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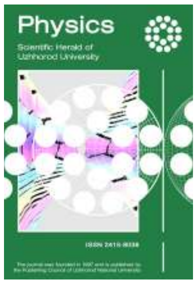

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Improvement of Thermometric Control of Nuclear Power Plant Equipment Based on the Study of the Possibility of Using Intelligent Sensors

Vitalii V. Levchenko*

SE "Zaporizhzhia NPP"
71504, 133 Promyslova Str., Energodar, Ukraine

Abstract

Relevance. The process of improving the safety of operation of nuclear power plants is in demand all over the world. Theorists, when interacting with practitioners, try to offer the best option for building a modern automated process control system (APCS). This paper discusses one of the problems faced by designers of modern automated process control systems, namely, an attempt is made to answer the question: how and by what criteria to select intelligent sensors for NPP equipment parameters that would meet the ever-growing requirements for reliability, accuracy and maximum automation of monitoring the state of the technological process. In this case, the object of research is modern intelligent temperature sensors and a resistive temperature detector TSP-0690, which are now widely used at nuclear power plants in Ukraine. Today the practice of using analogue thermal sensors is still widespread in the equipment of automated process control systems of NPP power units. However, the development of modern microchip technology allows organising more efficient and reliable automatic control systems for the technological process, but the lack of sufficient information about the ability of intelligent sensors to work effectively in nuclear power plants becomes an obstacle to their implementation.

Purpose. Theoretical and empirical analysis of existing intelligent temperature sensors aimed at identifying the most suitable temperature sensors that can be considered to replace obsolete analogue sensors.

Methods. A theoretical approach using the provisions of information theory adapted to measurement technology; experimental studies.

Results. Topical issues of assessing the applicability of intelligent digital temperature sensors in thermal control systems at nuclear power plants are considered. A comparative analysis of measuring temperature converters is carried out from the standpoint of the information and energy measuring theory. It was found that all the considered digital thermal sensors have better characteristics than the standard measuring device – the TSP-0690 resistive temperature detector, so the results are conclusions that further study is promising and relevant.

Conclusions. The DS18B20 temperature sensor is the most suitable for use in automated process control systems of NPP power units from the standpoint of information theory and its practical properties

Keywords: NPP safety, monitoring and control, temperature measurement, digital temperature sensor, computerised signal information processing

Introduction

Success in the development of the economy of any country is largely determined by the level of its energy potential and, above all, by the possibilities of generating electric energy. This forces countries to focus on the development of nuclear energy. Notably, nuclear power plants (hereinafter referred to as NPP), as objects of increased energy intensity and, accordingly, strategic importance, require special attention in terms of ensuring their nuclear and radiation safety by minimising the impact of possible risk factors [1]. Continuous improvement of control and measuring

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*Corresponding author

equipment of automated process control systems (hereinafter referred to as APCS), hardware modernisation and use of new algorithms in the management of information systems related to NPPs.

The possibility of using various modern digital technologies in the field of automation systems is often limited by the high cost of conducting the necessary research on new technical means. Therefore, there is a certain deficit in such studies. An obstacle to the widespread introduction of digital systems and technologies at nuclear power reactors of NPPs is also the fact that most of the latest developments of electronic equipment elements are imported, and the accompanying reference (rated) operating instructions are insufficient to comprehensively assess the possibility of applying the devices proposed for implementation in specific technical operating conditions. However, this fact does not exclude the fundamental suitability of new advanced developments and products of the world's leading manufacturers, but requires additional analysis of their functional reliability when performed in various automation devices at NPPs.

The functions performed by a modern NPP APCS are related to measurement, collection, transmission, processing of information, diagnostic analysis of the technological process, the output of control signals. The importance of primary transducers in NPP APCS, cannot be overestimated – the safety of nuclear power units largely depends on their functionality and reliability [2].

From numerous scientific sources, in particular [3-5], it can be concluded that in the future automation systems will be built mainly on intelligent sensors. This inevitably leads to the transition to digital channels and methods of transmitting signal information [6-8]. On the one hand, the advantage of analogue signal generation and transmission tools is the simplicity of implementing technical information processing tools and high performance. On the other hand, the significant disadvantages of analogue technology include high susceptibility to interference, which can lead to signal distortion and, consequently, contribute to various violations of the technological process, which is unacceptable in NPPs and can lead to emergency situations.

