

# Research Article **A Digital Controller for Reactivity Monitoring and Power Control**

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This paper introduces a controller unit for reactivity monitoring and automatic power control that was designed and constructed for the 500 kW Dalat Nuclear Research Reactor (DNRR). For power control and reactivity calculations, frequency signals from neutron measurement channels of starting and working ranges of the reactor are used. Two abovementioned independent functions were combined in an Artix-7 FPGA board for determining reactivity values by solving the point reactor kinetics equations with six delayed neutron groups and for stabilizing the reactor power at preset levels by determining the unbalance voltage signal to control the automatic control rod. With real-time calculations, the newly developed controller can monitor the reactor reactivity and control the reactor power online. The developed controller unit's reactivity measuring and power stabilizing capabilities were assessed using the DNRR in normal operation and assumed emergency conditions and compared with those of the preexisting imported BNO-102R1 module of the DNRR control and protection system, known as ASUZ-14R. The results of the experiments show that the produced FPGA-based unit and the BNO-102R1 unit have the same technical characteristics and features, with the disparities being less than 5% and 1%, respectively, in reactivity measurement and power stabilization. The experimental data of reactivity measurements by the FPGA-based unit and the calculation results were also compared and found that the relative deviations between those are also less than 10%. The developed controller unit is capable of carrying out a variety of training and operational experiments on the DNRR.

#### 1. Introduction

The period and power of a nuclear reactor are significant parameters that are directly tied to its ability to operate safely. The reactivity is the most significant time-dependent parameter because it is highly sensitive to the behaviour of the reactor power. It is important in many nuclear reactor applications, such as to determine the reactivity worth of reactor control rods and the Xenon worth, to monitor the reaction at the subcritical, near-critical, and critical levels, and to change power levels in the reactor.

Static, dynamic, and kinetic techniques can all be used to estimate a nuclear reactor's reactivity. In the static technique, change in reactivity is identified when the reactor power is maintained at a critical state. The in-hour equation can be used in the dynamic technique to determine reactivity, although it only works effectively for positive reactivity and has very little sensitivity to negative reactivity. By applying the point-kinetics equations to examine the time fluctuation of the reactor power level, the reactivity at each point in time can be calculated [1]. The kinetic technique is almost adaptable for online estimation of the reactivity of a nuclear reactor and is sensitive for both positive and negative periods.

The reactivity of nuclear reactors has so far been calculated using a variety of techniques. To measure the reactivity value of the control rods and other components of the Toshiba Training Reactor TTR-1 and record changes in reactivity during its startup, an analog computer technique was devised [2]. A compact digital reactivity meter based on a high-speed, 16-bit minicomputer system was developed. The device can be used to evaluate the physics of a reactor, monitor the reactivity at initial startup, verify the nuclear design after refuelling, and ensure safe operation [3]. To determine the reactivity of the TRIGA reactor at Oregon State University, a reactivity meter system based on a personal computer was developed. This device uses a fission chamber operating in current mode that is directly proportional to the thermal neutron flux of the reactor and a wide-range log power channel amplifier with a voltage output signal that is proportional to the logarithm of the reactor power [1]. Dedicated circuit assembly or a PCI data acquisition card combined with a personal computer and high-level visual basic real-time programming were used to design and develop a PC-based system for online measurement of the reactivity worth of control rods of the TRIGA Mark-II reactor in Bangladesh [4]. The same system has been used for continuous monitoring and measurement of reactivity inserted into or removed from the TRIGA Mark-II reactor in Malaysia [5]. Design and construction of a digital reactivity meter system for continuous monitoring of the reactivity of the Tehran research reactor included the use of a PIC16F877 microcontroller to digitize voltage signals first, followed by the computation of reactivity using MATLAB software running on a personal computer. Prior to being converted to voltage, the system's input signal was the fission chamber's amplified output in the current mode of the mA range [6]. To provide real-time monitoring for the Argonne fast source reactor, a compact reactivity meter was developed using a microprocessor. This reactivity meter uses a BF<sub>3</sub> ionization chamber as the nuclear detection unit, and the output of the chamber is amplified by a picoamperemeter before being converted to a digital form by a voltageto-frequency converter [7].

