Experience of Commissioning of BN-800 Core Diagnosing System (SDRU)

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1. SDRU designing purpose

The purpose to design the reactor facility (RF) diagnosing system (SDRU) is to enhance safety and reliability of RF operation by equipping the power-unit with instruments, which provide detection of anomalies in the core of RF BN-800 at the earliest stage.

2. SDRU functioning purpose

The core diagnosing system of reactor facility (SDRU) BN-800 is designed as an automatized system included in the technological processes automated control system (TP ACS) of RF BN-800. Its functioning purpose includes a comprehensive control and forecasting of development of the processes realized in the reactor in normal operating modes, failures of normal operating in the range of RF power changing from 0.1 to 120 % of Nnom [1-3].

The functioning purpose of the SDRU is a comprehensive analysis of changes in neutron-physical and technological parameters of the reactor based on the results of operation of diagnosing systems, early operative detection of parameters' deviations from permissible values in order to inform in time the operational personnel about arising and development of damages in the core including such anomalies as: sodium boiling in the core, arising of the "hot" spot, narrowing of flow sections in the channels of fuel sub-assemblies (FSA), melting of fuel elements in the core FSA, violation of distribution of loads in the intermediate heat-exchanger (IHE), self-movements of rods of the control and protection system (CPS), vibrations of the core in-vessel elements, violation of the core flow rate, failure of measuring channels.

3. SDRU software and hardware complex

The SDRU structural diagram is presented in Fig. 1.

Four sub-systems are included in the SDRU, namely: a neutron-noise diagnosing system (SNSHD); abnormal reactivity detection system (SOAR); core temperature monitoring system (STKAZ); complex analysis system (SKA).

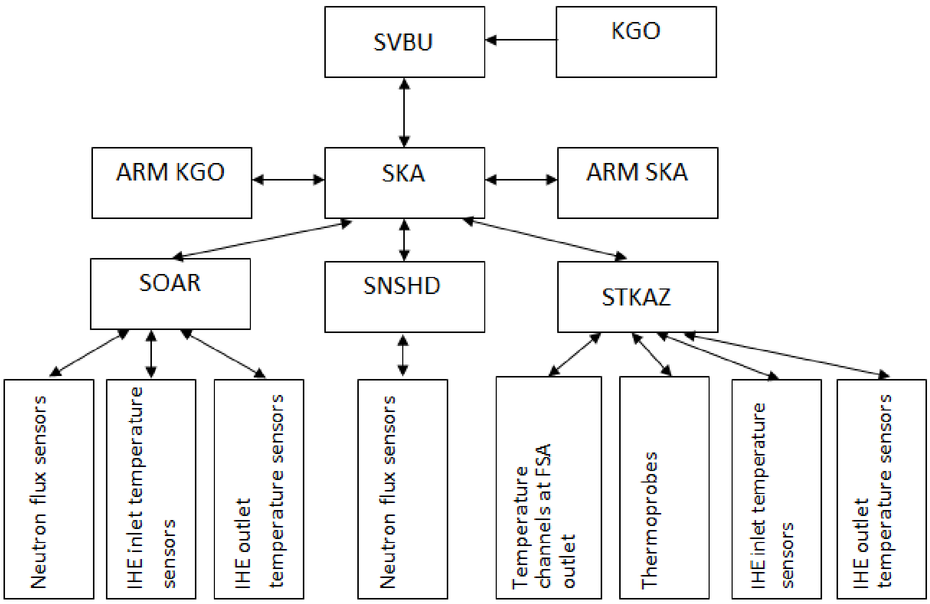

Fig. 1. SDRU structural diagram

The neutron-noise diagnosing system (SNSHD) consists of two channels of measuring of ionization chambers' current and performs measurements of current fluctuation spectrum within the following two frequency sub-ranges: from 0.1 to 3 Hz (a low one), and from 1 to 35 Hz (tentatively, a high one). The system is performing continuous monitoring of the current spectrum of reactor power noises and detection of disturbance in the spectrum shape and intensity caused by anomalies.

The abnormal reactivity monitoring system (SOAR) of reactor facility BN-800 consists of two autonomous channels of reactivity measuring, device of calculation of reactivity balance and 12 channels of temperature measuring at the inlet and outlet of each IHE.

The core temperature monitoring system (STKAZ) consists of 67 temperature monitoring channels, namely: 31 thermocouples are mounted on the bottom of the CPS column; 12 thermocouples are mounted at the IHE inlet and outlet; 24 thermocouples are mounted in three eight-zone thermoprobes. The STKAZ is determining the current values of sodium temperature at the FSA outlet, at the IHE inlet and outlet and thermoprobes. In addition, the STKAZ is analyzing natural fluctuations of temperature for the purpose to detect unsafe faults in the core cooling system and its separate FSA.

The complex analysis system (SKA) is designed for the comprehensive processing and analysis of the information received from low level systems SOAR, SNSHD, STKAZ in order to enhance reliability of diagnosing solutions, detect early indications of core damages and display corresponding messages to the operational personnel. The computerized workstation (CWS) of the system of monitoring of fuel elements claddings tightness (KGO) is connected to the SKA as well.

