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Original Article

Optimization of automatic power control of pulsed reactor IBR-2M in the presence of instability

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ABSTRACT

The paper presents the main results of computational and experimental optimization of the automatic power control system (AC) of the IBR-2M pulsed reactor in the presence of a high level of oscillatory instability. Optimization of the parameters of the AC made it possible to significantly reduce the influence of random and deterministic oscillations of reactivity on the noise of the pulse energy, as well as to sharply reduce the manifestation of the oscillatory instability of the reactor. As a result, the safety and reliability of operation of the reactor has increased substantially.

1. Introduction

Studies of the IBR-2M pulsed reactor showed that high (up to ~50%) fluctuations of pulse energy correspond to a complex frequency spectrum of oscillations. In addition to the white noise component and a number of harmonic oscillations, it includes a significant low-frequency component with a period of 10 s. The low-frequency oscillations are interpreted as self-oscillations associated with the attenuation of the fast power feedback (PF) during reactor operation [1]. One way to reduce the amplitude of self-oscillations is to optimize the parameters of automatic power control (AC). The paper presents the main results of the study of the optimization of the AC system in the presence of a high level of oscillatory instability.

2. Brief description of the dynamics model of the IBR-2M pulsed reactor

The IBR-2M intermittent action pulsed reactor has been in operation in Dubna (Russia) since 2012. The IBR-2M is an upgraded version of the IBR-2, which was decommissioned in 2006 due to the end of its service life [2]. The main parameters of the reactor are given in Table 1.

Optimization of the AC parameters is based on a model representation of the reactor dynamics as a pulsed AC system. The reactor model is based on a block structure and is a nonlinear AC system (Fig. 1). The model includes a kinetics block describing the nonlinear dependence of reactor power on reactivity, a block of PF caused by reactor heating and characterized by a nonlinear dependence on reactivity, an AC block, and a disturbing reactivity block. The latter allows modeling a variety of reactivity changes. A detailed description of the model is given in Refs. [3–5]. The linearized parts of the system are characterized by pulse transfer functions derived from the Z-transformation of the variables.

The mathematical model of the IBR-2M dynamics makes it possible to analyze both power transients and noises in self-regulation (without AC) and automatic regulation (with AC) modes. To optimize the AC parameters, it is necessary to simulate the reactor operation when the AC system and the fast PF system work together. For modeling convenience, the reactivity r is represented in the pulse fraction of delayed neutrons β_p [6]. As an adjustable parameter of the IBR-2M in the model the relative pulse amplitude $p_m = P_m/P_m^0$ was taken, where P_m, P_m^0 are the pulse amplitude and its base value, respectively. The AC block is considered further as a discrete subsystem in the general structure of the IBR-2M dynamics model.

Principle of operation and equations of an automatic controller. The main purpose of the IBR-2M AC system is to automatically bring the reactor to a predetermined power level and

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Table 1
Main parameters of the IBR-2M reactor.

Parameter	Value
Average power, MW	2
Fuel	PuO_2
Number of fuel assemblies	69
Coolant	Na
Nominal value of coolant flow rate, m^3/h	100
Maximum burnup, %	9
Pulse repetition rate, Hz	5
Pulse half-width of fast neutrons, μ s	200
Thermal neutron flux density from moderator surface, n/cm^2·s:	
time average	~10^{13}
burst maximum	~10^{16}

stabilize the power at the same level. The algorithm for forming the reactivity of the AC provides statistically optimal maintenance of the power level, namely, achieving a minimum standard deviation of pulse energy for the future power pulse based on the information corresponding to the previous pulses [5]. It was assumed that the reactor is affected by a random reactivity disturbance with a normal law of distribution, the statistical error of the corrective reactivity also follows a normal distribution.

The concept of the degree of information aging is introduced. As a result, it is shown that the AC should be an integrating link, the input of which is fed the deviation of the energy of the current power pulse from its base value. In general, the AC system is a regulating rod with a stepper motor and its control unit and a smoothing unit (Fig. 2). The smoothing unit is the inertial link, and the stepper motor together with the control rod and control unit are the integrating link [5]. The stepper motor moves the beryllium reactivity regulator through a mechanical drive.