Based on the rapid development and great advantages of digital electronics technology and digital signal processing (DSP) techniques, the field programmable gate array (FPGA) circuits have been widely applied in nuclear electronics design and construction. In this context, an FPGAbased reactivity meter, which can operate online with realtime calculation, was developed for the Tsing-Hua Open-Pool Reactor (THOR). The signals from the fission chamber were preprocessed by a preamplifier and then sent in parallel to pulse mode and current mode channels. The pulse mode channel was used for the reactor startup range operation, while the current mode channel was used for the reactor power range operation. The output signals from the two channels were sent to the FPGA boards to determine the reactor power, period, and reactivity [8]. Recently, the FPGA-based real-time implementation of a digital reactivity meter was developed using the Zynq FPGA model, which consists of the XC7Z010T-1CLG400 all programmable SoC, a hybrid between a dual-core ARM Cortex-A9 processing system and Artix-7-based FPGA [9]. This reactivity meter system used compensated ionization chambers to get the neutron flux measurement signal in the reactor power range.

This paper describes a digital controller unit for monitoring reactor reactivity and controlling reactor power based on a commercial board using the Xilinx FPGA Artix-7 XC7A100T, with an embedded microcontroller. The controller samples and filters the output pulses from the pulse amplifier of the start range and from the current-tofrequency converter of the working range of the DNRR control system and then calculates the reactivity and sends the obtained value to a personal computer for recording. As an alternative, the controller also has the ability to calculate and produce an unbalance value between the real reactor power and the preset power level in order to automatically stabilize the reactor power at the preset power level. The neutron detector unit of the DNRR instrumentation system has a unique design in that it consists of a fission chamber that operates in pulse mode for the starting range and a compensated gamma Boron ionization chamber that operates in current mode for the working range. The details of the DNRR instrumentation system are described in Section 2.

The designed FPGA-based controller unit has been carefully tested in the laboratory using the commercial pulse-generated simulator PGT-17R and then with the reactor using its instrumentation system. The reactivity monitoring and power control functions of the controller unit have also been compared with those of the BNO-102R1 unit, which was supplied by the Russian SNIIP Systematom Co. Ltd. The purposes of the FPGA-based controller development are to conduct experiments on the DNRR for manpower training and to replace the imported BNO-102R1 unit when needed. Main advantages of FPGA-based controller over microcomputer-based or microprocessor-based systems are flexibility for parameter adjustment, data analysis and maintenance, and reduction of developing cost. In addition, hardware-programmed data in FPGA is safe in contrast to software-based microcomputer systems [7, 8].

The paper is organized as follows: the neutron detector unit and the BNO-102R1 unit utilized in the DNRR control and protection system are briefly described in Section 2. The BNO-102R1 and FPGA-based controller units' connection block arrangement with the reactor instrumentation system is also provided in this section, along with a brief description of the features of the DNRR control system itself and the FPGA-based controller unit. Section 3 describes the theoretical considerations for calculating the reactor power, reactor period, reactor reactivity, and unbalance voltage; the principle diagram of the developed controller, the configuration algorithms for the FPGA board, and the flowcharts for hardware-based reactivity calculation in the Artix-7 FPGA board with the embedded MicroBlaze are provided. The collected experimental data are presented and discussed in Section 4. Finally, concluding remarks are derived in Section 5.

#### 2. Equipment

The neutron flux of the DNRR is detected by the BDPN-36R2 neutron detector unit, which was originally designed for each neutron flux measurement channel of the nuclear power plant instrumentation system [10]. There are three independent ionization chambers in each detector unit, including a high-sensitivity fission chamber (FC1), a low-sensitivity fission chamber (FC2), and a high-compensated gamma-background Boron ionization chamber (CIC). As usual, these chambers are dedicated to the source, intermediate, and power ranges, respectively, of a nuclear reactor. In the configuration for the existing instrumentation system of the 500 kW DNRR, as shown in

Figure 1, however, only two chambers (FC1 and CIC) are used, where the FC1 combined with a pulse amplifier working in the pulse mode is dedicated to the starting range of  $3 \times 10^{-7}$ % to  $1.0 \times 10^{-1}$ % Pnom (Pnom = 500 kW), corresponding to frequencies of about  $0.7 \times 10^{-1}$  Hz to 25 kHz, whereas the CIC combined with a current-to-frequency converter working in the current mode is dedicated to the working range of  $1.0 \times 10^{-3}$ % to  $1.2 \times 10^{2}$ % Pnom, which corresponds to frequencies of about 0.4 Hz to 40 kHz [10].

