

Algorithms for processing self-powered neutron detector signals important for determination of local parameters in each part of the VVER core

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Abstract. These investigation findings prove the possibility of an engineering solution for VVER core automatic protection during operation in both nominal and transient conditions within ICIS using local parameters (i.e. linear heat power of the most stressed fuel rod, departure from nucleate boiling ratio). Such engineering solution will be implemented by safety system software-hardware (PTK-Z) on the basis of signals coming from in-core neutron flux detectors, temperature sensors, primary coolant flow and coolant pressure transducers. The article presents the following: a list of in-core neutron flux detectors, a list of transducers of primary coolant monitoring for thermal engineering conditions (temperature, flow rate, pressure), whose signals are delivered to the terminals of instrumentation gauges (PTK-Z) for the purpose of actuating safety actions in accordance with local parameters. The paper shows arrangement of in-core neutron flux detector equipment, above view of self-powered neutron detector (SPND) location in safety channels, axial arrangement of SPND along the core, algorithms for processing SPND signals important for determination of local parameters in each part of the core in both normal and abnormal operation conditions.

1 Introduction

Realisation of protection function on the basis of local parameters is ensured by the following factors in reactor V-412:

- arrangement of ICIDs within the core, 54 in number, each of them being supplied with seven Rhodium SPNDs, with certain time transient characteristics;
- arrangement of coolant temperature sensors in cold legs, coolant flow detectors in the primary loops, and pressure transducers above the core;
- development and implementation of instrumentation equipment, which satisfies safety category 2 requirements (category indication 2NU as per [1], and 2NU/K2 as per [2]) for quality, velocity and metrology parameters of monitors or system responses, and software, using advanced data communication technologies intended for important challenges of the world market, and with satisfaction of IEC 880, IEC 987 standards and normative documentation requirements for category 2NU (as per [1]) hardware and software.

The technical solution of local protection system for the V-412 core should provide the following:

- automatic generation of protection signals and delivery to CPSE at reactor power ranging within 20 and 110% of nominal power in case if the local rod power exceeds the rated limit, or departure of nucleate boiling ratio drops below the rated limited value with a time delay of at least 3 s [3];
- probability of failure to respond with a scram function of PTK-Z should not exceed 5×10^{-7} within a 1 year time domain [4].

2 Selection and arrangement of in-core detectors

For the purpose of protection on the basis of local parameters, a beta-emission self powered neutron detector (SPND) with a Rhodium emitter has been selected as an in-core neutron flux detector for the following reasons:

- compatibility with VVER design;
- long operation within ICIS at VVER reactors;
- availability of experience and skills (proved by long operation of ICIS in VVER plants) in registration and application of processes of interaction of Rhodium with

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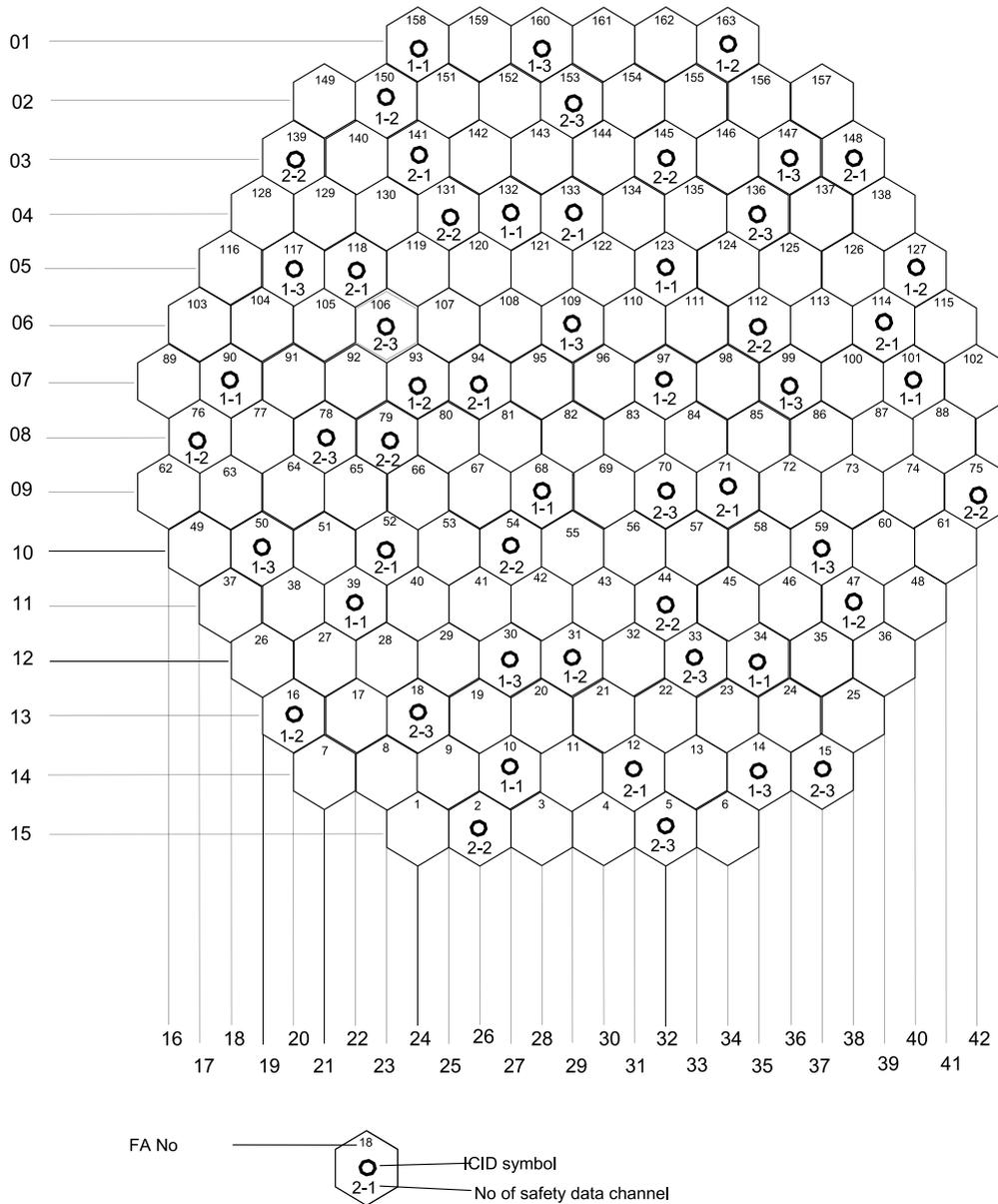


Fig. 1. ICID arrangement within V-412 core and distribution among safety channels.

neutrons, γ -quanta, β -fission electrons of generated isotopes, generation of electrical current (escape of Compton electrons, β -particles and associated electrons from emitter), etc.;

- availability of experience and skills in development of algorithm, software or metrology support, and instrumentation equipment or computer facilities.

The V-412 design provides the in-core arrangement of 54 in-core instrumentation detectors (Fig. 1) with Rhodium SPNDs arranged at seven axial elevations along the core [5].

In compliance with a 6-channel structure of NPP’s safety systems, and for the purpose of on-line monitoring of linear power of the most stressed fuel rod the design basis provides six Rhodium SPNDs arranged in each of the seven

axial levels, which correspond to axial elevations of SPND, around every (i, j) elementary part of the core and in the area of “influence function”.

“Influence function” (Fig. 2) is understood as the dependence of drop in neutron flux perturbation on the distance between FA centre, which makes an epicentre of the perturbation, and the detector that monitors such perturbation.