The digital signal, on the contrary, has a higher noise immunity, which allows achieving higher accuracy in transmitting information, but requires the use of complex analogue-to-digital transformations, which complicates the technical interface. The use of intelligent sensors is a promising alternative, since the entire process of converting an analogue signal to a digital one takes place in one device – the primary measuring converter, at the output of which a digital code is generated.

Currently there are several interpretations of the concept of intelligent sensor:

– a sensor with integrated electronics that performs one or more functions: logical (intelligent function); decision-making (control function); two-way communication function [9];

– adaptive sensor (a sensor whose parameters and/or algorithms may change during operation depending on the converter signals contained in it) with the function of metrological self-monitoring [10].

As a rule, when transmitting a digital signal, the last bits are cyclic redundant code (CRC), which is used to verify the accuracy of the received digital signal from the sensor [11]. CRC provides error detection when transmitting information with a probability of up to 99%. Therefore, switching to a digital signal should lead to an increase in the reliability of monitoring and automation systems, and as a result – to correct monitoring of the state and trends of the technological process.

The purpose of the study there is an introduction to modern digital intelligent temperature sensors, which can be considered as likely components for building modern digital APCS.

Theoretical Overview

Many sensors of technogenic information and actuators at NPPs, as before, are regarded as analogue devices according to the principle of their operation. The reason for this lies not in the high reliability of analogue equipment – just the reliability of digital equipment is significantly higher than analogue, but in the fact that full operation requires modern (new) knowledge and qualifications in the field of programming, system administration and understanding of the conditions and features of their use.

Gradually, it became clear that only the use of reprogrammed and universal devices would ensure the future of technical means of automating technological processes in order to ensure an increase in their functional reliability and safety (if such a potential threat, as in the case of NPPs, exists). To a greater extent, this applies not to specially programmable devices, but to fairly universal, reconfigurable ones. At this stage the development paths were divided into two lines:

– based on universal electronic computing machines (ECMs);

– based on simpler computers, but more optimised to perform the required task, and therefore, those that are not inferior in efficiency when used within the framework of a particular task.

Over the past 35 years of technology development, it has become clear that both of these approaches have the right to life. Moreover, it is their combination and provision of the desired quality that is commonplace today, although 20 years ago it seemed like fiction.

Comparing the level of general application technology itself in the areas of office applications and in the areas of automation, then the overall lag in the field of automation can be estimated at 1-2 generations of computer equipment. The reason for this lag is not the conservatism of the developed automation tools, but the fact that technical automation tools are usually subject to higher requirements than the more widespread office computing equipment. In addition, automation controllers are usually forced to work in much harsher operating conditions. The cost of failure in an automatic control system can also be much higher than in other information systems, since the control object needs to be managed constantly and in real time.

Returning to digital methods and information processing tools in ACS, these systems usually have a large number of different sensors and information converters of physical quantities such as temperature, pressure, liquid flow, speed, etc. These sensors convert the original physical quantity into some discrete standardised signal, for example, using a standard voltage range (from 0 V to 1 V) according to Kotelnikov theorem. In the future, the problem arises of converting this intermediate value into a digital form. Recently, a new generation of sensors has appeared and is rapidly developing, which have built-in controllers that perform a part of the function of converting a measured physical quantity into a measuring signal. Such a intelligent sensor itself becomes an element of the computer network. It becomes a micro-computer that supports the network protocol and transmits data already converted to digital form.

Often, the controller of such a sensor performs preliminary digital signal processing, for example, correction of systematic error of the converter, preliminary filtering of random interference, as well as performance monitoring. However, the development trend here is unequivocal – more and more technical means of ACS are becoming purely digital. Among the sensors, there are those in which the conversion takes place directly into digital form, and directly prepared for transmission over the communication channel.

Other components of ACS can also be arranged in the same way. Actuators, communication channels, action setpoints, filters, and so on can be digital and smart (with built-in microcontrollers) To date, the number of computers used to manage production processes has increased from 1 million in 1980 and more than 10 million in 2000 to more than 150 million in 2020 [12].

Figure 1 shows a graph of the growth in the number of computer applications in technological process (TP) control tasks.

