2010 – ESFAS-3 for Kozloduy-5.

The first ESFAS for Kozloduy NPP successfully passed Factory Acceptance Testing (FAT) in July 2008. Mounting of the first ESFAS at the site (ESFAS-2 of Kozloduy-6) started in September 2008. Installation prior to commissioning should be finished in an extremely short period (about one month). ESFAS-2 of Kozloduy-6 is now successfully operating.

The second ESFAS for Kozloduy NPP (ESFAS-2 of Kozloduy-5) successfully passed FAT in February 2009. This ESFAS commissioning is planned at Kozloduy NPP for April 2009.

VVER REACTOR AND ESFAS

The VVER (water-cooled and water-moderated energetic reactor) is a series of pressurized water reactors (PWRs) developed by the former Soviet Union and used now by Russia, Ukraine, Armenia, Bulgaria, Slovakia, Czech Republic, Hungary, Finland, Iran, India and China. The VVER-1000 design was developed.

The VVER-1000 was developed between 1975 and 1985 and is a four-loop system housed in a containment-type structure with a spray steam suppression system. VVER reactor designs have been elaborated to incorporate automatic control, passive safety and containment systems associated with Western third generation nuclear reactors.

The Russian abbreviation VVER stands for water-cooled, water-moderated energy reactor. This describes the pressurized water reactor design. Reactor fuel rods are fully immersed in water kept at 15 MPa of pressure so that it does not boil at normal (220 to over 300 °C) operating temperatures. Water in the reactor serves both as a coolant and a moderator which is an important safety feature. Should coolant circulation fail the neutron moderation effect of the water diminishes, reducing reaction intensity and compensating for loss of cooling, a condition known as negative void coefficient. The whole reactor is encased in a massive steel pressure shell. Fuel is low enriched (2.4–4.4% ^{235}U) uranium dioxide (UO_2) or equivalent pressed into pellets and assembled into fuel rods.

Intensity of the nuclear reaction is controlled by control rods that can be inserted into the reactor from above. These rods are made from a neutron absorbing material and depending on depth of insertion hinder the chain reaction. If there is an emergency, a reactor shutdown can be performed by full insertion of the control rods into the core.

ESFAS for VVER-1000 performs control, diagnostic, information and servicing functions (see below).

ESFAS based on the digital safety I&C "Radiy" platform performs the following control functions [3,4]:

– formation and issuance of process safeguard and interlock signals for automatic control of actuators in accordance with process algorithms

– formation and issuance of output discrete signals for automatic control of actuators when the monitored process parameters exceed their limit values in accordance with prescribed algorithms

– remote control of actuators from the Control Room in accordance with process algorithms

– transmission of discrete signals to other systems.

The ESFAS performs these diagnostic functions:

– self-diagnostics of hardware and software

– validity control of received/transmitted data packages

– automatic control of input and output circuits.

The ESFAS performs these information functions:

– collection, transformation and visualization of values and condition of continuous and discrete input signals obtained from process parameter sensors

– imaging, registration and archiving of process, diagnostic information and operator actions

– formation of process signaling and its display for Control Room operators

– display of data on trip conditions of process safeguards and interlocks

– semi-automatic report formation

– information exchange with power unit information systems via Ethernet under TCP/IP protocol.

ESFAS performs these servicing functions:

– semi-automatic checks of process safeguard and interlock algorithms

– semi-automatic calibration of measurement channels, and accuracy checks of set-point actuation.

DIGITAL SAFETY I&C PLATFORM "RADIY"

The digital safety I&C "Radiy" platform comprises both upper and lower levels [3,4].

The upper level is created on purchased IBM-compatible industrial workstations. Software for the upper level "Radiy" platform was developed by RPC "Radiy" and is loaded on the workstations.. The functions of the upper level workstations are as follows:

– receipt of process and diagnostic information

– creation of man-machine interface in the Control Room

– display of process information on each of the control algorithms relating to control action executed by I&C system components

– display of diagnostic information on failures of I&C system components

– registration, archiving and visualization of process and diagnostic information.

The lower level of the "Radiy" platform consists of standard cabinets including standard functional modules (blocks).