The reactor control and protection system uses seven control rods positioned symmetrically in the reactor core, consisting of two protection rods (PR), four shim rods (SR), and one automatic regulating rod (AR). The PR and SR rods are made of boron carbide and may operate at a maximum speed of 3.4 mm/s. The AR rod is made of stainless steel and may operate at a maximum speed of 20 mm/s. Each rod hangs from a flexible cable connected to its own electric motor-drive. The PR and SR rods can be fully inserted into the core in less than one second via free drop under the influence of gravity to stop the chain reaction. The absorption length of each rod is 650 mm, which is sufficient to completely cover the active height of the reactor core. Based on the unbalance voltage generated by the BNO-102R1 unit or the FPGA-based controller, the automatic power stabilization of the reactor at the preset levels is performed by the AR rod combined with the magnetic amplifier named UVAR-19 and the 110 V motor-drive. The input signals of UVAR-19 amplifier are the unbalance voltage from the controller unit with a value from zero to 5 V for moving the AR rod up or down [11, 12].

Figure 1 shows the connection block scheme of the BNO-102R1 and the FPGA-based controller units in combination with the reactor instrumentation channel for reactivity monitoring and power control. The BNO-102R1 unit consists of the frequency signal receipt module PChC-24R1, the microprocessor-based data acquisition and processing module PNO-121R5, the analog output module PVK-97R1, the module for display and setting initial parameters PKC-162R, and the power supply module PNN-359R. The software of the BNO-102R1 unit has neither standard basis system of input/output nor a dialogue operational system and is developed in the C language. Monitoring of the reactor reactivity by the BNO-102R1 unit is performed by a six-group model of the nuclear reactor, and this unit can measure the reactivity in the range from -15.200 pcm to 760 pcm [10].

The new controller unit was developed using the Artix-7based FPGA model, which consists of XC7A100T- FGG676ABX1842 with a working frequency of 5 MHz, a DDR3 RAM MT41J64M16JT, a MT25QL128 SPI flash for configuration, and  $2 \times 64$  I/O circuits for end-users. Other functional input and output circuits, such as the frequency signal receipt, the analog output, the display and setting initial parameters, and the power supply, were designed to adapt for the specific features of the DNRR instrumentation. Besides, the controller unit has also used the fission chamber FC1 and the CIC of the DNRR instrumentation system to obtain the neutron flux signals in the starting and working ranges, respectively, for determination of the reactor power, period, and reactivity.

#### 3. Theoretical Considerations and Configuration for FPGA Circuits' Method

3.1. *Theoretical Considerations*. The algorithms used for reactivity calculations in the FPGA-based controller unit follow the reactor point-kinetics equations, as defined in the following equations:

$$\frac{\mathrm{d}P(t)}{\mathrm{d}t} = \frac{\rho(t) - \beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_i C_i(t), \qquad (1)$$

$$\frac{\mathrm{d}C_{i}(t)}{\mathrm{d}t} = \frac{\beta_{i}}{\Lambda}P(t) - \lambda_{i}C_{i}(t), \qquad (2)$$

where P(t) is the reactor power at time t,  $\rho(t) = [k(t) - 1]/k(t)$  is the reactor reactivity at time t,  $C_i(t)$  is the concentration of the *i*-th group delayed neutron precursors,  $\lambda_i$  is the decay constant of the *i*-th group,  $\beta_i$  is the fraction of the delayed neutron for the *i*-th group,  $\beta$  is the total delayed neutron fraction, and  $\Lambda = l/k$  is the mean neutron generation time of delayed neutron precursors. Note that a neutron source was ignored in equation (1).