The smoothing unit forms a continuous step output signal $\tilde{p}_n$ from the input signal, which is a sequence of pulses with amplitudes p_{mn-1}, p_{mn}, p_{mn+1} etc., according to the inertial law. The height of the step $\tilde{p}_n$ in the time interval between pulses with numbers n and $n+1$ is formed according to the law

$$\tilde{p}_n = \tilde{p}_{n-1} + \frac{1}{q}(p_n - \tilde{p}_{n-1}), \quad (1)$$

where q is the smoothing coefficient. There is a choice of 32 fixed values of q, equal to 1, 2, 3 … 32. After the smoothing unit, a continuous stepping signal is generated to control the AC motor:

$$\Delta\tilde{p}_n = \tilde{p}^0 - \tilde{p}_n = 1 - \tilde{p}_n. \quad (2)$$

The AC motor control unit provides a choice of four fixed proportional coefficients between unbalance $\Delta\tilde{p}$ and speed of the stepper motor. This is carried out by selecting one of the four possible values of the parameter Δ (0.05, 0.10, 0.15 and 0.20), i.e. the correspondence between the unbalance $\Delta\tilde{p}$ (when $\Delta\tilde{p} = \Delta$) and the speed of the stepper motor $v_A = 167$ steps/s is chosen. Each motor step results in a $m_A = 6.16 \cdot 10^{-4}\ \beta_p$ change in AC reactance. As a result, the reactivity introduced by the motor is described by the equation

$$\frac{dr_A}{dt} = \beta_p k_A \Delta\tilde{p}. \quad (3)$$

Here k_A is the gear ratio of the motor and the AC rod (in β_p/s):

$$k_A = \frac{v_A m_A}{\Delta}, \quad (4)$$

where $v_A m_A = 0.1\ \beta_p$/s, $\beta_p = 1.57 \cdot 10^{-4}$. In the IBR-2M dynamics model, instead of the AC equations (1)–(4), the equations for discrete moments (5)–(7) derived from them are used, in which relative deviations are used as variables:

$$\Delta\tilde{e}_{pn} = \Delta\tilde{e}_{pn-1} + \frac{1}{q}(\Delta e_{pn} - \Delta\tilde{e}_{pn-1}), \quad (5)$$

$$\delta\tilde{e}_{pn} = \Delta\tilde{e}_p^0 - \Delta\tilde{e}_{pn}, \quad (6)$$

$$\Delta r_{An} = \Delta r_{An-1} + \beta_p k_A T \delta\tilde{e}_{pn-1}. \quad (7)$$

Parameters of the fast PF. Since the reactor dynamics significantly depends on the fast PF parameters, the values of these parameters were experimentally evaluated. Transient pulse energy changes caused by rectangular periodic oscillations of reactivity in the self-regulation mode were studied [7,8]. The measurements were taken at two reactor power output values obtained in 2015 and 2019.

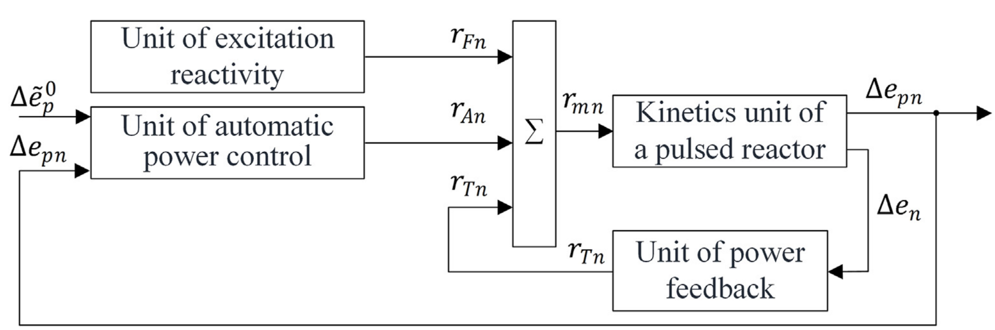

Fig. 1. Block-scheme of model dynamics of the IBR-2M with automatic power control.