Table 1 – Basic parameters of SDRU measuring channels

Measuring parameter	Reactivity	Temperature	Chamber current
The number of measuring channels, pcs.	2	12 SOAR 67 STKAZ	2 SOAR 2 SNSHD
Measuring range	from -1.0 β to +0.2 β	from 20 to 600 °C	from 10^{-7} to 10^{-3} A
Absolute error	10^{-4}dk/k	3.5 °C	2 % of SOAR 0.5 % of SNSHD
Intrinsic noise		0.15 °C	$2 \cdot 10^{-11}$ A of SOAR $1 \cdot 10^{-11}$ A of SNSHD
Measured fluctuations of parameters		0.15 °C	$1 \cdot 10^{-4}$ of the set range

4. The algorithm of core diagnosing

The mathematical apparatus of the SDRU diagnosing model is based on the following provisions:

– anomalies appear as a set of symptoms i.e. diagnosing signs;

– the set of symptoms make possible determination of the anomaly type i.e. to state a diagnosis.

The symptoms are those facts when the values of diagnosing parameters are beyond the assigned setpoints. Both the statistical parameters, such as an average one and root-mean-square error (MSE) of measured parameters (temperature, ionization chambers' current), and the results of special diagnosing models (for example, abnormal reactivity – the result of balance calculation, shape of spectral density of the process and so on) could be considered as diagnosing parameters. The values of setpoints determining the margins of parameters' changing under normal functioning of the reactor are formed at the stages of power launch and pilot operation. They are determined depending on the level of power and the number of operating loops in the reactor.

The sub-systems included in the SDRU (SOAR, SNSHD, STKAZ) and the system of monitoring of tightness of fuel elements claddings (KGO) are forming the following **diagnosing signs**:

– abnormal reactivity (SOAR);

– violation of power distribution over operating loops (STKAZ);

– violation of balance for generated and carried out powers (STKAZ);

– exceeding of the temperature setpoint in the core i.e. "hot spot" (STKAZ);

– exceeding of the setpoint for temperature MSE in the core (STKAZ);

– exceeding of the setpoint for chamber's current MSE (SNSHD);

– occurrence of resonance of spectral power density (SPD) of chamber current in the low frequency (LF) area (under 3 Hz) (SNSHD);

– occurrence of SPD resonance of chamber current in the high frequency (HF) area (over 3 Hz) (SNSHD);

– increase of indications (gas depressurization) in the gas system of tightness monitoring of fuel elements claddings (KGO) (GSKGO);

– increase of indications (failure of fuel tightness) in the sectoral system of tightness monitoring of fuel elements claddings (KGO) by delayed neutrons (SSKGO).

Based on the diagnosing signs, the SKA is forming diagnoses determining the technical state of the core.

– possible boiling of sodium in the core FSA (initial stage);
– boiling of sodium in the core FSA;
– local violation of temperature in the core FSA;
– abnormal reactivity;
– over-standard increase in the amplitude of reactor power swinging;
– over-standard increase in the amplitude of core elements vibrations.

The elements of matrix “symptoms – diagnosis” are as follows: -1; 0; +1. That means correspondingly: the parameter value is beyond the low setpoint, the parameter value is the same, the parameter value is beyond the high setpoint. The diagnosis is described as a vector with specified values of elements. The diagnosis list and corresponding reference vectors are compiled in advance and inserted in Table. The vector of current values of symptoms is compared with a list for diagnosing of the situation. The diagnosis is considered as a reliable one if a scalar product of reference vector $\vec{E}$ and vector of measured symptoms $\vec{S}$ is maximal:

$$D = \max_j(\vec{E} \times \vec{S}) = \sum_{i=1}^{N} e_i s_i \qquad (1)$$

where e_i, s_i – components of vectors, N – dimension, M – the number of possible diagnoses.

The structure of diagnosing results displaying at the main SKA screen to the specialists of Department for Nuclear Safety & Reliability (DNS&R) at Beloyarsk nuclear power plant (NPP) is presented in Fig. 2. For visual perception on the SKA screen for the comprehensive analysis results, the technical state of the reactor core is marked by color (“core diagnosing light”):

1. Green level (standard) is specifying a low probability of damage arising in the core.
2. Blue level (warning) is determining a general warning about deviation of RF operation from a normal mode. The operational personnel must control the functioning operability of measuring channels. The higher attention must be paid to indications of the systems of temperature monitoring in the core, power and reactivity monitoring, and KGO systems.
3. Yellow level (heightened) is determining a considerable risk of damage arising in the core. The operational personnel must heighten their vigilance, come into contact with the specialists of DNS&R and begin to reveal the reasons of deviation from the normal mode and arising of anomaly.
4. Orange level (high) is determining a possibility of damage occurrence in the core. That event requires to call immediately the DNS&R specialists and take measures on elimination of the cause of anomaly.
5. Red level (extremely high) is specifying a direct threat of arising of sodium boiling in the core and damage of fuel elements claddings or significant damage in the core. In an event of impossibility to eliminate the cause of damage by operative measures, the decision to shutdown the reactor must be taken.

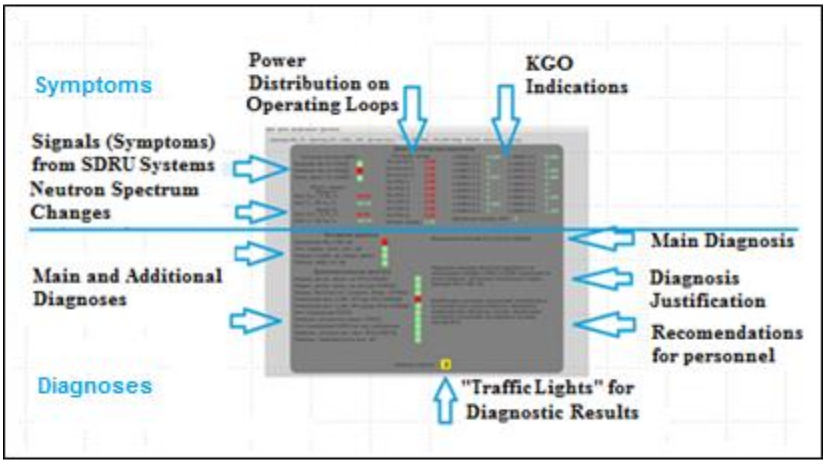

FIG. 2. The structure of diagnosing results displaying

5. Pilot operation results

All measurements of SDRU parameters were performed in a background mode in the process of realization of physical launch and at the stages of setting power of 5 %, 10 %, 15 %, 35 %, 50 %, 67 %, 85 %. Parameters of temperature measuring channels were assessed in the process of isothermal mode realization within the temperature range of (243÷312) °C. The obtained results have confirmed those presented in the technical assignment (TA). The diagram of changing of deviation of measured values of IHE thermocouple channels from the average temperature in totality is presented in Fig. 3.

