Readings correction and on-line monitoring of fluid level measuring channels at NPP

A A Kalashnikov
JSC «Rusatom automated control systems», Moscow, Russia
E-mail: AIAleKalashnikov@rasu.ru

Abstract. Presently the international program has gained momentum aimed at increasing the power of nuclear power plants (NPP) with WWER- and PWR-types reactors up to 107% and also at extending the automated process control system (APCS) repair intervals up to 18 months, which places higher requirements to the accuracy of measurements of NPP technological parameters. To enable the implementation of this program, an algorithm for processing the measurement signals has been designed that ensures high precision in readings correction of hydrostatic level sensors for all operating modes of technological equipment. Methods for correction of readings based on the developed algorithm have been implemented in Russian nuclear power industry. In addition to the correction of readings the algorithm also provides on-line monitoring to identify all possible defects of fluid level measuring channels including hidden defects that are not detected by existing facilities of NPP control system. The paper describes the algorithm and its application to the tasks of readings correction and on-line monitoring of fluid level measuring channels at NPP. As result the article represents one of the first steps to methodological development of the correction reading and on-line monitoring to detection and minimization of hidden defect on NPP measuring channels of all thermotechnical parameters.

1. Introduction
The article summarizes the many years of experience in commissioning nuclear power plants (NPP). It includes research methodology from readings correction to on-line monitoring of fluid level measuring channels. Achieved research results allowed to revise methods of fluid level measuring in part of readings correction and after that they were introduced in nuclear industry. This paper includes these methods and opens up perspective to development of on-line monitoring systems for other industries.

Development of these methods in nuclear industry caused by international program to NPP power increasing. Presently the international program has gained momentum aimed at increasing the power of nuclear power plants with WWER- and PWR-types reactors up to 107% and also at extending the APCS repair intervals up to 18 months [1]. The program places higher requirements in regard of safe operation, accuracy of thermotechnical parameters measuring, accuracy of automatic control and calculation of technical and economic indicators. To enable the implementation of the program we had to develop principles for processing measuring signals of hydrostatic level sensors that permit improved metrological reliability of their indications under different operating modes of technological equipment.

The paper presents main provisions on the development of a universal algorithm for processing the measuring signal of hydrostatic level sensors, which can be an instrument not only for high-precision correction of readings but also for on-line monitoring of measuring channels (MC) of fluid level at NPP.
Mathematical construction that form the basis of the algorithm are given for the level measurement scheme using a single-chamber leveling vessel [2] which is most common in nuclear industry and thermal power industry.

2. Level measurement using a single-chamber leveling vessel

A typical scheme for measuring the fluid level by hydrostatic method (by differential pressure sensors) using a single-chamber leveling vessel is shown in figure 1.

\[
\Delta P = P_{\text{plus}} - P_{\text{minus}} = P_{\text{in}} + \rho_1 g (h_1 + H) - P_{\text{in}} - (\rho_2 g h_1 + \rho g L) = \\
= \rho_1 g H + (\rho_1 - \rho_2) g h_1 - \rho g L,
\]

where \(\Delta P\) is the measured pressure differential;
\(P_{\text{plus}}\) is the overall pressure exerted on the side of the plus sensing line;
\(P_{\text{minus}}\) is the overall pressure exerted on the side of the minus sensing line;
\(P_{\text{in}}\) is the pressure/vacuum inside the storage vessel;
\(\rho_1\) is the fluid density in the plus sensing line and the leveling vessel;
\(\rho_2\) is the fluid density in the minus sensing line and the leveling vessel;
\(g\) is the local gravity acceleration;
\(L\) is the fluid level in the storage vessel;
\(\rho\) is the fluid density in the storage vessel.