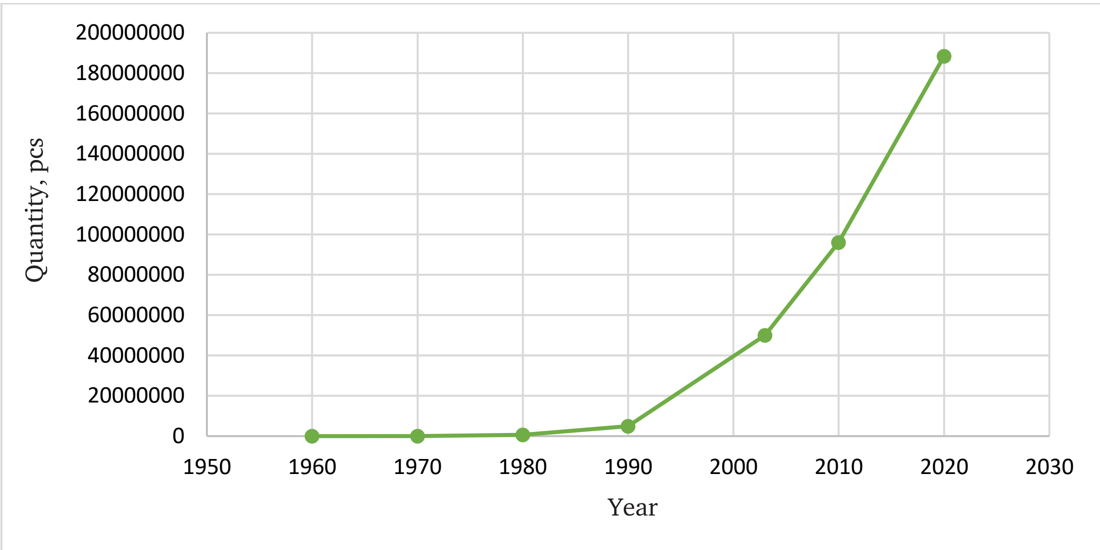

Figure 1. Historical growth in the number of computer applications in control tasks

It can be stated that the nature of the growth in the number of computers in control tasks is almost exponential. This takes into account the facts of using control task in solving the problem, and not the total number of processors. Taking into account the number of processors, the growth is much faster.

A modern NPP power unit is a complex control object with a large number of measured (from 5000 to 10000) and controlled (up to 4000) parameters. A generalised graph of the distribution of measured physical quantities on a single power unit is shown in Figure 2. Green colour shows the number of measurement points in the turbine compartment, blue – in the reactor compartment. This graph shows that temperature measurements prevail over other measurements.

Due to a large number of temperature sensors, it is worth focusing on the temperature control of technological processes and on the temperature measurement technology. An intelligent sensor (hereinafter referred to as IS) is an electronic device that combines a sensitive element, signal conversion schemes, and microprocessor technology. An intelligent sensor is a sensor with built-in electronics that includes:

– analogue-to-digital converter;
– microprocessor;
– digital signal processor;
– a system on a chip, etc.;
– digital interface with support for network protocols for communication.

Thus, an intelligent sensor can be included in a wireless or wired sensor network, due to the function of self-identification in the network along with other devices.