The diagrams reveal that maximal deviation from an average measured value of temperature does not exceed ±1.7 °C within the range of (243±213) °C. Temperature measuring increment is about 0.07 °C.

The time of diagnosis forming is important for finding the solutions to the tasks of diagnosing. It is connected with the time of performance of measurements and response time (response speed) of the sensor. In the given case, the response time of temperature channels is determining the informative bandwidth of the measuring channel, which must be reasonable for diagnosing of the process of coolant boiling and be not less than 2 Hz.

The diagram of changing of thermocouple channels over the core in an event of power drop is presented in Fig. 4. The diagrams reveal that for different thermocouples the delaying time of the measured temperature value in the STKAZ differs much while power is decreasing. Under condition, the thermocouples could be divided into three groups, the slower thermocouples could be used for diagnosing with some restrictions.

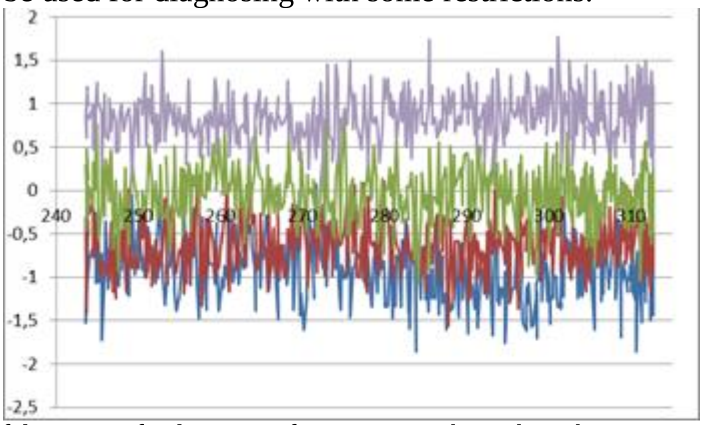

FIG. 3. Dependence of deviation of indications of temperature channels in the STKAZ on the average value of temperature

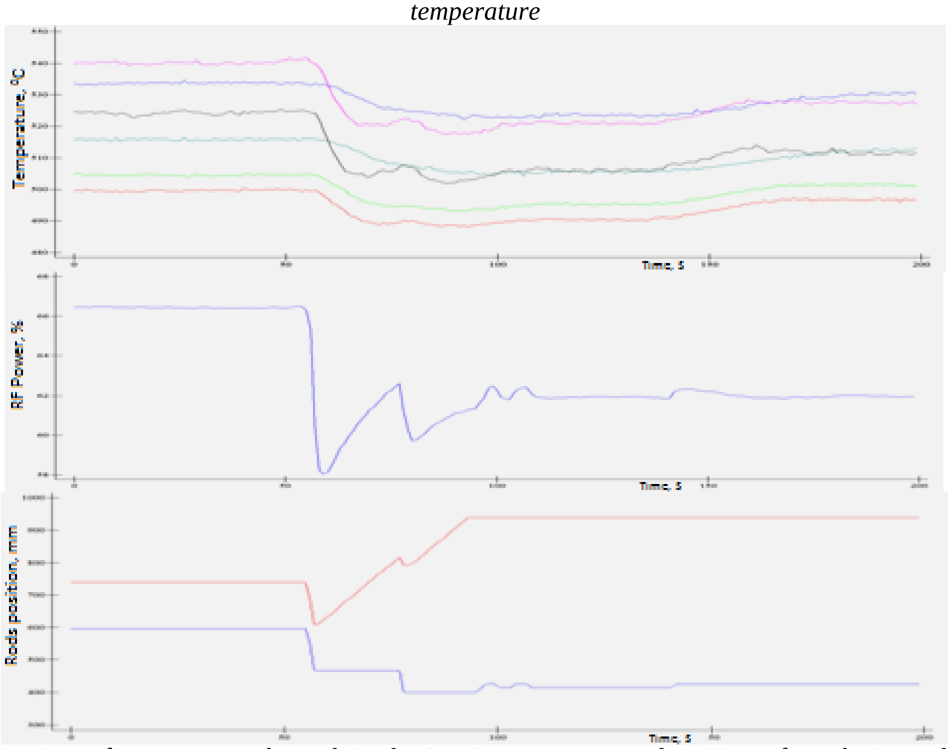

FIG. 4. Indications of temperature channels in the STKAZ, RF power and position of regulating rods (RR) upon power maneuver

The diagram of dependence of temperature channels MSE in the STKAZ on power maneuver is given in Fig. 5. The diagram reveals that according to the MSE value the temperature channels could be also divided into three groups: with an MSE value being over 7 °C, with an MSE value being under 5 °C, with an MSE value being within the range from 5 to 7 °C.