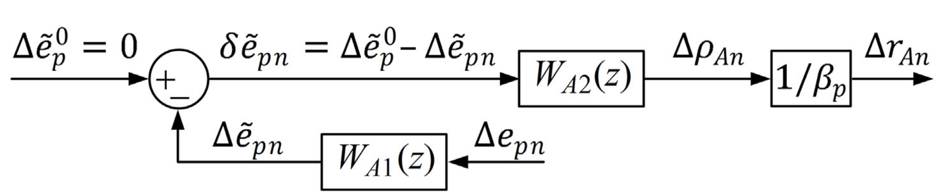

Fig. 2. Block-scheme of automatic power control of the IBR-2M. $W_{A1}(z)$, $W_{A2}(z)$ – pulse transfer functions of the filter and automatic regulator, respectively.

Table 2
Parameters of AC and fast PF of the IBR-2M for optimization.

Parameter	Range of the parameter change	Current value
Filter smoothing coefficient q	1, 2, 3 … 32	8
Coefficient of proportionality Δ between unbalance $\Delta\tilde{p}_n$ and speed of stepper motor v_A	0.05, 0.10, 0.15, 0.20	0.2
Total transfer coefficient of the fast PF $k_T = \sum_j k_{Tj}$, β_p/MW:		
2015	−5.14	Decrease in absolute value
2019	−4.67	

A brief description of the AC parameter optimization technique. The following scheme was used to select the optimal AC parameters. As part of the mathematical dynamics model, all values of the two main parameters of the AC were varied: the filter smoothing coefficient q and the coefficient of proportionality Δ between the unbalance $\Delta\tilde{p}_n$ and the speed of the stepper motor v_A. Varying the AC parameters was performed for two combinations of fast PF parameters corresponding to the reactor state in 2015 and 2019. The values of the varying parameters are shown in Table 2. The influence of the AC parameters on the power transients and on the transfer function of the reactor was examined.

3. Influence of AC parameters on power transients

In this section the results of the analysis of the influence of the AC parameters on the power transients under regular and random reactance disturbances are given:

a) regular disturbance in the form of a jump $\Delta r_F = -0.1\beta_p$,
b) random disturbance in the form of white noise with dispersion $\sigma_r^2 = 0.05^2\ \beta_p^2$.

All processes were simulated in both self-regulation and automatic power control modes.

Regular disturbance of reactivity in the form of a jump. As an example, Fig. 3 shows the transient processes of pulse energy change at reactance jump in the modes of self-regulation and automatic regulation at different values of energy output. Transient quality parameters are also shown there.

The simulations evaluated the following direct indicators of transient quality: the settling time or transient duration t_{st} and the maximum of transient Δe_{pmax}. Fig. 4 shows the quality indicators of transients in the automatic control mode, depending on the parameters q and Δ at different generated power values.

