REACTIVITY MEASUREMENT BY NOISE TECHNIQUE AND APPLICATION TO THE DALAT REACTOR

Nguyen Minh Tuan, Tran Tri Vien, Trang Cao Su, Huynh Ton Nghiem and Le Vinh Vinh
Nuclear Research Institute, 01 Nguyen Tu Luc, Dalat

Abstract: For many years, analysis of the fluctuating signals from ion-chambers installed in a nuclear reactor has been a powerful tool for getting information about the reactor behavior, in particular the information concerning the kinetic response of the reactor. This report presents the results of reactivity measurement by noise technique at the Dalat reactor. The noise technique suitable for the Dalat reactor is auto or cross power spectral density (APSD/CPSD) analysis method. Cross power spectral density from two compensated ion-chambers (KHK-56 type) with high efficiency was measured and analyzed. The main objective of this research focus on the procedure to measure the reactivity. The values of reactivity determined by the noise technique were compared to the values determined from the experiments of control rod calibration based on the double time period method.

Keywords: *Ion-chamber (I.C), Reactivity (ρ), Transfer function H(ω), Power spectral density (PSD), Autocorrelation function, Cross-power spectral density (CPSD), Rossi-α parameter, Neutron generation time (ℓ)*

I. INTRODUCTION

Noise is a general concept referring to those random, unpredictable, and undesirable signals, or changes in signals, that mask the desired information content. It is extremely difficult or there is no way to remove it. However, in many cases, the noise reflects the nature and behavior of a physical system, which we are interested in. The main objective of noise analysis is to exploit the fluctuating signals for getting the necessary information about the system dynamics.

When a nuclear reactor operates at the steady states, the output signal measuring the power level from a neutron detector is always an unstable value and fluctuates with a small amplitude around the mean value. These fluctuations are not completely random and follows some distribution law. This law can be determined experimentally, it contains important information about the reactor kinetics. In general, the fluctuating signals are due to the fluctuations in neutron population inside the reactor core and other observable fluctuations such as fluctuation of the temperature, flow, vibration and noise in electric circuits, etc.

For the nuclear systems at zero power (power level which does not lead to any reactivity feedback mechanism becoming effective), the main sources of fluctuation in neutron population come from the random nature of the physics processes occurring in the nuclear reactor, for example fission, slowdown, diffusion and absorption processes, etc. These processes primarily follow Poisson distribution law. Due to these fluctuations occurring in a neutron multiply medium such as the reactor core that will lead to the fluctuations in neutron flux, it also means the fluctuations in measuring signals. When these fluctuations are small compared with the mean value and the core multiply coefficient of *k* is approximately equal to 1, an approximate, the nuclear reactor can be considered as a linear dynamics system. In this case, the square of transfer function module of the reactor is proportion to power spectrum density (PSD). The PSD can be determined by Fourier expansion of autocorrelation of signals obtained from a compensated ion-chamber, which is used to measure the reactor power level. From that, the reactor kinetic parameters such as Rossi-α parameter, β_{eff}/l ratio and reactivity can be determined by analyzing autocorrelation, PSD or CPSD, experimentally.

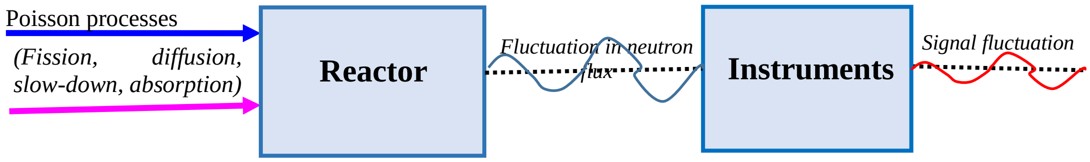

Fig 1. Model of fluctuating processes in a nuclear reactor

In this report, the theory, instruments and experiments, as well as the results of measuring and analyzing the cross power spectral density (CPSD) of signals from 2 ion-chambers placed in the Dalat reactor will be presented.

II. THEORY

Theoretical basis of noise method using CPSD functions is summarized here mainly taken from the references [3].