When the level is measured using this method, the main causes of error are as follows: increase of temperature and pressure of the process fluid in the storage vessel, different temperature conditions in the plus sensing line (SL) and in the storage vessel; different phases of the fluid (water and steam) in the storage vessel; mismatch of the construction characteristics and MC settings. These causes result in the change of MC readings in general. Hence, to ensure the reliability of MC readings, the «hot» scale correction with proven the value sensor base is required.
When the process fluid temperature in the storage vessel equals to ambient temperature, the corresponding scale of measurement which provides reliable readings, is conventionally referred to as «cold» scale. When the process fluid temperature is higher than ambient temperature, the corresponding scale of measurement is conventionally referred to as «hot» scale.

In order to perform the correction of the MC readings in real time, which implies recalculation of ρ·h=H·h, ρ=ρ', where ρ is the density of steam inside the storage vessel. ρ' is the density of water inside the storage vessel; γ is the length of the section of the plus SL within its height above the minus SL (∑ i=1 H i = H); h is the length of the j section of the plus SL within its height above the minus SL (∑ h j = h₁); ρ' is the density of water inside the storage vessel; ρ‘ is the density of steam inside the storage vessel.

To simplify the industrial calculation procedure it is convenient to use the resulting function transformed to the following form (2):

\[ L = k \cdot L_{cs} + b, \]

where the correction factors k and b are calculated as follows:

\[ k = \frac{(\rho_{cs}' - \rho_{cs}'' \cdot \rho')}{\rho' \cdot \rho''}, \]

\[ b = \frac{\sum_{j=1}^{m} \rho_{1j} \cdot H_{j} + \sum_{j=1}^{m} \rho_{1j} \cdot h_{j} - \sum_{j=1}^{k} \rho_{2y} \cdot h_{j} - H (\rho_{cs}' - \rho_{cs}'' \cdot \rho')}{\rho' \cdot \rho''}. \]

Formulas (1) and (2) take into account a lot of fluid parameters and MC characteristic including uneven temperature distribution into the storage and sensing lines. It allow to realize the high-precision correction of MC readings in dynamic.

In order to implement the correction of the level readings to the nominal values of the process fluid, initially the correction factors K, B are calculated using the previously derived formulae. The density of water and steam required for the calculation are determined according to the reference book [4] for the nominal values of pressure and temperature of the process fluid. The calculated correction factors are entered in the software and hardware complex that is part of MC structure. This ensures a continuous recalculation of the level readings for the «hot» scale (Figure 2).

Figure 2 shows that this method of readings correction allows the control of level both at the «cold» and «hot» scales (at the nominal characteristics of the fluid) without additional resetting of the sensor. If necessary, it is possible to provide automatic bumpless switching of the level readings from the «cold» to «hot» scale in the software-hardware complex.

The single drawback to this method of correction is that the reliable range of level readings is limited for only two operational modes of technological equipment. During transient processes, when thermal and chemical characteristics of the fluid do not reach the nominal values, the reliability of the readings is not provided.
$\Delta P \rightarrow I$

Software and hardware complex

Digital signal

I $\rightarrow L_{cs}$

$K \cdot L_{cs} + B$

ADC

The «Hot» scale correction

L_{cs} $\rightarrow$ L_{hs}

Operator console

The main output of the level readings L_{hs} (the «Hot» scale)

The additional output of the level readings L_{cs} (the «Cold» scale)

$\Delta P$

Software and hardware complex

ADC

The «Hot» scale correction

K $\cdot$ L_{cs} + B

Operator console

The level readings output

$P, T$

Density calculation according to IAPWS

Correction factors K, B calculation

$\Delta P$

LE

Figure 2. An explanatory diagram for the measurement signal processing with the correction at the nominal characteristics of the fluid

$\Delta P$ is the measured pressure differential; LE is a differential pressure sensor adjusted to the «cold» scale (according to GOST 22520-85); I is the output current sensor signal; ADC is analog-to-digital converter; $L_{cs}$ is the «cold» scale level readings; $L_{hs}$ is the «hot» scale level readings.