The set of coupled differential equations (1) and (2) can be reduced to a single integrodifferential equation for P(t). In consideration of the delayed neutron kernel, one can get the following equation [6, 8, 13]:

$$\rho_n = \frac{\beta_{eff}}{1 + l\tau} + \frac{l\tau}{1 + l\tau} - \frac{1}{P_m(1 + l\tau)} \sum_{i=1}^6 \lambda_i \beta_i S_{im}.$$
 (3)

Equation (3) is used to develop the algorithm for the reactivity calculation of the designed reactivity meter module, where

$$\tau = \frac{P_m - P_{m-1}}{P_m \Delta t},\tag{4}$$

$$S_{im} = S_{im-1}e^{-\lambda_i\Delta t} + \frac{1}{\lambda_i}\left(1 - e^{-\lambda_i\Delta t}\right)\left[P_{m-1} - \frac{P_m - P_{m-1}}{\lambda_i\Delta t}\right] + \frac{P_m - P_{m-1}}{\lambda_i},\tag{5}$$

FIGURE 1: Connection block scheme of the FPGA-based controller combined with the measurement channel of the DNRR control system.

where  $P_m = P(t)$  is current power of the reactor,  $P_{m-1} = P(t - \Delta t)$  is history of reactor power,  $\Delta t$  is the sampling rate (in milliseconds),  $\beta_{eff}$  is the delayed neutron fraction of DNRR that equals  $7.551 \times 10^{-3}$ , as shown in Table 1, and  $S_{im}$  is the parameter related to the reactor power history for the *i*-th group of delayed neutron precursors, as described in equation (5).

The initial value  $S_{i0}$  which is the mean power level of the reactor at a critical state is given by

$$S_{i0} = \frac{P_0}{\lambda_i}.$$
 (6)

An initial reactivity is equal to zero. The kinetic parameters l,  $\lambda_i$ ,  $\beta_{eff}$ , and  $\beta_i$  of the DNRR are defined in Table 1 [14].

The reactivity of the DNRR is performed by a six-group model of nuclear reactors and estimated by measured reactor power data. The reactor power always fluctuates around a mean level, so the moving average in DSP circuits is shown in equation (7), which is used to filter out noise. When calculating sequential values, a new value comes into the sum, and the oldest value moves out; n is the coefficient or window of a filter [15, 16].

$$\overline{P}_{\rm SM} = \overline{P}_{\rm SM, pre} + \frac{1}{n} \left( P_M - P_{M-n} \right), \tag{7}$$

where  $\overline{P}_{SM}$  is the average value,  $\overline{P}_{SM,pre}$  is the previous average,  $P_M$  is the new sample,  $P_{M-n}$  is the *n*-th old sample, and *n* is a window of a simple moving average filter.

The reactor power level is proportional to the reactor neutron flux; therefore, the output frequencies from the pulse amplifier and the current-to-frequency converter are proportional to the reactor power levels. By the design of the DNRR's control system, the relationship between the reactor power at the starting range (PSR) and the output frequency of the pulse amplifier (FSR) is calculated by the function of PSR = KSR × FSR × 10<sup>-6</sup>, where coefficient KSR can be corrected between 4.0 and 4.05. The relationship between the reactor power at the working range (PWR) and the output frequency of the converter (FWR) is calculated by the function of PWR = KWR × FWR × 10<sup>-3</sup>, where coefficient KSR can be corrected between 2.25 and 2.30 [11].

The reactor period is calculated by the FPGA-based controller unit according to the following equations:

$$T_{\rm sr} = \frac{F {\rm sr}_m}{F s r_m - F s r_{m-1}} \times \Delta t, \qquad (8)$$

$$T_{\rm wr} = \frac{F {\rm wr}_m}{F {\rm wr}_m - F {\rm wr}_{m-1}} \times \Delta t, \qquad (9)$$

where  $T_{sr} = T_{sr}(t)$ ,  $Frs_m$ , and  $Fsr_{m-1}$  are reactor period, current frequency, and history of frequency, respectively, in the starting range;  $T_{wr} = T_{wr}(t)$ , Fwsm, and  $Fwr_{m-1}$  are reactor period, current frequency, and history of frequency, respectively, in the working range;  $\Delta t$  is the sampling rate.