The area of “influence function” for our case denotes the area of a circle whose radius equals the length of the distance where “influence function” decreases to 5% of the value measured in the epicentre. In our case we investigate the detectors that are located within the radius of approximately 650–700 millimetres (which corresponds to decrease of influence function to 5.5%).

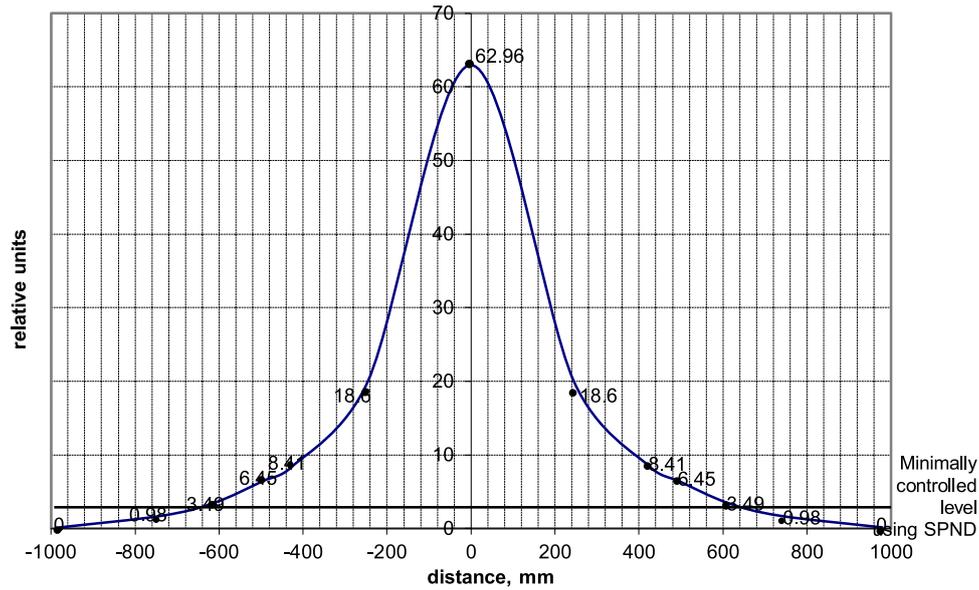


Fig. 2. Influence function.

Table 1. List of detectors whose signals pass to the inlet of PTK-Z instrumentation equipment.

Parameters measured	Type of signal	Number of signals	Source of signal
Neutron flux density	Analog	54×7	SPND (ICID)
Inlet coolant temperature in FA	Analog	50	thermocouple (ICID)
Outlet coolant temperature in FA	Analog	100	thermocouple (ICID)
Coolant temperature under reactor top head	Analog	4	thermocouple (ICID)
Coolant temperature in the primary hot legs	Analog	6×4	RTD
Coolant temperature in the primary cold legs	Analog	6×4	RTD
Pressure difference in RCPS	Analog	6×4	Pressure difference transducer
Frequency of RCPS supply	Analog	6×4	Frequency detector
RCPS actuation	Discrete	6×4	Relay (dry contact)
RCPS trip	Discrete	6×4	Relay (dry contact)
RCPS capacity	Analog	6×4	Capacity detector
Pressure above the core	Analog	6	Pressure transducer

Term “influence function” makes it possible to simplify the identification of six most robust SPNDs that surround each of the 163 core sections at each of the seven core levels. Also the SPND arrangement within six separate safety channels of safety system software-hardware (Fig. 1), and also to make a preliminary estimation of SPND statistical weight during statistical treatment of the signals.

Detector connection lines of the aforementioned six ICIDs are installed in two separate groups of cable lines (for both kits of equipment PTK-Z one and PTK-Z two), which are either located in different rooms, or separated by the distance of 3 meters or some barriers [6].

In addition to that, 6 kits of thermal engineering detectors are installed in the reactor in-line equipment (PCP, RCPS). The signals from such detectors are

delivered to PTK-Z (6×4 measures of coolant temperature in cold legs, 6×4 measures of pressure gradient in RCPS, 6×4 measures of RCPS power supply frequency, pressure transducer above the reactor core) (Tab. 1).

3 Arrangement of instrumentation equipment and computer facilities

In order to perform the function of automatic protection in response to local parameters (scram, PP) the following apparatus should be used: instrumentation equipment and computer facilities of safety category 2 (category indication 2NU as per [1] and 2NU/K2 as per [2]), which is integrated in every safety channel of the plant as a part of safety

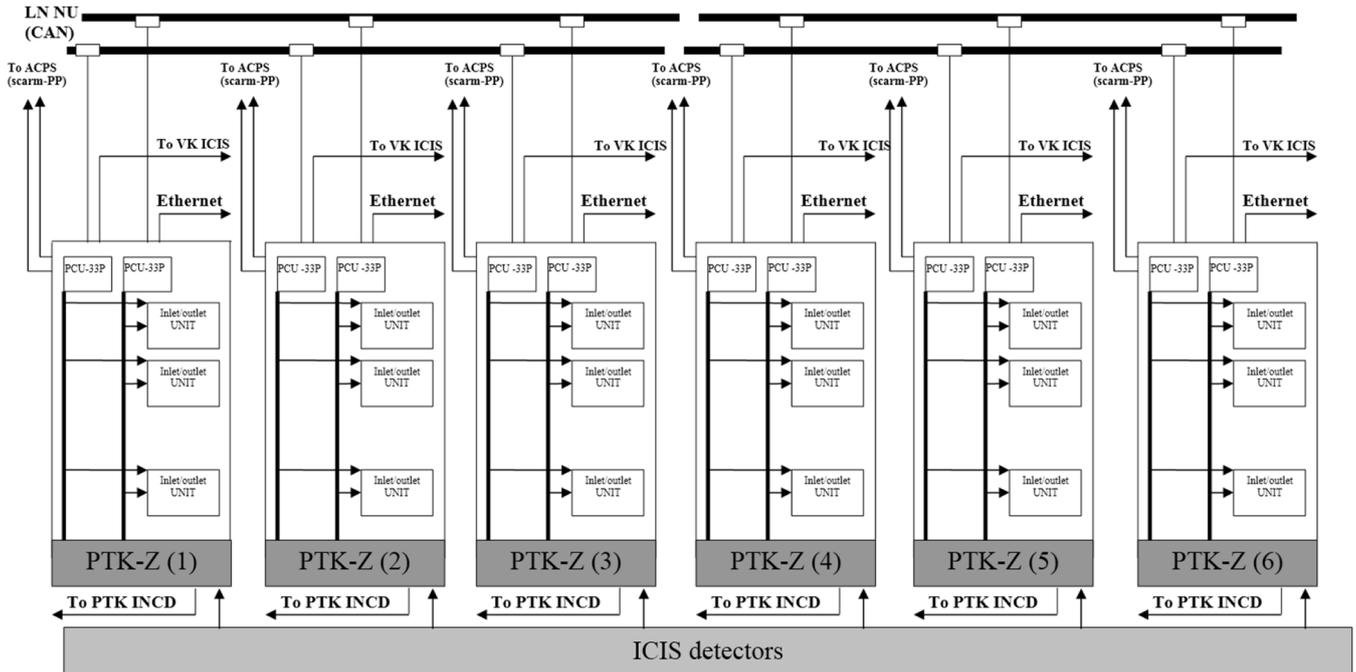


Fig. 3. PTK-Z scheme.

system software-hardware (PTK-Z). Every PTK-Z cabinet is connected to thermal engineering detectors via cable lines to their respective safety channels.

Cabinets PTK-Z and cabinets of various safety categories are furnished with connection via local net of lower level of safety category 2, (category indication 2NU as per [1] and 2NU/K2 as per [2]). This enables every safety channel processor taking decisions using the whole amount of data on in-core processes and deliver protection signal to CPSE of the applicant safety channel. PTK-Z block scheme is given in Figure 3.