The obtained distribution could be explained by the fact that the thermocouples with a low response time can better monitor the changes in coolant temperature and, correspondingly, their MSE are maximal, and the thermocouples with low MSE values and slower ones are most likely in the stagnant area.

The recorder chart of thermocouples mounting over the core and distribution of the temperature channels MSE over the core upon power manoeuvring is given in Fig. 6. The recorder chart of thermocouples mounting over the core and distribution of the temperature channels MSE over the core upon the stable power level of 85 % of Nnom is given in Fig. 7. Figures reveal there are two areas in the core, namely with a low and large values of the temperature MSE.

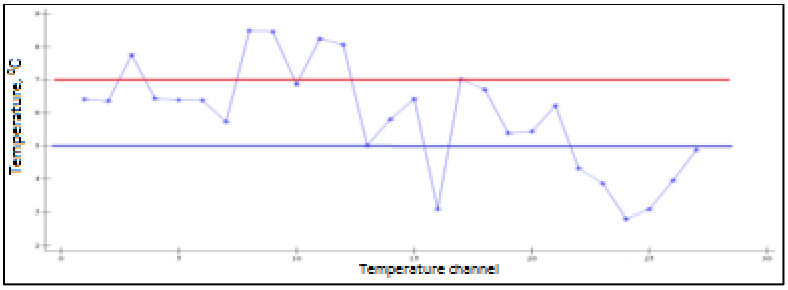

FIG. 5. Dependence of the temperature channels MSE over the core in the STKAZ on power manoeuvring

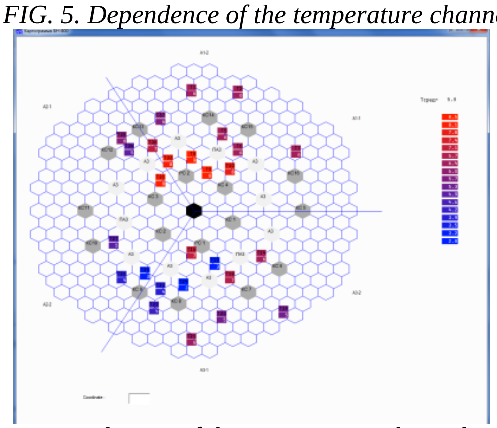

Fig. 6. Distribution of the temperature channels MSE over the core upon power manoeuvring

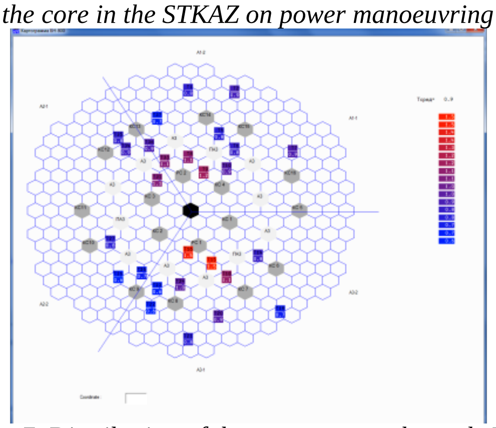

Fig. 7. Distribution of the temperature channels MSE over the core upon the RF power level of 85 % of Nnom

Comparison of Fig. 5, Fig. 6, Fig. 7 is showing coincidence of areas with low and large values of temperature distributions MSE in the reactor core.

The results of temperature measuring at the IHE 1 inlet (the left diagram) and IHE 2 inlet (the right diagram) upon power manoeuvring are presented in Fig. 8. Distinction in values of the response time for separate measuring channels can be seen in the diagrams as well. It is presumed to perform the analysis of the revealed features in behavior of temperature channels at the following stages of power-unit pilot operation.

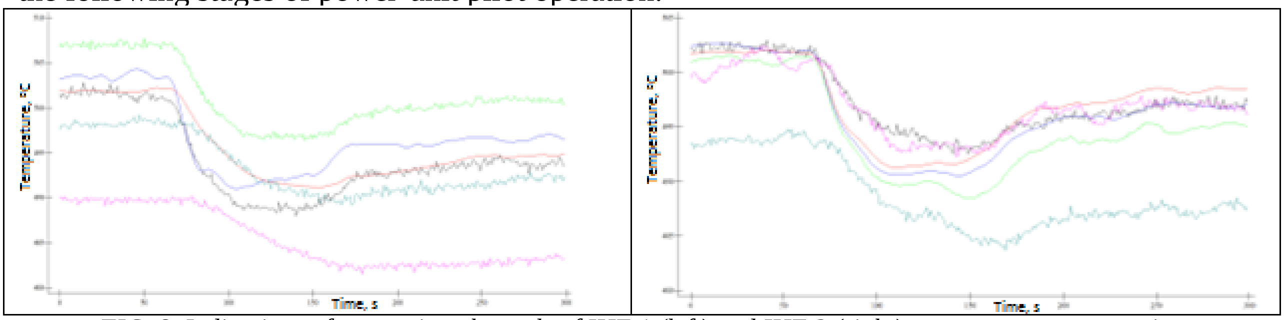

FIG. 8. Indications of measuring channels of IHE 1 (left) and IHE 2 (right) upon power manoeuvring

Assessment of linearity and error in measurements of ionization chambers' current in the SNSHD and SOAR was realized by comparison with indications of standard channels of the neutron flux monitoring equipment (NFME) while setting the power level of 50 % of Nnom. The results of comparison of current channels indications from the SDRU and NFME are presented in Fig. 9, Fig. 10.

Figure 9 shows that deviation of the measured value of average current in the SNSHD from a linear one is much less than 1 %. Figure 10 shows that deviation of the measured value of average current in the SOAR from a linear one is less than 2 %.