The function of automatically keeping the reactor power at preset levels can be performed in a range from  $2 \times 10^{-1}$ % to  $1 \times 10^{2}$ % Pnom. The unbalance voltage is calculated by the controller unit and sent to the magnetic amplifier UVAR-19 combined with the 110-VDC motor-drive to control the AR moving up or down. For the ASUZ-14R control and protection system of the DNRR practically, the unbalance voltage U is calculated by the following equation as used in [11]:

$$Prel = \frac{(Pcur - Pset)}{Pset},$$
 (10)

where Pset is the preset power level and Pcur is the current power of the reactor.

When Prel < 0 then  $U = -(|Prel| \times 100 - B) \times K^-$ , When Prel > 0 then  $U = (|Prel| \times 100 - B) \times K^+$ , (11) If  $(|Prel| \times 100) < B, U = 0$ ,

where B = 0.2 is the UVAR-19's sensitivity voltage and K+ and K-, the amplifier coefficients, are 1.3. If considering B is very small and omitted, the equation for calculating U is simplified as follows:

$$U = |Prel| \times 130. \tag{12}$$

The unbalance voltage is in the range of  $-5 V \le U \le +5 V$ . However, because there are 2 inputs *Uup* and *Udown* in the UVAR-19 unit which are positive voltages in the range of 0 V < U < +5 V, they should be processed:



Family, <i>i</i>	Decay constant, $\lambda_i$ (s <sup>-1</sup> )	Relative yield, $a_i = \beta_i / \beta$	Effective yield, $\beta_i$ 2.648 $E$ – 04*
1	1.334E - 02	3.507E - 02	
2	3.273E - 02	1.804E - 01	1.363E - 03
3	1.208E - 01	1.742E - 01	1.315E - 03
4	3.030E - 01	3.843E - 01	2.902E - 03
5	8.503E - 01	1.594E - 01	1.204E - 03
6	2.856E + 00	6.666E - 02	5.033E - 04
Total delayed neutro	7.551E - 03		
Prompt neutron life	8.925E - 05		

\*Read as  $2.648 \times 10^{-4}$ .

$$U \text{down} = U \text{ and } U \text{up} = 0, \quad \text{if } U > 0,$$
  

$$U \text{up} = |U| \text{ and } U \text{down} = 0 \quad \text{if } U < 0.$$
(13)

From equations (8) and (9), we can see that the reactor period does not take part in the power sustaining function. It means the reactor is in a steady-state operation when the automatic power stabilization function was executed.

3.2. Configuration for FPGA Circuits. For reactivity monitoring and automatic regulation of the reactor power, the FPGA-based controller unit performing the reactor power, period, and reactivity calculations by the principle block scheme is shown in Figure 2.

Figure 3 depicts the principle diagram of the developed controller for the reactivity monitoring function. The FPGA board consists of two main parts separated by an interface unit. The hardware part is configurated in the FPGA circuits to conduct two counter-based sampling units and three units, each one for power, period, and reactivity calculation separately. The software part is the microcontroller-based 32-bit MicroBlaze Xilinx with a 50-MHz on-board clock and 128 kbyte RAM.

Functions of each unit in the principle diagram of Figure 3 are described, with two high-speed 32-bit counters for sampling signals from the pulse amplifier and the current-to-frequency converter. In the reactivity calculation unit zoomed in, the filters are used to filter sampled pulses by the moving average technique.  $S_{1m}$  and  $S_{6m}$  are the reactor power history for six groups of delayed neutron precursors.

The output frequencies from the pulse amplifier of the starting range ( $F_{SR}$ ) and from the current-to-frequency converter of the working range ( $F_{WR}$ ) are sampled and filtered by hardware circuits on the Artix-7 FPGA, in which the current reactor power ( $P_m$ ) and the reactor power history ( $P_{m-1}$ ) are determined.  $S_{im}$  ( $S_{1m}$ , ...,  $S_{6m}$ ) and  $S_0$  values are also calculated by hardware circuits using equations (5) and (6), respectively. The embedded MicroBlaze with developed firmware calculates the reactor reactivity using equation (3) and sends the calculated values to the on-board display LCD and the PC for recording every 100 ms. The on-board keypad is used to set the initial parameters.