4 Signal interpretation algorithms

4.1 Preliminary signal interpretation

Every delivered analogue signal shall pass a rejection process, which consists of comparing the signal against limitations established [5]:

$$A_{\min} \leq A \leq A_{\max}, \quad (1)$$

where A is the current signal indication; A_{\min} – is an extremely small design signal indication; A_{\max} – is an extremely large design signal indication.

After a rejection procedure, every signal, except SPND signals, should pass a smoothing procedure in accordance with the following formula:

$$A_c(t) = k_c \cdot [A(t) - A_c(t-1)] + A_c(t-1), \quad (2)$$

where A is a signal indication; A_c – is a smoothed signal indication; t – denotes a current polling cycle; $(t-1)$ – denotes a previous polling cycle; k_c – is an individual smoothing coefficient ($0.1 \leq k_c \leq 1$).

The value of k_c depends on the magnitude and character of electromagnetic induction at signal transfer lines from the detectors to the equipment of certain power units, and it can be determined at CA stage.

4.2 Interpretation of normalised signals from the transducers of general process measurements

The transducers of general process measurements comprise of pressure and pressure difference transducers, detector of boron acid concentration, RCPS capacity sensor, etc [5]. The normalised signals from these detectors are converted into physical units of measurement according to the following formula:

$$W = \frac{W_{\text{up}} - W_{\text{low}}}{A_{\text{up}} - A_{\text{low}}} \cdot (A - A_{\text{low}}) + W_{\text{low}}, \quad (3)$$

where A – is the value of normalised signal (mA or V); W_{up} – is the upper margin of normalised signal values (in physical units of measurement); A_{up} – is the upper margin of normalised signal (mA or V); W_{low} – is the lower margin of normalised signal (in physical units of measurement); A_{low} – is the lower margin of normalised signal (mA or V).

4.3 Rhodium detector signal rejection and elimination of time delay

4.3.1 If SPND current rejection

For the purpose of rejecting Rhodium SPND signals, dynamical “gates” are applied, which are capable to account for the VVER core dynamics, physics of current

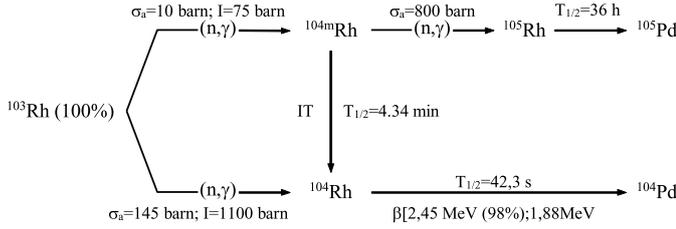


Fig. 4. Current generating processes in Rhodium SPND shema.

generating in Rhodium SPND, type and magnitude of a certain detector signal [7–10] measured and equipment polling cycle using the following formulas:

$$A_{im}^{\min}(t) \leq J_{im}(t) \leq A_{im}^{\max}, \quad (4)$$

where $A_{im}^{\min}(t) = J_{im}(t - 0, 16c) \cdot K_n^{\min}$; $A_{im}^{\max}(t) = J_{im}(t - 0, 16c) \cdot K_n^{\max}$; where $J_{im}(t)$, $J_{im}(t - 0, 16c)$ – are the measured or normalised currents of i , m -th SPND ($i = 1, \dots, 7$ is and axial number of SPND; $m = 1, \dots, 54$ is ICID No.) at time points t and in the previous polling cycle, accordingly. A normalised current is dc SPND value after elimination of time delay; K_n^{\min} , K_n^{\max} – are the coefficients that define the lower and the upper margins of rejection gates; $n = 1, 2, 3$ – is the gate No.

The values of the coefficients are determined proceeding from the physics of active nature of current generating in a Rhodium SPND, and a selected type of filter.

4.3.2 Elimination of time delay

For the purpose of function of time delay elimination, this technical solution discusses two filters, these are a corrective filter and Kalman filter [7,8].

A nuclear reaction in view of main current generating processes within a detector emitter [5,7–10], may be depicted in the following way (Fig. 4).

The scheme (Fig. 4) shows the share of ^{103}Rh isotope in the natural mixture, reaction sections and half-life of generated nuclides.

The mathematical model of current generating in Rhodium SPND under the influence of neutron flux, is expressed by a system of differential equations:

$$\frac{\partial m_1(t)}{\partial t} = a_1 n(t) - \lambda_1 m_1(t), \quad (5)$$

$$\frac{\partial m_2(t)}{\partial t} = a_2 n(t) + \lambda_1 m_1(t) - \lambda_2 m_2(t), \quad (6)$$

$$i(t) = cn(t) + \lambda_2 m_2(t), \quad (7)$$

where $n(t)$ – is neutron flux; $i(t)$ – is outlet SPND current; λ_1 and λ_2 – are constants of β -decay ^{104m}Rh and ^{104}Rh ($\lambda_1 = 0.0027 \text{ s}^{-1}$, $\lambda_2 = 0.0164 \text{ s}^{-1}$); a_1 , a_2 – are the constants proportional to the section of Rhodium (^{103}Rh) consumption with generating of isotope ^{104m}Rh and isotope ^{104}Rh ($a_1 = 0.061$, $a_2 = 0.879$); $a_1 + a_2$ – is the share of activation component ($a_1 + a_2 = 0.94$); c – is the share of instantaneous component $c = 6\%$.

In one of the options of this problem solution, the time delay elimination must be performed by multiplying a measured signal by the reverse matrix of transient function of Rhodium SPND. Hereinafter, this procedure will be referred as processing by a corrective filter.

Brief description of the procedure:

- determine the parameters of SPND transfer function or (which is similar) of an analogue filter (Rhodium SPND is an analogue filter in relation to neutron flux) by way of solving the system of differential equations of mathematical model of current generation in Rhodium SPND using Laplace transformation (P_s);
- convert the parameters of analogue filter into the parameters of digital filter P_z by way of bilinear transformation ($P_s \Rightarrow P_z$);
- calculate the parameters of a reverse digital filter P_z^{-1} .

Thus, the obtained digital corrective filter completely compensates the dynamic uncertainty (time delay). However, this filter boosts the associate noise.

The application of the Laplace transformation to equations (5)–(7) yields the following formula of SPND transformation function:

$$P_s = \frac{I(s)}{N(s)} = \frac{s \cdot A_3 + s \cdot A_2 + 1}{s \cdot B_3 + s \cdot B_2 + 1}, \quad (8)$$

where $A_2 = c T_1 T_2$, $A_3 = (1-c) T_3 + c (T_1 + T_2)$, $B_2 = (1-c) T_3 + c (T_1 + T_2)$, $B_3 = T_1 T_2$, $T_1 = 1/\gamma_1$, $T_2 = 1/\gamma_2$, $T_3 = (T_1 a_2)/(a_1 + a_2)$, $T_1 = 384.6$, $T_2 = 60.6$, $T_3 = 353.9$, where $I(s)$ – SPND current in the domain of Laplace transformations; $N(s)$ – is neutron flux in the domain of Laplace transformations; s – is a complex variable (an argument in the domain of Laplace transformations).

For the purpose of calculating a digital filter, which will correct the SPND inertia properties, first it is required to convert the analogue filter, which is represented by transformation function P_s (8), into digital format ($P_s \Rightarrow P_z$) [5]. For this purpose we make the following substitution of the variables (bilinear transformation):

$$s \rightarrow 2f_s \frac{z - 1}{z + 1} \quad (9)$$

where f_s – is the digitisation frequency.

