Designing Instrumentation and Control System for Power Control and Shutdown System of RDE

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Abstract. The development of an experimental power reactor (Reaktor Daya Eksperimental/RDE) is one of the BATAN’s prioritized programs. Its engineering design has been performed since 2015. This paper describes the designing process of the instrumentation and control system for power control and shutdown system of RDE in order to ensure its safe operation. The engineering design steps have been applied. They include design philosophies have been the preparation of design philosophy and design requirements, selection of standard and code, and development of the engineering design. The power control system that employs two controllers, main and slave controllers, is discussed. The I&C architecture for control and shutdown system is presented. It consists of process interface, data acquisition and control system, communication network, and man-machine interface.

1. Introduction

Experimental power reactor (Reaktor Daya Eksperimental/RDE), which is a high-temperature gas-cooled reactor, in addition to generating electricity, has cogeneration features through its heat application for hydrogen production, seawater desalination, enhanced oil recovery, coal gasification and liquefaction, and other applications. RDE, as one of the Generation IV nuclear energy system, promotes principles of sustainability, economic competitiveness, safety and reliability, as well as proliferation resistance and physical protection [1].

Considering that RDE has low power density and high safety margin and employs modular design, which ensures containment of radioactive fission products through passive and inherently secured measures, BATAN has decided to make the RDE construction as a prioritized program. Under BATAN’s auspice, the conceptual design of RDE having capacity of 10 MWth was completed in 2015 by RENUKO [2]. RDE has characteristics that offers relatively small capacity, which is suited to an archipelago country such as Indonesia. Similar to RDE, which is a modular pebble bed type reactor, a 10-MW high temperature gas-cooled reactor (HTR-10) successfully developed in China [2]. A steam generator with a straight tube bundle for RDE has been studied recently using a CC-THERM CHEMCAD [2].

To ensure RDE’s safe operation, its power control should be very well managed. Control rods containing B₄C are used to manage the power of HTGR [3,4,5]. This paper describes the design of instrumentation and control system for managing RDE power through the adjustment of control rod.
insertion. Digital reactor protection system has been designed and applied for the HTR-10 [6] and HTR-PM [5]. Instrumentation and controls for HTGR protection system has been outlined by Wilson et al. [7] and new HTGR sensors of temperature, pressure, and flow as well as neutron detectors have been proposed by Ball et al [8].

2. Theory

2.1. Experimental Power Reactor (RDE)
This Indonesian RDE is a high-temperature gas-cooled reactor with pebble bed core and 10 MWth capacity. Its fuel is low-enriched UO2 pebble coated with tristructural Isotropic (TRISO) layers, i.e. inner pyrocarbon (IPyC), silicon carbide (SiC), and outer pyrocarbon (OPyC). The reactor core is 1.8 m in diameter and 1.97 m high and surrounded by graphite reflector [9].

Helium gas is used as a coolant that removes and transfers the generated heat from the core to steam generator to produce steam. In the power conversion unit, the steam drives a turbine-generator to generate electricity. The steam coming out from the turbine is condensed in a condenser and the water produced is sent back to the steam generator [9].

Heat removal system of RDE is based on passive system, i.e. natural circulation. Heat dissipates through core structural material by conduction and radiation heat transfer to reactor vessel. This heat will propagate and enter the reactor cooling system located in the reactor building wall. This passive system uses natural circulation principle and removes decay heat to air by air cooling.

RDE employs two shutdown systems: control rods and small absorber balls containing boron carbide (B4C). These shutdown systems located in the reflector are able to shut down the reactor because of their negative reactivity. Another way to shut down the reactor is by turning the helium circulator off [9].

2.2. Control Rod
Control rods are used for hot shutdown and temperature adjustment. These control rods are inserted into the side reflector and are designed to bring the reactor to zero power and subcritical state under any operation condition and postulated operational events. RDE employs ten control rods that can be used the reactor in subcritical state for relatively long period to allow the installation management to make decision for the subsequent operation, i.e. cool down or restart [9].

These ten control rods consist of several elements combined together. Absorber material, which is ring-shaped and sintered B4C is located between coaxial tubes in each element. The absorber is cooled in the inner and outer section with cold helium gas flow. Each control rod can move freely in the reflector column [9].

Each control rod is equipped with position indicator to measure the rod position in its position range. The mechanism of the control rod is accessible for maintenance operation when the reactor shuts down. Its movement mechanism is installed at the upper part of thermal shield with air isolated barrier to prevent air entering into the core. This barrier is fabricated continuously with the core barrel, upper thermal shield, and other superstructure of the upper part of thermal shield [9].

2.3. Small Absorber Ball System
Small absorber ball system is provided for cold and long period shutdown. These eighteen small absorber balls are distributed uniformly in the core perimeter and above the thermal shield. Each ball, which is made of graphite, contains 10% volume B4C with diameter 10 mm.

The small absorber balls are designed to make the core into subcritical condition under any postulated operational conditions that do not require swift reactivity change. They are used for relatively long period cold shutdown.
2.4. Shutdown using Circulator
In case a failure occurs in the shutdown system using control rods and small absorbers, other measure to shut down the reactor is by stopping the primary flow coolant, i.e. by shutting down the circulator. This action will raise core temperature and further make it subcritical due to negative temperature coefficient reactivity. Whenever the reactor tripped, the primary coolant flow is stopped by turning the circulator off and closing the circulator damper [9].