In order to perform correction of the level readings in real time (including transient processes), it is necessary to arrange in the software-hardware complex the calculation of correction factors K, B taking into account the actual values of the density of water and steam.

In turn, the density of water and steam in real time may be determined on the basis of «International Formulation Equations IAPWS» [5]. In this case the initial data for the calculation of density are the related actual readings of the pressure and temperature sensors in the storage vessel (Figure 3).

$P, T$

Density calculation according to IAPWS

Correction factors K, B calculation

Figure 3. The explanatory diagram for dynamic correction

P is the actual pressure value in the storage vessel; T is the actual temperature value in the storage vessel.

This method of dynamic correction, as opposed to the previous one, ensures the reliability of readings in all possible operational modes of the equipment. “The other side of the coin” here concerns the higher requirements to the computing capacity of the software-hardware complex and the use of additional pressure and temperature measurement channels.

Depending on specific conditions, requirements to the accuracy of measurements/automatic control, and depending on the capabilities of APCS, the most appropriate of the suggested methods of correction can be chosen at NPP.

As a result we lift the readings correction procedure of hydrostatic level sensors from static to dynamic mode by algorithm with simplest realization. Dynamic error of MC readings was minimized until to 3%. This 3% error is minimum caused by pressure and temperature measurements accuracy [3].
Moreover it allow to realize on-line monitoring based on constructing of virtual sensor readings that will be present in the paper. The main purpose of this on-line monitoring is to detect the hidden defects of measuring channels without stopping the process. This is real step to increase the NPP safety.

4. Application of the developed algorithm for processing of measurement signals in the tasks of MC on-line monitoring

This algorithm for processing measurement signals of hydrostatic level sensors allows modeling of a virtual level sensor (mathematical model which uses the real MC readings and generates the level value) to perform on-line monitoring of MC metrological operability. Such a method of on-line monitoring is of particular relevance for existing NPP, where the implementation of the developed dynamic correction of readings is not possible due to absence of digital software-hardware complex in APCS structure. In such cases, modeling of the readings of virtual sensor provides opportunities for an independent high-precision control of level, including transient modes of technological equipment.

Mathematical modeling of a virtual sensor (Figure 4), similar to the developed correction methods, is based on calculating the level values taking into account the correction factors $K$ and $B$, the difference being that the initial data are the measured values of differential pressure on the sensors rather than the readings of $L_{cs}$ channel:

$$L_M = K \Delta \bar{P} + B$$

where:

$$K = (\rho'' - \rho) \cdot g^{-1} ;$$

$$B = \frac{\sum_{i=1}^{n} \rho_{i} \cdot H_i + \sum_{j=1}^{m} \rho_{j} \cdot h_j - \sum_{i=1}^{n} \rho_{i} \cdot H - \rho' \cdot H}{\rho' - \rho''} + h_0 .$$

where $L_M$ is simulated readings of the level sensor; 
$\Delta \bar{P}$ is the average value of the measured pressure differential on the redundant level sensors; 
$H$ is a value of the MC level base found using results of specialized geodetic measurements.

The value of $\Delta \bar{P}$ included in the formula (3), is determined as follows:

$$\Delta \bar{P} = \rho_{mc} g \cdot H_{mc} - \left( \rho'_{mc} \cdot \left( k^{-1} \cdot \sum_{i=1}^{k} L_i - h_0 \right) \right) + \rho'' \cdot g \cdot \left( H_{mc} - k^{-1} \cdot \sum_{i=1}^{k} L_i - h_0 \right) \Delta P_0 .$$

where $\rho_{mc}$ is the density of water in the plus sensing line, which is included in the settings of MC; 
$H_{mc}$ is the base value in the settings of MC; 
$\rho'_{mc}$ is density of water inside the storage vessel; 
$\rho''$ is value of steam density inside the storage vessel; 
$L_i$ is the reading of the $i$ measurement channel; 
$k$ is the total number of duplicating MC.