From Fig. 4*a* shows that for a 1500 MW·day generated power at

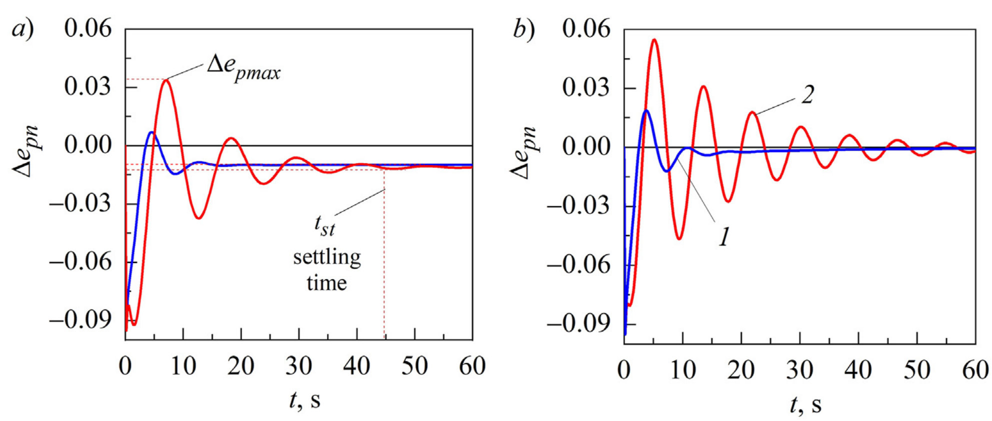

Fig. 3. Relative deviation of the pulse energy Δe_{pn} at jump reactivity $\Delta r_F = -0.1\ \beta_p$ in the modes self-regulation and automatic regulation at different values energy output of reactor: 740 MW·day (*1*) and 1500 MW·day (*2*); t − time. Parameters of AC: $q = 8$ and $\Delta = 0.2$ (standard values).

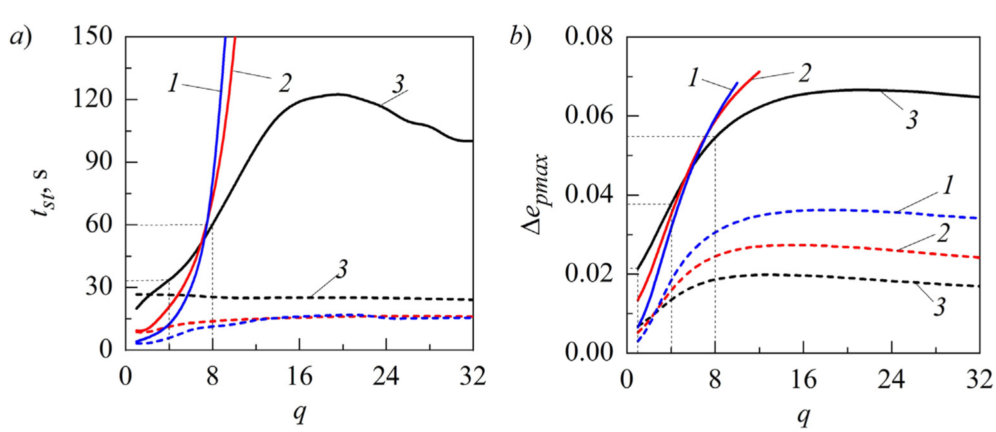

Fig. 4. Settling time and maximum of relative deviation of the pulse energy dependence on parameters of AC q and Δ at different values of energy output of reactor 740 and 1500 MW·day (solid and dash lines, respectively): $\Delta = 0.05$ (*1*), $\Delta = 0.1$ (*2*) and $\Delta = 0.2$ (*3*).

values $q < 4$, the duration of the transient process increases with increasing $\varDelta$; at $q = 8$ - practically does not change at different values of $\varDelta$, and at $q > 8$ - is outside the permissible level and increases very rapidly at $\varDelta$ <0.2. The best quality transient process is observed at $q = 1$, i.e., when there is no AC smoothing unit. For security reasons, this option is not possible. As q increases, the oscillation increases. As the generated power increases at $q > 11$ and $\varDelta <$ 0.2, an self-oscillatory process is observed in which the oscillation amplitude increases over time and reaches a large asymptotic level. Thus, if only regular reactivity disturbances are taken into account, it is reasonable to use $q < 4$ and $\varDelta =$ 0.2. In addition, simulations have shown that transients become worse with increasing generated power in both self-regulation and automatic control modes.

Amplitude-frequency response of the IBR-2M depending on the smoothing parameters (*q*) and the AC unit response (Δ). The influence of harmonic oscillations of reactivity with frequency f of the form $\varDelta r_F = A_r \sin(2\pi f t + \phi_r)$. on the reactor is considered. Under such influence the relative deviation of the pulse energy will also be sinusoidal $\varDelta e_p = A_e \sin(2\pi f t + \phi_e)$ with the same frequency as the reactance frequency, but with the amplitude A_e and phase ϕ_e, depending on the frequency f.