To assess the delaying time for standard parameters transmitted to the SDRU from the upper level control system (ULCS), the comparative analysis of indications of the ULCS standard parameters and parameters monitored in the ULCS was realized. Changes in values of the average current in the SNSHD and power level upon small changes in the RF power are presented in Fig. 11. The diagrams given in Figures reveal that delaying time for the measured value of average current in the SNSHD from the value of power is less than 2 s.

In the process of STKAZ pilot operation the assessment of the main diagnosing signs at different power levels for formation of values of parameters corresponding to the standard ones was performed.

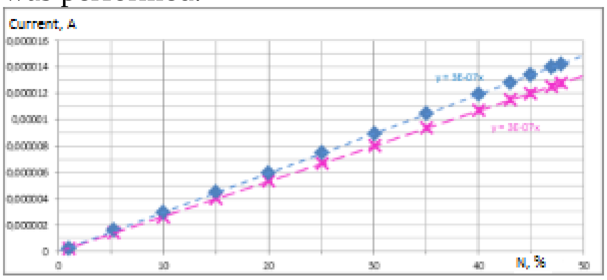

FIG. 9. Dependence of the value of average current in the SNSHD ionization chambers on the RF power level

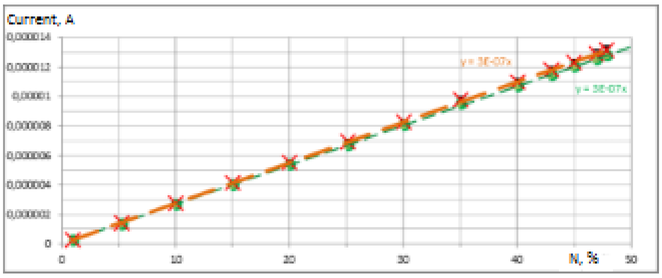

FIG. 10. Dependence of the value of average current in the SOAR ionization chambers on the RF power level

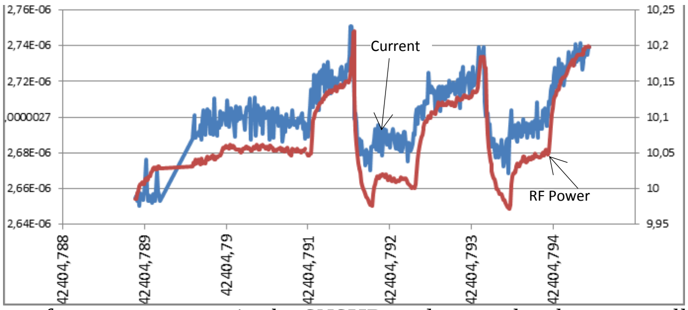

FIG. 11. Changes in values of average current in the SNSHD and power level upon small changes in the RF power

Assessments of the values of reciprocal spectral density (RSD) and coherence between the current fluctuation measuring channel in the SNSHD and core temperature channels in the STKAZ at a power level of 30 %, 60 %, 85 % of Nnom. in the frequency band range of (0.1÷3.0) Hz are given in Fig. 12. The 30 % power level is marked in blue color, 60 % power level is marked in green color, power level of 85 % of Nnom. is marked in red color.

Assessments of the values of reciprocal spectral density and coherence between the current fluctuation measuring channel in the SNSHD and core temperature channels in the STKAZ IHE1 inlet and outlet at a power level of 30 %, 60 %, 85 % of Nnom. in the frequency band range of (0.1÷3.0) Hz are given in Fig. 13.

Assessments of the values of reciprocal spectral density and coherence between the current fluctuation measuring channel in the SNSHD and core temperature channels in the IHE2 inlet and outlet are given in Fig. 14. The 30 % power level is marked in blue color, 60 % power level is marked in green color, power level of 85 % of Nnom. is marked in red color.

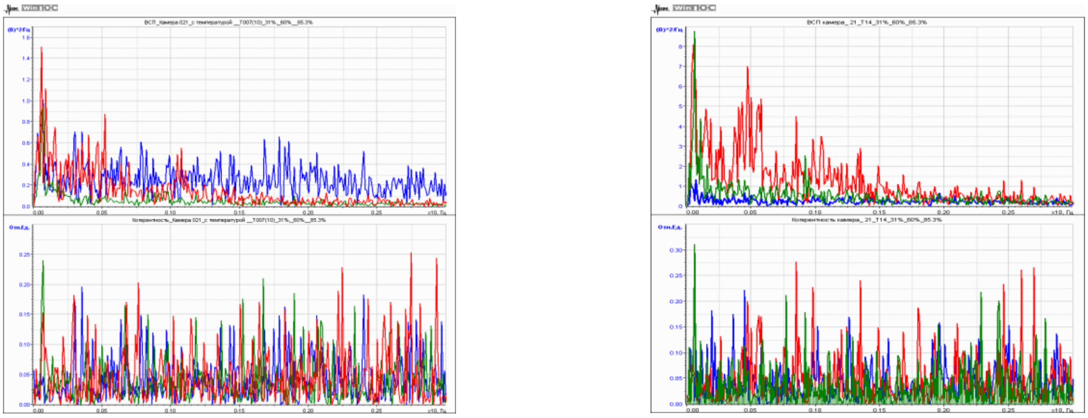

FIG. 12. RSD and coherence for current and thermocouples upon changes in the power level

