Investigation of dynamics of the IBR-2M pulsed reactor with energy-production up to 1200 MW·day

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Abstract. The operation of the IBR-2 pulsed reactor (1987-2006) showed that a total transfer coefficient of the power decreases during the operation of the reactor, therefore each reactor cycle has its own transfer coefficients [1] and stability margins. Hence, the study of dynamics of the new reactor IBR-2M (modernized version IBR-2, since 2011) is extremely important. In this paper, the results of an experimental and a modelling study of dynamics of the IBR-2M are presented, for the reliable and safe operation of reactor. For this purpose, model dynamics of the IBR-2M has been developed, which includes experimental data on reactor feedback parameters in period 2015-2017 at a mean power of 0.5 MW. Using the model dynamics of the IBR-2M, the stability margins of the reactor in different regimes its operation (self-regulating and automatic regulating) were estimated. It shown that during the analyzed time of the operation reactor with energy production up to 1200 MW·day significant changes in dynamics of reactor has not occurred. The reactor has been working in the stability region.

1. Introduction

In the IBR-2M pulsed reactor of periodic operation reactivity pulses are produced by the reactivity modulators, which rotate near the core. When the two reflectors pass the core simultaneously, a reactivity pulse develops and for a short time (450 µs) the reactor stops being in a supercritical state with prompt neutrons. As the reflectors move away from the core, the reactor becomes deeply subcritical. As a result, the reactor generates powerful neutron pulses (power pulse) with a frequency of 5 Hz and amplitude 1830 MW [2]. The operation of the pulsed reactor has a specific feature, in which knowledge of transitional processes is extremely important for the safe and reliable operation of the reactor. For example, the reactor is equipped with an emergency protection system (EPS), including the deviation of peak power by +100 and −50% and mean power by ±20% of the set values. Due to the high sensitivity of the pulsed reactor to fluctuations in reactivity, random changes in the peak power are sufficiently large and reach ±25% of the mean level (for comparison, in a stationary reactor with uranium fuel, the power fluctuations are 14 times smaller). This means that the reserve of power disturbances before the switching of the EPS is small. In addition, the parameters of dynamic of the reactor are changing during its operation. The model constructing based on a modular structure using discrete transfer functions of the kinetics unit, a power feedback (PFB) unit due to the heating of the reactor, and an automatic regulator (AR) unit and involves many nonlinear dependencies [3, 4]. For a confident prediction of the behavior of the reactor at rated power, it is important to imagine how the reactor parameters change during the course of energy production. However,
the necessary experiments for this purpose was held at a reduced reactor power, not nominal power. This work is a continuation of the cycle of work on the dynamics of the pulsed reactor on fast neutrons of periodic operation.

2. Experimental and modelling study of the dynamics of the IBR-2M

Based on the dynamics equations corresponding to the pulsed reactor \([5, 6]\), a mathematical model of the dynamics of the IBR-2M reactor was developed \([3, 4]\). The dynamics model includes a wide range of programs. It allows:

- to simulate transient processes under various perturbations of reactivity, including as an abnormal perturbations,
- to evaluate the change of the reactor parameters by comparing the registered transients processes with the results of modelling one,
- to calculate the frequency characteristics of the reactor as a whole system and its constituent elements,
- to establish the reactor stability margins in the self-regulating and the automatic regulating regimes.

The dynamics of the reactor depends significantly on the feedback caused by heating of the reactor. In the IBR-2M reactor fuel temperature is not measured. Therefore, in the model use power feedback (PFB: power-reactivity), not temperature to evaluate the effect of the heating on reactivity. The structure and parameters of the PFB are estimated by mathematical processing of the registered transient processes of the energy of the power pulse \((\Delta e_p)\) caused by square oscillation of the reactivity \((\Delta r)\). In the pulsed reactor, the reactivity is more convenient to express in fraction of \(\beta_p\) (delayed neutrons fraction per pulse)\([7]\).