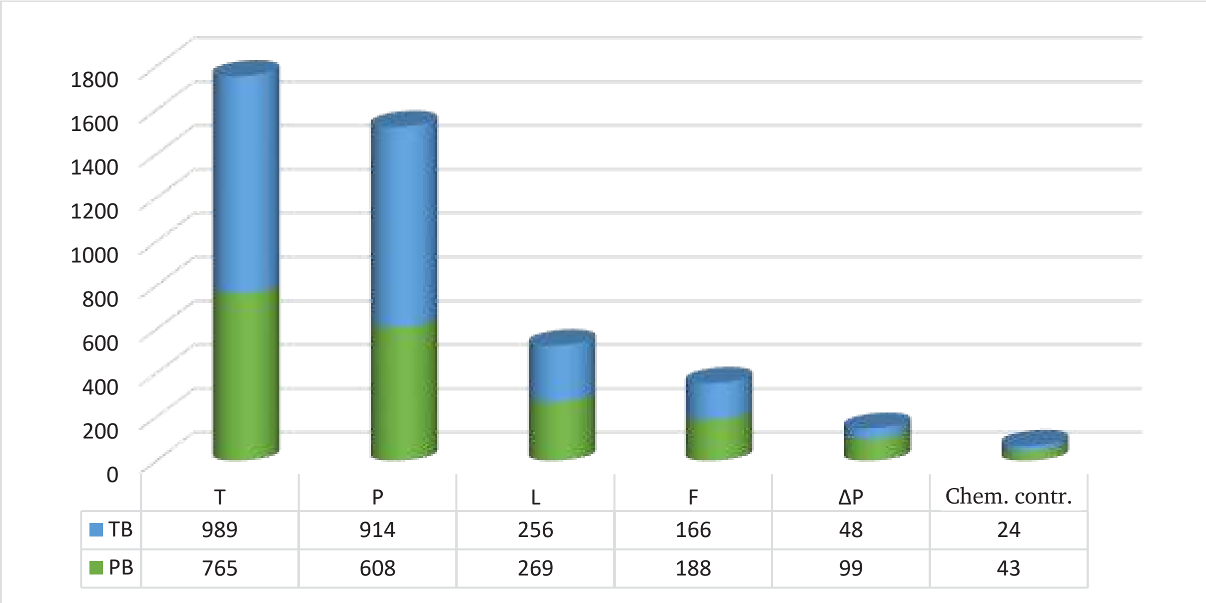

Figure 2. Average number of measured physical parameters per power unit
Note: TC – turbine compartment; RC – reactor compartment; T – temperature; P – pressure; L – level; F – flow rate; ΔP – pressure drop

Nowadays, there are many manufacturers of digital sensors and various technical solutions for building automated process control systems. However, the correct choice of the type of sensors used, the interface and well-written software depends on the reliability, durability, and accuracy of measurements of the developed systems. Therefore, the choice of a primary converter is given special attention at the design stage of automation systems and metrologically provided control of technological processes.

Materials and Methods

For further analysis, the authors have selected modern sensors according to the following criteria:

– measuring range from -25°C to 125°C;
– DC power supply voltage from 3 V to 5.5 V;
– bit depth from 9 bits to 12 bits.

More information about the selected sensors is provided in their technical specifications [13-17].

The study uses a TSP-0690 resistive temperature detector, a measuring device that is widely used at Ukrainian NPPs to measure the temperature at power units. For clarity and convenience, the main technical and metrological characteristics of the sensors under study are summarised in Table 1.

Table 1. Main technical and metrological characteristics of sensors

Sensor	Measuring range, °C	Maximum measurement Time, sec.	Accuracy, °C		Interface	Bit depth, bits	Supply voltage, V	Maximum current, μA
			in a limited range	in the operating range				
ADT-75	-55÷125	0.06	±2	±3	I²C	12	3÷5.5	525
DS18B20	-55÷125	0.75	±0.5	±2	1-Wire	9÷12	2.7÷5.5	15
LM92	-55÷150	0.5	±0.5	±1.5	I²C	12	2.7÷5.5	625
TMP100	-55÷125	0.6	±2	±3	I²C	9÷12	2.7÷5.5	75
TSP-0690	-50÷150	0.4	±3		4	–	5	100 mA

To conduct a comparative analysis, the study used the provisions of information theory adapted to measurement technology. Thus, it was found that the energy sensitivity threshold C, being a cumulative characteristic of the accuracy, sensitivity, power consumption and speed of measuring devices, can be expressed as a dependence of the form (1):

$$C = \gamma^2 P t \qquad (1)$$

where γ – measuring accuracy; P – power expended during the measurement by the device, W; t –measuring time, sec.

Energy sensitivity threshold of measuring devices C, according to the author, is a fairly informative generalised indicator of their quality, which unambiguously determines such information characteristics of these devices as energy efficiency η_e, loss of accuracy χ and loss of information Δq (2-4):

$$\eta_e = \frac{W_s}{C} = \frac{\pi e k \Theta}{C} \quad (2)$$

$$\chi = \sqrt{\frac{C}{W_s}} \quad (3)$$

$$\Delta q = 0.5 lg \frac{C}{W_s} \quad (4)$$

where W_s, J – sound energy value; k –Boltzmann's constant, J/K; Θ – absolute temperature, K.

At the same time, it is taken into account that the transfer of information from the measurement object to the measuring device can only occur through energy interaction. In the absence of energy exchange between the object and the measuring device, information transmission and measurement is impossible. Notably, with an increase in energy metabolism, the possibility of obtaining more information that reflects the equation (5) also increases [18]:

$$q_s = 9.3 + 0.5\lg{(Pt)} \quad (5)$$

where q_s – the maximum amount of information obtained during the measurement, expressed in energy units (J). This relationship sometimes shows a not entirely obvious connection between information and energy.