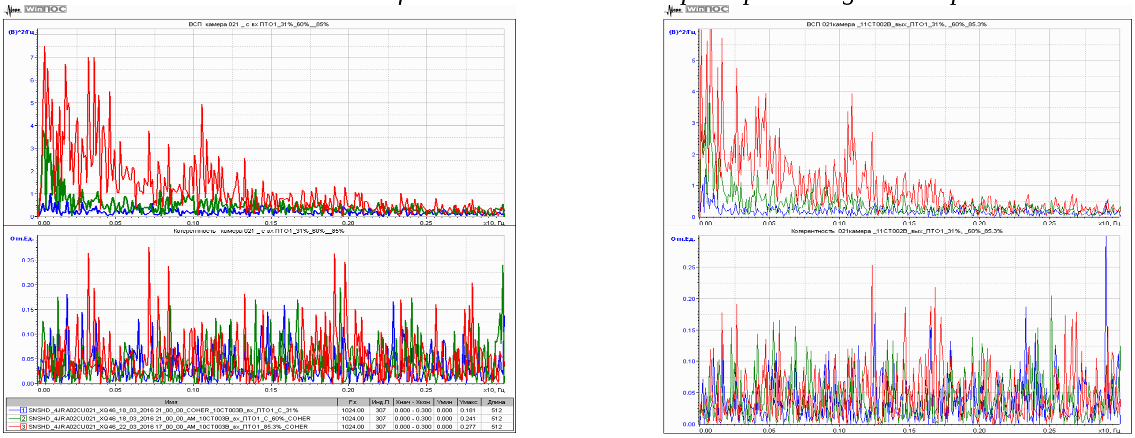

FIG. 13. RSD and coherence for current and IHE1 thermocouples at different power levels

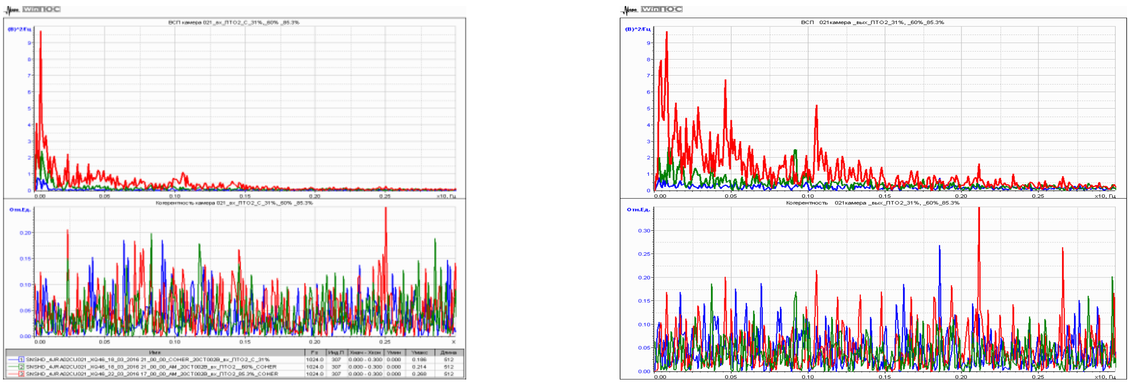

FIG. 14. RSD and coherence for current and IHE2 thermocouples at different power levels

Assessment of the temperature channels MSE for thermoprobes has revealed significant decrease in the MSE value while moving off from the core. It seems, that is concerned with a process of mixing of coolant flows from different FSA upon transportation to the inlet window of the heat-exchanger.

Realization and assessment of the MSE values for temperature channels of thermoprobe 8 (from left to right A÷H) at a power level of 85 % of Nnom. is presented in Fig. 15. Assessment of auto-spectral density for temperature channels of thermoprobe 8 at a power level of 85 % of Nnom. is presented in Fig. 16. The diagrams reveal there is not only decrease of MSE while moving off from the core section, but decrease in the maximal value of auto-spectral density and the area of informative frequencies is narrowed.

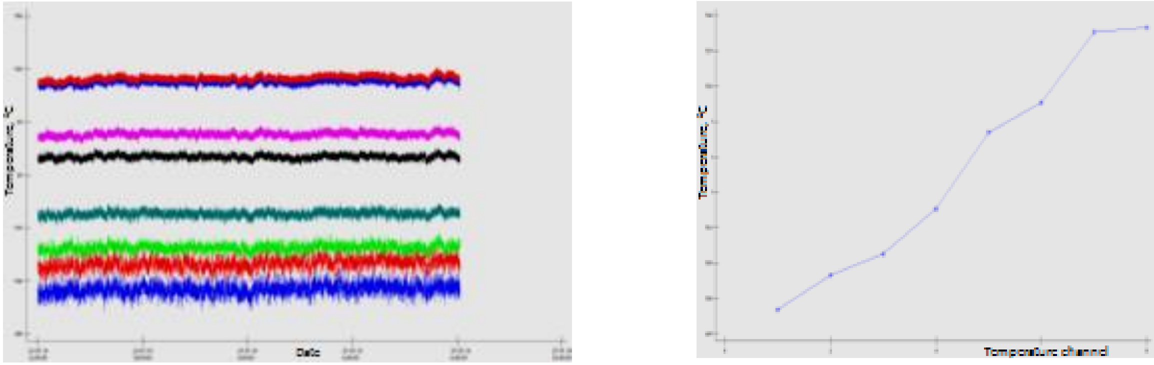

FIG. 15. Realization and changes in indications of temperature channels of thermoprobe 8 at a power level of 85 % of N_{nom}