After digitisation is carried out, we determine the opposite to initial digital filter P_z^{-1} by using a bilinear transformation.

Thus, equation (8) may be written anew as:

$$I(z) = N(z) \cdot P_z. \quad (10)$$

If we multiply both the right and the left part of equation (10) by P_z^{-1} , the above equation will have the following view:

$$N(z) = I(z) \cdot P_z^{-1}. \quad (11)$$

Thus, the corrective digital filter (K-F) is capable to compensate a dynamic error at full rate. However, if the signal (SPND current) is accompanied by noise, such noise will be boosted.

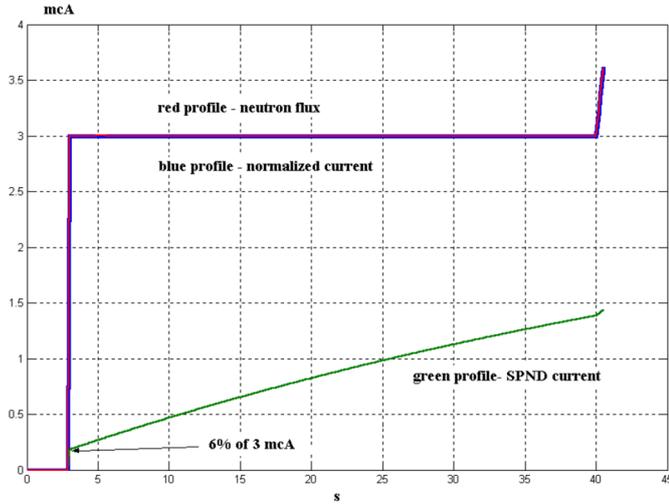


Fig. 5. Effect of corrective filter application.

With precise compensation of dynamic error (time delay after correction makes at most 0.1 s) of nominal SPND (diameter_{Rh} = 0.5 mm, c = 0.06 mm), the signal noise increases by ≈ 17 times. Figure 5 shows neutron flux (red line) with a jump at time point ($t = 2.5$ s) and remaining constant up to 40 s, the SPND current (green line) that corresponds to this neutron flux and SPND current $J_n(t)$, which was restored (normalised) by a corrective filter and which perfectly coincides with neutron flux (blue line). At time point ($t = 40$ s) neutron flux starts to increase. This is caused by CPS CR ejection without compensation by APC (at a rate of 40% per second), and the normalised current follows the neutron flux with a time delay at most 0.05 s [5].

The application of corrective filter yields processed signals that passed the rejection “gates” (formula 4) with $K_2^{min} = 0.96$ and $K_2^{max} = 1.04$. This filter application is preferable for fast processes (fluctuation velocity of local power density amounts to 40% per second). In certain cases, the precise compensation of time delay (at most 0.05 seconds), which causes significant increase of noise and electrical induction that are sometimes associated with Rhodium SPND signals, will not be required, if the fluctuation velocity of local power density does not exceed 5% per second.

In these cases, an optimal combination of capability to eliminate a delay, on one hand, and ensure both accuracy and noise resistance, on the other, is a feature of Kalman filter, when it is integrated with transformation function of Rhodium SPND. Application of this filter makes it possible to optimise the extent of dynamic error removal and noise increase by way of parameter selection.

For the purpose of our option (Rhodium diameter is 0.5mm, c=6%, velocity of local power density increase is at most 5% per second), calculated and performed a survey of Kalman filter parameters (F-K) [5–8]. Kalman filter is capable to take into account the SPND transformation function and ensure the value of noise boost coefficient as six at most (almost three times less than a corrective filter) with time delay 0.5 second at most. Figure 6 shows the effect of filter Kalman application (F-K).

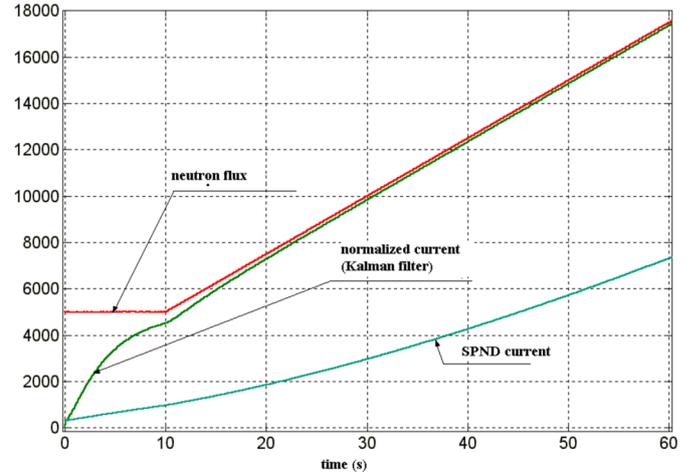


Fig. 6. Effect of Kalman filter application.

Figure 6 also shows the following transient process: at time point 0 neutron flux jumps from 0% to 100%, during next 10 seconds it keeps constant, at time point of 10 s neutron flux starts to increase at a rate of 5% per second. The axial axis presents the values of neutron flux, normalised current and SPND current in ADI scale division:

- red curve denotes neutron fluxes (rate of increase is 5% per second);
- blue curve stands for SPND current;
- green curve denotes normalised SPND current (processed by Kalman filter).

Elimination of time delay of SPND current is carried out the following way:

$$P = I_m(t) - Cs1 \cdot Ja(t-1) - Cs2 \cdot M(t-1) - Cs3 \cdot Jn(t-1) \quad (12)$$

$$Ja(t) = Fs11 \cdot Ja(t-1) + Fs12 \cdot M(t-1) + Fs13 \cdot Jn(t-1) + Ks1 \cdot P, \quad (13)$$

$$M(t) = Fs22 \cdot M(t-1) + Fs23 \cdot Jn(t-1) + Ks2 \cdot P, \quad (14)$$

$$Jn(t) = Fs33 \cdot Jn(t-1) + Ks3 \cdot P, \quad (15)$$

where $Jn(t)$ – is normalised SPND current (without time delay); $I_m(t)$ – is measured SPND current (without background compound); $Ja(t)$ – is activation compound of SPND current; P – is difference between measured and expected values of SPND currents; $M(t)$ – is a variable that takes into account the decay of isotope ^{104m}Rh ; t – denotes a current polling cycle; $(t-1)$ – denotes a previous polling cycle; Fs11 – Fs13, Fs22, Fs23, Fs33, Ks1 – Ks3, Cs1 – Cs3 – are coefficients universal for all SPND signals, which can be changed as necessary. The changing procedure will be described in operation instruction.

The initial values of the magnitudes are calculated the following way:

$$Ja(0) = K1 \cdot I_m(0), \quad (16)$$

$$M(0) = K2 \cdot I_D(0), \quad (17)$$

$$Jn(0) = I_m(0), \quad (18)$$

where $K1$, $K2$ – are the coefficients universal for all SPND signals.

The application of Kalman filter yields processed signals that passed the rejection “gates” (formula 4) with $K_3^{min} = 0.99$; $K_3^{max} = 1.01$.

4.3.3 SPND rejection in terms of rate

The in-core processes with velocity of neutron flux increase ranges between 40% per second to 120% per second may be detected by SPND signals that passed the rejection “gates” (formula 4) with $K_1^{min} = 0.88$, $K_1^{max} = 1.12$ and rejected by rejection “gates” with $K_2^{min} = 0.96$, $K_2^{max} = 1.04$ according to the following formula [5]:

$$\begin{aligned} \bar{v} &= \frac{1}{5} \sum_{k=1}^5 \frac{(I(t_k) - I(t_{k-1}))}{I(t_{k-1}) \cdot \Delta t} \cdot 100 \% \\ &= \frac{1}{5} \sum_{k=1}^5 \frac{(I(t_k) - I(t_{k-1}))}{I(t_{k-1}) \cdot \Delta t} \cdot 100 \%, \end{aligned}$$

where \bar{v} – is average velocity of neutron flux increase in 5 polling cycles; t_k – is a time point when polling cycle k finishes; $I(t_k)$ – is SPND current at the end of polling cycle k ; $I(t_{k-1})$ – is SPND current at the end of polling cycle $(k-1)$; Δt – is one polling cycle length ($\Delta t = 0.16$ s).