The software-hardware “Radiy” platform comprises the following standard cabinets:

– Normalizing Converter Cabinets (NCC) – perform inputting and processing of discrete and analog signals as well as feeding sensors;

– Signal Forming Cabinets (SFC) – perform inputting and processing of discrete and analog signals, processing of control algorithms, and formation of output control signals

– Cross Output Cabinets (COC) – receive signals from three control channels (signal formation cabinets) and form output signals by “two of three” mode

– Remote Control Cabinets (RCC) – control 24 actuators on the basis of Control Room signals, automatic adjustment signals and interlocks from signal formation cabinets

– Signaling Cabinets (SC) – form control signals for process annunciation panel at Control Room

– Connection with Information System Cabinets (CIC)

– Power Supply Cabinets (PSC)

– Force Control Cabinet (FCC)

– Sensor Supply Cabinets (SSC)

– Unified Current Signal Distribution Cabinets (CDC) and

– Intermediate Clamp Cabinets (ICC) – for signal switching.

The cabinets include functional modules (blocks). The totality of cabinets and modules forms the “Radiy” platform. The platform includes the following main modules:

– chassis and backplanes
– Power Supply Modules
– Analog Input Modules
– Normalizing Converter Modules, Thermocouples
– Normalizing Converter Modules, Termistors
– Discrete Input Modules
– Discrete Information Input Modules, Pulse
– Potential Signals Input Modules, High Voltage
– Protection Signal Forming Modules (Logic Modules)
– Analog Output Modules, Voltage
– Analog Output Modules, Current
– Discrete Output Modules
– Potential Signal Output Modules
– Solid-State Output Modules
– Relay Output Modules
– Actuator Control Modules
– Fiber Optic Communication Modules
– System Diagnostic Modules
– Fan Cooling Modules
– terminal blocks, cables, wire and fiber optic sets
– power distribution hardware.

Protection Signal Forming Module which performs the main logic functions is presented in Figure 2. The module in Figure 2 contains four the main parts.

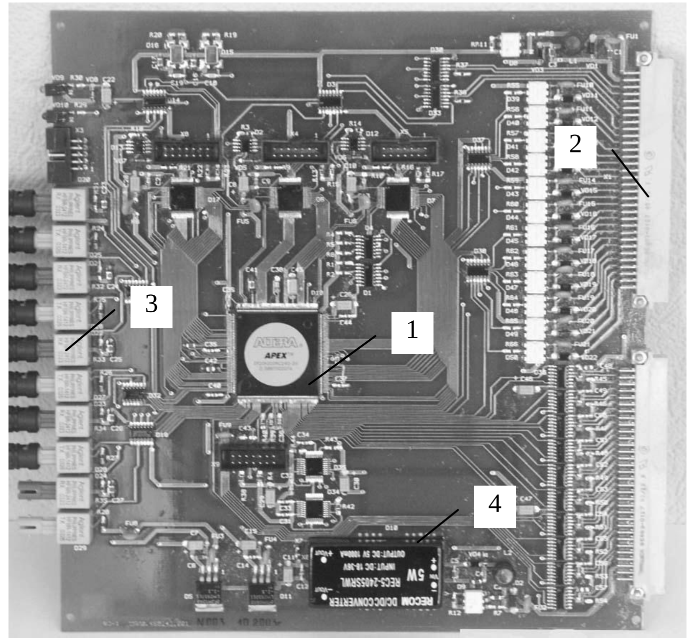

Figure 2. Protection Signal Forming Module of digital safety I&C “Radiy” platform (1 – FPGA-chip; 2 – signals inputs; 3 – fiber optic communications; 4 – module power unit)

STRUCTURE OF ESFAS FOR KOZLODUY-5, KOZLODUY-6

In order to form process safeguards, signals on each process parameter are fed from three independent sources (one for each ESFAS channel). Only one source of corresponding parameter may be used to form process interlocks.

ESFAS comprises upper and lower levels.

The ESFAS structural diagram is shown in Figure 3. Cabinets of ESFAS are joined in the following four main subsystems:

– Subsystem of Protections and Blocking Forming
– Subsystem of Automatic Regulation
– Subsystem of Remote Control and
– Subsystem of Signaling and Connection with Information System.

Input signals come to each channel from independent sensors. A part of the input signal is transformed at Normalizing Converters Cabinets (SFC-10). Signals from Signal Forming Cabinets come to Remote Control Cabinets, Cross Output Cabinet and Signaling Cabinets. Each Remote Control Cabinet may control 24 actuators.