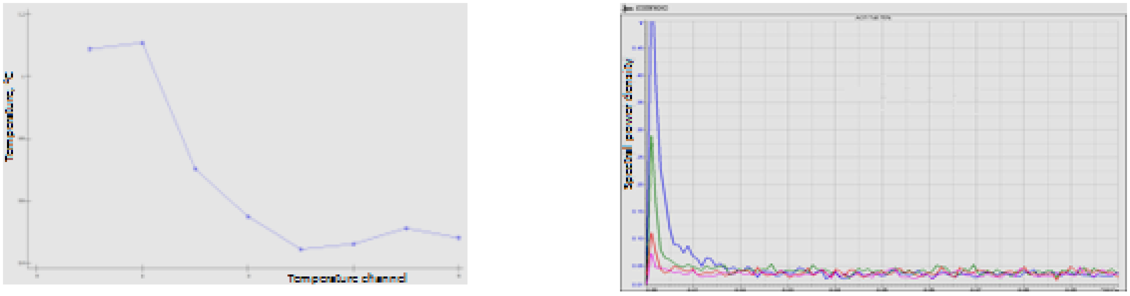

FIG. 16. Changes in MSE values for temperature channels of thermoprobe 8 and assessment of auto-spectral density at a power level of 85 % of Nnom.

In the process of SNSHD pilot operation, the assessment of main spectral and statistical parameters at different power levels for formation of values of parameters corresponding to standard ones and obtaining of the initial data for performance of the signature analysis was realized.

Prior to that, the activities were taken on option for the type of filtration window upon performance of Fourier transform and determination of sample size in order to obtain optimal correspondence between resolution and self-descriptiveness. At that point, the instability was revealed in assessments of auto-spectral density of ionization chambers' current upon selection of different time intervals while operating the RF at a given level of power.

The results of assessment of auto-spectral density of ionization chamber's current at a power level of 85 % of Nnom. in different time intervals performed during two days are presented in Fig. 17. The diagrams show changes in the amplitude of auto-spectral density, existence of resonances, changes in the amplitude and resonance shape at different time intervals.

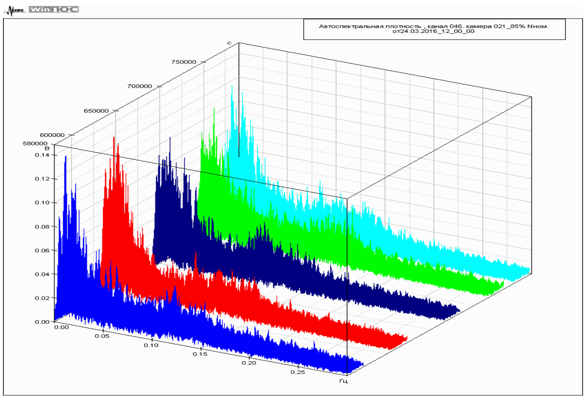

FIG. 17. The diagram of auto-spectral density of ionization chamber's current at a power level of 85 % of N_{nom}

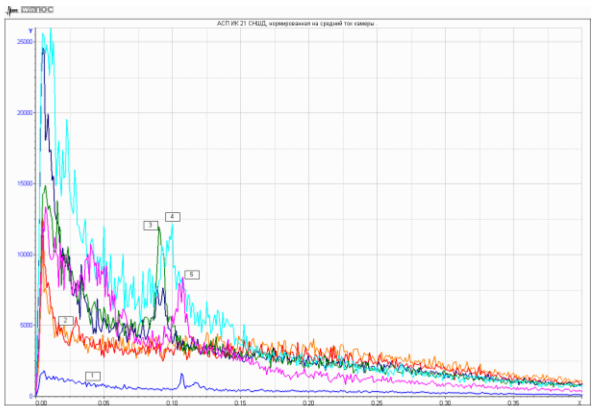

FIG. 18. The results of assessment of auto-spectral density of ionization chamber's current at power levels of 25 % (1); 35 % and 45 % (2); 60 % and 68 % (3); 77 % (4) and 85 % (5)

The results of assessment of auto-spectral density of ionization chamber's current normalized to a value of average chamber's current at different power levels of the RF are presented in Fig. 18. Assessments are performed under 10 Hz frequency of scanning of low-frequency channels with fast Fourier transform (FFT) being within a frequency band range of (0.1÷3) Hz.

The diagrams show increase in the amplitude of auto-spectral density, existence of resonances, changes in locations of resonances upon changes in RF power. To decrease the effect of uncorrelated noise of chamber’s current on assessment of spectral parameters and reveal the fine structure of parameters of resonances of RF neutron noise, estimation of reciprocal spectral density and coherence for two ionization chambers in the SNSHD was realized.

The results of assessment of reciprocal spectral density and correlation of ionization chambers’ current at RF power levels of 30 %, 60 %, 85 % of Nnom. are presented in Fig. 19.

The diagrams show considerable increase in the amplitude of reciprocal spectral density for two ionization chambers in the SNSHD, the process of arising of resonances and changes in location of resonances (at a level of 60 % and 85 %) upon increasing the RF power. Coherence for two ionization chambers also increases upon increasing the RF power and reaches the value of 0.97. The points of maximums in coherence functions correspond to the points of maximums for reciprocal spectral density.

It should be noted the point of maximum in the 0.87 Hz frequency area at a power level of 60 % of Nnom. has shifted to the 1.09 Hz frequency area at a power level of 85 % of Nnom. In addition, the extra resonances have arisen in the 0.25 Hz and 0.4 Hz frequency areas at a power level of 85 % of Nnom.

Based on the earlier performed experimental investigations in neutron noises parameters [4-5], in an event of arising of sodium boiling in fast reactors, the specific features are expected to be revealed in the MSE, auto- and reciprocal spectral functions within the frequency range of (0.5÷2.0) Hz. Dependence of the MSE of chambers’ current fluctuations in the SNSHD within the frequency range of (0.5÷2.0) Hz on the RF power level is presented in Fig. 20.

