Preliminary Development of the FPGA based Reactor Protection Systems for Reaktor Daya Eksperimental (RDE)

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Abstract. The reactor protection system is a very vital and essential system to ensure the safe operation of the Reaktor Daya Eksperimental (RDE). The current reactor protection system mostly uses a lot of analog components. The analog system is more sensitive to the noise, and more expensive compared with the digital system. Therefore, this study aims to design and model the reactor protection system based on a digital platform using Field Programmable Gate Array (FPGA). The FPGA platform is selected because of the high reliability, easy for reprogrammed and having high loop rate execution. This research method covers the preliminary design of the reactor protection system using FPGA CompactRIO. The verification and validation are then employed to ensure the reliability of RPS. Furthermore, this system is tested with various postulated initiating event of the RDE’s design basic accident. The result of this research is that FPGA has excellent reliability and has a fast response. It can be concluded that the simulation of the reactor protection system using FPGA can be used in the reactor protection system after being verified and validated.

Keywords: Reactor protection system, experimental power reactor, FPGA

1. Introduction
RDE or Experimental Power Reactor is a nuclear reactor that can be used for electricity generation, heat generation and to produce hydrogen. Experimental Power Reactor is a type of High-Temperature Gas-cooled Reactor (HTGR). The construction of the Experimental Power Reactor (RDE) is intended as a first step in the construction of a Nuclear Power Plant (NPP) in Indonesia before stepping into the construction of large-scale nuclear power plants. The use of RDE, in addition to electricity generation, will also be an experimental heat treatment process reactor in order to master the concept of cogeneration based on the applicable laws and regulations that can be built and operated by BATAN as the Implementing Agency.

In the construction and development of the Experimental Power Reactor (RDE), an instrumentation and safety control system are needed, which serves to keep the reactor in a safe condition and ensure to avoid the release of radioactive substances into the environment. Thus the reactor safety system is an essential facility and must always function properly. Protective safety action, consist of several measurement and limit detections are initiated by the Reactor Protection System (SPR) automatically.

High-temperature gas-cooled reactors (HTGR) have very well integrated security features such as
strong negative feedback coefficients, large heat capacity from the core, inert helium gas as coolant, etc. These characteristics of the reactor ensure safety without relying heavily on sophisticated, active safety systems. Thus, innovative HTGR has excellent economic benefits because it can achieve the same level of security needed for current reactors with a simple passive security system.

The current reactor protection system mostly uses analog components. The conventional analog reactor (RPS) protection system devices have weaknesses and relatively expensive. However, digital RPS has been applied to several nuclear power plants in recent years. Digital RPS has many advantages, such as a smaller size for the similar functions, component reduction, reduction of connection lines, network techniques that are more simple, stable, have high precision, not susceptible to noise, low distortion in the process of transferring information, insensitivity to false signals and circuit deviations. Besides, digital RPS has advantages in modifying logic during the design phase.

2. Theory
2.1 Description of RDE
Experimental Power Reactor (RDE) instrumentation and control systems are carried out to measure, monitor, and control RDE installations. Instrumentation and control equipment is divided into operational systems, protection systems, and accident monitoring systems. Instrumentation and operational control systems are non-safety related systems and are used to operate the installation under normal conditions and to monitor operating conditions. Information needed to monitor operating conditions is displayed in the central control room. Instrumentation and digital control systems have also been used in nuclear power plant installations. This system is applied to monitoring systems, control systems, nuclear installation protection, and mitigation systems. Instrumentation and control equipment for reactor protection systems is related to safety and serves to prevent excessive loads on essential components and systems and to minimize the impact of accidents on the environment. Meanwhile, the equipment protection system is not safety-related and is designed to guarantee the automatic protection of necessary equipment units. The accident monitoring system is related to safety to ensure that sufficient information regarding the condition of the installation and its impact on the installation and the environment is given during and after the accident and a series of events that are outside the design basis.
The instrumentation system is also responsible for channeling control decisions to the installation actuator and storing installation status records and control decisions. The RDE instrumentation system provides process information needed to maximize power production and to protect the value of installation investments. Instrumentation and control systems such as the RDE installation nervous system and affect all aspects of RDE installation operations.