The amplitude-frequency response (AFR) of the reactor was estimated as $a(f) = A_e(f)/A_r(f)$, and the phase-frequency response - $\varDelta\phi(f) = \phi_e(f) - \phi_r(f)$. In this case it was taken $\phi_r(f) =$ 0 and $\varDelta\phi(f) = \phi_e(f)$. Fig. 5 shows the results of modeling the AFR of IBR-2M in the AC mode depending on the smoothing coefficient q at two values of the AC response parameter: $\varDelta = 0.05$ and 0.2 and at power generation of 740 MW$\varDelta$ day (2015) and 1500 MW$\varDelta$ day (2019). The red lines in Fig. 5 show the currently available IBR-2M AFRs.

Fig. 6 shows the IBR-2M AFR at the PF parameters corresponding to the reactor operation in 2015 and 2019 and the change in the resonance amplitude in the AFR when changing the parameter q.

It can be seen from Figs. 5 and 6 that there is a resonance region at ~0.1 Hz in the AFC of the reactor, and the resonance peak a_0 strongly depends on the parameters of the fast PF.

Analysis of the data shows that the resonance amplitude peak at $1 \le q \le 11$ grows almost linearly with increasing q, and becomes almost constant at $q > 11$ (at $\Delta = 0.2$). At $\Delta < 0.2$ and $1 \le q \le 10$ the resonance peak also grows with the increase of q linearly, but greater than in the previous case. At $q > 10$, the reactor state is unstable and cannot be modeled.

In order to compare the calculated and real changes in the resonance of the AFC in pulse energy fluctuations, Fig. 7 shows the spectral densities of pulse energy fluctuations measured in the reactor cycles before and after changing the smoothing factor q (was $q = 8$, became $q = 4$). Fig. 6 clearly shows that the low-frequency oscillating component of the spectrum ($f < 0.5$ Hz) when reduced q to four significantly changed (almost two times) in the calculation.

Random disturbances of reactivity. The IBR-2M is affected by many sources of random reactivity disturbances, such as vibrations of blades of moving reflectors, vibrations of cassettes and fuel rods in the core, various kinds of vibrations from the core cooling system, etc. Because of the reactor's high reactivity sensitivity, the total pulse energy fluctuations are large (the swing of the fluctuations is ~50%). Fig. 8 shows the correlations of the standard deviations of the pulse energy at random perturbations of reactivity with a dispersion of $\sigma_r^2 = 0.05^2\ \beta_p^2$ at different values of the AC and PF parameters. Fig. 8 shows that with random reactivity disturbances

