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NEUTRON FLUX CONTROL SYSTEMS VALIDATION

HAŠČÍK R.
VÚJE Trnava, Inc.

ABSTRACT

In nuclear installations main requirement is to obtain corresponding nuclear safety in all operation conditions. From the nuclear safety point of view is commissioning and start-up after reactor refuelling appropriate period for safety systems verification. In this paper, methodology, performance and results of neutron flux measurements systems validation is presented. Standard neutron flux measuring chains incorporated into the reactor protection and control system are used. Standard neutron flux measuring chain contains detector, preamplifier, wiring to data acquisition unit, data acquisition unit, wiring to display at control room and display at control room. During reactor outage only data acquisition unit and wiring and displaying at reactor control room is verified. It is impossible to verify detector, preamplifier and wiring to data acquisition recording unit during reactor refuelling according to low power. Adjustment and accurate functionality of these chains is confirmed by start-up rate (SUR) measurement during start-up tests after refuelling of the reactors. This measurement has direct impact to nuclear safety and increase operational nuclear safety level. Briefly description of each measuring system is given. Results are illustrated on measurements performed at Bohunice NPP during reactor start-up tests. Main failures and their elimination are described.

1. INTRODUCTION

In Slovakia main electricity grid supply two Nuclear Power Plants. One of them is Bohunice NPP and other one Mochovce NPP, both situated in southwest part of country.
Bohunice NPP includes two plants, each having two units of VVER 440. In the older plant V-1, commissioned in 1979 and 1980 respectively, reactors of V-230 type are used [1]. In the newer plant V-2, commissioned in 1984 and 1985 respectively, reactors of V-213 type are used. During the years 1991 – 1992 so called "Small reconstruction" was done and from 1996 to June 2000 "Gradual upgrading" of NPP units V-1 has been performed. The aim of these reconstructions was to increase the operational nuclear safety. The part of Gradual upgrading was replacement of the initial neutron flux control system INEJ with the new one TELEPERM-XS. The new system has been in operation since April 1999 at Unit 2 and since

June 2000 at Unit 1. Special measurements were carried out at the beginning of TELEPERM-XS system operation. The aim of these measurements was to compare the characteristics of both systems (INEJ and TELEPERM-XS), to judge the correctness of adjusting and calibration accuracy of the new system.

Based on the above listed facts the Bohunice NPP operator has ordered verification and validation of the new neutron flux control system from Nuclear Power Plants Research Institute Inc. Therefore a new test based on neutron flux measuring chain verification by asymptotic reactor period measurement was designed. Neutron flux measuring chain consists of detector instrumentation located in reactor biological shielding (ex-core detectors) and additional cabling, amplifier and converter that convert detector output signal to physics value. After successful realisations of these measurements at two units of plant V-1 we expanded this measurement to next two units of plant V-2 and at present we realise the same measurement also in Mochovce NPP. The paper presents results of the asymptotic reactor period measurements from Bohunice NPP units.

2. NEUTRON FLUX CONTROL SYSTEMS DESCRIPTION

2.1 TELEPERM-XS DESCRIPTION

The purpose of the system TELEPERM-XS is to monitor the neutron flux within complete range of operation from cold status up to nominal reactor power [1]. The signals are provided for:

- Monitoring of neutron flux density for all operational states
- Control room personnel, indication of reactor power and reactor period
- Reactor protection system
- ROM and ARM
- Control room alarm system
- PAMS
- PIS

