REACTOR THERMAL/HYDRAULIC PROCESSES MONITORING AND AID TO DIAGNOSIS, USING ACOUSTICAL SIGNAL AND ON-LINE CALCULATIONS.

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Abstract

The instrumentation and control (IC) systems used in most nuclear power plants (NPP) are aimed at providing information for the purpose of safe start-up, power operation and shutdown. These tasks gained even more importance as a result of the Three Mile Island incident in the seventies. Substantial advancements in sensor and computer technologies make possible cost effective on- and off-line monitoring and diagnostics (MD). At present MD technology provides the necessary tools, techniques and procedures to obtain information about the condition of equipment and provide them to the operation, maintenance and engineering staff. Access to this information allows individuals to make timely decisions toward achieving the safety and economic goals of NPPs.

Introduction

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Purpose

Several incidents have affected the internal structures (IS) of NPP units (core barrel, control rods, thermal shield, etc.) and have resulted in costly repairs. A similar situation has affected main coolant pumps (MCP) and steam generators (SG). In order to provide maintenance on such units it is desirable to detect all abnormal behaviour at a sufficiently early stage. In order to detect anomalies as soon as possible it is important to characterise various statistical features of signals acquired under normal operating conditions. Early detection has two specific features. First, if operations staff can detect the anomalies at the earliest stage possible, negative effects on plant operation can be reduced. Second, a short detection time and high background noise level leads to large statistical errors during anomaly discrimination.

To obtain satisfactory information in real time and for wide-range surveillance depending on power level, and coolant parameters neural networks must be applied for the purpose of MD. The major advantages provided by an artificial neural networks must be applied for improvement of MD. The major advantages provided by an artificial neural network (ANN) and an expert system are system diagnostics through the use of outputs from the neural network and a large amount of plant operation knowledge directed toward the operator. To make the expert system powerful it is necessary to find the appropriate rule bases by which a degree of equivalence between the measured signals and estimated values of the network can be recognised. The expert systems must identify the type and place of an anomaly with a knowledge base that is written in rules. Of course it is preferable to use an adaptive method to make the plant model more accurate during the course of operation.

Results

Practical and theoretical results of NPP coolant monitoring and aid to diagnosis are based on the created mathematical model of coolant pressure (acoustical) oscillation. Experiences with reactor noise diagnostics systems show that acoustical signals are suitable for the above-mentioned purpose. This adaptive model describes the quantitative dependencies between coolant oscillations eigenfrequencies and NPP running parameters including emergency situations with steam appearance.

For the theoretical calculation of characteristic frequencies of the circuit, it is easier to use simplified models of circular systems, the equivalent electrical circuits. The principle of transition from a hydraulic system as equivalent to an electrical one is given in [1].

The calculation of the frequencies of the self-oscillations [2] of the heat-transfer medium, f_0 in the reactor, volume compensator, steam generator and circuit pipes are accomplished with the help of the following formula:

$$f_0 = \frac{1}{2\pi\sqrt{mC}}$$

The results of calculations by means of the formula for the nominal working regime of the fourth block of Novovoronjeskaja NPP are given in [2].

The same results of low frequency oscillation value were calculated and measured in NPP with PWR and VVER by other researchers [3,4,5,6]. Paper [7] shows that coolant pressure standing waves control the neutron flux noises in reactor core and can be utilised for interpretation purposes.

A comparison of calculation results while steam generation is present and during its absence shows that the spectrum line characterising oscillation of the heat-transfer medium in the reactor shifts towards the area of lower frequencies. The nature of steam generation, too, affects the value of the self-frequency of oscillation in the reactor. Thus, with the help of change in f_0 of reactor, the steam generation process can be detected in the reactor core. Valuable results are presented in paper [8], which concerns experiments of blockage detection in sodium-cooled fast reactors. Detection of steam generation in the reactor core due to blockage effect was effectuated by measuring the deviation of the coolant main frequency.

A good agreement of the results of calculation of f_0 and direct measurement on the fourth block of Novovoronjeskaja NPP shows that the adopted calculation plan for analysis of the oscillation spectrum can be used for quantitative evaluation of characteristic frequencies. It is known that during the normal functioning of reactor VVER-440, surface boiling does take place in the reactor core. As was shown above, the presence of steam in the reactor core leads to a decrease in the frequency of self-oscillation of the heat-transport medium in the reactor. This discrepancy between the calculated frequency (during the absence of boiling 22 Hz) and the result measured during functioning (18 Hz) can be explained due to the presence of a certain quantity of steam in the reactor core.

