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Development of a Signal Generator for Verification of Ex-core Neutron Flux Monitoring System in Digitalized Nuclear Power Plants

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1. Introduction

Within nuclear power plants various Instrumentation and Control (I&C) systems are in place to ensure safe operations. Globally the digitalization of I&C systems is being pursued to enhance the safety of nuclear power plants[1]. Digital systems provide enhanced reliability and safety for nuclear reactors compared to analog signals. In the event of an accident in a digitized nuclear power plant, monitoring systems automatically detect changes in various parameters such as reactor pressure, temperature, and power output[2,3]. However, the digitalization process has brought forth a range of issues concerning risk analysis. The digitalized I&C systems must prove their ability to operate accurately during normal conditions and swiftly detect hazards during accidents. Nonetheless, it is not feasible to replicate the actual reactor environment or intentionally reproduce accident scenarios. Consequently, there is a need for a signal generator that can emulate real reactor signals.

This paper addresses the process of implementing a neutron signal generator for the verification of the Ex-core Neutron Flux Monitoring System (ENFMS). ENFMS is an I&C system that predicts reactor power based on neutron signals generated proportionally to the power during fission [4]. ENFMS employs different methods to detect neutron signals for three ranges of power levels. The start-up range (SR) typically covers the lowest seven decades of power from about 10^{-10} to 10^{-4} percent power, the intermediate range (IR) covers about seven decades of power from 10^{-5} to 10^{2} percent power, and the power range (PR) covers top three decades of power from about 10^{-1} to 10^{2} percent power [5]. To demonstrate the proper functionality of ENFMS, a signal generator encompassing all operational ranges is necessary.

In addition to neutron signals, reactors emit various radiation signals such as gamma rays and alpha particles. Among these, gamma rays are significant noise in neutron signal detection. To ensure the correct operation of ENFMS, it is essential to verify its ability to effectively remove noise. Hence, the ENFMS signal generator should be capable of simulating both neutron and gamma ray signals.

This paper presents the implementation of a signal generator using Python to produce neutron and gamma ray signals across the SR, IR, and PR ranges. Additionally, a Graphical User Interface (GUI) has been developed to facilitate easy manipulation of signal input and output.

2. Signal Modeling

This section involves modeling the reactor signals detected in the Advanced Power Plant 1400(APR 1400) and analyzing the characteristics of neutron and gamma-ray signals.

2.1 Modeling Reactor Signals

During nuclear fission, various reactor signals such as neutrons, gamma rays, and alpha particles are generated within the reactor and detected by the ENFMS detector known as the fission chamber [6]. Reactor signals are detected as electrical signals in the form of tail pulses within the fission chamber and they are modeled by the following equation [4].

$$i_q(t) = I_0(e^{-t/t_d} - e^{-t/t_r}) \quad (1)$$

Where t_r is the rise time, t_d is the decay time and I_0 is the maximum amplitude. These three parameters can be adjusted to depict the characteristics of detected signals.

A fission chamber is coated a small amount of fissile material (${}^{233}_{92}U$, ${}^{235}_{92}U$, or ${}^{239}_{94}Pu$) on at the electrodes to ionize neutron signals into ionization pairs. The advantage of coating fissile material onto the electrode is that it enables more precise detection of neutron because neutron-induced fission fragments produce many more ionization pair in the chamber per interaction than another radiation. The characteristics of neutron signals and characteristics of gamma-ray signals which represent the predominant noise in fission chamber are summarized in Table 1.

	Neutron signal	Gamma-ray signal
Rise time	0ns~100ns	0ns~50ns
Decay time	100ns~950ns	100ns~350ns
Pulse width	100ns~1000ns	100ns~400ns
Mean of height	0.9524 μA	0.42 μA
Variance of height	0.0286 $(\mu A)^2$	0.0064 $(\mu A)^2$

Table 1. Characteristics of neutron and gamma-ray signal

Reactor Power P(*t*) [%]	Pulse rate *n* [*cps*]	ENFMS mode of operation		
		Start-up range	Intermediate range	Power range
10^{2}	10^{10}		O	O
10^{1}	10^{9}		O	O
10^{0}	10^{8}		O	O
10^{-1}	10^{7}		O	O
10^{-2}	10^{6}		O	
10^{-3}	10^{5}		O	
10^{-4}	10^{4}	O	O	
10^{-5}	10^{3}	O	O	
10^{-6}	10^{2}	O		
10^{-7}	10^{1}	O		
10^{-8}	10^{0}	O		
10^{-9}	10^{-1}	O		
10^{-10}	10^{-2}	O		

Table 2. Pulse rate per second according to reactor power and ENFMS mode of operation

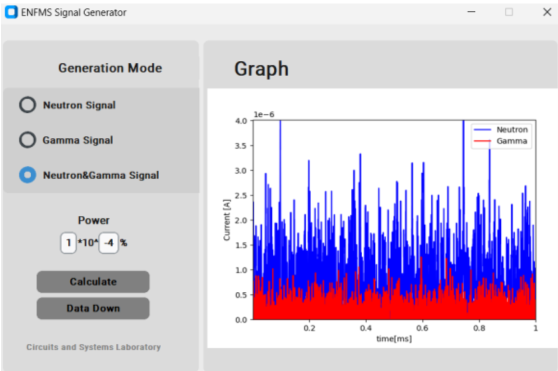

Fig. 1 GUI environment for signal generators with gamma-ray noise added to neutron signals