![Figure 1. Transient processes caused by square oscillation reactivity \(\Delta r_0\) of the IBR-2M reactor at mean power of 0.5 MW (a) and 2 MW (b) in 2015. \(\Delta e_p\): the deviation of the energy power pulse and \(n\): number of pulses](image)

The reactivity oscillations by moving an automatic regulator (AR), which was withdrawn from the automatic control loop (The reactor worked in the self-regulating regime). The transient power processes were registered at different mean power levels: 0.5 (Fig.1.a), 1, 1.5 and 2 MW (Fig.1.b) and at a nominal coolant flow rate of the IBR-2M \((100 \text{m}^3/\text{h})\)\([8]\). In this paper shown that at the mean power of 0.5 MW, PFB is sufficient to represent by only one aperiodic element. That is, the PFB reactivity depends on the power pulse as a exponentially:

\[
\Delta r_0 \propto e^\beta_p \Delta e_p \Delta n
\]
Figure 2. Transient processes caused by square oscillation reactivity $\Delta r_0$ of the IBR-2M reactor at mean power of 0.5 MW in 2016 ($a$) and 2017 ($b$). $\Delta e_p$-the deviation of the energy power pulse and $n$-number of pulses

$$
\Delta r_{Tn} = [\Delta r_{Tn-1} + \frac{k_T}{T_p} \Delta E_{n-1}] \exp\left(-\frac{T_p}{T_T}\right)
$$

where, $\Delta r_T$-the deviation of power feedback reactivity expressed in portions of $\beta_p$, $k_T$-the transfer coefficient of the power feedback, $T_T$-the time constant of the power feedback, $\Delta E$-the deviation of total energy for the period of pulses $T_p$, $T_p$ - the power pulse period ($T_p = 0.2$ s) and $n$-the number of power pulse.

This character of the transient process still have in recorded processes in the next two years 2016 and 2017 (Fig. 2). From a comparison of the recorded transient processes with the simulated one in the model during the period 2015-2017, PFB parameters are estimated (Tab. 1).

Table 1. Power feedback parameters of the IBR-2M reactor of periodic operation with mean power of 0.5 MW.

| Date       | Parameter | $k_T$, $\beta_p$/MW | $T_T$, sec |
|------------|-----------|----------------------|------------|
| 2015.09.25 |           | -8.07                | 6.87       |
| 2016.10.09 |           | -6.54                | 5.98       |
| 2017.09.26 |           | -6.44                | 6.49       |

In nominal regime, the reactor operates with the automatic regulator (AR), which corresponds to the criterion of statistical optimal [9] and is characterized by two parameters ($q$ and $\Delta$). The parameter $q$ reflects the degree of smoothing of the signal with noises to enter to the input of the AR. The larger $q$, the stronger smoothing this signal ($q = 1, 2, 3, ..., 32$).

The AR velocity is characterized by the parameter $\Delta$. The larger $\Delta$, the smaller the AR velocity with the same signal at its input.

Pulsed reactor exposed to both random and regular reactivity perturbations. Faster AR provides better quality of transients with regular perturbations of reactivity, and slower for random perturbations. AR parameters are chosen from the condition of a compromise between these two contradictory tendencies [9, 10, 11].
Figure 3. The deviation of the energy of pulses ($\Delta e_{pm}$) accompanying abrupt change of reactivity ($\Delta r_0 = -0.1 \beta_p$) in the self-regulation regime, i.e., without an automatic regulator (solid curves) and in automatic regulating regime (dashed curves).

The nominal regimes of the IBR-2M reactor operation in 2015-2017, corresponded to the values of the AR parameters, indicated in Tab. 2. [12].

Table 2. Nominal parameters of the automatic regulator in 2015-2017

| Year | AR parameters $q$ | $\Delta$ |
|------|------------------|----------|
| 2015 | 16               | 0.2      |
| 2016 | 8                | 0.2      |
| 2017 | 8                | 0.2      |

Figure 2 shows the transient processes simulated by the model both in the automatic regulating regime (with the AP parameters specified in Table 2) and in the self-regulating regime.