The experiments show that a deviation pattern of acoustical signal in a fault situation with steam appearance matched to pre-defined patterns may be used for diagnosis either off-line or on-line.

The quantitative model created [9] to calculate the pressure oscillation in the coolant has the following form:

$$\frac{d^2\Delta P}{dt^2} + \left(\frac{1}{CR_d} + \frac{R}{m}\right)\frac{d\Delta P}{dt} + \frac{1}{C(\Delta P)}\frac{dC(\Delta P)}{d\Delta P}\left(\frac{d\Delta P}{dt}\right)^2 + \frac{\frac{R}{R_d}+1}{mC}\Delta P = \frac{\Delta P_0}{mC} \tag{1}$$

Here:

ΔP	- variable (pulsation) component of pressure drop;
t	- time;
C	- acoustical capacitance;
R_d	- acoustical differential resistance;
m	- acoustical inductance;
ΔP_0	- pressure drop between circulating pump inlet-outlet.

Acoustical capacitance is determined by the value of a small oscillation velocity in the steam-water mixture. The calculation methods to determine the compressibility of a steam-water mixture in real operating conditions on NPP which are utilised at present are very approximate. Due to this reason a new method of small oscillations velocity evaluation was created [9]. This method attempts to take into account the total list of thermohydraulic, geometric and operating conditions at the steam generating duct.

Taking into consideration the dependence between f_0 and steam content [10], it is possible to calculate the changes of f_0 due to x variation.

Based on the parameters (R, R_d, m, C) the formula to determine the self-frequency of coolant oscillation can be obtained in the following manner:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{a^2\rho_m}{\rho l l_m}} \tag{2}$$

Here:

l	- the length of pipe containing water;
l_m	- the part of pipe containing two-phase mixture;
ρ,ρ_m	- density of liquid and water-steam mixture accordingly;
a	- sound velocity in the water-steam mixture.

Using this formula the boundary subdivided the liquid and steam containing media in the pipe was indicated. It should be emphasised that it is not possible to obtain this information only through the help of regular technological control systems. The difference between calculated and measured values of frequency was insignificant. Based on these results recommendation were given about steam content diagnostics to use the measured frequency of the coolant oscillation.

It is very important to indicate that the influence of steam and gas presence on coolant oscillations can lead to an increase in reactor facilities' vibrations [11]. As is commonly known, the most important interaction between coolant and structure components takes place in resonance cases. Another problem is stipulated by the thermohydraulic instability which occurs as a result of definite relations between steam contents in the loop and operating regimes [9].

This phenomenon is extremely important when the system of heat output from the reactor core must be operated under extreme emergency situations, especially in the event of melting reactor core structures. As a result of such cases, it can been seen that the emergency cooling system must be constructed taking thermohydraulic instability and hydraulic shock into consideration.

Additionally considering the important influence of C-parameters on the appearance of self-oscillations it is necessary to keep in the mind the data about steam generating processes in the system (cavitation, sub-cooling boiling, emergency situations with boiling).

Steam generation and leakage processes have both been studied on a double-circuit one-loop industrial steam generating installation (ISGI) [12]. Whole circuit coolant oscillation and mechanical vibrations of parts of piping have been recognised. A noise signal spectrum recordings analysis has been carried out for normal and emergency coolant leakage conditions.

In Figure 1 the time realisation of pressure oscillations which were obtained at pump stop are shown.

The curve characterises the frequency depending on thermo-mechanical parameters of the coolant. This dependence of the main frequency on steam quantity in the coolant is illustrated in Figure 2, where the pressure oscillation is measured during pump stop in an emergency situation. This emergency situation took place due to coolant leakage and steam generation in the pipe between the pressuriser and primary loop.

Looking at Figure 3 and Figure 4 it is possible to demonstrate that in an emergency regime the frequency began at approximately 4 Hz instead of 1 Hz, which is the frequency in normal regime. The amplitude also increased approximately 6.5 times. Hence, the level of hydrodynamical loading of the structures had increased 100 times.

Taking into consideration the fact that pressure oscillation of coolant is the reason for induced vibrations in equipment, it is possible to form a conclusion concerning the appearance of additional loading of the structures by the cyclic hydrodynamical forces depending on operating conditions.

The coherence function between vibration and pressure oscillation signals from the traducers placed on the pressuriser pipe [12] is presented in Figure 3.

The most important interaction between coolant and structure components takes place in cases of resonance.