Wide-range measuring channel operates in source range in count rate mode with logarithmic displaying of reactor power and period. In the intermediate and power range as well the channel operates with alternating current and linear logarithmic displaying of parameters. Pre-amplified impulse signals passing the amplifier that processes the amplitudes. All impulses, which are exceeding adjustable threshold of discriminator, are led to the input of TELEPERM-XS reader unit. Adjustable threshold of discriminator can suppress the background noise of cables, electronics and gamma-radiation as well. To reach the high reading frequencies and to avoid the count losses due to detector dead time, the frequency divider is used in higher frequency area, which requires the correction during numerical calculations. The alternating current signal from pre-amplifier is processed in adjustable amplifier and lead to processing computer in order to create wide-range signal. Electric change impulses generated in the lower measurement range of fission chamber are summarised in upper range of measurement into the fluctuating direct current. The fluctuations added to direct current are qualified as alternating current signal. According to Campbell's theorem [2] on general statistic,

$$\overline{\sigma_i^2(t)} = \frac{r.Q^2}{\tau} \qquad (1)$$

where $\sigma_i^2(t)$ is detector current root mean square

r - events rate

Q - the charge produced for each event in the detector

τ - detector effective measurement time.

Average quadratic alternating current added to direct current is exactly expressing neutron flux density. Alternating current signal is a linear signal divided into several automatically changing sub-ranges. The impulse and alternating current enters processing computer, which creates logarithmic wide-range signal. The transition from impulse signal to alternating signal is fluent without impact. Parallel course of both signals allows ratio calculation. If the ratio is close to the number "1", the overlapping is performed. If the ratio is not equal to the number "1", overlapping is not performed and channel transmits failure announcement. Wide-range signal is filtered by filtering algorithm with time constant dependent on signal. Double-filtered wide-range signal is processed for gradient of neutron flux density, which exactly corresponds to the reverse value of reactor period. Neutron flux monitoring system is one unit consisting of 6 wide-range measuring channels divided into 2 redundancies. All of them have the same construction and existing measuring ranges SR, IR, PR are integrated into one wide-range. Each wide-range channel consists of detector, represented by fission ionisation chamber PHILIPS CFUL08 protected by shock absorbing springs to avoid shocks from seismic activities and one-way short circuits in leading pipes around reactor. Their positions are rope fixed. Output from detectors is led into analogue unit Hartman & Braun located in annular channel, which converts the signal into the level appropriate for computer TELEPERM-XS. Computerised data processing system consists of individual plug-in to the electric modules, creating processing unit in the layer. The layers are build-in to the electronic racks allocated for individual redundancies 1 and 2. The neutron flux indicators are located in desk 3P in control room.

2.2 SUGAN DESCRIPTION

The purpose of the system SUGAN is to monitor the neutron flux in reactor within the range 10^{-10} – 120 % of nominal power [3]. The instrumentation converts the neutron flux, into electrical signal, which is proportional to the neutron flux and reactor period. The output signals are provided for:

- Reactor protection system
- ROM and ARM
- Information- computing system
- Reactor operator control desk
- Reactivity computer

The system SUGAN consists of measuring channels and associated instrumentation. Each channel processes signal from one detector. The output is analogue electrical signal proportional to the neutron flux and the discrete signal on exceeding of protection set points of power, reactor period and the beginning of measuring range. Associated instrumentation processes output signals, which are provided for indication and registration in operator control desk. The system monitors neutron flux within the range 10^{-1} – $1.2x10^{11}$ n/cm^2s (in the position of detector). The whole range is divided into three sub-ranges:

- Source range (10^{-1} – 10^5 n/cm^2s)
- Intermediate range (10^4 – 10^{10} n/cm^2s)
- Power range (10^9 – $1.2x10^{11}$ n/cm^2s)

For each range different detectors with different sensitivity are used. Standard start-up instrumentation consists of source range detectors. It provides reactor power and period control and protection during reactor start-up from cold zero power. Intermediate range detectors insure control and protection from neutron flux and reactor period overrun during reactor power increase from hot zero power. The power range channels ensure the reactor protection within operation at higher power levels (app. from 3% - 110% of nominal power). SUGAN consists of 20 measuring channels. Individual channel includes following detectors: KNK15 for source range, KNK4 for intermediate range and KNK3 for power range, pre-amplifier and measuring unit. Detectors are located in the pipes inserted in the external biological shield of reactor vessel. The signal generated in detector passes pre-amplifier located in annual channel around the reactor cover in reactor hall and enters instruments located in Reactor Protection system room. The measuring channels belong to reactor protection system.