Figure 4 details the flowchart of the reactivity calculation process in the FPGA hardware part, which is described in the zoomed reactivity calculation unit shown in Figure 3. Figure 5 details the flowchart performed by software in the embedded MicroBlaze of the Artix-7 FPGA for receiving the calculated values of the reactor power, period, and reactivity, and unbalance voltage from the hardware part and then sending them to the LCD and PC.

#### 4. Experimental Results and Discussion

4.1. Testing in the Laboratory. In the laboratory, the reactivity measurement function of the developed controller was tested in parallel with the imported BNO-102R1 unit for parameter adjustment, as shown in Figure 6. In that case, the obtained measurement data from the BNO-102R1 unit were assumed to be the calibration data in order to adjust the parameters of the developed controller to get the same result. Main parameters that needed to be adjusted were the filter parameters, the sampling time, the time required to send data to the computer, the synchronization time between data obtained from the BNO-102R1 unit and those obtained from the developed module to determine the response time, and the curve slope of reactivity values relative to the change of the power value.

The accuracy of the reactivity measurements was checked based on the stable period by using the simulated signals from the PGT-17 simulator module at a positive period of 80 s, as depicted in Figure 7. This simulator operated as a single-channel frequency generator, allowing simulation of the reactor period signal, i.e., the frequency of the exponential changed according to the following equation:

$$F_t = F_0 \times e^{t/T},\tag{14}$$

where  $F_0$  is the initial frequency in Hz,  $F_t$  is the frequency at time *t*, and *T* is the period value.

The PGT-17 pulse-generated simulator module can also simulate the reactor power signal. This module was designed by the SNIIP Systematom Co. Ltd., for testing and calibration of the functional modules and units of the DNRR control and protection system.

The experiments were performed in the power range up to  $5.0 \times 10^{-1}$ % Pnom for about 11,000 s, which covers the full starting range and a part of the working range. The obtained results show that the reactivity reached about 55.4 pcm and 56.7 pcm by the PGA-based controller and the BNO-102R1 unit, respectively; the power reached  $5.0 \times 10^{-1}$ % Pnom after



FIGURE 2: Principle block scheme for calculation of the reactor power, period, and reactivity by the FPGA-based controller.



FIGURE 3: Principle diagram of the FPGA-based controller for reactivity monitoring function.

about 8,900 s; the reactivity reached zero after about 1,500 s. The relative discrepancy of the reactivity measurement values between the BNO-102R1 unit and the PGA-based controller is less than 10%.

4.2. Experiments for Reactivity Measurement at the Reactor. The experiments were conducted based on the block scheme shown in Figure 1. The power and reactivity of the DNRR were monitored from subcritical to full power of 100% Pnom



FIGURE 4: Flowchart of reactivity calculation by hardware in Artix-7 FPGA.



FIGURE 5: Flowchart of data reading and sending by software in the embedded MicroBlaze.



FIGURE 6: Scheme for testing of the FPGA-based controller in the laboratory.

by the FPGA-based controller and the BNO-102R1 unit, as depicted in Figure 8.

The experimental results in Figure 8 show that the reactivity values obtained by the developed controller and those obtained by the commercial unit are equivalent with the relative discrepancy of about 5%. Reactor startup procedures from subcritical to nominal power of 100% Pnom were performed with short stabilization at three power levels of  $5.0 \times 10^{-1}$ %,  $5.0 \times 10^{1}$ %, and  $8.0 \times 10^{1}$ % Pnom for time durations of 300 s, 700 s, and 540 s, respectively, with the total time of each experiment about 3700 s. The reactor working range is from  $1.0 \times 10^{-3}$ % to  $1.2 \times 10^{2}$ % Pnom, so the first stabilization power level of  $5.0 \times 10^{-1}$ % Pnom, which is corresponding to a frequency of about 220 Hz, was controlled by the working range. This frequency is high enough for automatic stabilization of the reactor power. As a result, the reactivity was clearly monitored by both the BNO-102R1 unit and the FPGA-based controller, whereas in a power range below 0.5% Pnom, especially below  $1.0 \times 10^{-1}$ % Pnom, the subcritical reactivity of the reactor in the starting range was unstable due to low neutron flux with high fluctuations, so strong filter parameters were needed. As a result, the response in the starting range was slower than that in the working range with higher neutron flux and lower fluctuations, and weaker filter parameters were needed. In addition, there were wide overlaps between the starting and working ranges because only two chambers, FC1 and CIC, respectively, were used instead of the three chambers, FC1, FC2, and CIC that correspond to the source range, intermediate range, and power range, respectively.