3. Proposed Signal Generator

3.1 Modeling Multi Signals

By randomly generating Equation (1) for a single pulse in the time domain, a multi-pulse with randomly distributed generation times can be achieved. The formula for multi-pulse signals is defined as follows:

$$I_Q(t) = \sum_n I_0 (e^{-t/t_d} - e^{-t/t_r}) \qquad (2)$$

A single neutron generates one tail pulse, and the creation of tail pulses depends on the number of interactions. The count of tail pulses generated per second is expressed as cycle per second (*cps*). Neutron flux is proportional to power hence the pulse rate (*cps*) is determined by the power. The relationship between pulse rate *n* and reactor power P(*t*) is given by equation (3) and information about the operational ranges of ENFMS is summarized in Table 2.

$$n = P(t) \times 10^8 [cps] \qquad (3)$$

3.2 Noise Signal

Gamma-rays, similar to neutrons, are detected in proportion to the reactor power and they function as noise within the operation of ENFMS. ENFMS employs operations such as pulse shaping and signal/noise discrimination to eliminate gamma ray signals[7,8,9]. Signal generator capable of simultaneously producing neutron and gamma ray signals is required to verify effective noise removal.

3.3 Graphical User Interface (GUI)

The Graphical User Interface (GUI) is a visual interface utilized interaction with computer programs or device and can display information in a more intuitive than text-based interfaces. The proposed signal generator is implemented through a GUI environment using Python. The pulse generator operating within the GUI framework presents the output signal aligned with the input signal through graphical representation upon pressing the “Calculate” button. In order to validate the ENFMS operation in an environment with noise, the Generation Mode offer three options: Neutron Signal mode, Gamma Signal mode and Neutron & Gamma Signal mode. Lastly, pressing the “Data Down” button yields output value suitable for signal analysis and provides the output data in formats such as text file, CSV file and Excel file. Fig 1 shows a signal generator in the GUI environment.

4. Result

4.1 Start-up Range

This range corresponds to the initial operation of the reactor and encompasses the lowest power levels from 10^{-10} to 10^{-4} percent of the reactor power. In this range, the pulse mode of ENFMS operation is verified[10]. The pulse mode is an operation of counting the number of pulses to calculate the neutron flux. Fig 2 shows the neutron signal output for the start-up range.

4.2 Intermediate Range

This range encompasses 7 decades from 10^{-5} to 10^{2} percent power. In the Intermediate range pulses begin to overlap making it impossible to count each neutron signal accurately [10,11]. Additionally signals are not significantly overlapped resulting in smaller signal magnitudes. In this range it is necessary to amplify and process the signals for computation and the Mean Square Voltage (MSV) mode of ENFMS operation is verified, where signals are squared and then the average is computed over time. The values obtained through the MSV mode represent the variance of neutron signals, and this variance exhibits a proportional relationship with reactor power. Fig 3 shows the neutron signal output for the intermediate range.

4.3 Power Range

This range covers 3 decades from 10^{-1} to 10^{2} percent power. In the power range, there are excessive interactions leading to significant overlap of neutron signals and neutron signals within this range exhibit magnitudes that are sufficiently large for computation. In this range the Current mode of ENFMS operation is verified where signals are averaged over [10]. The values obtained through the Current mode are proportional to reactor power. Fig 4 shows the neutron signal output for the power range.

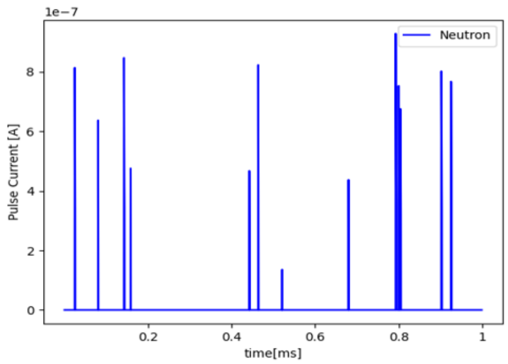

Fig. 2 Neutron signal output for the start-up range when the power is 10-6

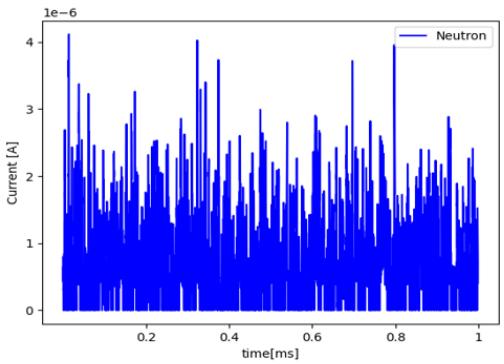

Fig. 3 Neutron signal output for the intermediate range when the power is 10^{-4}

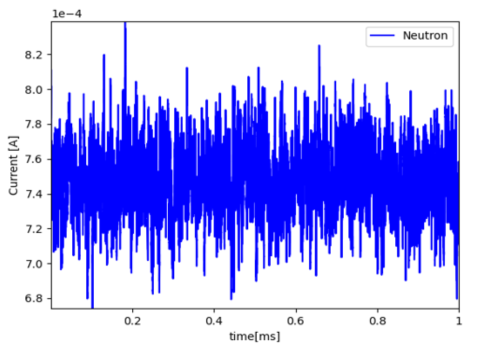

Fig. 4 Neutron signal output for the power range when the power is 10^{-1}

5. Conclusions

To verify the proper operation of the Ex-core Neutron Flux Monitoring System (ENFMS) a signal generator of producing neutron signals within the start-up range (SR), intermediate Range (IR) and power range (PR) is necessary. Additionally a signal generator of simultaneously producing neutron and gamma-ray signals is required for evaluating noise removal capability. In this paper signal generator operating in the SR, IR and PR ranges is implemented generating both neutron and gamma-ray signals depending on the generation mode. This generator is implemented as a GUI environment on Python so that users can enter reactor power and press a button to obtain an output value and view the output waveform. Utilizing the proposed signal generator in this paper easily obtain reactor signals for verification of all operations of ENFMS.

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