If the process velocity ranges within 40% and 120% per second, protection signal will be generated.

4.4 Calculation of mass coolant flow in the primary loops

If the RCPS is in operation (direct current), the mass coolant flow G_i in the primary i-loop will be calculated using a velocity head value according to the following formula:

$$\begin{aligned} G_i &= \left[A_i \cdot \left(\frac{f_i}{f_i^0} \right) + B_i \cdot \left(\frac{f_i^0}{f_i} \right) \cdot \left(\frac{\Delta P_i}{\rho_i \cdot g} \right) \right. \\ &\quad \left. + C_i \cdot \left(\frac{f_i^0}{f_i} \right)^3 \cdot \left(\frac{\Delta P_i}{\rho_i \cdot g} \right)^2 \right] \cdot \rho_i, \end{aligned} \quad (19)$$

where A_i , B_i , C_i – are coefficients stated in RCPS certification document of the i-loop and to be proved during commissioning activities for the purpose of accounting for design differences between a calibration rig and the actual RCPS location (location and design of taps, etc.); f_i – is power supply frequency of RCPS in i-loop; f_i^0 – is a calibrated RCPS supply frequency in an i-loop; $\rho_i = \rho(P_{inl}, \rho_i^c)$ – is coolant density in cold leg of an i-loop; P_{inl} –

is inlet core pressure; T_i^c – is cold leg temperature in an i-loop; ΔP_i – is pressure gradual in RCPS in an i-loop; $g = 9.81$ m/s² – is free fall acceleration.

In transient condition of loop operation after RCPS trip the period of T_{run} , which depends on RCPS “run-out”, the mass coolant flow in the primary loop is defined by the mass coolant flow before the RCPS trip. When the RCPS “run-out” is finished, the calculation is carried out according to reverse current formula:

$$G_i = -F_{RCPS} \cdot \sqrt{\frac{2 \cdot \rho_i \cdot \Delta P_i}{\xi_i}}, \quad (20)$$

where ξ_i – is a coefficient of hydraulic resistance to reverse RCPS current in an i-loop, assigned in RCPS certification document; $\rho_i = \rho(P_{inl}, T_i^c)$ – is coolant density in cold leg of an i-loop; P_{inl} – is inlet core pressure; T_i^c – is cold leg temperature in an i-loop; ΔP_i – is pressure gradual in RCPS in an i-loop.

4.5 Determining temperature values using resistive thermometer signals

The temperature in the location of platinum resistive thermometer is determined using formula [5]:

$$T_{Pt} = \frac{\sqrt{A^2 + 4 \cdot B \cdot \left(\frac{R}{R_0} - 1 \right)} - A}{2 \cdot B}, \quad (21)$$

where A , B , R_0 – are individual coefficients intended for each platinum resistive thermometer, which are defined by the thermometer performances indicated in the certification document; R – is measured resistance.

Copper resistive thermometers are also possible. The following formula is valid for this kind of thermometers:

$$T_{Cu} = \frac{100}{W_{100} - 1} \left(\frac{R}{R_0} - 1 \right), \quad (22)$$

where W_{100} , R_0 – are individual coefficients of copper resistive thermometer, indicated in certification document; R – is measured resistance.

4.6 Determination of temperature values by means of thermocouple signals

The equation of coolant temperature in the location of i-thermocouple is given below:

See equation (23) below.

where A_1 , B_1 , C_1 – are the coefficients of cubic polynomial for the range 0-170 C; A_2 , B_2 , C_2 – are the coefficients of

$$T = \begin{cases} A_1 \cdot U^3 + B_1 \cdot U^2 + C_1 \cdot U, & \text{for } 0 < U \leq 7.0 \text{ mV} \\ A_2 \cdot U^2 + B_2 \cdot U + C_2, & \text{for } 7.0 < U \leq 14.3 \text{ mV} \end{cases} \quad (23)$$

quadratic polynomial for the range 170-350 °C; U – is thermocouple thermoelectromotive force (thermo-emf) in relation to 0 °C.

The value of U is calculated by formula:

$$U_i = (U_{CJ})_i + (U_{TC})_i, \quad (24)$$

where $(U_{CJ})_i$ – is a thermo-emf of the i -th thermocouple at temperature equal to the temperature of cold junction; $(U_{TC})_i$ – is a measured thermo-emf of i -th.

The value of $(U_{CJ})_i$ is calculated by formula:

$$U_{CJ} = A_{CJi} \cdot T_{CJi}^3 + B_{CJi} \cdot T_{CJi}^2 + C_{CJi} \cdot T_{CJi}, \quad (25)$$

where $(A_{CJ})_i$, $(B_{CJ})_i$, $(C_{CJ})_i$ – are the coefficients of cubic polynomial for converting the temperature of cold junction into thermo-emf of an i -th thermocouple; T_{CJi} – is the temperature of cold junction of an i -th thermocouple, which is determined by resistive thermometer.

Coefficients A_1 , B_1 , C_1 , A_2 , B_2 , C_2 , A_{CJ} , B_{CJ} , C_{CJ} are determined by calibrated thermocouple characteristics.

4.7 Calculation of reactor thermal power using thermal hydraulic characteristic of the primary circuit

The reactor heat power is calculated on the basis of thermal hydraulic characteristic of the primary circuit according to the following formula:

$$Q_{IK} = \sum_{i=1}^4 Q_i, \quad (26)$$

where Q_i – is the heat power in an i -th loop.

The value of Q_i is determined by formula:

$$Q_i = G_i \cdot (i_h - i_c) - N_{RPCS}, \quad (27)$$

where G_i – is coolant flow in an i -th loop; $i_h = i(P_{out}, T_i^h)$ – is the enthalpy in the hot leg in an i -th loop; $i_c = i(P_{int}, T_i^c)$ – is the enthalpy in the cold leg in an i -th loop; P_{out} – is the outlet core pressure; P_{inl} – is the inlet core pressure; T_i^h – is the temperature in the hot leg in an i -th loop; T_i^c – is the temperature in the cold leg in an i -th loop; N_{RPCS} – is RPCS power.

4.8 Calculation of reactor heat power using SPND signals

The reactor heat power is calculated on the basis of SPND signals according to the following formula [5]:

$$Q_{SPND} = K1 \cdot L_{FA} \cdot \frac{\sum_{m=1}^{54} \sum_{k=1}^7 \xi_{km} \cdot \lambda_{km} \cdot J n_{km}}{\sum_{m=1}^{54} \sum_{k=1}^7 \xi_{km}}, \quad (28)$$

where $J n_{km}$ – is normalised current of k SPND in m ICID; λ_{km} – is sensitivity of k SPND in m ICID, adjusted to FA

length unit and which is periodically displayed by VK ICIS; ξ_{km} – is the indicator of serviceability of k SPND in m ICID (0 or 1); $L_{FA} = 163 H_c$ – is the total fuel length of all FAs; H_c – is the core height; $K1$ – is the coefficient of ratio of the power in all FAs to the power of FA with ICID, and which is calculated on the basis of recovered power density and which periodically delivered from VK ICIS.