With assumption that: $k \approx 1$ (*k* is multiplication factor) and power level fluctuation in the reactor is small in comparison with its mean value, in this case the reactor can be considered as a linear dynamics system and the equation expressed the relationship between input and output signals of the system can be established as follows:

$$G_{yy}(\omega) = \left|H(\omega)\right|^2 \left|H_{Inst.}(\omega)\right|^2 G_{xx}(\omega) \qquad (1)$$

In which:

- $\omega = 2\pi f$: Angular frequency (rad/s)
- f : Frequency (Hz)
- $G_{xx}(\omega)$: PSD function of the input signal
- $G_{yy}(\omega)$: PSD function of the output signal
- $H(\omega)$: Transfer function of the zero power reactor
- $H_{Inst.}(\omega)$: Transfer function of the instrument

It is well known that transfer function of the zero-power reactor is given by [1]:

$$H(\omega) = \frac{n}{i\omega\left(\ell + \sum_i \left(\frac{\beta_i}{\lambda_i + i\omega}\right)\right)} \approx \frac{n}{i\omega/\ell + \beta}, \text{ when } \omega > \lambda_i \qquad (2)$$

Since the fluctuations of the reactor input signal are random, therefore $G_{xx}(\omega)$ will be considered as constant. From Eq. s (1) and (2), the CPSD of the reactor output signal can be written as follows:

$$G_{yy}(\omega) = \left|H_{Inst.}(\omega)\right|^2 \left[\frac{A}{\omega^2 + \alpha^2} + B\right] \tag{3}$$

When performing more in detail calculations, the coefficient A and B can be obtained as:

$$A = \frac{2\varepsilon^2 q^2}{\ell n}\left(\frac{\overline{\nu^2} - \overline{\nu}}{\overline{\nu}}\right) \tag{4}$$

$$B = \frac{2q^2 \varepsilon n}{\ell} \tag{5}$$

Where:

- β_i, λ_i : Abundance and decay constant of the i^{th} delay neutron group
- $\alpha = \frac{\rho - \beta_{eff}}{k\ell}$: Decay constant of prompt neutron (Rossi-α parameter)
- q: Average electric charge generated in the C.I.C when it absorbs one neutron
- n: Total number of neutron in the reactor
- ε : C.I.C neutron efficiency
- $\overline{\nu}$: Average neutron number produced in one fission
- ℓ : Life-time of prompt neutron
- k: Multiplication factor

In a similar way, referring to reference [3], when analyzing the CPSD of fluctuating signals between two different ion-chambers, the uncorrelated component in Eq. 3 (B term) will become null, only the correlated component is remained. Finally, a formula similar to Eq. 3 is found with term B=0 as follows:

$$G_{y1y2} = C\left|H_{Inst.}(\omega)\right|^2 \left|H(\omega)\right|^2 = C.\left|H_{Inst.}(\omega)\right|^2 \frac{A}{\omega^2 + \alpha^2} \quad (6)$$

Where:

- $G_{y1y2}(\omega)$: Cross power spectrum density of the signal from two ion-chambers
- C: Proportional constant

Eq. (6) is basis of the noise method, which was applied to the Dalat reactor and presented in this report. By using 2 high efficiency C.I.Cs installed near the reactor core to measure the power level fluctuation over time and by analyzing CPSD between 2 measuring signals from 2 C.I.Cs, the square module of the zero-power transfer function can be obtained. When fitting experimental data with Eq. 6, the Rossi-α parameters of the reactor will be determined, and then the parameters such as the β_{eff}/l ratio and reactivity were also determined.

III. INSTRUMENT

To carry out the measurements of CPSD, an instrumentation system, which consists of 2 independent channels of neutron measurement, was installed in the reactor. The connection schema is shown in Fig. 2 as follows:

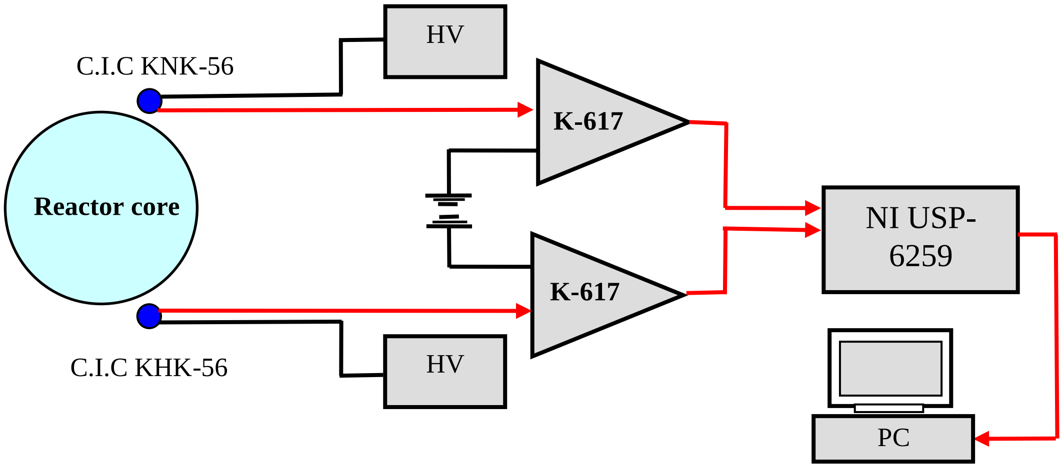

Fig. 2. Block schema of reactor noise measurement system

In which:

- C.I.C: Compensated Ion Chamber of KHK-56 (Russian product) with efficiency of 1.0 - 3.0 10^{-14}A/nV
- K-617: Keythley-617 meter
- NI USP-6259 (National instrument board with ADC-16bits, 2MHz sampling rate)
- PC computer and software (data acquisition, display, fast Fourier, APSD and CPSD calculation function)

The schema of installation of 2 KHK-56 C.I.Cs in the reactor is shown in the Fig. 3 as follows:

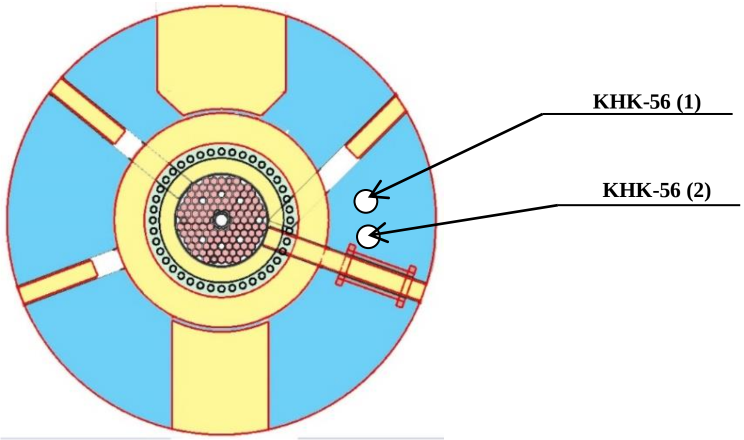

Fig. 3. Schema of installation of 2 KHK-56 C.I.C in the reactor

IV. EXPERIMENT AND RESULTS

1. Dalat reactor

The Dalat reactor is swimming pool type, 500 kW thermal power which is moderated and cooled by light water with a graphite reflector. Fuel assembly of VVR-M2 type consists of 2 kinds of enrichment, high enrichment of 36% (uranium- aluminum alloy) and low enrichment of 19.7 % (UO_2 dispersed in aluminum matrix). The core was loaded 106 fuel assemblies, in which there are 6 fuel assemblies of 19.7 % enrichment and 100 fuel assemblies of 36 % enrichment. The reactor control system consists of 4 shim rods, safety rods, which made of Carbide boron, and one automatic rod made of stainless steel.

2. Experimental setup

The experimental conditions were selected to be ensure that the reactor was completely un-poisoned and the reactor power was at very low level of 0.01 – 5 W (10^{-5} % - 10^{-3} % of the rated power), and coolant temperature was maintained from 20 to 22 ^{o}C.

During the experiments, 2 safety rods were withdrawn from the reactor core and fixed at the top position, the automatic control rod was also fixed at the position of 300 mm, while 4 shim rods were withdrawn step by step by manual mode. At the every sub-critical states, the reactor was auto-stabilized in few minutes.