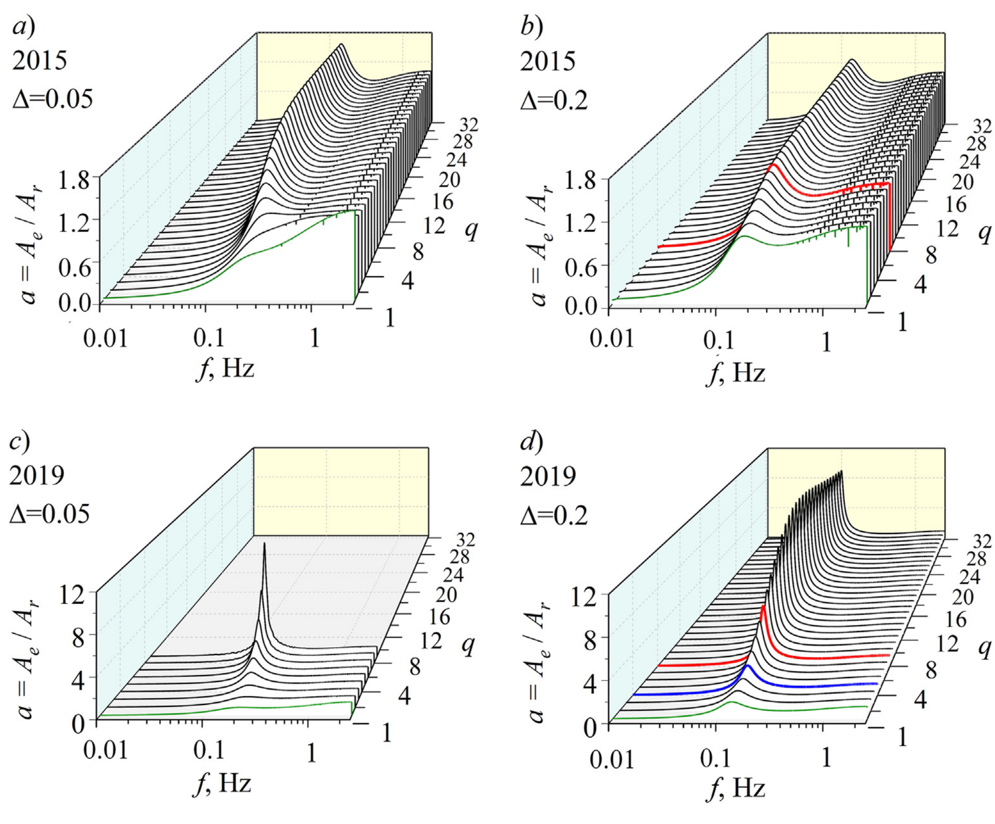

Fig. 5. Amplitude-frequency response of the IBR-2M in automatic regulation regime dependence on smoothing coefficient q at two values of speed parameter of AC ($\varDelta =$ 0.05 и 0.2) at different values of energy output of reactor: *a-b*) 740 MW · day (2015), *c-d*) 1500 MW · day (2019). The red lines show AFR at standard values of AC $q =$ 8, $\varDelta = 0.2$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

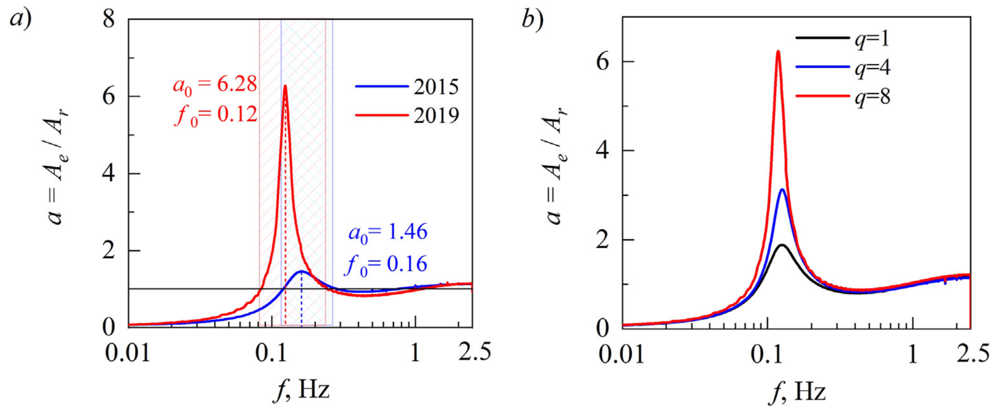

Fig. 6. Amplitude-frequency response of the IBR-2M in automatic regulation regime in different period of reactor operation at standard values of parameters of AC $q = 8$, $\Delta = 0.2$ (a) and at $\Delta = 0.2$, but different values of smoothing coefficient q (b). Resonance is visible in the frequency region of 0.1 Hz.

