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# Design of a FPGA-based digital reactivity meter for Dalat Nuclear Research Reactor

Vo Van Tai, Nguyen Van Kien, Nguyen Nhi Dien, Le Van Diep

*Dalat Nuclear Research Institute*
*01 Nguyen Tu Luc, Dalat city, Vietnam*
*Email: taivnchn@gmail.com*

**Abstract:** This paper describes a digital reactivity meter module based on solving the inverse kinetics equations and the time behavior of the output pulse frequency from the amplifier, which is proportional to the power of the Dalat Nuclear Research Reactor (DNRR). The designed reactivity meter, which operates online with real-time calculation, was tested using the PGT-17R simulator signals in comparison with the existing imported module PNO-121R5 of the DNRR's control and protection system. The experimental results show that the technical characteristics and functions of the two modules are equivalent.

**Keywords:** *Digital reactitvity meter, reactor power, reactor period, FPGA.*

## I. INTRODUCTION

Signals of reactor power (P), reactor period (T) and reactor reactivity (ρ) are important parameters that are directly related to the safety operation of a nuclear reactor. The digital reactivity meters have been designed for a variaty of applications including determination of Xenon worth, reactor control rod worth and so forth. A method for determining the stable or asymptotic period to calculate the reactivity from the inhour equation is good for positive periods but not for the negative periods due to the longest delayed neutron decay and giving very low sensitivity to negative reactivity [1]. The measured reactivity using the kinetic technique is good agreement for both the positive and the negative periods. The reactivity of a nuclear reactor is continuously monitored by analyzing the time behavior of the reactor power level using point kinetics equations. Nowadays, fast integrated FPGA-based devices are widely used in nuclear physics experiments and nuclear engineering for measurement, data storage, and acquisition systems, such as radiation measurements with high resolution X-ray spectroscopy with pulse height analyzer [2] and so on.

The output frequency of a pulse amplifier is proportional to the reactor power level because the reactor power level is proportional to the reactor neutron flux. Based on the design of the DNRR's digital control system, the relationship between reactor power at start range ($P_{SR}$) and pulse amplifier output frequency can be calculated as [3]:

$$P_{SR} = K_{SR} \times F_{SR} \times 10^{-6} \qquad (1)$$

Where, $P_{SR}$ is the reactor power at the start range, $K_{SR}$ is a coefficient, and $F_{SR}$ is the output frequency from the pulse amplifier, which is connected to the fission neutron chamber for monitoring in the range from $10^{-6}$ to $10^{-1}$ % Pnominal (Pnominal = 500 kWt).

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This paper presents the designed of FPGA-based digital reactivity meter using the Xilinx FPGA Artix-7 with embedded microcontroller to sample and filter the output pulses from the amplifier, calculate the reactivity and send its value to personal computer for recording. This designed module was tested and compared in reactivity measuring to the imported reactivity meter module PNO-121R5 by using the simulated signals from the simulator module PGT-17 that were designed by the Russian SNIIP Systematom Co. Ltd.

## II. ALGORITHM OF REACTIVITY CALCULATION

Reactivity is an important parameter that indicates a reactor's power fluctuation from critical status, and is used to calculate whether the neutron density in a reactor will remain constant or change. The reactor is in critical state or operates at the steady power level when $k_{eff} = 1.0$. If $k_{eff} < 1.0$, the reactor is subcritical or operates at the power level is decreasing. If $k_{eff} > 1.0$, the reactor is supercritical or the power level is increasing. Equation (2) [1, 4] describes reactivity as follows:

$$\rho = (k_{eff} - 1) / k_{eff} \qquad (2)$$

Where, $\rho$ is reactivity and $k_{eff}$ is effective multiplication factor of the reactor.

The time behavior of the reactor power level in a nuclear reactor can be expressed by the point kinetics equations shown in equations (3) and (4) [1, 4, 5] as:

$$\frac{dP(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} P(t) + \sum_{i=1}^{6} \lambda_i C_i(t) \qquad (3)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} P(t) - \lambda_i C_i(t) \; for \; i = 1,2,\ldots,6. \quad (4)$$

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, and $\Lambda = l/k$ is the mean neutron generation time. It should be noted that a neutron source was not considered in equation (3).