In order to monitor sub-critical states of the reactor corresponding to different experimental configurations, the counting rates obtained from the 3 independent channels of neutron flux control of the ASUR-14R control system were exploited to draw the curves of inverse counting rate ($1/N_i$) in accordance with 4 shim rods position (N_i is counting rate of the i^{th} channel). From the curves (Fig. 4) by extrapolating ($1/N_i$) values to zero, the criticality of the reactor was predicted at the shim rods position of 275 mm with the automatic control rod position 300 mm as shown in Fig. 4.

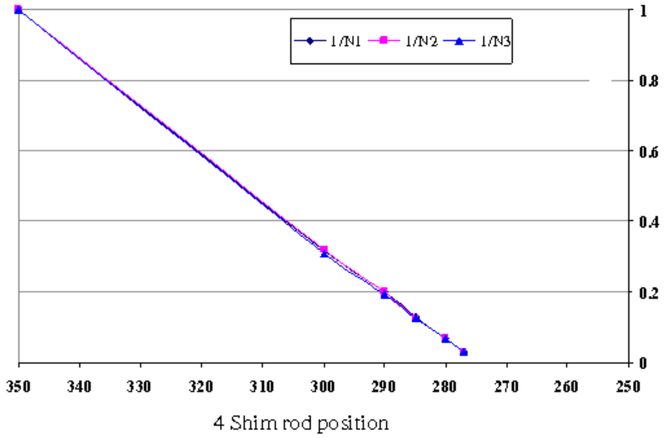

Fig. 4. The curves of inverse-count rates versus 4 shim rods positions

An important measurement in this study is to determine the transfer function module of the Keithley-617 device. That was performed by using a DC current generator, which has a constant amplitude but the frequency (range) varies from 0.1 mHz to 1.0 kHz. The output signals from the generator were connected to the input of the Keithley-617 device and the output signals of the Keithley-617 device were connected to the NI USP-6259 board with 16 bits ADC. The normalized transfer function module of the Keithley-617 device was experimentally determined as shown in Fig. 5.

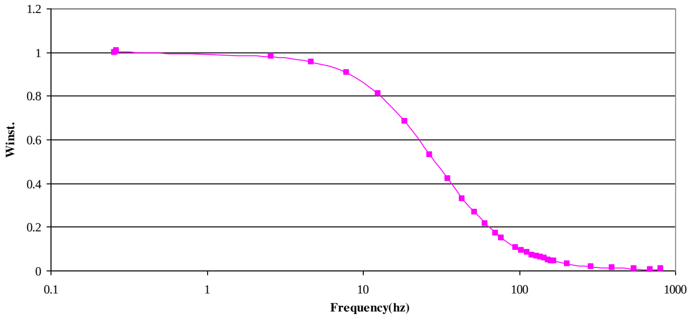

Fig. 5. The curves of inverse-count rates versus 4 shim rods positions

In these experiments, 4 shim rods were withdrawn step by step to the positions of 350, 300, 290, 285, 280 and 277 mm, respectively, and the waiting time was about 5 minutes needed for stabilizing the reactor state, then the acquisition system was started with sampling time of 0.2 m seconds. The measurements were repeated several times with the measuring time of 20 minutes.

3. Results and discussion

The experimental CPSDs were calculated from the experimental data by using the Mathlab software and the results of measurement are shown in Fig. s from 6 to 11. Then, Rossi-α parameters for each the position of 4 shim rods were determined by fitting the Eq. (6) with the experimental CPSDs. The value of α_c (β_{eff}/l ratio) is determined by extrapolating the curve of α_i to the critical position (275 mm) as shown in Fig. 12. Finally, the reactivity values were calculated by Eq. 7 as follows:

$$\rho_i = (\alpha - \alpha_c)/\alpha_c \tag{7}$$

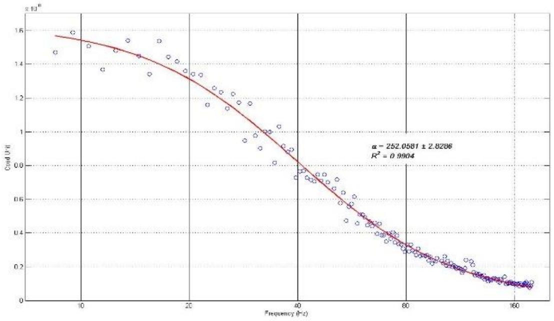

Fig.6. CPSD at the 4 shim rods position of 350 mm

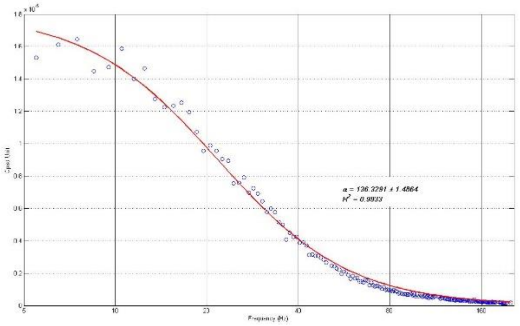

Fig. 7. CPSD at the 4 shim rods posittion of 300 mm

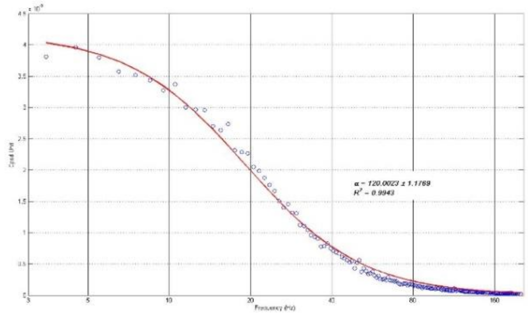

Fig. 8. CPSD at the 4 shim rods position of 290 mm

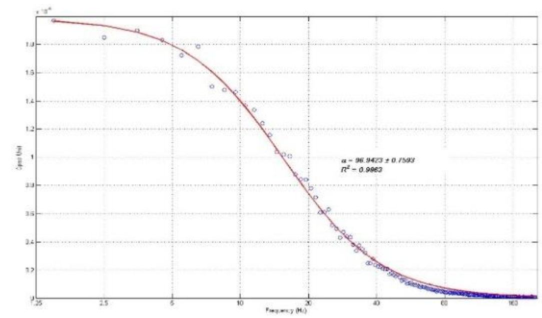

Fig. 9. CPSD at the 4 shim rods position of 285 mm

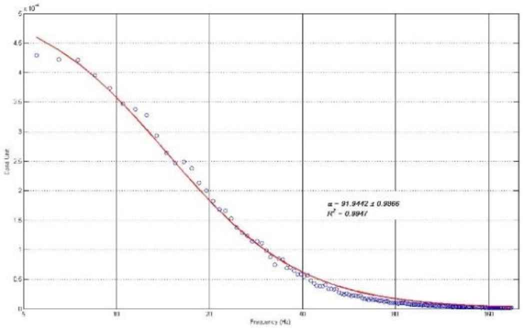

Fig. 10. CPSD at the 4 shim rods postion of 280 mm

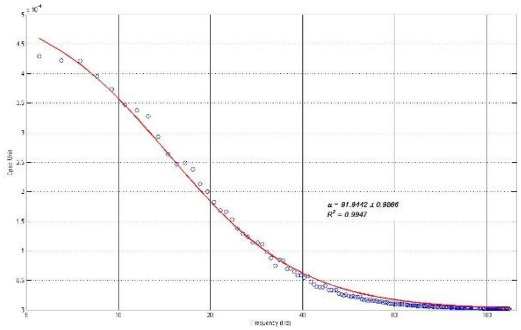

Fig.11. CPSD at the 4 shim rods position of 277 mm

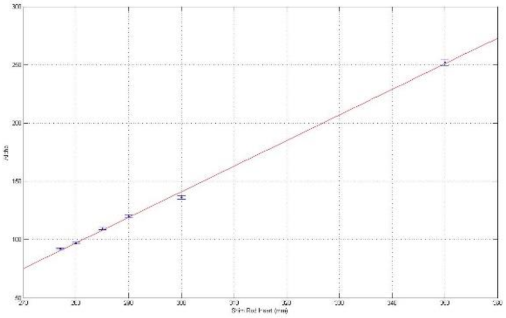

Fig. 12. The plot of α versus the 4 shim rods positions

The Table 1 summarizes the experimentally determined results corresponding to different sub-critical configurations.