A similar effect can be observed at transient processes on NPP with VVER and PWR reactors, when the electrical supply of main circulating pump (MCP) is interrupted. Figure 4 demonstrates the calculated results of time dependence of the main parameters in a circulating loop; this was obtained in a situation when four MCP NPP VVER-1000 were stopped.

Here:

H_P - water level in pressuriser;
P_I - primary circuit pressure;
t_{out} - coolant temperature in reactor outlet.

In accordance with these results the two-phase mixture is present in a definite time period in the tube interconnected pressuriser and hot part of the loop.

Figure 1. a) Time realisation of pressure oscillation at pump stop
b) Time realisation of pressure oscillation at pump start

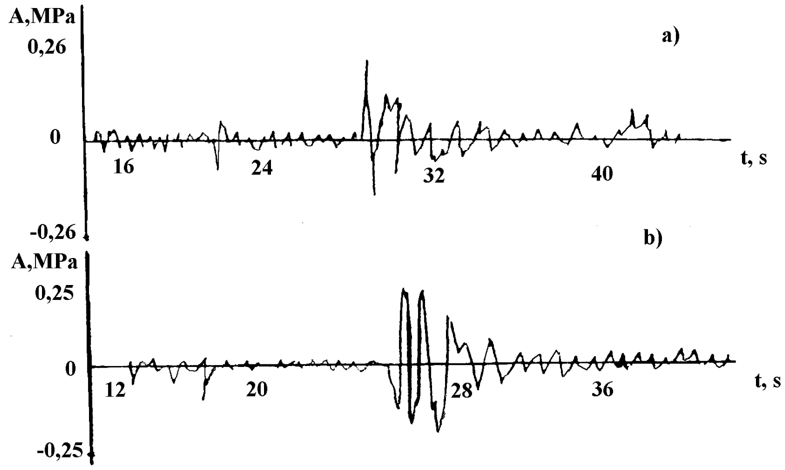


Figure 2. Time realisation of pressure oscillation after pump stopping in emergency regime accompanied by steam cavity appearance

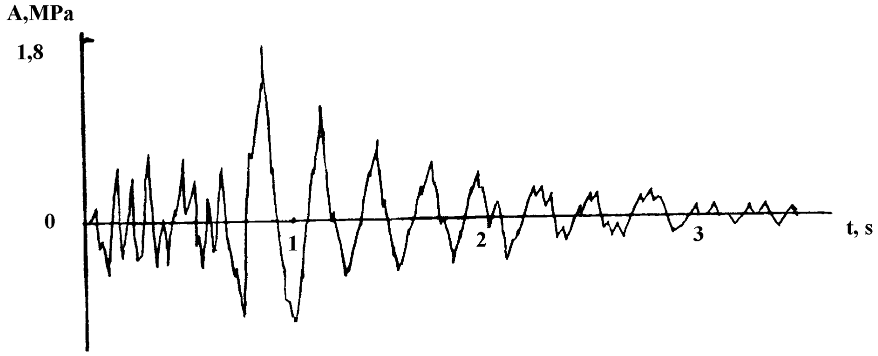


Figure 3. Coherence function of vibration and pressure pulses measured on pressuriser pipe