![Figure 1. RDE Technology System Scheme](image-url)
In general, the RDE-10 specification can be seen in table 1. From the table, it is stated that the Experimental Power Reactor (RDE) is designed not only to produce electricity in the amount of 3-4 MW, but also to be used for hydrogen production, water desalination and coal liquefaction in the future. After RDE technology is established in the future, by increasing its capacity, RDE can also be applied in eastern Indonesia.

### Table 1. Specification of RDE

| Basic Data                     | Value         |
|--------------------------------|---------------|
| Reactor power (thermal)        | 10 MW (Thermal) |
| Mean power density             | 2 MW/m3       |
| Core diameter                  | 1.8 M         |
| Mean core height               | 2.0 M         |
| Primary system pressure        | 30 Bar        |
| Flow direction                 | Downwards     |
| Primary coolant temperature    | 250/700 °C    |
| Fuel                           | Low-enriched uranium (LEU) |

### Table 2. Core nuclear of RDE

| Equilibrium core nuclear data  | Value           |
|--------------------------------|-----------------|
| No. of radial enrichment zones | 1               |
| No. of fuel element recyclies (avg.) | 5              |
| Heavy metal charge             | 5 g/fuel element|
| No. of fuel elements in the core | 27,000 pcs.    |
| Integral fuel element residence time | 1,160 VLT    |
| Fuel element dwell time        | 230 VLT        |
| Enrichment                     | 17 w/o         |
| Target burn-up                 | 80,000 MWd/MgU |
| Mean fuel element output       | 0.37 kW/fuel element |

### 2.2 Description of the Reactor Protection System

The SPR working principle is based on priority control. Priority control always prioritizes executing commands from the SPR, compared to commands from other operational signals. Commands from priority control are forwarded to the reactor safety system until a scram occurs if a system failure occurs. The fundamental purpose of the safety design is the confinement of radioactive material in the reactor so that the risk of harm to the environment can be avoided during normal operation or after an accident. Modular HTR is designed so that all postulated accidents can occur due to physical or technical problems that do not lead to the release of radioactive material into the environment. In other words, if an accident occurs due to physical or technical problems, the reactor safety system guarantees no radioactive material released into the environment.

The reactor safety design utilizes natural properties that guarantee inherent safety so that the nuclear reactor has a safe and safe system for errors made by the operator. Besides that, nuclear reactors are equipped with safety equipment designed using the following principles:

1. Separation: different components of the safety system are physically separated from each other.
2. Diversity: there is always more than one way to do a job.
3. Redundancy: there is always more than one component needed.
4. Mutually dislike: the safety system is not compatible with others.
5. Safe failure (fail-safe): it is intended that if a component/system fails, it will automatically stimulate
to move in a safe condition.
The boundary values as a criterion for initiating a protective action are determined as the basis of the limit value resulting from the permissible physical value and is a boundary for safe installation conditions. The parts of the reactor system that must be controlled and limited in value (magnitude) for their safety are found in the following systems: reactor systems, coolers, confinement, ventilation, electrical power, experiments, loading of core elements, and earthquake systems.

**Table 3. Initiating event of RDE Reactor Protection System**

| Initiation Criteria | Accident | Setting Point | Action |
|---------------------|----------|---------------|--------|
| Thermally corrected neutron flux ≥ max | Reactivity accident at start-up | Max. 120% | Action type 1a |
| Negative sliding for therm. corr. neutron flux ≥ max | Reactivity increase in power operation | Max. 120% | Action type 1a |
| Intermediate-range neutron flux ≥ max | Reactivity decrease in power operation | Max. 20% | Action type 1a |
| Period ≤ min | Blower failure / inadvertent operation of blower damper | Max. 20% | Action type 1a |
| Hot gas temperature ≥ max | Reactivity accident at start-up | Max. 120% | Action type 1a |
| Cold gas temperature ≥ max | Reactivity increase in power operation | Max. 740°C | Action type 1a |
| Neg. sliding limit value of main steam pressure ≥ max | Feedwater line break | Max. 280°C | Action type 1a |
| Moisture in primary system ≥ max | Steam generator tube break | Max. 800 vpm | Action type 1a |
| Mass flow ratio, primary to secondary ≤ min / ≥ max | Primary system depressurization | Max. ratio 1.3 | Action type 2b |
| | Blower failure / inadvertent operation of blower damper | Min. ratio 0.75 | Action type 1a |
| | Feedwater line break | | Action type 1a |
| | Emergency power operation | | Action type 3c |