4.9 Calculation of weighted average of reactor thermal power

The weighted average of reactor thermal power is calculated by the following formula:

$$Q_{ave} = \frac{\mu_{1K} \cdot Q_{1K} + \mu_{SPND} \cdot Q_{SPND}}{\mu_{1K} + \mu_{SPND}}, \quad (29)$$

where Q_{1K} – is reactor thermal power according to thermal hydraulic parameters of the primary circuit; Q_{SPND} – is reactor thermal power according to SPND signals; μ_{1K} , μ_{SPND} – are statistical weights of thermal power calculated on the basis of thermal hydraulic characteristics of the primary circuit and SPND signals, respectively. They are determined in the analysis of thermal power values deviations from the truest value, which are to be determined by various methods. Such analysis is performed in PTK-VU.

4.10 Algorithm of determining a fuel rod linear power density and generating a protection signal on the basis of this parameter

The value of linear power of the most stressed fuel rod in an (i,j) -th part of the core is determined by averaging of linear power values, which were determined from the signals of six SPNDs of the most close ICID that belong to various PTK-Z channels, where j is FA No according to the map of core loading (Fig. 1). Correspondence between j -th FA and $j(n)$ -th ICID in each FA is shown in Table 2 (the Table gives the Nos. of FAs. with ICID, the distance between ICID and applicable FA is given in the brackets) [5].

SPND numbering in ICID corresponds to elevation numbering in FA (Fig. 7).

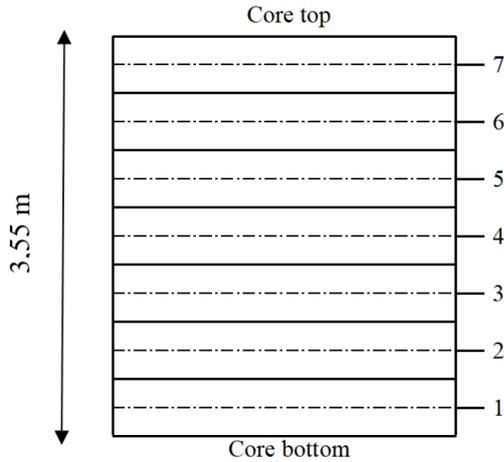
Statistical summarising (averaging) for the neighbouring SPND is performed according to the following formula [5]:

$$\bar{A}_{ij} = \frac{KK_{ij}}{311} \cdot \frac{\sum_{n=1}^6 q_{ijj_n} \cdot \eta_{ij_n} \cdot \frac{KV_{ij} \cdot J_{ij_n} \cdot \lambda_{ij_n}}{KV_{ij_n} \cdot Kc_{ij_n}}}{\sum_{n=1}^6 q_{ijj_n} \cdot \eta_{ij_n}}, \quad (30)$$

where KK_{ij} – is a linear power peaking factor of the most stressed fuel rod of the (i,j) section of the core; Kc_{jn} – is a mean linear power peaking factor of six fuel rods surrounding a tube with ICID in the (i,j) section of the core; KV_{ij} – is relative power density of the (i,j) section of the core; KV_{ij_n} – is relative power density in n SPND location associated with (i,j) section of the core; j_n – are

Table 2. List of six FAs located in the close vicinity of ICID and used for power density calculation in every FA.

FA No.	Channel 1	Channel 2	Channel 3	Channel 4	Channel 5	Channel 6
1	10(2)	16(4)	30(4)	12(4)	2(2)	18(2)
2	10(2)	16(5)	30(4)	12(4)	2(0)	5(3)
3	10(1)	16(5)	14(5)	12(2)	2(2)	5(2)
...
161	158(3)	163(2)	160(1)	148(5)	145(2)	153(1)
162	158(4)	163(1)	160(2)	148(4)	145(2)	153(2)
163	158(5)	163(0)	147(3)	148(4)	145(2)	136(4)

**Fig. 7.** Core levels whose geometrical centres (from 1st to 7th) correspond to SPND emitters (1, 2, ..., 7).

ICID Nos. that surround j -th FA ($n = 1, \dots, 6$); λ_{ij_n} – is the sensitivity of i -th SPND in the j_n -th ICID converted into the unit of FA length measurement; η_{ij_n} – is the sign of (i, j_n) SPND availability; J_{ij_n} – is normalised F current of i SPND in j_n ICID; q_{ij_m} – is statistical weight of j_n SPND signal in calculation of linear power density in ij section of the core.

q_{ij_m} shall be originally determined according to formula:

$$q_{ij_n} = \frac{F(r)}{F(o)}, \quad (31)$$

where $F(r)$ is a relative value of “influence function” at distance r from the centre of (j) th FA to location of j_n -th SPND at i level; $F(o)$ is a relative value of “influence function” in the centre of j -th FA (Fig. 2.).

Correspondence of statistical weights to the distance between ICID and FA is given in Table 3.

Relative power density 3-dimensional in core distributions are gained during power density recovery process in VK ICIS. Power density recovery algorithm is based on mathematical model including equation of connection between the results of measurements and the field to be found, and also the neutron diffusion equation. To work out the diffusion equation and definition neutron-physical model parameters the iteration method is used. To decrease

Table 3. Correspondence between statistical weight and distance between ICID and FA.

Distance between ICID and FA	Statistical weight
0	1
1	0.2954
2	0.1336
3	0.1024
4	0.0554
5	0.005

deviation between neutron-physical model and transducer signals adaptation of material parameter and division section, based on measurement results is carried out.

For the purpose of calculation accuracy of fuel rod [11] linear power density and reliability of protection signal, which generates on the basis of this parameter, the value of linear power of the most stressed fuel rod of FA that contains working group CPS CR in (i, j) section of the core is determined on the basis of duplicated statistical summarising according to the following formula [5]:

$$\overline{A_{ij}} = \frac{KK_{ij}}{311} \cdot \frac{\sum_{l_j=0}^6 KV_{ij} \cdot \overline{KV}_{ilj} \cdot q_{ijlj}}{\sum_{l_j=0}^6 KV_{ilj} \cdot q_{ijlj}}, \quad (32)$$

where \overline{KV}_{ilj} – is the value of relative power density calculated on the basis of formula:

$$\overline{KV}_{ilj} = \frac{\overline{A}_{ilj}}{KK_{ilj}} \cdot 311, \quad (33)$$

where \overline{A}_{ilj} – is the magnitude to be determined using formula (30) for every FA adjacent to the j FA ($l_j = 0, \dots, 6$), if $l_j = 0$ $Kv_{ilj} = Kv_{ij}$.

In the base condition, arrays KK , Kc , KV λ and η are periodically delivered from VK ICIS and ensure on-line monitoring of linear power of the most stressed fuel rods by way of on-line measuring of SPND currents.

The acquired \bar{A}_{ij} values are compared against the design limitations (PP, scram), which are individual for every axial core section.

If a design limitation is achieved or exceeded at any of the core sections, an applicable protection signal shall be sent to scram – PP system.

The process of preparation, verification and display of the above mentioned magnitudes to PTK-Z is called calibration of protection system instrumentation channels on the basis of local parameters, which is required for sustaining ICIS metrology characteristics at applicable level within a considered function.