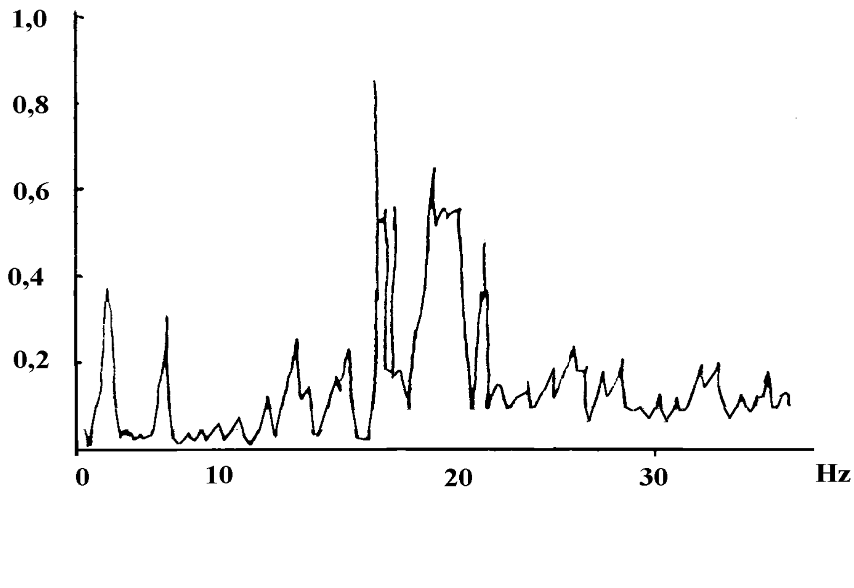
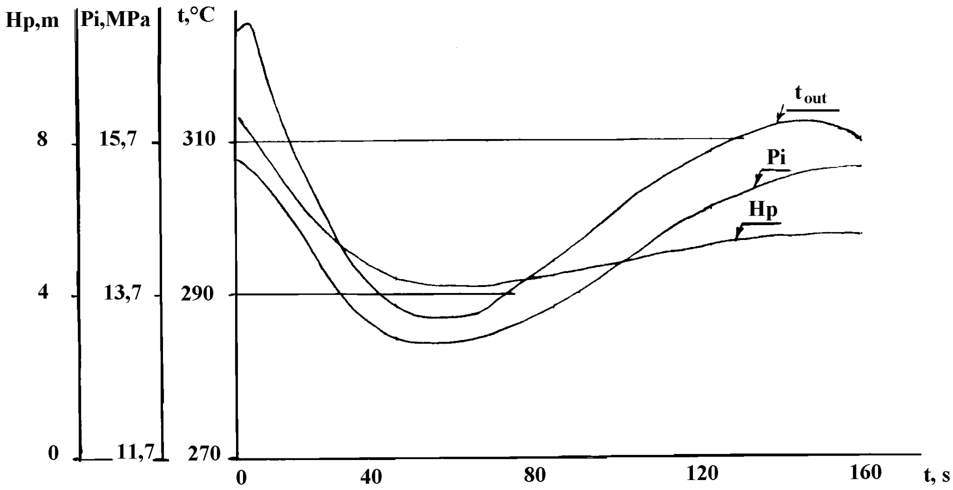


Figure 4. Time dependences of main parameters in circulating loop VVER-1000



Our evaluation of main frequencies' value in this system shows that the variation is in the range 0.04-4.0 Hz. Taking into consideration the rotation velocity change of MCP in transient process, the conditions for the production of resonance interaction between coolant and equipment are very likely.

Using pressure pulse detectors (PPD) installed in the outlet-inlet of MCP and in the pressuriser, we measured and analysed various operating regimes on NPP with VVER-440 through an experimental diagnostic system. The method of processing acoustical spectra gives the characteristics obtained with different time observation particularly in on-line measuring. It was observed that frequency peaks which depend on the moment of measurement moves in the range of 8-12 Hz, the so called "transparent window". In the case when operating situations change it provides the possibility of detecting faults before a traditional alarm system is triggered even in dynamic situation. When the result of fault is steam appearance it is possible indicate it, as it was done in emergency situation on ISGI.

Thus an early warning system be created by means of detecting the cause of steam appears. It is based upon dynamic model to indicate the steam appearance in parallel with the process. The model outputs are then compared with respectively plant measurement.

A two level display hierarchy can be chosen, where the warnings are given with colour symbols in a top level picture (including time history) with a global overview guiding the operator to the lower level detailed displays containing much more information including steam localisation and possible explanation of necessary actions.

The evaluation experiment was therefore considered as an integral part of the developed acoustic method of steam content diagnostics, as such, will indicate the direction for future work.

The basic objective of the experiment was to test the method in realistic situation and thereby to assess whether it performed in accordance with calculated expectations.

The experimental data [11]about the dependence main frequency oscillation values from reactor core power level had been obtained due to measurement fulfilled on NPP with channel boiling reactor RBMK-1500. The autospectra of pressure pulses correspond to the different electrical power levels of the reactor were determined. To each regime of operating, i.e. to certain value of steam production in the technological channels of reactor core it was revealed that the definite main frequency of coolant oscillation corresponds. The calculating method of evaluating the steam content in the coolant [9] was used.

Theoretical and practical results show an appreciable decrease in the sound velocity due to steam appearance in the coolant hence the coolant pressure fluctuation eigenfrequencies also. Three variants of theoretical model have been analysed to evaluate the sound velocity in two phase mixture in reactor core and steam volume over it. More precise result corresponds to model which takes into account the local hydraulic resistances influence. The main resume of this estimation due to monitoring purposes is capability to detect boiling process on early stage. Evaluation had provided for VVER-1000 shows that even little steam content in the reactor core gives essential reactor coolant eigenfrequency chagement: from~ 19.0 Hz at normal operating to ~3.0 Hz when boiling anomalies is occurred. It is important to underline that nonsinglevalued dependencies between steam content and eigenfrequency values are obtained.