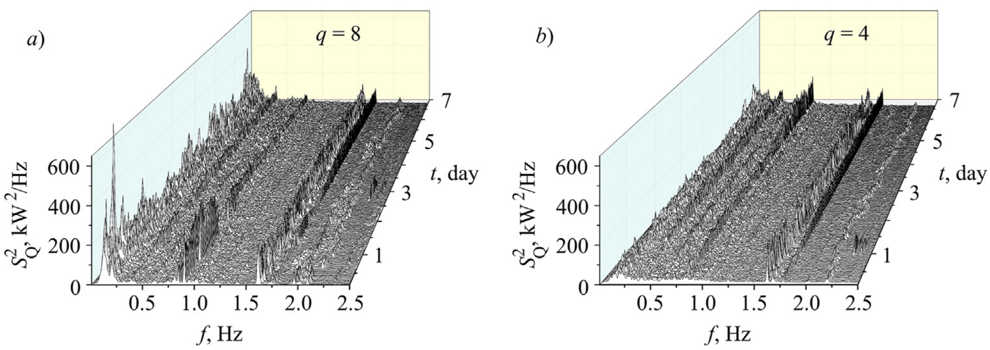

Fig. 7. Power spectrum of IBR-2M pulse energy fluctuations (S_Q^2) with various values of smoothing coefficient: $q = 8$ (a) and $q = 4$ (b).

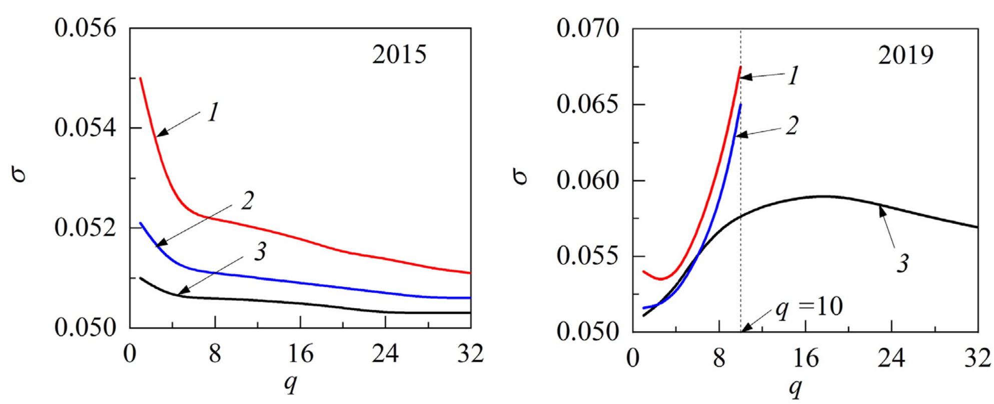

Fig. 8. Standard deviations of the pulse energy σ as a function of smoothing coefficient q: $1 - \Delta = 0.05$, $2 - \Delta = 0.1$ and $3 - \Delta = 0.2$.

at $q = 4$ for both sets of PF parameters, the value of σ decreases as Δ increases.

4. Conclusions

From the analysis of transients with regular reactance disturbances, it follows that the best transients correspond to the following values of the AP parameters: $q \le 4$ and $\Delta \le 0.2$. The ideal values of AC parameters for transient smoothing $q = 1$ (no smoothing unit) and $\Delta = 0.05$ (motor speed of AC selected as the highest) cannot really be used, because they do not reflect the whole range of power fluctuation suppression.

From the analysis of transients under random as well as regular sinusoidal reactivity disturbances that take place during normal reactor operation, it follows that it is reasonable to choose the AC parameter values, as in the previous case, equal to $q \le 4$ and $\Delta \le 0.2$. The above parameters correspond to the best AC optimization.

The weakening of the fast PF occurring during the reactor operation leads to the amplification of the resonance at 0.1 Hz in the AFC of the reactor. It is possible to halve the resonance amplitude when parameter $q = 8$ is reduced to $q \le 4$.

As a result of the research, it is shown that the optimal values of the AC parameters are $q \le 4$ *and* $\Delta \le 0.2$. This is true both for reactivity jumps, random noise, harmonic oscillations, and for the occurrence of resonances in the core.

In general, optimization of parameters of the IBR-2M AC system made it possible to significantly reduce both the influence of random and deterministic reactivity fluctuations on pulse energy noises and the occurrence of oscillatory instability of the reactor.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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