The performed analysis of assessments of reciprocal spectral density and coherence for ionization chambers’ current within the frequency range of (1÷30) Hz has only revealed the existence of specific features within the frequency range of (0.5÷1.5) Hz almost at all power levels of the RF with such specific features while the analysis was realized within the frequency range of (0.1÷3.0) Hz.

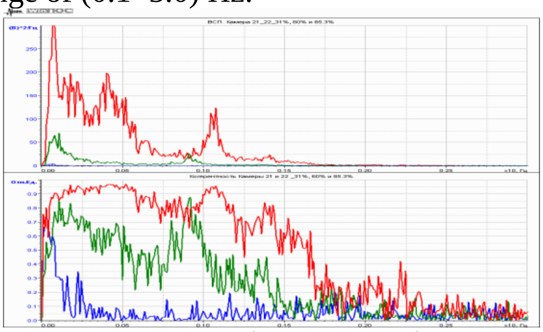

FIG. 19. The results of assessments of reciprocal spectral density and coherence for ionization chambers’ current at power levels of 30 %, 60 %, 85 % of Nnom.

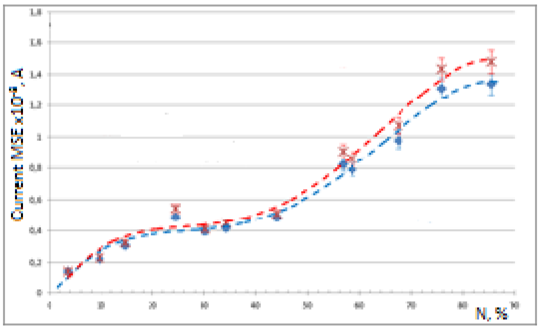

FIG. 20. Dependence of MSE of ionization chambers’ current in the SNSHD within the frequency range of (0.5÷2.0) Hz on the RF power level corrected to a value of squared coolant rate

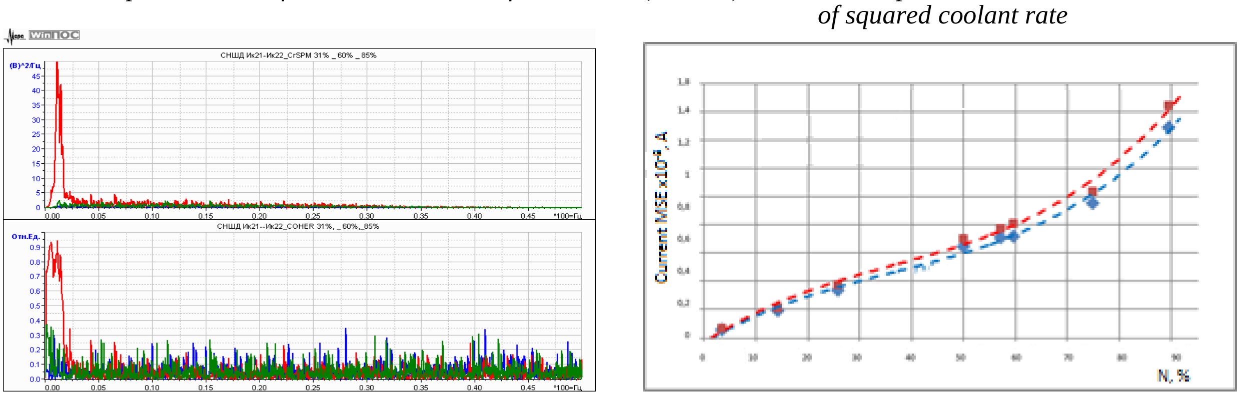

FIG. 21. The results of assessment of reciprocal spectral density and coherence for ionization chambers’ current at power levels of 30 %, 60 %, 85 % of Nnom. within the frequency range of (1÷35) Hz

In the area of recycling frequency of pumps in the primary circuit, the existence of specific features within the frequency range of (1÷35) Hz has not been revealed. The results of assessment of reciprocal spectral density and coherence for ionization chambers’ current at power levels of 30 %, 60 %, 85 % of Nnom. and dependence of MSE of ionization chambers' current in the SNSHD on the RF power level within the frequency range of (1÷35) Hz are presented in Fig. 21.

6. Conclusion

Pilot operation of the designed monitoring system of the RF has confirmed correspondence of the SDRU and technical assignment. Operability in detection of deviations from normal operation is provided by technical solutions on measurements of the primary diagnosing parameters, algorithms of determination of diagnosing signs and their deviations from standards.

Reliability and authenticity of transmitting to the NPP operator the warning signal on detection of anomaly in the core of RF BN-800 is provided by comprehensive data analysis algorithms received from SOAR, SNSHD, STKAZ, gas and delayed neutrons KGO systems, and technological and operating parameters of RF operation, which are received from the TP ACS (ULCS).

For the first time the statistical assessments of temperature distributions, reactivity values, statistical and spectral characteristics of neutron-noise temperature channels upon RF operation at power levels in the range of (0.1÷85) % of Nnom, and the results of pilot operation of the complex system of monitoring the RF BN-800 core were obtained for fast reactors.

To reach maximal sensitivity to anomalies, determination and correction of normal state types (boundary values of diagnosing signs) of the SDRU for different technological modes of RF operation have been performed.

The data and results obtained at the stage of pilot operation must be used for correction of diagnosing algorithms and broadening of functioning opportunities of the SDRU.

Identification of the revealed specific features in spectral parameters is requiring performance of additional measurements and accumulation of the sufficient quantity of statistical data on changing of parameters with change of power-production of the RF.

References

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