2.3 AKNT-07 DESCRIPTION

The purpose of the AKNT-07 neutron flux control system is to monitor the relative physical power, reactor period and reactivity calculation according to thermal neutron flux within the range 10^{-10} – 120 % of nominal power [4]. The instrumentation converts the neutron flux density into the current signal, which is proportional to the neutron flux and reactor period. The signals are provided for:

- ALOS
- ROM and ARM
- SVRK
- Control room signalisation -BELT
- Refuelling machine during fuel reloading
- Emergency control room
- Displaying and recording equipment

Neutron flux control system AKNT-07 is a part of reactor protection and control system. Instrumentation is divided into:

- Basic system that provide reactor control from cold state to nominal power. Basic system provides outputs signals to reactor protection system, reactor power control unit, for reactor control room and information-computing system.
- Control system during fuel reloading is used for neutron flux control during fuel reloading. Output signals are provided for refuelling machine desk.
- Control system for emergency control room is used for neutron flux control by three SR (start-up range) measuring channels (detectors are located in the pipes inserted in the external biological shield of reactor vessel). Output signals are displayed on emergency control room desk and are also provided for recorder.

- Reactivity computer AKR-02R is designated for reactivity calculation and displaying. Input signals are impulse signals proportional to neutron flux from the basic system and control system during fuel reloading.
- Neutron and technological parameters displaying instrumentation is used for information output about reactor power, reactor period, reactor power and period boundaries and technological parameters.

Basic system measuring range is divided into two sub-ranges:

- Start-up range (SR)
- Working range (PR) is divided into two sub-ranges:
  - Logarithmic range (PRlog)
  - Linear range (PRlin)

Start-up and working range-measuring channels have their own detectors. SR channels generate standard start-up equipment. SR channels control and protect reactor from neutron power and reactor period boundary overrun by reactor start-up. Logarithmic range channels control and protect reactor from neutron power and reactor period boundary overrun from reactor start-up to 1% of nominal power. Linear range channel controls and protects reactor from neutron power and reactor period boundary overrun from 1% to 120% of nominal power. Reactor operator is able to check reactor period on control desk in reactor control room with delay following the power change. It is due to reactor period calculation method used in neutron flux control system AKNT-07.

3. TEST METHODOLOGY

The test methodology is as follows:
The reactor is in stable critical state. It means that all relevant reactor parameters are constant. At time t after reactivity insertion the neutron flux follows the equation:

$$n(t) = n_0 \exp(t/T) \qquad t > T \tag{2}$$

where $n(t)$ is neutron flux at time t

n_0 - neutron flux on the start of measurement

t - time [s]

T - reactor period [s]

In accordance with operating manuals we apply T > 80 s. After this time the exponential section of neutron flux corresponding to a selected section of reactor asymptotic period is chosen and using the regression analysis evaluation is on the base of Eq. (2) estimated T_{theor}.
Inverse reactor period value, usually named start-up rate, can be estimated from

$$R = \frac{1}{T} = \frac{1}{n(t)}\frac{dn(t)}{dt} \tag{3}$$

Measurement of neutron flux is characterised by its fluctuations. Therefore the instantaneous start-up rate can change dynamically due to neutron flux derivation. Therefore start-up rate calculation method in Siemens reactor control system TELEPERM-XS uses filter of exponential type. Values of neutron flux and start-up rate are recorded with 1 s period. Relative deviation between experimental and theoretical value of reactor asymptotic period is defined as:

$$\varepsilon = \frac{T_{exp} - T_{theor}}{T_{theor}} \cdot 100\,\% \tag{4}$$

where T_{exp} is the mean value from selected time interval of the reactor period measured by the portable measurement system from reactor protection and power control system SUGAN or TELEPERM-XS

T_{theor} - the mean value of the reactor asymptotic period is defined as a slope of the neutron flux measured by the portable measurement system from reactor protection and power control system SUGAN or TELEPERM-XS in the same time interval as T_{exp}