The commissioned ESFAS-2 for Kozloduy-6 contains the following seventy three cabinets (Figure 3):

– five CDC-1
– four SFC-10
– three SFC-5
– one COC-4
– one SFC-11
– one SFC-8

– eighteen RCC-2 consisting of Automatic Regulation Subsystem and seventeen RCC-2 consisting of Remote Control Subsystem

– one FCC-1

– two SC-1

– one CIC-2

– six PSC-1

– three SSC-3

– eight ICC-5 and one ICC-6

– one Computer Cabinet (workstation).

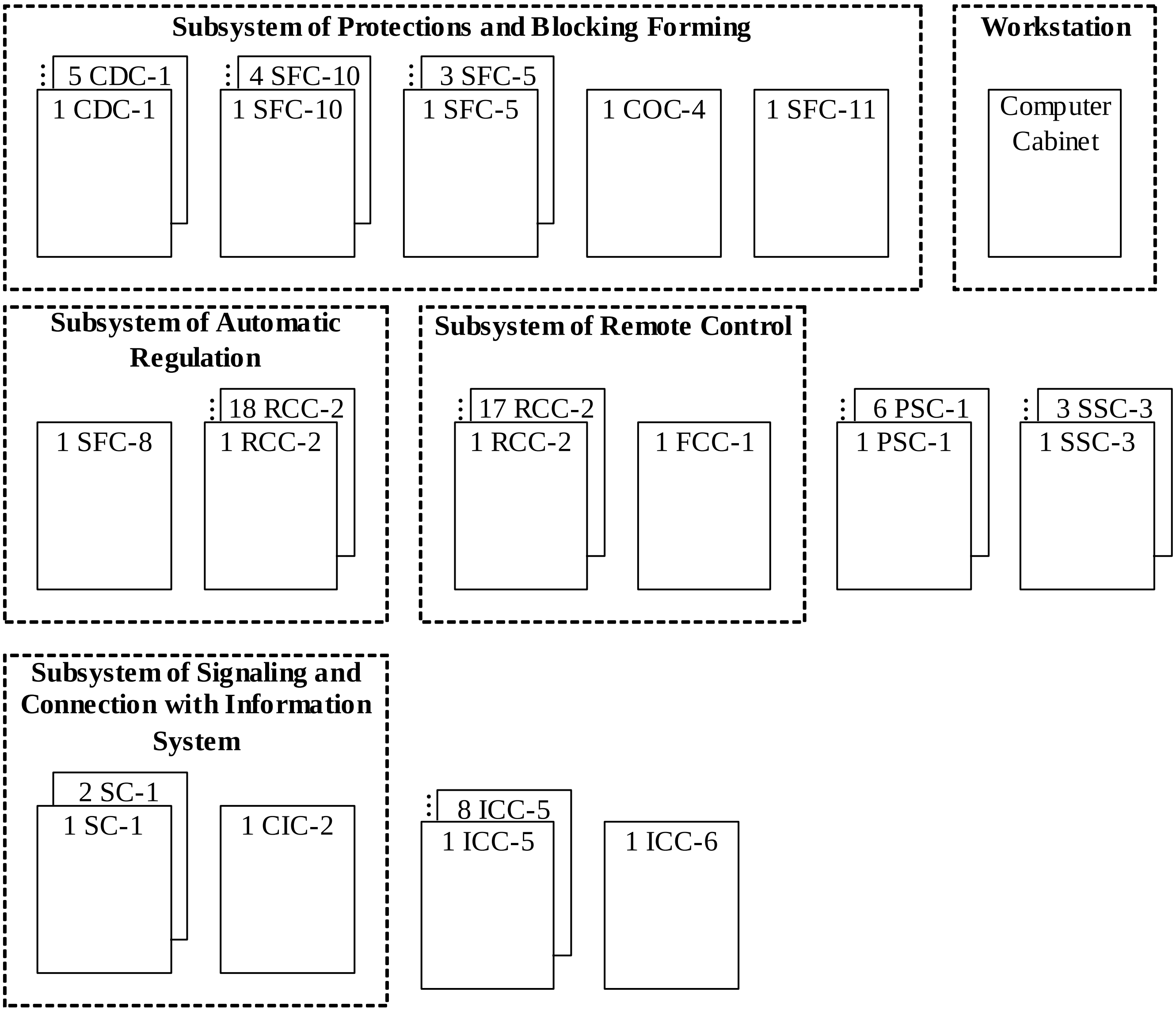

Figure 3. A structure diagram of ESFAS

FEATURES OF ESFAS FUNCTION IMPLEMENTATION BASED ON FPGAS

The following three technologies are used to design FPGAs projects [5-7].