Table 1. Results of measurement

Shim rods position (mm)	Reactor power (W)	Value α	R_{sqr}	Reactivity	
				Noise technique	Double time period method
350	0.12	252.05 ± 2.83	0.9904	1.9265	2.0132
300	0.38	136.33 ± 1.48	0.9933	0.5828	0.5915
290	0.60	120.00 ± 1.17	0.9943	0.3932	0.4116
285	0.95	109.56 ± 1.07	0.9941	0.2709	0.2732
280	1.75	96.94 ± 0.76	0.9963	0.1255	0.1359
277	3.95	91.94 ± 0.98	0.9947	0.0675	0.0643

The value of α_c determined by extrapolating the curve of α_i to the critical position (275 mm) is 86.13 ± 1.15 (as shown in Fig. 12). This is the first time, β_{eff}/l ratio of the Dalat reactor has been experimentally determined and it is in good agreement with previously calculated value (value ≈ 89) [4]. The values of reactivity (see Table 1) measured by noise technique were also in good agreement with the double time period method within the error of 5 %. It it noted that the double time period method is routine method for the measurement of reactivity at the Dalat reactor.

V. Conclusion

The reactor noise experiments using CPSD analysis method and 2 compensated ion-chambers were performed for the first time at the Dalat reactor. The advantage of this technique is that high-accuracy measurements can be made without affecting normal operation of the reactor. In order to measure reactivity, a series of the kinetic characteristics of the reactor such as transfer function of the zero-power, Rossi-α parameters, β_{eff}/l ratio were determined. The research results showed that the values of reactivity measured by CPSD analysis method are in good agreement with the double time period method within the error of 5 %.

Reference

[1] ROBERT E.UHRIG, Random noise techniques in nuclear reactor systems, The Ronald press company, (1970).
[2] CHARLES ERWIN COHN, A Simplified Theory of Pile, Nuclear Science and Engineering, 472-475, (1960).
[3] OM PAL SINGH, Lecture notes on reactor noise, IAEA training course in Bandung, Indonesia, (1987).
[4] Nuclear Research Institute, Safety analysis report for Dalat nuclear reactor, 2012.

ĐO ĐỘ PHẢN ỨNG BẰNG KỸ THUẬT TIẾNG ỒN
VÀ ÁP DỤNG TRONG LÒ ĐÀ LAT

Nguyen Minh Tuân, Trần Trí Viễn, Trang Cao Sủ, Huỳnh Tôn Nghiêm and Lê Vĩnh Vinh
Viện Nghiên Cứu Hạt nhân, 01 Nguyên Tử Lực, Đà Lạt

Tóm tắt: Từ nhiều năm nay, phân tích các tín hiệu thăng giáng từ các buồng ion hoá (ion-chamber) đặt trong một lò phản ứng hạt nhân là một công cụ mạnh để thu nhận các thông tin về trạng thái lò phản ứng, đặc biệt là các thông tin liên quan đến đáp ứng động của học lò phản ứng. Báo cáo trình bày các kết quả đo độ phản ứng bằng phương pháp phân tích tiếng ồn trên lò Đà Lạt. Kỹ thuật tiếng ồn thích hợp cho lò Đà Lạt là phương pháp phân tích hàm mật độ phổ và mật độ phổ chéo công suất (APSD/CPSD). Hàm mật độ phổ chéo công suất (CPSD) tín hiệu thu nhận từ 2 buồng ion hoá (loại KHK-56) có hiệu suất cao được đo và phân tích. Mục tiêu chính của nghiên cứu này tập trung vào quy trình đo độ phản ứng. Các giá trị độ phản ứng đo được bằng kỹ thuật tiếng ồn được so sánh với các kết quả đo chuẩn thanh điều khiển dựa trên phương pháp chu kỳ nhân đôi.

Từ khóa: *Buồng ion hóa (I.C), Độ phản ứng (ρ), Hàm truyền H(ω), Hàm mật độ phổ (PSD), Hàm tự tương quan, Hàm mật độ phổ chéo (CPSD), Tham số Rossi-α, Thời gian sống giữa các thế hệ neutron (ℓ)*