The experiment for monitoring the positive reactivity in the starting range was conducted. When the power level was stable at  $4 \times 10^{-3}$ % Pnom (equivalent to 20 W) and the reactor period was in infinity, which was supposed to be 999 s, the positive reactivity insertion by withdrawing the AR rod of 57 mm from the position 367 mm to 310 mm was performed. As illustrated in Figures 9(a) and 9(b), the effective reactivity values of a 57 mm upward movement of the AR rod were measured by the BNO-102R1 unit and the FPGAbased controller, respectively.

The experiment for monitoring the positive reactivity in the working range was also conducted with the same procedures done with the starting range. When the initial power level was set at  $5 \times 10^{-1}$ % Pnom (equivalent to 2,5 kW), the positive reactivity insertion by withdrawing the AR rod of 59 mm was from position 369 mm to 310 mm. The effective reactivity values of a 59 mm upward movement of the AR rod were measured by the BNO-102R1 unit and the FPGAbased controller, and the results are illustrated in Figures 10(a) and 10(b), respectively.

Table 2 summaries the obtained results of both experiments for measuring the positive reactivity values in the starting and working ranges when withdrawing the AR rod.

In case of the starting range, the results demonstrate that when the AR rod moves from 367 mm to 310 mm, the reactor power continues to increase to  $6 \times 10^{-3}$ % (equivalent to 30 W) due to the hysteresis effect [11, 15]. The reactivity values measured by the BNO-102R1 unit and FPGA-based controller are 53.1 pcm and 52.7 pcm, respectively, whereas the calculated reactivity value in accordance with the



FIGURE 7: Test results obtained using the PGT-17R simulator with the positive period of 80 s.



FIGURE 8: Obtained results using real signals from the DNRR during startup by (a) BNO-102R1 unit and (b) FPGA-based controller.

operation logbook in December 2011 is 53.4 pcm. The relative deviations between experimental data and the calculated result are less than 5%, which is below the ASUZ-14R system's permitted relative deviation limit of 5%. Furthermore, at the low power level of 20 W in the starting range, it is less susceptible of temperature effects of the reactor, and the frequency is sufficient and appropriate for selection as a power level to measure the effective reactivity of the AR rod.

In case of the working range, the results indicate that when the AR rod moves from 369 mm to 310 mm, the reactor power continuously increases to 2.35% (equivalent to 11.75 kW). The reactivity values measured by the BNO-102R1 unit and FPGA-based controller are 72.1 pcm and

71.5 pcm, respectively. The relative deviation between the measured reactivity values of two units is less than 10%. However, when considering the measured reactivity values by the BNO-102R1 unit and FPGA-based controller for both the starting and working ranges, it shows that the reactivity values in the working range were higher than those in the starting range, with the relative discrepancy of around 26%. The reason for the difference is that in the working range, there are other effects such as temperature effects of the reactor, the different power measuring scale, the different positions of four SRs and the AR rod, the different properties (materials used, sensitivity, and working modes, as detailed in Section 2 mentioned above) of the neutron detector FC1 for the starting range and CIC for the working range.



FIGURE 9: Correlation between the measured reactivity and reactor power in the starting range by (a) BNO-102R1 unit and (b) FPGA-based controller.



FIGURE 10: Correlation between the measured reactivity and reactor power in the working range by (a) BNO-102R1 unit and (b) FPGAbased controller.

TABLE 2: Maximum value of the measured reactivity when withdrawing the AR rod from 367 mm to 310 mm.