In order to use calibration data it is required to write formula 30 anew in the following format:

$$\bar{A}_{ij}(t) = \frac{KK_{ij}(0)}{311} \cdot \frac{\sum_{n=1}^6 q_{ijn} \cdot \eta_{ijn} \cdot \frac{KV_{ij}(0) \cdot J_{ijn}(t) \cdot \lambda_{ijn}(0)}{KV_{ij(n_{jn})}(0) \cdot Kc_{ijn}(0)}}{\sum_{n=1}^6 q_{ijn} \cdot \eta_{ijn}}, \quad (34)$$

and formula (32) in the following format:

$$\begin{aligned} \bar{A}_{ij}'' &= \frac{\sum_{l=0}^6 \bar{A}_{ijl_j} \cdot q_{ijl_j}}{\sum_{l=0}^6 q_{ijl_j}} \\ &= \frac{KK_{ij}(0)}{311} \cdot \frac{\sum_{l_j=0}^6 \frac{KV_{ij}(0) \cdot \overline{KV}_{ijl_j}(t)}{KV_{ijl_j}(0)} \cdot q_{ijl_j}}{\sum_{l=0}^6 q_{ijl_j}}, \end{aligned} \quad (35)$$

where l_j are the numbers of FAs adjacent to the j -th FA if $l_j = 0$, $l_j = j$.

All the coefficients and magnitudes, except $J_{ijn}(t)$, are valid for the time when calibration was performed.

4.11. Algorithm for calculation of minimal value of departure from nucleate boiling ratio and generating a protection signal on the basis of this parameter

The aggregate coolant mass flow G^{1K} in the primary loops is calculated by the following formula [5]:

$$G^{1K} = \sum_{k=1}^4 G_k, \quad (36)$$

where G_k – is the coolant mass flow in k -th loop.

An average water mass velocity in FA cell (ρw) is calculated using the following formula:

$$\rho w = \frac{G^{1K} \cdot (1 - K_{leak})}{163 \cdot F_{FA}} \cdot K_{peak}, \quad (37)$$

where K_{leak} – is a coefficient that accounts coolant leakages; $F_{FA} = 0.0246\text{m}^2$ – is the area of FA cross section without central channel and channels for AR; $K_{peak} = 0.98$ – is a coefficient that accounts the mass velocity peaking along FA cross section.

For every FA, the coolant inlet temperature is determined using the following formula:

$$T_j^{inl} = \frac{\sum_{k=1}^4 T_k^c \cdot G_k \cdot P_{kjm} \cdot F_k}{\sum_{k=1}^4 G_k \cdot P_{kjm} \cdot F_k}, \quad (38)$$

where j – FA No; T_k^c – is coolant temperature in cold leg of k -th loop; F_k – is the sign of RCPS actuation in k -th loop; G_k – is coolant flow in k -th loop; m – is a code making $F_{18} + F_{24} + F_{32} + F_4$; P_{kjm} – is a coefficient of k loop temperature influence on the temperature of j the FA with m -th condition of values of signs F_k .

For each selected core section (i, j), enthalpy I_{ij} is calculated according to the following formula:

$$I_{ij} = \frac{\frac{H_c}{8} \cdot \left(\frac{\bar{A}_{1j}}{8} + \sum_{n=1}^{i-1} \bar{A}_{nj} + \frac{\bar{A}_{ij}}{2} \right) \cdot 10^6 \cdot \frac{1}{3}}{\rho w \cdot F_{cell}} \cdot K_t + I_i^{inl}, \quad (39)$$

where $K_t - K_t$ is margin coefficient in preheating; $I_i^{inl \text{ } o=0} = I(P_{inl}, H_c^{o=0})$; H_c – is the core height; P_{inl} – is inlet pressure in the core; F_{cell} – is the area of cross section of the cell under consideration.

For each selected core section (i, j) relative enthalpy X_{ij} is calculated in accordance with the following formula:

$$X_{ij} = \frac{I_{ij} - I(P_{inl})}{r(P_{inl})}, \quad (40)$$

where $I(P_{inl})$ – is water enthalpy in saturation line; $r(P_{inl})$ – is specific heat of vaporisation.

For each selected core section (i, j) the value of critical heat flux Q_{ij}^{cri} is calculated using the following formula:

See equation (41) below.

$$Q_{ij}^{cri} = f_F \cdot 0.795 \cdot \left((1 - X_{ij})^{0.105 \cdot P_{inl} - 0.5} \right) \cdot (\rho w)^{0.311 \cdot (1 - X_{ij}) - 0.127} \cdot (1 - 0.0185 \cdot P_{inl}), \quad (41)$$

where f_F – is form factor calculated by formula:

See equation (42) below.

where $P_{inl} = 22,115$ MPa is critical water pressure.

Departures from nucleate boiling ratio (DNB_{ij}) are determined according to formula:

$$DNB_{ij} = \frac{Q_{ij}^{cri} \cdot \pi \cdot d \cdot (1 - K_f)}{\bar{A}_{ij} \cdot K_q}, \quad (43)$$

where K_f – is the error of formula for critical heat flux; K_q – is margin coefficient for power; $= 3.1416$; $d = 0.0091$ m – is fuel rod diameter.

From all the obtained DNB_{ij} values the smallest DNB_{min} value is selected and compared against the design limitations (PP, scram). Should the design limitation be reached or fall below, an applicable protection alarm signal shall be sent to system PP-scram.

5 Uncertainty calculations

5.1 General description

The whole set of uncertainties of local protection system may be split into two parts: dynamic and statistical [5].

Dynamic uncertainties are defined by:

- increase velocity of local linear power density, method selected for elimination of time delay of SPND currents and uncertainty in determining the value of the instant component of SPND signals, which comprise the system (σ_{K-F} , σ_{F-K});
- uncertainty in determining the instant component (σ_{Kdin}).
- scope and manner of CPS CR movement within the time period between calibration actions (σ_{Rb}).

Allowable difference between current calibration coefficients and those transmitted to PTK-Z (σ_{Calibr}).

Statistical uncertainties are defined by:

- distance between the controlled section and transducer (σ_K);
- uncertainty of calibration coefficients (σ_{VV});
- uncertainty of the equipment, which in our case depends on the share of random component of uncertainty in measuring SPND currents, and also by interference and induction on

the way of passing a signal from Rhodium SPNDs and methods that are used for their elimination σ_{equip} .

Both uncertainties of tolerance values for fuel production and assembly-to assembly gaps are taken into account in calculation of engineering uncertainty coefficient. The uncertainty of reactor thermal power is taken into account in calculation of uncertainty coefficient for keeping reactor power. Both the uncertainty coefficient and safety factor are taken into account in calculation of ultimate tolerable values of power density in a certain fuel loading.

5.2 Analysis of dynamic uncertainty

It is adopted in the system:

- for monitoring the processes with velocities ranging within 4% per second and 40% per second to apply a corrective filter;
- for monitoring the processes with velocities ranging within 0.1% per second and 5% per second to apply a Kalman filter.

Any of these filters has a 0.6 s response cycle, emitter diameter of 0.5 mm (instantaneous component is close to 6%). The corrective filter is capable to completely eliminate the delay, while Kalman filter is intended to allow a 0.5 s delay and reduced coefficient of interference elimination.

Investigation proved that:

- corrective filter provides a time delay at 0.05 s for its range of processes of time changes, and this time delay may be neglected. In this case, the uncertainty, which comprises the influence of interference and induction, is defined by rejection “gates” and does not exceed $\pm 4\%$;
- kalman filter, provides a time delay at 0.5 s for its range of processes of time changes, and this time delay may be also neglected. In this case, the uncertainty, which comprises the influence of interference and induction, is defined by rejection “gates” and does not exceed $\pm 1\%$.