For a relative assessment of the information perfection (efficiency) of the measurement process, it seems appropriate to use the concept of information efficiency of the measurement [17], which can be expressed by the following equation (6):

$$\eta_i = \frac{9.3 + 0.5\lg W_s + 0.5\lg \eta_e}{9.3 + 0.5\lg W_s} \quad (6)$$

The advantage of this indicator is that it is suitable for comparing a wide variety of measurements (electrical, chemical, optical, etc.), regardless of the principle of operation of primary measuring converters and the equipment used in general. This evaluation approach is in good agreement not only with the principles adopted in computer science, but also with the provisions used in the nuclear power industry [19-20].

To characterise the relative perfection of devices, it is convenient to use a relative logarithmic indicator – an indicator of the energy Q-factor of the measuring instrument (a specific measuring device) (7):

$$pC = \frac{lgC}{lgW_s} \quad (7)$$

When using an "ideal" device for which $C=W_s$, $\eta_e=100\%$ and $\eta_i=100\%$, this indicator will be pC=100%. However, in practice, for all measuring devices, this indicator is located within the limits of the interval from 0% to 100%.

The analysis also takes into account that during observation, no information about the measured process may be obtained from the measuring equipment – during the so-called "dead time" of the measuring device, which is a cumulative generalised indicator of the accuracy and speed of measuring equipment (8):

$$\tau = \gamma^2 t \quad (8)$$

Results and Discussion

All calculations related to the analysis performed were performed in the Mathcad software environment. The results of the calculations performed are summarised in Table 2 and graphically presented in Figures 3-6.

Table 2. Calculated temperature sensor readings

Sensor type	Energy sensitivity threshold, J	Energy Q-factor indicator, %	Information efficiency, %	Dead time of measuring device, sec
ADT-75	4.8×10^{-8}	37.7	46.8	1.7×10^{-5}
DS18B20	7.6×10^{-9}	41.8	53.8	9.3×10^{-5}
LM-92	1.3×10^{-7}	35.6	37	3.7×10^{-5}
TMP100	6.9×10^{-8}	37	38.6	1.7×10^{-4}
TSP-0690	4.5×10-5	22.4	23	3.6