4. TEST PERFORMANCE

The sequence of test instruction as follows: The reactor is in a critical state. It means that all reactor parameters are constant and should preserve the following values [5]:

- The reactor power is in the range 10^{-2} % of nominal power, if not, it is necessary to adjust the reactor power to this range using the 6^{-th} group of emergency, regulation and compensation rods (in abbreviation 6^{-th} control rod group).
- The reactivity change 0 ± 14 pcm/hour is accepted for neutron flux changes.
- The concentration of boron acid is equal in primary circuit, pressurizer and deaerator. Equal means that the concentration difference is less than 0.1 g/kg.
- Average temperature of primary coolant is 260 ± 5 °C.
- Pressure is equal to pressure at the water saturation limit in the pressurizer. It is about 12.6 MPa.
- 1^{-st} to 5^{-th} control rod groups are fully withdrawn; 6^{-th} control rod group is on the working position between 150 and 200 cm.

After verifying and recording the parameters of initial state listed above we start recording the following signals:

- Reactor power in source range
- Reactor period in source range
- Reactor power in wide range
- Reactor period in wide range

from all ionisation chambers of source range and wide range.

- Neutron flux
- Reactivity from reactivity computer
- Temperature in hot and cold legs of primary circuit

- Reactor average pressure
- 6^{-th} control rod group position from non-standard measuring system.

Than we insert the 6^{-th} control rod group in one-step, about 12 cm, in to the core. After the reactor power decrease to the range 10^{-5} % of nominal power, we stabilize reactor power in critical state by withdrawing the 6^{-th} control rod group in 1 to 3 steps. On this power level stabilization about 10 minutes is included and the position of the 6^{-th} control rod group is recorded.

Withdrawing the 6^{-th} control rod group in two steps about 5 cm with delay of 3 s between steps set up the stabilized reactor period between 100 and 90 s and books the position of the 6^{-th} control rod group. After achieving a required value of reactor period it is strongly recommended not to change the position of 6^{-th} control rod group and follow the reactor period to the range 0.5 to 1 % of nominal power. On this power level we stabilize reactor in critical state with inserting of 6^{-th} control rod group and book the position of the 6^{-th} control rod group.

5. RESULTS

The time behaviour of start-up rate and reactor power from measurements performed at Unit 4 and Unit 2 Bohunice NPP last year is shown in Figures 1 and 2.

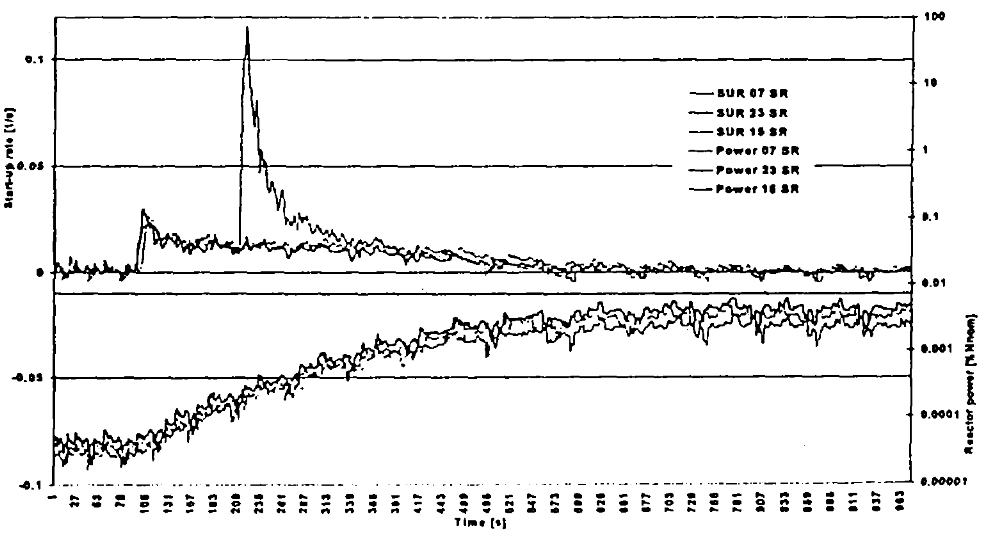

Figure 1: Measurement with reactivity worth 0.098 $ for first train SR (Unit 4, Bohunice NPP) – reactor power and start-up rate during power increasing