*a Reactor trip (reflector rods drop under gravity, primary gas blower tripped, secondary system isolated)

*b Steam generator relief

*c Primary system isolation
3. Methodology

The current reactor protection system mostly uses a lot of analog components. The analog system is more sensitive to the noise, and more expensive compared with the digital system. Therefore, this study aims to design and model the reactor protection system based on a digital platform using Field Programmable Gate Array (FPGA). The FPGA platform is selected because of the high reliability, easy for reprogrammed and having high loop rate execution. This research method covers the preliminary design of the reactor protection system using FPGA CompactRIO.

The research is carried out covering experimental and simulation. Planning to design the RDE reactor protection system uses inputs in the form of sensors in reactors such as a thermocouple, level sensors, pressure sensors, and others that are simulated using the function generator. The simulated sensor with the function generator is then connected via the NI compactRIO interface to be connected and programmed through LabVIEW on the PC, as shown in Figure 3. The sensor in the reactor that will give value, then the value will be forwarded through the hardware NI compactRIO, the value will be programmed in the LabVIEW software so that all parameters are following the initiating event of the RDE reactor protection system.
The initial step of this research is to study the subject of the Experimental Power Reactor (RDE). This is done to determine the variables and to initiate events used for reactor protection systems. The next step is setting up the connection between NI compactRIO and LabVIEW software on the PC. This step requires testing so that compactRIO NI can be connected to a PC, after NI compactRIO is connected to a PC, then proceed to create a program in the block diagram and front panel on LabVIEW. In order for the system to run well and following the expected results, testing of the system is needed. The systems and programs created will be analyzed and evaluated and can be changed until the expected results can be achieved. Then, the system can be used for RDE reactor protection systems.

4. Result and Discussion
The program created in LabVIEW FPGA consists of two parts. The first part is a program created on the FPGA. This section functions as an input from a sensor and is part of the conversion between input values and values that will be displayed and processed later. While the second part is a program created as HOST, this section functions as an interface and gives a threshold value to the system that has been programmed on the FPGA.
Figure 5. Block Diagram of FPGA RPS RDE

(a) Input configuration and data rate
(b) Conversion and comparison

Sent data to HOST

Logic operation of postulated initiating event

Figure 6. (a) and (b) Section of the FPGA block diagram

Figure 5 and figure 6 is a block diagram of the FPGA. The LabVIEW FPGA front panel configuration input function is to determine the type of signal that will be received by the compactrio module, and the data rate is used to determine the speed of the data to be sent to the FPGA, the data rate on the NI 9232 ranges from 0.985 kS/s to 102.400 kS/s. This value is determined when the program will run. The conversion section functions as the value of the input value conversion with the value to be displayed and processed later. While comparison functions as a logic operation from initiation criteria. The send data to the host part serves as the sender of data to the RT Target (HOST), this data can be issued in the HOST program and can display interface. The logic data of the postulated initiating event is a logic operation that can identify if an accident occurs in the reactor.
Figure 7. Section of the HOST block diagram

In Figure 7 (a) is the program to specify the address of I/O cRIO to determine the RIO devices and determine input configuration and data rate that will be used. This data will be configured with the FPGA block diagram. Figure 6 (b) is a figure that controls the program via the HOST and gives the threshold/setting point input value specified in the table initiating event. This input value is written on the HOST that will be sent to the FPGA. This function can provide an input value or accept the output value from the FPGA program that can be displayed in the HOST program, which can then be made to display the interface in the front panel HOST program. Figure 6 (c) is data sent from FPGA to HOST. This data can be used to create waveforms on the HOST front panel. Then this data can be stored in a file and record every data received.
The first method on the system setup tab is to enter a cRIO I / O address on the tab “RIO Device” to configure the RIO device that is used. This address search will be done automatically. The program will detect the device when the device is connected to a PC. Select the speed in the “data rate” tab to determine the speed of the data to be received from the FPGA. A host loop update means how much time will be used to update the loop. If an error occurs in the FPGA program or HOST program, the program will stop and display the error on the error tab.