Procedure of diagnostics support realisation includes following:

1. Inquire of eigenfrequencies calculation in case of running parameter variation;

2. Reveal the trend of eigenfrequencies changement;

3. Check boiling as follows:

   - Preserve in the operating memory 5 bytes which correspond to certain steam value (from 0 to 1) at the reactor core outlet;

   - Identify peaks on the autospectra in the frequency zones, where the eigenfrequency changes are expected (3 Hz - 20 Hz in case of VVER-1000);

   - Calculate the eigenfrequencies which correspond to running coolant parameters and different steam content values at the reactor core outlet (the calculating program was provided at MPEI by U. Simon);

   - Compare the frequencies and their displacement due to criteria above mentioned;

Running coolant parameters, eigenfrequencies values as well as protocol about diagnosis prognosis results are presented on the monitor screen.

Steam content diagnostics in nuclear power plants (NPP) can be considered as one of the main tasks for operator support system.

Steam generating process in the reactor core at NPP with BWR and RBMK reactors is realised in definite range of steam content. When the steam content is increased correspondingly normal value i.e. when unexpended or unplanned situations occur the task for operators is to identify the status of the process.

Steam generation in the PWR (VVER) is abnormal process which can take place due to emergency situation and the main tasks for operator is early identification of root cause and consequences.

The passive identification experiment allowed to establish a set of significant trend of frequency and mathematical model allowed to obtain the best form of functional relationship between the steam content parameter and the frequency of coolant oscillations. The acoustic steam control and diagnostic's method (ASCDM) can be useful in diagnosis and prognosis of off-line and on-line operator support systems.

Description of the process in a disturbance situation include different surveillance systems for detection, diagnosis and prognosis.

The diagnosis block tries to indicate the root cause of the disturbance, while the prognosis block tries to predict possible effects. Both of these systems use information from the detectors, as well as other process data. The prognosis block could as well use information from the diagnosis, suggested root causes from the diagnosis systems and suggested possible effects from prognosis systems are then presented to the operator.

To provide operator work more effective instead of actual diagram of equipment and processes the schematic diagram are usually used.

Conclusions

The new method of transfer from real complex thermohydraulic NPP loops to their equivalent in dynamical meaning much more simple electronic schema is created in [9]. This method based on theoretical research. Author proves the reliability of distribution very known electrohydridynamical analogy method to describe non linear processes in the thermohydraulic loops of NPP containing steam generating ducts.

Utilisation of this method let some essential advantages to operating personnel:

- Presentation of visual information in more assimilated form;
- Relatively simple and suitable to running process analyses mathematical model;
- Simplification root cause determination and physical interpretation of accident.

Root cause is the primary cause of the disturbance in the coolant loop in the NPP. It may be or may be not directly detectable trough the available process instrumentation. Often the root cause will only be detectable trough it's consequences. The appearance of the steam / gas fraction in the PWR coolant may be not directly detectable without trend of main coolant frequency oscillation measuring, the same is in the channel boiling reactor, when the steam content in the coolant began to change due to any faults.

The changes of main frequency oscillations corresponding to definite unit of reactor loop are the symptoms constitute the set of consequences at the root cause which at a given time are directly detectable trough the process instrumentation.

The instrumentation stage includes the detection of pressure oscillations and their statistical interpretation. Diagnosis and prognosis modules try to find the root cause and the possible effects, respectively, using the mathematical model of two-phase coolant oscillations.

Possible effects constitute the rest of the root cause and future possible consequences.

Suggested root cause from the diagnosis block and suggested possible situations from the prognosis block are then presented to the operator for future automatic or manual actions must be provided to prevent dangerous effects.

Alarm systems for early fault detection is based upon running small process models in parallel with the process. The model outputs are then compared with respective coolant oscillation measurement. The differences between calculated and observed status are called deviations. The deviation pattern is in a fault situation matched against pre-defined patterns; each corresponding to one or several diagnosis hypotheses.

The deviations, which are monitored continuously and are the parameters for diagnosis process will always data at the appropriate model and thereby limit the search space.

Traditional process alarm systems disadvantage with fixed alarm limits is that after the occurrence of failure it may take a long time before the alarms are triggered.

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