1. Graphic diagrams using standard and additional (specially created) library primitives created in a CAD environment.

2. Software models using special languages for digital device description (VHDL, AHDL, Verilog, etc.).

3. Software code used in a microprocessor emulator environment to be implemented in an FPGA crystal in the form of a separate functional core.

The above technologies are applied in the “Radiy” software-hardware platform in the following ways.

– Graphic diagram functions are presented in the form of power unit equipment process control algorithms, for instance, emergency and preemptive reactor protection, process safeguards and interlocks, actuator automatic and remote control, and process parameter alarms

– Digital device description languages are used as additions to graphic diagrams, for example, in the creation of mathematical computations that need precise diagrams to be developed

– Auxiliary functions, such as input signal processing, diagnostics, data reception and transmission, are performed in a software code executed in a microprocessor emulator environment.

All these three development technologies may be joined within the frameworkof a single FPGA project (see Figure 4).

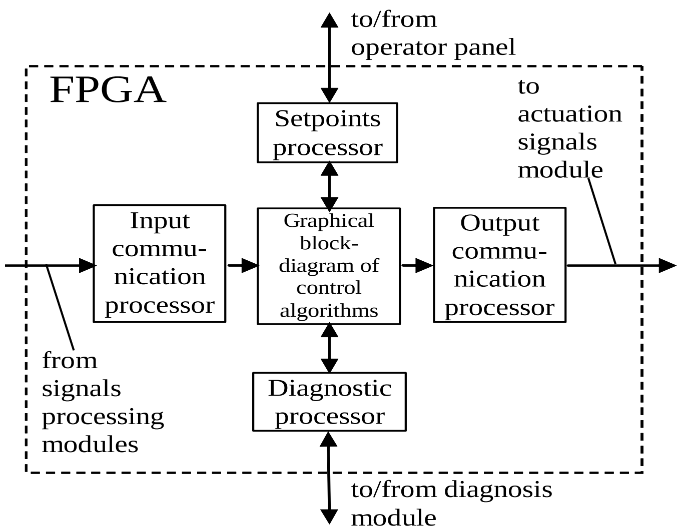

Figure 4. A structure of FPGA-project for signals forming module

RESULTS OF ESFAS SAFETY ASSESSMENT

A third party assessment has been performed in accordance with IAEA and IEC standard requirements to prove the adequacy of ESFAS safety requirements [8,9]. The safety assessments have been conducted by the Ukrainian State Scientific Technical Center on Nuclear and Radiation Safety (SSTC NRS), which is the supporting organization of the Ukrainian Regulatory Authority. Experts of SSTC NRS have considerable experience in the area of FPGA-based systems safety assessment, as they have performed reviews of all thirty three FPGA-based safety systems supplied at Ukrainian NPP units since 2003.

The following independent safety reviews have been conducted by SSTC NRS experts:

– safety review of System Requirement Specification (Term of References)

– safety review of Software Verification Plan and Report

– safety review of Reliability Analysis Report.

In the safety review of the System Requirement Specification, the compliance of this document with safety requirements has been evaluated.

NPP I&C systems as developed by RPC “Radiy” meet these requirements of IAEA standards:

– IAEA NS-R-1. Safety of nuclear power plants - design

– IAEA NS-R-2. Safety of nuclear power plants - operation

– IAEA NS-G-1.1. Software for computer based systems important to safety in nuclear power plants

– IAEA NS-G-1.2. Safety assessment and verification for nuclear power plants

– IAEA NS-G-1.3. Instrumentation and control systems important to safety in nuclear power plants

– IAEA NS-G-1.6. Seismic Design and Qualification for Nuclear Power Plants

– IAEA NS-G-2.3. Modifications to nuclear power plants.