We have equation (5) by solving equations (3) and (4). (5).

The equation (5) is used to create an algorithm for calculating the reactivity of the designed digital reactivity meter module for the DNRR.

$$\rho_n = \frac{\beta_{eff}}{1+l\tau} + \frac{l\tau}{1+l\tau} - \frac{1}{P_m(1+l\tau)} \sum_{i=1}^{6} \lambda_i \beta_i S_{im} \qquad (5)$$

Where,

$$\tau = \frac{P_m - P_{m-1}}{P_m \Delta t} \qquad (6)$$

$$S_{im} = S_{im-1} e^{-\lambda_i \Delta t} + \frac{1}{\lambda_i}\left(1 - e^{-\lambda_i \Delta t}\right)\left[P_{m-1} - \frac{P_m - P_{m-1}}{\lambda_i \Delta t}\right] + \frac{P_m - P_{m-1}}{\lambda_i} \qquad (7)$$

Where, $P_m = P(t)$, $P_{m-1} = P(t-\Delta t)$, $\Delta t$ is the sampling rate (in seconds), $\beta_{eff}$ is the delayed neutron fraction of DNRR = $7.464.10^{-3}$, and $S_{im}$ is the reactor power history.

The initial value $S_{i0}$ that is the mean power level of the reactor at critical state, is given by equation (8):

$$S_{i0} = \frac{P_0}{\lambda_i} \qquad (8)$$

An initial reactivity is equal zero. Kinetic parameters $l, \lambda_i$, $\beta_{eff}$ and $\beta_i$ of the DNRR are shown in Table I.

**Table I.** Kinetic parameters of the DNRR [6]

| Group | Effective yield $\beta_i$ | % of delayed neutrons $a_i=\beta_i/\beta$ | Decay constant $\lambda_i$ |
|---|---|---|---|
| 1 | 2.626E-04 | 3.518 | 1.334E-02 |
| 2 | 1.351E-03 | 18.10 | 3.273E-02 |
| 3 | 1.301E-03 | 17.44 | 1.208E-01 |
| 4 | 2.867E-03 | 38.41 | 3.028E-01 |
| 5 | 1.186E-03 | 15.90 | 8.499E-01 |
| 6 | 4.959E-04 | 6.644 | 2.854E+00 |
| $\beta_{eff}$ | 7.464E-03 | | |
| $l$ | 8.044E-05 | | |