3. Methodology
In designing the instrumentation and control system for power control and shutdown system of this RDE, the methodology used consists of the following steps:
- Preparation of design philosophy
- Development of design requirements
- Selection of standard and code
- Development of engineering design
- Evaluation of design
- Finalization of design

4. Results and Discussion

4.1. Design Philosophy
The following design philosophy is considered in designing the I&C system for power control and shutdown system of RDE [10,11]:
- Redundancy
  It provides protection towards single failure and prevents random and independent failure on a component or system from occurring.
- Separation
  Separation refers to the use of a systematic physical separation such as barrier or distance and the use of decoupling instrument, such as isolating buffer to separate components or system having similar functions.
- Fail-safe Mode
  This mode has been applied widely in the instrumentation and control system for safety related component or system.
- Level of Automation
  Automation is applied to mitigate consequences of an accident where operator’s manual action is not required in order to prevent radioactive release to environment.
- Protection
  It is applied to shut down the main components or installation if further operation might cause risks or endanger environment and important components.
- Diversity
  Diversity minimizes any possible risks of an error or mistakes in the design or maintenance. Diversity can be provided through the use of device or software of different component that performs the same function.
- Remote Shutdown
  Remote shutdown is provided to anticipate any emergency condition in case the main control room cannot be operated and/or equipment in the main control room does not work.

4.2. Standard and Code
The standard and code that can be applied in this design activities includes [10,11]:
- IEEE 279 – Criteria for Nuclear Power Generating Station Protection Systems
The design requirements for I&C system for power control and shutdown system of RDE are as follows:

- I&C system for power control and shutdown system should provide automatic control and monitoring functions for electricity generation, start-up/shutdown, and refuelling of RDE;
- I&C system for power control and shutdown system should accommodate the performance and transient characteristics of RDE;
- I&C system for power control and shutdown system should facilitate the normal operation of RDE;
- I&C system for power control and shutdown system should be capable of managing the operation of electricity generation, start-up/shutdown, and refuelling of RDE;
- I&C system for power control and shutdown system should facilitate the operation of RDE at various power level;
- I&C system for power control and shutdown system should be able to provide control over any actuators and device required for power control and start-up/shutdown of RDE;
- The design of I&C system for power control and shutdown system should be based on proven technology to support the licensing of RDE;
- The design, structure, and components of I&C system for power control and shutdown system should be standardized;
- I&C system for power control and shutdown system should include any features for automatic power control during start-up and shutdown of RDE;
- The workstation for I&C system for power control and shutdown system should be designed user-friendly.

4.4. RDE Power Control System

The reactor power level of RDE corresponds to its control rod position, which can be obtained through a control system. This control system involves secondary feed water as a feed forward input, steam temperature as the first level of measured variable, and neutron flux as the second level of measured variable. The output of the power control system is actuation of upward/downward movement of RDE control rods. The schematic diagram for the control system of control rods is shown in Figure 1.

It is apparent that the control system employs a flow sensor (SF) and temperature sensor (ST), flow controller (FC), temperature controller (TC), and neutron flux controller (NFC). The flow rate of feed water, which is sensed by the flow sensor is transmitted to the flow controller and used as a feed forward input. Meanwhile, the steam temperature measured by the temperature sensor is transferred to the temperature controller and used as a feedback input. These two variables are combined to obtain a setting point for controlling the neutron flux. The neutron flux control receives an input from a detector for comparison with the predefined setting point. Therefore, control rod actuation can be executed.
The block diagram for RDE power control system has been developed and shown in Figure 2. The difference between the steam temperature setting point \( Y_{sp1} \) with controller gain \( K \) and measured temperature \( Y_{m1} \) generates an error, \( E_1 \). This error is forwarded to a proportional, integral, and derivative (PID) controller, which is a master controller with a combined transfer function \( G_{PID} \) to achieve a control. The resulted output is coupled with the feed water \( (FW) \) flow, which is a feed forward input with transfer function \( G_F \). This addition gives a setting point \( Y_{sp2} \) of neutron flux for the second level controller (slave controller) with transfer function \( G_P2 \). That slave controller output is also used as a feedback with transfer function \( G_{m2} \). The deviation between \( Y_{sp2} \) and the measured flux neutron \( Y_{m2} \) generates an error, \( E_2 \), which is then used as an input to the slave controller to actuate the upward/downward movement of the control rods. The changes in position of the control rod are affected by a proportional controller with transfer function \( G_{P1} \). It regulates the steam temperature, \( Y_1 \), which is then fed back to the master controller having transfer function \( G_{m1} \).
4.5. I&C Architecture for Control and Shutdown System

The I&C architecture for control and shutdown system of RDE consists of four levels, which are process interface, data acquisition and control system, communication network, and man-machine interface, as shown in Figure 3. At process interface, there are some sensors/transmitters that measure the parameters required for control and monitoring, i.e. neutron flux, temperature, pressure, coolant flow rate, and circulator speed.

Next, the data obtained are transferred to data acquisition and control system level, comprising data acquisition, power control, and process control. This control system level is then connected to redundant communication network that can be accessed via wireless and/or wired network by control console available at man-machine interface level. The control parameters are shown on mimic display or LCD monitors. Tiles for alarm are also provided at this level.

![Figure 3. Schematic I&C Architecture for Control and Shutdown System of RDE](image)

5. Conclusion

Instrumentation and control system for power control and shutdown system of RDE has been designed. The design process follows the engineering design methodology. Design philosophy and design requirements that have been developed are used in the design process of this I&C system. In addition, standard and codes of IEEE, IEC, and USAEC are considered.

A two-level controller is employed in the design of RDE power control system, which implements proportional, integral, and derivative controller. Meanwhile, the I&C architecture for control and shutdown system contains four levels (process interface, data acquisition and control system,
communication network, and man-machine interface). The use of display/monitor and alarm tiles is indicated.

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