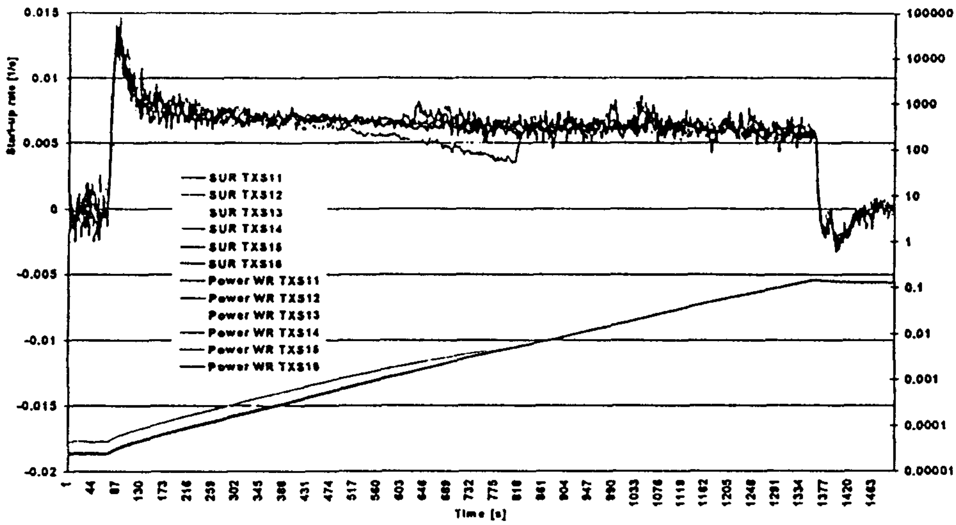

Figure 2: Measurement with reactivity worth 0.06 $ for WR (Unit 2, Bohunice NPP) - reactor power and start-up rate during power increasing

6. CONCLUSION

The following acceptance criteria have been assumed:

- First criterion - calculation of inverse reactor period (start-up rate) is correct. (i.e. $\varepsilon \leq 10$ % rel. for TELEPERM-XS system and $\varepsilon \leq$ 30 % rel. for SUGAN system according to Eq. 4)
- Second criterion - reactor period (start-up rate) time behaviour of individual channels do not include anomalies (unreasonable peaks, deviation of time behaviour of one channel from others)

The measurement results presented in this paper show that not all tested systems at Bohunice NPP units worked properly in the range specified for acceptance criteria. After successfully errors detection and localisation were these eliminated and systems were ready for reliable operation. Due to listed facts and increased safety, measurements at all NPP units in Slovakia were expanded. These measurements are able to find detector signal faults or anomalies in reactor period calculations and localize it. This measurement can also shorten the process of reload start-up process because the experimental sequence and recorded data can be used for another evaluations, e.g. power feedback and the reactivity computer checking and adjusting needed for start-up tests performed at our NPP units.

LIST OF NOMENCLATURE

AKNT	- neutron flux control system
ALOS	- Reactor protection system
ARM	- Reactor power control system
INEJ	- initial neutron flux control system at V-1 units in Bohunice NPP
IR	- intermediate range
KNK	- ionization chamber
NPP	- Nuclear Power Plant
pcm	- percent milli-rho, unit of reactivity (1/1000 of % reactivity)
PAMS	- Post-accident monitoring system
PIS	- Process information system
R	- inverse period (usually named Start-up rate)
PR	- power range
ROM	- Reactor power limitation system
SR	- source range
SUGAN	- neutron flux control system at V-2 units in Bohunice NPP
SUR	- Start-up rate
SVRK	- In core monitoring system
T_{exp}	- measured reactor period
T_{theor}	- calculated reactor period
VVER	- water-cooled and water-moderated energetic reactor

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