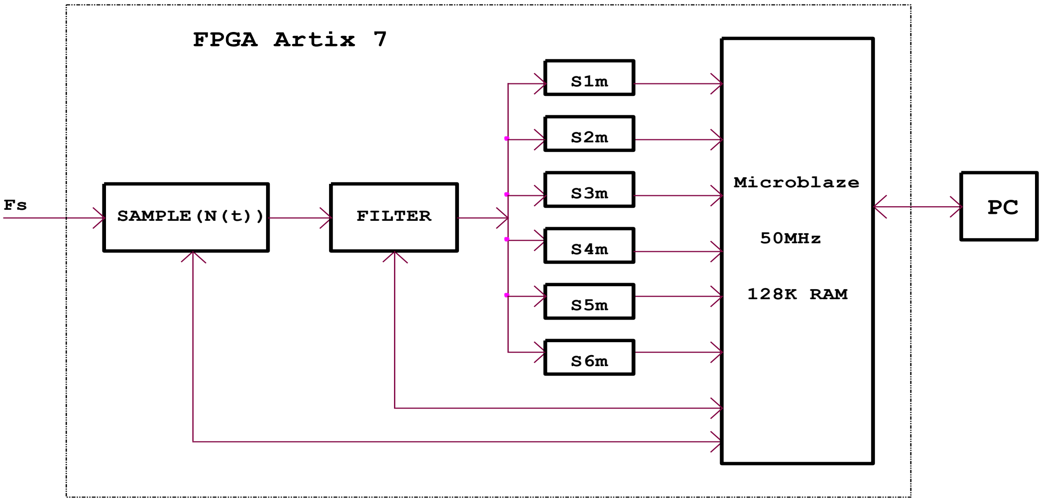

**Fig. 1.** The designed digital reactivity meter module's block diagram

The functions of each unit in Fig. 1 are summarized as follow: Fs is the output pulse frequency from the pulse amplifier, which is proportional to the reactor power; SAMPLE (N(t)) is for sampling pulse frequency Fs; FILTER is for filtering sampled pulses by using moving average technique; $S_{1m}$ to $S_{6m}$ are reactor power history for six groups of delayed neutrons; Microblaze is a microcontroller with 50-MHz on-board clock and 128 kbytes RAM for reactivity calculation; and PC is a computer for recording reactivity.

Fig. 2 depicts the flow chart of the designed digital reactivity meter. The output frequency from a pulse amplifier is sampled and filtered by hardware on FPGA Artix-7. In which, the current reactor powers of $P_m$ and $P_{m-1}$ are determinated as the reactor power history, and $S_0$ and $S_{im}$ ($S_{1m}$ .... $S_{6m}$) are also calculated using Eqs. (8) and (7), respectively. The Microblaze uses Eq. (5) to calculate reactor reactivity and sends its results to the on-board display LCD and the PC for recording.

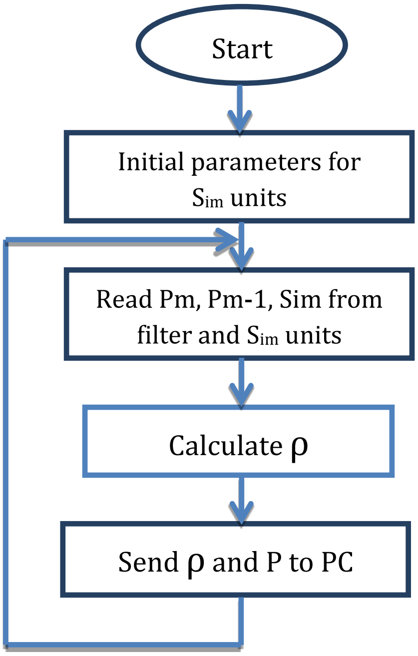

**Fig. 2.** Flow chart of FPGA Artix-7 reactivity calculation with embedded Microblaze

## III. EXPERIMENTS, RESULTS AND DISCUSSION

The designed reactivity meter module was tested using the pulse-generated simulator PGT-17R to compare with the imported PNO-121R5 module, as shown in Fig. 3.