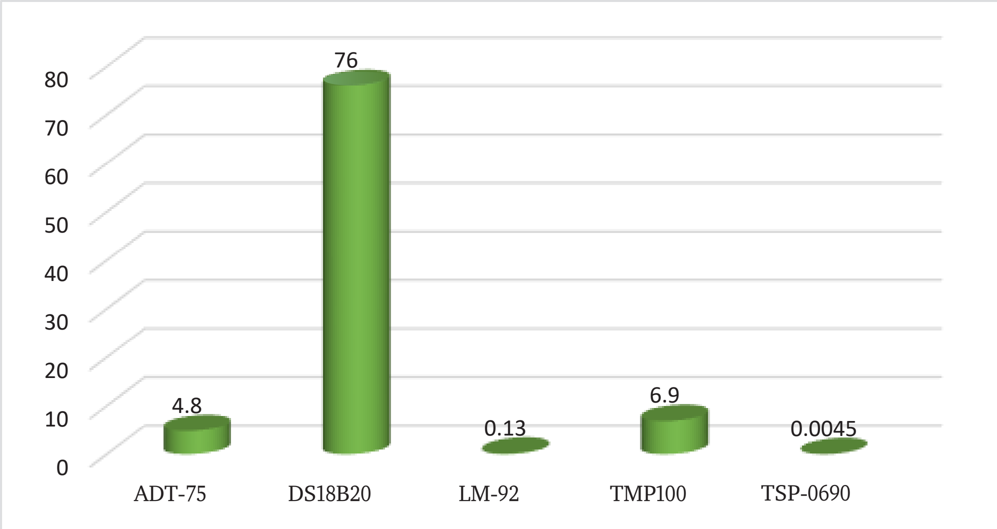

Figure 3. Comparison diagrams of the "energy sensitivity threshold" indicator

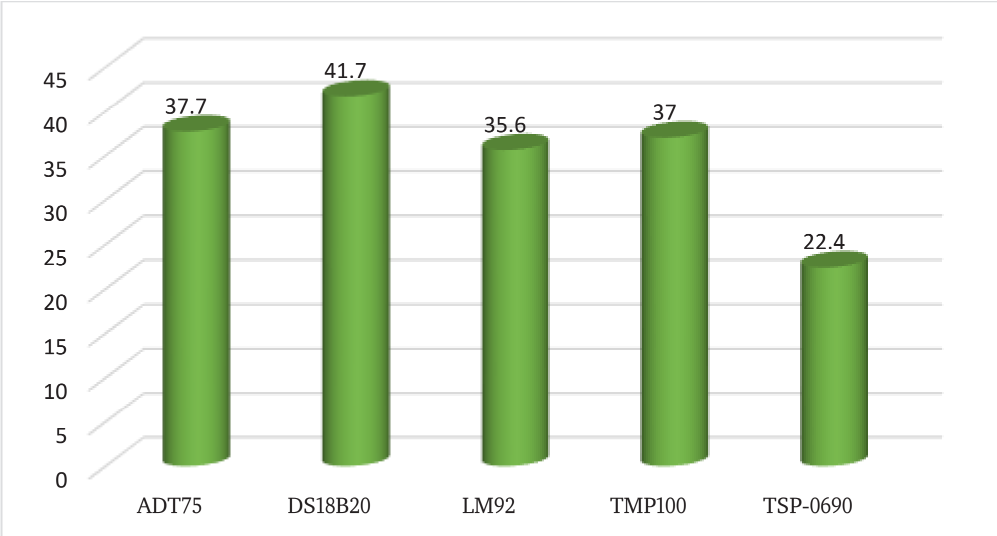

Figure 4. Comparison diagrams of the "energy Q-factor" indicator

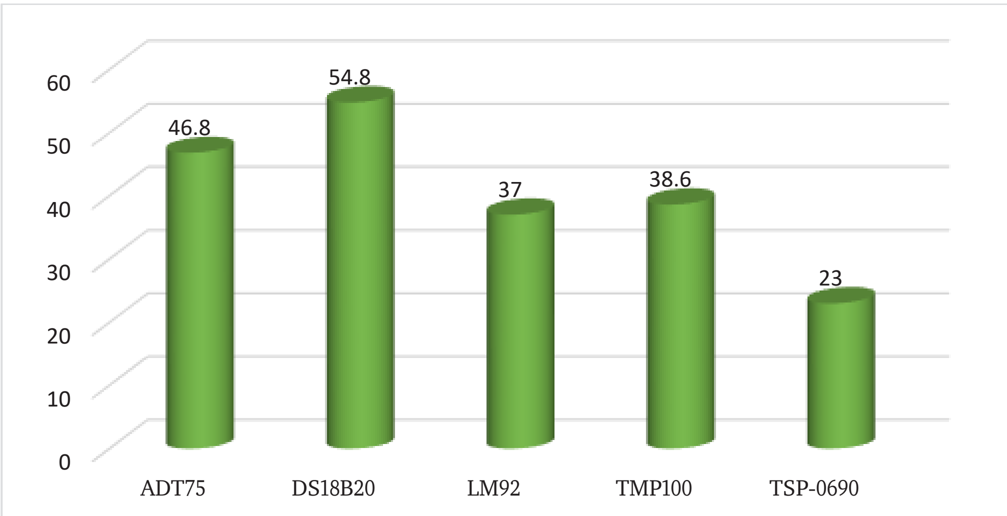

Figure 5. Comparison diagrams of the "information efficiency" indicator

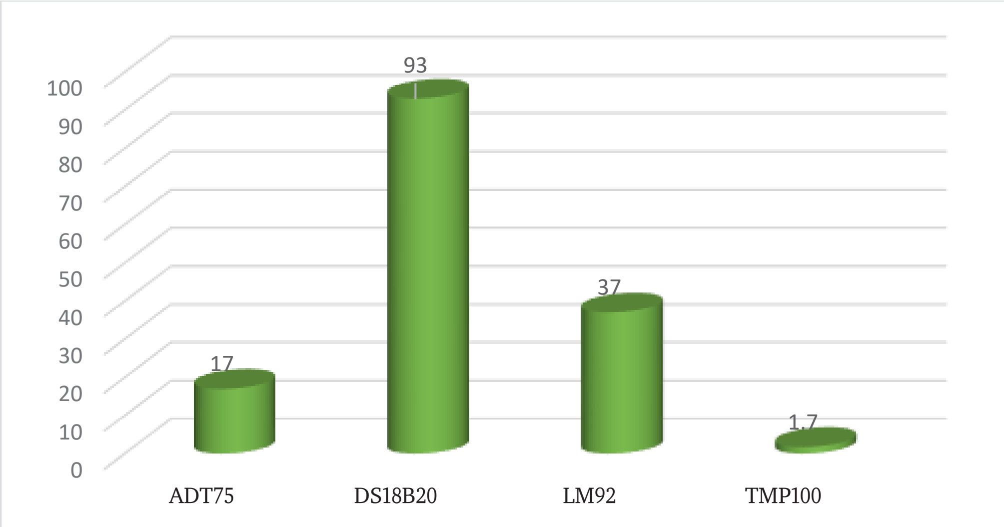

Figure 6. Comparison diagrams of the "dead time of measuring devices" indicator

The comparison shows that all digital thermal sensors have better characteristics than a standard measuring device (TSP-0690). At the same time, it can be concluded from the analysis that out of the five proposed temperature sensors, the DS18B20 temperature converter has the best characteristics. Of particular note is the availability of this converter and its low cost. The DS18B20 intelligent sensor can be considered as an active functional element of modern 1-Wire measurement technology, the implementation of which at NPPs seems promising due to the widespread transition of NPP technological equipment to ACS.

This measurement technology (1-Wire) allows creating multidimensional measurement networks using dozens and hundreds of similar sensors and on this basis provide a previously unattainable degree of informatisation of NPP safety systems – due to the prompt receipt and analysis of more extensive and detailed information on the distribution of temperature fields characteristic of station thermo-mechanical equipment.

Feasibility and practical interest in using DS18B20 digital sensors and 1-Wire technology at NPPs is well understood, for example, due to the production need for regular thermometric monitoring and monitoring of the steam turbine unit of the power unit. Measuring the temperature of the turbine unit elements by conventional means (only at the currently accepted control points) does not give a complete picture of the thermal state of the turbine unit and does not allow an objective assessment of the level of its current functional reliability. The application of the network digital concept of measurement control and monitoring of temperature fields can significantly increase the information content of measurements necessary to ensure the safe operation of the power unit's technological equipment.

Regarding the discussion of the study results, it is worth noting that most previous studies and related publications devoted to intelligent temperature sensors [21-23] reveal only the practical side of using these sensors in standard conditions, without conducting important scientific research for nuclear power regarding previously unplanned new operating conditions. Therefore, conducting new studies, the findings of which are given above, with further analysis of the data obtained, can hopefully allow using the studied intelligent sensors for temperature control of technological processes of equipment operation at NPP power units.