With the help of the Nyquist criteria, an analysis of the stability of the IBR-2M reactor was carried out at the mean power of 0.5 MW and the nominal flow rate of 100 m$^3$/h for the self-regulating regime and the automatic regulating. For each regime of operation, the reactor was represented in the form of a single-loop closed system [11], [12]. According to the frequency characteristics of the open system (Fig. 3), the stability parameters are defined (Table 3).

Stability analysis has shown as a following: 1) In the automatic regulating regime, gain and phase margins of the reactor did not changed for the same values of the AR parameters. 2) In the self-regulating regime, gain margin has increased, and phase margin has decreased insignificantly over time. In all the considered regimes, the evaluated values of the margins correspond to a very good quality of the stability.

Conclusions
Analysis of the dynamics of the IBR-2M reactor at mean power of 0.5 MW and nominal coolant flow rate 100 m$^3$/h has shown that transients and stability margins were not changed significantly when reactor work energy production up to 1200 MW-day during the period 2015-2017. As a transient processes at the mean power of 0.5 MW and 2 MW are different in the character (Figure 1), a similar analysis is planned for the nominal power of 2 MW.
Figure 4. Amplitude-phase frequency characteristic of the open part of the system $W(j\omega)$ in the complex plane when reactor work self-regulating (a) and automatic regulation (b) modes.

Table 3. Stability margins of the IBR-2M reactor at a mean power of 0.5 MW and a coolant flow rate 100 m$^3$/h in the different regimes its operation

| Regime of the reactor operation | Year | Stability margins in gain ($a$) | Stability margins in phase ($\Delta \varphi$) |
|---------------------------------|------|-------------------------------|-------------------------------------|
| Self-regulating                 | 2015 | 46.5                          | 125                                 |
|                                 | 2016 | 56.5                          | 116                                 |
|                                 | 2017 | 76                            | 108                                 |
| Automatic regulating            | 2015 | $607^*$                       | 100                                 |
|                                 | 2016 | 295                           | 107                                 |
|                                 | 2017 | 296                           | 104                                 |

* $a = 293.5$ and $\Delta \varphi = 113.5$, if $q = 8$ (the same in 2016 and 2017).

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References
[1] Li Yong Chan, Pepelyshev Yu N 2008 The change of fast reactivity effects in the operation of the IBR-2 pulsed reactor. *Preprint JINR, P13-2008-1*.
[2] Dragunov Yu G, Tretiyakov I T, Lopatkin A V and et al. 2012 *At. Energy* 113(1) 29.
[3] Pepelyshev Yu N, Popov A K and Sumkhuu D 2015 *Ann. Nucl. Energy* 85 488.
[4] Pepelyshev Yu N, Popov A K, Sumkhuu D and Sangaa D 2015 *Phys. Part. Nucl. Lett.* 12(3) 435.
[5] Bondarenko E A, Pepelyshev Yu N and Popov A K 2004 *Fiz. Elem. Chastits At. Yadra* 35(4) 928.
[6] Popov A K 2012 *Fundamentals of Nuclear Reactor Control* (Moscow, Moscow State University Press).
[7] Bondarenko I I and Stavisskii Yu Ya 1959 *At. Energy* 7(5) 417.
[8] Pepelyshev Yu N, Popov A K and Sumkhuu D 2017 *At. Energy* 122(2) 75.
[9] Marachev A A, Pepelyshev Yu N, Popov A K and Sumkhuu D 2017 *At. Energy* 123(3) 172.
[10] Marachev A A, Pepelyshev Yu N and A K Popov 2008 *Ann. Nucl. Energy* 35 1779.
[11] Pepelyshev Yu N, Popov A K and Sumkhuu D 2017 Stability analysis of the IBR-2M pulsed reactor of periodic operation at self-regulating regime. *Proceedings of International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering*, Jeju, Korea, April 16-20, 2017, on USB (2017).
[12] Pepelyshev Yu N, Popov A K and Sumkhuu D 2018 EPJ Web of Conferences 173 04012