The factors $K$ and $B$ for the respective temperature and pressure values are calculated either with using the data from the reference book [4] or with using of IAPWS International Formulation Equations.

![Figure 4. Mathematical modeling of virtual level sensor](image-url)
The readings of each of the redundant MC of level are verified against modeled readings of the virtual sensor to realization the metrological diagnostics in real time. As a result we calculate the standard deviation:

\[
\sigma = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} (L_n - M[L_M])^2} = \sqrt{\frac{1}{N-1} \sum_{l=1}^{M} \left( L_n - \frac{1}{N} \sum_{n=1}^{N} L_{Mn} \right)^2}
\]

where \( \sigma \) is the standard deviation over time period \( N \); 
\( L_n \) is the current value of MC readings at the \( n \) time moment; 
\( M[L_M] \) is the expectation value of the modeled readings \( L_M \) for the entire time period; 
\( L_{Mn} \) is the current readings of the modeled sensor at the \( n \) time moment.

The fact of MC fault is identified when the standard deviation exceeds the set limit of admissible deviation (Figure 5).

\[\text{Figure 5. Standard deviation exceeding the preset limit}\]

Analysis of the graph of the dependence of the standard deviation on time enables the identification not only of visible defects but also of invisible defects of MC. For example:

1) The constant standard deviation indicates a systematic measurement error, which most likely cause are concealed faults:
   - The MC settings not matching the actual value of level sensors base;
   - Correction of MC readings does not correspond to nominal thermal and physical characteristics of the process fluid.

2) The main causes for gradual and/or short-term growth of the standard deviation are:
   - Partial emptiness of the sensing lines and the leveling vessel;
   - “Zero drift” of the sensor;
   - The deviation of sensor from the required metrological characteristics.

3) Instant significant increase of the standard deviation usually may be caused by the following main reasons: breakage of cable lines, deterioration of electrical contact, malfunction of any technical device in the measuring channel. These defects are visible, and most likely they would be identified with in-service standard self-diagnosis system of the APCS. Such defects are fixed by operational personnel immediately after they are detected.

4) When tracing the long history of standard deviation over many fuel loadings of the reactor plant, it is possible to identify the degradation of cable circuit and other elements that are part of MC structure.

The examples given above show that the proposed method of on-line monitoring solves the main task of maintenance, that is to timely diagnose a particular defect before it results in a critical failure/error of the process equipment. Application of this method opens up the possibility to monitor and ensure the metrological reliability of MC readings in the context of extended interrepair intervals of NPP control and measuring instruments. Known methods such as balance and neural networks, regression methods [6 – 9] did not reveal a lot of above reasons.
As a result, the introduction of represented readings correction and on-line monitoring methods allowed to revise all previously used methods at Russian NPP and allowed to reduce MC dynamic error to 3 %.

5. Conclusion
The described algorithm for processing of measuring signals for correction of MC level readings allowed to revise the approaches applied and to provide high accuracy of measurement results for different operational modes of technological equipment and for any technical characteristics of MC. The developed methods of readings correction were implemented during putting into operation of new power units of Russian NPP.

The developed mathematical model of the virtual level sensor for on-line monitoring enables diagnostics of visible faults as well as invisible faults of MC. The practical significance of this on-line monitoring method is the possibility of remote metrological diagnosis of MC during continuous technologic process. It is also possible to provide timely identification of the probable cause of the fault and, therefore, to inform the staff about the scope and volume of repair work, thus reducing the troubleshooting time (which is of particular relevance in the restricted area). Besides, the use of this method does not require any intervention into the functioning of MC.

Developed methods improve NPP operational safety and provide opportunities for implementation of the program aimed at increasing the NPP power and extending interrepair intervals of APCS equipment.

The positive results from implementation developed methods at NPP opens up perspective to development of on-line monitoring system for other thermotechnical parameters at the energetic industry.

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