NPP I&C systems as developed by RPC “Radiy” meet these IEC requirement standards:

– IEC 60780:1998. Nuclear power plants – Electrical equipment of the safety system – Qualification

– IEC 60880:2006. Nuclear power plants – Instrumentation and control systems important to safety – Software aspects for computer-based systems performing Category A functions

– IEC 60980:1989. Recommended practices for seismic qualification of electrical equipment of the safety system for nuclear generating stations

– IEC 60987:2007. Nuclear power plants – Instrumentation and control important to safety – Hardware design requirements for computer-based systems

– IEC 61226:2005. Nuclear power plants – Instrumentation and control systems important to safety – Classification of instrumentation and control functions;

– IEC 61513:2001. Nuclear power plants – Instrumentation and control for systems important to safety – General requirements for systems

– IEC 62138:2004. Nuclear power plants – Instrumentation and control for systems important to safety – Software aspects for computer-based systems performing Category B or C functions

– IEC 62340:2007. Nuclear power plants – Instrumentation and control systems important to safety – Requirements for coping with common cause failure (CCF).

Assessment of compliance with IAEA and IEC safety requirements can be performed in the following ways:

– technical documentation analysis

– qualification testing

– analytical calculations

– functional validation testing

– software verification.

Compliance to the following requirements is assessed by technical documentation analysis:

– requirements of defense from common case failures

– requirements of single failure criterion

– requirements of redundancy principle

– requirements of independency principle

– requirements of personal errors avoidance

– requirements of security

– requirements of human-machine interface

– requirements of quality.

Compliance to the following requirements is assessed by qualification testing:

– requirements of timing characteristics

– requirements of technical diagnostic
– requirements of stability against environment impacts
– requirements of stability against mechanical and seismic impacts
– requirements of stability against power supply parameters changing
– requirements of electromagnetic compatibility.

Compliance to the following requirements is assessed by analytical calculations:
– requirements of reliability indicators
– requirements of accuracy.

Compliance with the requirements of functions performance is assessed by validation testing.

Compliance with the requirements of software is assessed by verification.

Experts found the System Requirement Specification complies with the regulatory requirements of Bulgaria as well as with regulatory requirements of IAEA and IEC standards.

The safety review of the Software Verification Plan and Report (SVPR) included the following actions [10-12]:
– an analysis of ESFAS software structure
– an analysis of SVPR compliance with requirements of IAEA, IEC and ISO standards
– an analysis of results of ESFAS software verification.

Features of FPGA-projects were taken into account during the safety review of SVPR. FPGA projects were treated as a kind of software and included:
1) graphic diagrams of digital devices that display technological algorithms of signals forming
2) PID-regulator realized in FPGA
3) a code in C programming language executed in the microprocessor emulator environment, implemented in FPGA.

Multi-stage development and verification processes were created for every FPGA-project part. Integration of FPGA-projects and ESFAS software was accompanied by verification of integrated products.

The SVPR has been analyzed for compliance with requirements of the following standards:
– IEC 60880:2006. Nuclear power plants – Instrumentation and control systems important to safety – Software aspects for computer-based systems performing Category A functions
– ISO/IEC 12207:1995. Information technology – Software life cycle processes
– ISO/IEC 9126-1:2001. Software engineering – Product quality – Part 1: Quality model.

SSTS NRS experts found that the SVPR complies with the following requirements of the above standards:
– requirements of Software Verification Plan structure and content
– requirements of Software Verification Report structure and content
– requirements of defense of software against common case failure
– requirements of organization and management of verification process
– requirements of verification methods
– requirements of analysis methods
– requirements of verification tools
– requirements of independence of verification
– requirements of software quality assurance
– requirements of detected software anomalies analysis and elimination.

Analysis of ESFAS software verification results included the following steps:
– verification results of software requirements
– verification results of signals forming algorithms
– verification results of regulators mathematical models
– verification results of design of Nios software
– verification results of design of upper level software
– verification results of program models of signals forming algorithms in design environment
– verification results of regulator program models in design environment
– verification results of Nios code software modules
– verification results of upper level software code modules
– verification results of the integrated program model of signals forming algorithms in a design environment
– verification results of the integrated program model of regulators in design environment
– verification results of integrated Nios software
– verification results of integrated upper level software
– verification results of integrated FPGA-projects
– verification results of integrated ESFAS software.

The Reliability Analysis Report (RAR) includes the following:
– common ESFAS description
– ESFAS reliability requirements
– ESFAS hardware and equipment
– common case failures analysis
– reliability analysis technique (Reliability Block Diagrams)
– assumptions for reliability analysis
– input data for reliability analysis
– Reliability Block Diagrams of ESFAS functions
– results of calculations
– conclusions.