In this block diagram the setting event of initiation criteria is determined. The operator can change its value. There is also an indicator that will light up if the value achieved is not appropriate or outside the threshold of the value of the setting event.
Figure 10. Analog waveform of RDE Reactor Protection System

Figure 10 represents the waveform of the analog graph of the value received by the sensor. This system is tested with various postulated initiating events of the RDE’s design basic accident. The waveform can be seen as the graph rate of each sensor. The indicator on the left side is an indicator of initiation criteria. This indicator will turn on if the received value is outside the setpoint value limit. The indicator on the top side is an indicator of the design of a basic accident that will continue to blink in the event of an accident. In the event of an accident, the reactor will scram and carry out the action as specified in the table of the design basic accident.

Figure 11. Digital waveform of RDE Reactor Protection System

Figure 11 shows the waveform of a digital graph from the design of a basic accident. From the graph, it can be seen which signal first gives a scram signal, making it more accessible in tracking and analyzing if several criteria outside the threshold occur at almost the same time.
Figure 12. Data recorded on file

Figure 12 shows the data recorded from the program received. We can determine where to save the file. All data is recorded along with the time so that analysis can also be done from recorded data.

5. Conclusion

The result of this research is that FPGA has excellent reliability and has a fast response. The digital RPS system has many advantages than analog conventional RPS systems. Digital RPS is easier in programming, has low noise, and has relatively comparable performance with the analog. Thus it can be concluded that the simulation of the reactor protection system using FPGA can be used in the reactor protection system after being verified and validated. Data can also be recorded well, making it easier to track if an accident occurs.

Reference

[1] IAEA-TECDOC-1198 2001 Current Status and Future Development of Modular High Temperature Gas-Cooled Reactor Technology in IAEA (Wina, Austria)
[2] BATAN 2014 Cetak Biru Pembangunan Reaktor Daya Eksperimental (RDE) 2014-2020 vol. No. CB001/RN01/SEN Rev.0
[3] BATAN 2014 Program Evaluasi Tapak Reaktor Daya Eksperimental Vols. No. PET-001/RN01/SEN, Rev.01
[4] BATAN 2014 Sistem Manajemen Evaluasi Tapak Reaktor Daya Eksperimental Vols. No. SMET001/RN01?SEN, Rev.01
[5] Sukmana, Jaja. Jonnie A Korua, S Suwarto 2006 Kajian Kinerja Sistem Proteksi Reaktor dan Batas Persyaratan Operasi pada Pengendalian Operasi RSG-GAS (Tangerang, Banten, Pusat Reaktor Serba Guna - BATAN) p 165-174
[6] Kazuhiko Kunitomi, Shusaku Shiozawa 2004 Nuclear Engineering and Design p 45-58
[7] Fu Li, Zijue Yang, Zhencai An, Liangju Zhang 2002 The first digital reactor protection system in China, Nuclear Engineering and Design p 215-225
[8] 1997 Comittee on Application of Digital Instrumentation and Control System to Nuclear Power Plant Operation and Safety in Digital Instrumentation and Control Systems in Nuclear Power Plants, (Washington DC, AS: National Research Council)

[9] IAEA 1999 Modern Instrumentation and Control for Nuclear Power Plants: a Guidebook (Wina, Austria)

[10] T. Taryo 2016 The Current Status of Indonesia Experimental Power Reactor 10 MW (RDE) Prosiding Seminar Nasional Teknologi Energi Nuklir p 961-968

[11] J. Sukmana 2003 Pengendalian Operasi RSG-GAS dengan Sistem Proteksi Reaktor (Yogyakarta: STTN)

[12] H. Reutler 1988 Plant Design and Safety Concept of the HTR-Module p 335-340

[13] M. Sunargo 2009 Reaktor Nuklir

[14] Setyono 2003 Management of Maintenance, Training Course, Batan-JAERI

[15] 1989 Safety Analysis Report MPR-30 Rev.7, PRSG-BATAN

[16] 2015 Final Report Front and Engineering Design in The Document Preparation of Preliminary Engineering Design of the Experimental Power Reactor p 1-11

[17] 2017 Penyusunan Dokumen Basic Engineering Design Reaktor Daya Eksperimental in Sistem Proteksi Reaktor dan Emergency Shutdown p 17