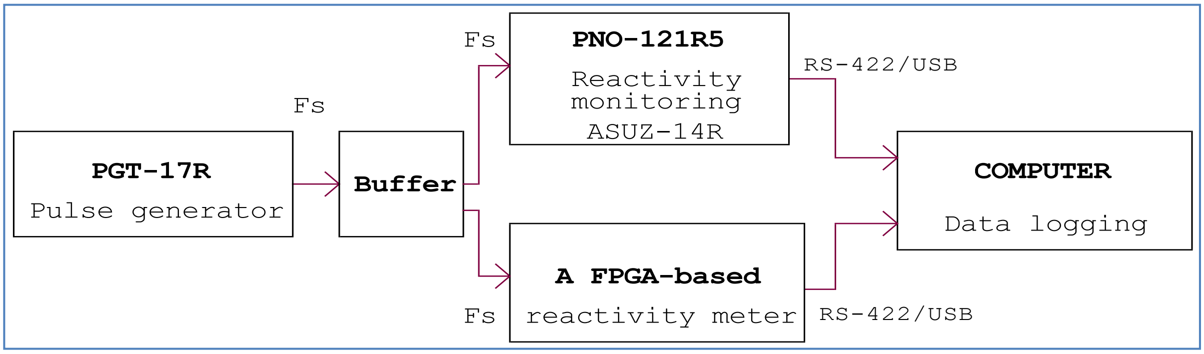

**Fig. 3.** Testing block diagram for comparing results between designed and PNO-121R5 modules

**Table II.** Results of three experiments on the DNRR with the reactor period of 120s

| T = 120s | | |
|---|---|---|
| $\rho/\beta_{eff}$ calculated by using inverse hour [7] | $\rho/\beta_{eff}$ by module PNO-121R5 | $\rho/\beta_{eff}$ by FPGA-based module using Eq. (5) |
| 0.0777 (\$) | 0.0766 (\$) | 0.0779 (\$) |

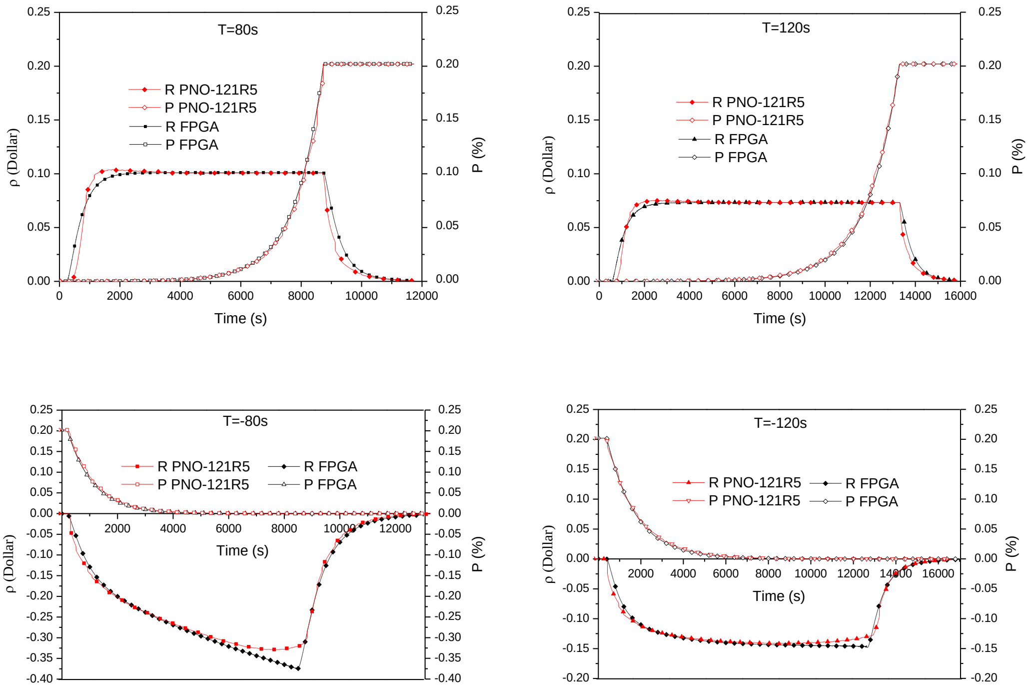

**Fig. 4.** PGT-17R pulse-generated simulator testing results

Figure 4 depicts the measured reactivity as the reactor power changes from $4.10^{-5}$ % to $2.10^{-1}$% at T = 80s, -80s, 120s and -120s. The results obtained by the designed module and the PNO-121R5 module are equivalent with 10% difference. Table 2 shows that some experimental results are equivalent.

## IV. CONCLUSION

A digital reactivity meter module was designed and developed. The output pulses of the amplifier, which are proportional to the reactor power, are sampled and filtered by hardware in the FPGA. The tasks for solving the point reactor kinetics equations and calculating reactivity are carried out in parallel on the FPGA hardware and embedded Microblaze. The experimental results of measured reactivity by the FPGA-based module versus PNO-121R5 show that the designed reactivity meter module can be used to measure and monitor the reactivity of the DNRR.

The obtained results are only the first step toward future experiments to measure the effective reactivity of control rods including compensation rods and automatic regulation rod of at the DNRR using the rod drop method.

## V. ACKNOWLEDGEMENTS

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