Reactor power range	Power level changed (% Pnom)	AR rod position (mm)	Reactivity value in logbook (pcm)	Reactivity by BNO-102R1 (pcm)	Reactivity by FPGA-controller (pcm)
Starting	$4 \times 10^{-3}$ to $6 \times 10^{-3}$	367 to 310	$53.4\pm0.05\%$	$53.1 \pm 5\%$	$52.7 \pm 5\%$
Working	$5 \times 10^{-1}$ to 2.35	369 to 310	N/A	$72.1 \pm 5\%$	$71.5 \pm 5\%$

Negative reactivity was monitored based on neutron absorption due to shutdown of the reactor immediately by an emergency signal. As can be seen in Figure 11, the reactor power was automatically maintained at a full power level of 100% Pnom. After around 2,000 seconds, the reactor was shutdown by the emergency button from the control console. As a result, two safety and four shim rods dropped into the reactor core's brake zone at a position of roughly 600 mm, and the reactor control system then automatically directed all rods to descend to the bottom position of 650 mm [11]. The reactivity was simultaneously monitored by both BNO-102R1 and the FPGA-based controller units.

The experiment yielded a negative reactivity of about -7,222 pcm by the BNO-102R1 unit and about -6,910 pcm by the FPGA-based controller at about 3,000 s, and the maximum relative discrepancy in the reactivity between the BNO-102R1 unit and the FPGA-based controller was estimated at about 5%. Figure 11 demonstrates how, as the reactivity approached zero, the reactor power dropped from 100% to  $6.0 \times 10^{-3}$ % Pnom at roughly 8,700 s.



FIGURE 11: Test results with the assumed emergency shutdown condition.



FIGURE 12: Graph of (a) unbalance voltage values of BNO-102R1 unit and FPGA controller and (b) fluctuation of reactor power maintained by FPGA controller.

The reactivity measurement test by the designed controller using real signals from the DNRR and data obtained by monitoring the reactivity was considered complete when the reactor attained full power and shutdown conditions were met.

4.3. Experiments for Automatic Reactor Power Stabilization at the Reactor. These experiments were conducted following the block scheme shown in Figure 1. According to the ASUZ-14R design, the function of automatic power stabilization at a preset level can be performed in the range from  $2 \times 10^{-1}$  to  $1 \times 10^{2}$ % Pnom with the allowable deviation less

than  $\pm 1\%$ . The FPGA-based controller unit calculates and generates the unbalance voltage value and sends it to the amplifier UVAR-19 to control the motor-drive for the movement of the AR rod up or down.

Figure 12(a) depicts the unbalance voltage values calculated by the BNO-102R1 unit and the FPGA-based controller in an automaintaining mode at full power level of 100% Pnom. The measurement results show that the difference of output unbalance voltage between the two units is less than  $\pm 0.5\%$  with the absolute value of  $\pm 1$  V. As a result, the relative deviation between the current power and the preset power in Figure 12(b) is less than  $\pm 1\%$  that meets the technical specification of the DNRR control system ASUZ-14R [10].

The obtained experiment results from Figure 12 show that the FPGA-based controller unit performs well the function of reactor power stabilization at the full power level.

#### 5. Conclusions

The FPGA-based digital controller unit for reactivity monitoring and automatic power control for the DNRR was designed and developed. The controller was evaluated and calibrated in the laboratory using the BNO-102R1 unit in the starting range and up to  $5.0 \times 10^{-1}$ % Pnom of the working range. The controller was tested at the reactor to monitor the reactivity for both the starting and working ranges up to 100% Pnom during normal operation and in assumed emergency conditions. The positive reactivity measurements were conducted by withdrawing the AR rod during the reactor operated at the starting and working ranges, and the negative reactivity measurements were conducted by emergency shutdown of the reactor at the full power level. The experimental reactivity data obtained by the controller unit were compared with those obtained by the BNO-102R1 unit, as well as with the calculated results. The relative discrepancy between measured data from two units is less than 10% and between the measured data from the FPGA-based controller unit and calculated values are less than 5%. When a reactor's power is stabilized automatically at the full power level, the fluctuation amplitude is less than 1%, which meets the specifications of the ASUZ-14R supplier.

The experimental results also show that the FPGA-based controller has a good response time, a wide-range of reactivity monitoring, and less noise at low power levels. The developed controller's response time is fast enough to allow for the monitoring of reactor power excursion and safetyrelated reactivity. Also, the experiments show that raising frequency sampling of the developed controller can lower its relative error.

The obtained experimental results and technical characteristics of the FPGA-based controller demonstrate that it can be used for carrying out a variety of training and operational experiments on the DNRR.

#### **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

### **Conflicts of Interest**

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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