The safety review of RAR included analysis ESFAS compliance with reliability requirements as well as an independent reliability assessment by Fault Tree Analysis (FTA) technique.

SSTS NRS experts found RAR results comply with the reliability requirements of System Requirement Specifications. Results of independent FTA confirm the correctness of reliability indicators values in RAR.

CONCLUSIONS

Since 2005 RPC “Radiy” designed, produced, supplied and commissioned eight ESFASs for units of Yuzhno-Ukrainsk NPP and Rivne NPP (Ukraine). The longest operational time of such equipment at power unit Yuzhno-Ukrainsk-1 is about four years.

All ESPAS hardware, software, FPGA-projects and configuration tools are qualified to the requirements of international standards.

The first ESFAS for Kozloduy NPP successfully passed Factory Acceptance Testing (FAT) in July 2008. Installation of the first ESFAS at the site (ESFAS-2 of Kozloduy-6) started in September 2008. Installation prior to commissioning should be finished in an extremely short time (about one month). The ESFAS-2 in Kozloduy-6 is now successfully operating.

A successful feature of the first part of the project was the use of the flexible FPGA-based “Radiy” platform, which permitted the adaption of the existing functional module in a short time. The Kozloduy ESFAS project is an example of rapid nuclear application of the “Radiy” platform to existing and prospective reactors.

Digital safety I&C “Radiy” platform can benefit the general nuclear community because the following advantages:

– input modules are capable to process all the types of input signals which are used at NPPs with any reactor type

– output modules are capable to generate all the types of input signals which are used at NPPs with any reactor type

– FPGA-technology provides tools for rapid development and verification of all the types of NPP technological algorithms

– diagnostic modules realize technical diagnostics procedures with high depth, efficiency and credibility

– “Radiy” platform exceed in operational performance (reliability, availability, timing characteristics) another digital safety I&C platforms

– “Radiy” platform ensures high rapidity of modernization (full Reactor Protection System replacement during refueling cycle

– “Radiy” platform is certified against European requirements (IEC, IEAE); at present a certification process against USA requirement (US NRC, IEEE, EPRI) is fulfilled.

Thus “Radiy” platform can be successfully used modernization of existing and prospective reactors.

REFERENCES

1. J. Lach, W. Mangione-Smith, M. Potkonjak, Enhanced FPGA Reliability through Efficient Run-Time Fault Reconfiguration, IEEE Trans. on Reliability, 49, pp. 296-304 (2000).
2. G. Doerre, D. Lackey, The IBM ASIC/SoC Methodology – A Recipe for First-time Success, IBM Journal of Research and Development, 6, pp. 649-660 (2002).
3. M.A. Yastrebenetsky (edit), Safety of Nuclear Power Plants: Instrumentation and Control Systems, Technika, Kyiv & Ukraine (2004).
4. V. Kharchenko, V. Sklyar (edits), FPGA-based NPP Instrumentation and Control Systems: Development and Safety Assessment., RPC “Radiy”, National Aerospace University “KhAI”, State STC on Nuclear and Radiation Safety, Kharkiv & Kirovograd & Ukraine (2008).
5. A. Melnyk, A. Salo, Automatic generation of ASICS, Proceeding of NASA/ESA Conference AHS-2007, Edinburgh, UK, pp. 311-317 (2007).
6. D. Caporossi, “Use ASIC Design Methodology for Your Next FPGA Design”, Xcell journal, 48, pp. 48-51 (2004).
7. A. Barkalov, M. Wegrzyn, Design of Control Units with Programmable Logic, Zelena Gura, Poland University of Zelena Gura Press, Poland (2006).
8. N. Leveson, Safeware: System Safety and Computers, Addison-Wesley (1995).
9. Preckshot G., Method for Performing Diversity and Defense-in-Depth Analysis of Reactor Protection Systems. NUREG/CR-6303, LLNL, Livermore, USA (1994).
10. M.R. Lyu, Handbook of Software Reliability Engineering. McGraw-Hill Company, 1996. 805 p.
11. L. Pullum, Software Fault Tolerance Techniques and Implementation, Artech House Computing Library (2001).
12. V. Kharchenko, O. Siora, V. Sklyar, Design and Testing Technique of FPGA-Based Critical Systems, Proceeding of Conference CADSM’2009, Lviv, Ukraine, pp. 305-314 (2009).