A complimentary time difference, caused by a probable uncertainty of instantaneous component ranging within $\pm 17\%$ ($c = (6 \pm 1)\%$), (for instance, the filter is adjusted for an instantaneous component of 6%, while SPND has a 5% instantaneous component), has the value of ± 0.05 s for a corrective filter and for Kalman filter ± 0.5 s. This brings to additional maximal errors: for corrective filter at most $\pm 2\%$, for Kalman filter at most $\pm 2.5\%$, respectively.

$$f_F = \begin{cases} \left(\frac{5}{8} \right)^{3,79-19,61 \cdot (Pinl/Pcri)+17,86 \cdot (Pinl/Pcri)^2}, & i = 1 \\ \left(\frac{2,06 \cdot \bar{A}_{1,j} + \bar{A}_{2,j}}{3,24 \cdot \bar{A}_{2,j}} \right)^{3,79-19,61 \cdot (Pinl/Pcr)+17,86 \cdot (Pinl/Pcr)^2}, & i = 2 \\ \left(\frac{0,24 \cdot \bar{A}_{i-2,j} + 2 \cdot \bar{A}_{i-1,j} + \bar{A}_{i,j}}{3,24 \cdot \bar{A}_{i,j}} \right)^{3,79-19,61 \cdot (Pinl/Pcr)+17,86 \cdot (Pinl/Pcr)^2}, & i = 3, \dots, 7 \end{cases}, \quad (42)$$

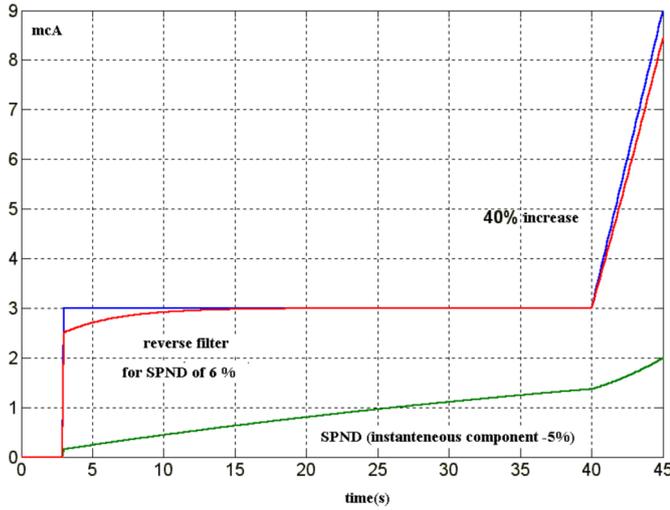


Fig. 8. Influence of incorrect accounting the instantaneous component upon the increase of corrective filter lagging behind.

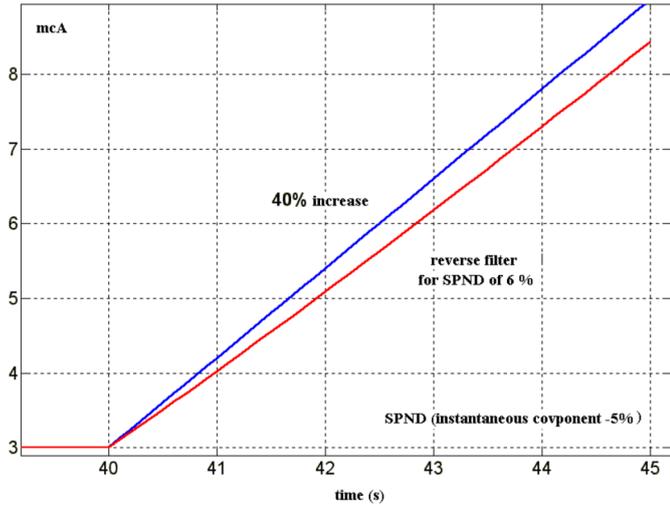


Fig. 9. Influence of incorrect accounting the instantaneous component upon the increase of corrective filter lagging behind.

For instance, [Figures 8 and 9](#) depict the reaction of lagging behind of a corrective filter with fluctuation of neutron flux velocity of 40% per second. In this case, the coefficients of the filter were adjusted for the instantaneous component of 6%, while the actual instantaneous component of SPND was 5%.

[Figure 10](#) depicts the reaction of lagging behind of Kalman filter with fluctuation of neutron flux rate of 5% per second.

In this case, the coefficients of the filter were adjusted for the instantaneous component of 6%, while the actual instantaneous component of SPND was 5%. The error discussed herein actually has a significantly smaller value, because the tolerance values for variance in diameters of Rhodium wire are small.

Thus, the aggregate dynamic uncertainty:

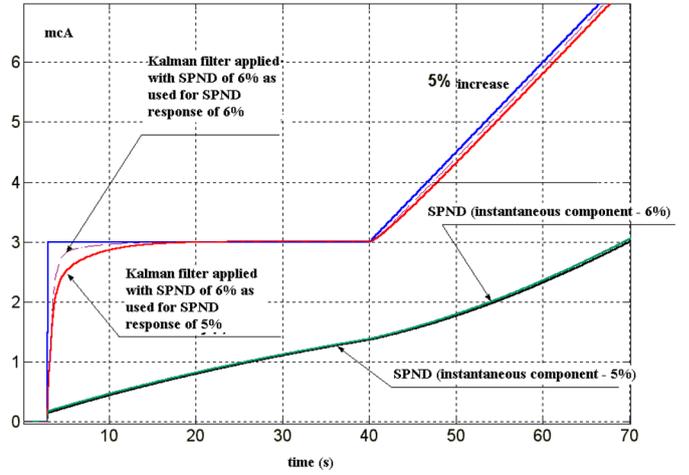


Fig. 10. Influence of incorrect accounting the instantaneous component upon the increase of Kalman filter lagging behind.

– for corrective filter does not exceed:

$$\sigma_{\text{DIN}K-F} = \sqrt{(\sigma_{K-F})^2 + (\sigma_{Rh})^2} = \sqrt{(4\%)^2 + (2\%)^2} \leq 4.5\%,$$

– for Kalman filter does not exceed:

$$\sigma_{\text{DIN}F-K} = \sqrt{(\sigma_{F-K})^2 + (\sigma_{Rh})^2} = \sqrt{(1\%)^2 + (2.5\%)^2} \leq 2.7\%,$$

and for the processes with velocities less than 1% per second Kalman filter uncertainty may be neglected.

6 Conclusion

For the purpose of protection on the basis of local parameters, a beta-emission detector (SPND) with a Rhodium emitter has been selected as an in-core neutron flux detector for the reasons compatibility with VVER design, long operation within ICIS at VVER reactors, availability of experience and skills (proved by long operation of ICIS in VVER plants) in registration and application of processes of interaction of Rhodium with neutrons, γ -rays, β -fission electrons of generated isotopes, generation of electrical current (escape of Compton electrons, β -particles and associated electrons from emitter), etc., and in development of algorithm, software or metrology support.

Power density recovery algorithm is based on mathematical model including equation of connection between the results of measurements and the field to be found, and also the neutron diffusion equation. To work out the diffusion equation and definition neutron-physical model parameters the iteration method is used. To decrease deviation between neutron-physical model and transducer

signals adaptation of material parameter and division section, based on measurement results is carried out.

Conflict of interests

The authors declare that they have no competing interests to report.

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Author contribution statement

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Stepan Lys and Alexandr Kanyuka. The first draft of the manuscript was written by Stepan Lys and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. CRediT taxonomy: conceptualization: Stepan Lys; methodology: Alexandr Kanyuka; formal analysis and investigation: Stepan Lys, Alexandr Kanyuka; writing - original draft preparation: Stepan Lys; writing - review and editing: Stepan Lys, Alexandr Kanyuka; resources: Alexandr Kanyuka; supervision: Stepan Lys. For the purpose of protection on the basis of local parameters, a beta-emission detector (SPND) with a Rhodium emitter has been selected by the author Lys Stepan, as an in-core neutron flux detector for the reasons compatibility with VVER design. To work out the diffusion equation and definition neutron-physical model parameters the iteration method is used, proposed by the author Alexandr Kanyuka.

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