Conclusions

Thus, as a result of the analysis, it is possible to draw the following conclusions:

– digital temperature sensors have better metrological and informational characteristics promising for use at NPPs in the process of modernisation of control and measuring equipment compared to standard analogue-type measuring converters;

– the use of intelligent digital temperature sensors should reduce the error both during the measurement procedure and during the transmission of signal information for its further use;

– the use of digital signals in operational data transmission channels, in particular – from temperature sensors, should lead to the unification of equipment and simplify the process of integrating new means of change and control from different manufacturers, which, in turn, would lead to increased competition of suppliers and would contribute to the continuous improvement of equipment produced and supplied to NPPs;

– the transition from the analogue signal transmission and processing systems to digital systems would improve the information reliability of thermometric control systems, provide increased risk informatisation in process management and ensure the safety of NPP equipment;

The findings of this study can be recommended for use in the design of modern information and measurement systems for NPP power units after testing the considered measuring instruments in real operating conditions of the power plant.

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Удосконалення термометричного контролю обладнання аес на підставі дослідження можливості використання інтелектуальних датчиків

Віталій Вікторович Левченко

ВП «Запорізька АЕС»
71504, вул. Промислова, 133, м. Енергодар, Україна

Анотація

Актуальність. Процес підвищення безпеки експлуатації атомних електричних станцій у всьому світі є затребуваним. Теоретики при взаємодії з практиками намагаються запропонувати оптимальний варіант побудови сучасної автоматизованої системи управління технологічним процесом (АСУ ТП). У даній статті розглядається одна із проблем, з якою стикаються проектувальники сучасних АСУ ТП, а саме робиться спроба відповісти на питання: яким чином та за якими критеріями підібрати інтелектуальні датчики параметрів обладнання АЕС, які б відповідали постійно зростаючим вимогам до надійності, точності та максимальній автоматизації контролю за станом технологічного процесу. В даному випадку у якості об'єкту дослідження виступають сучасні інтелектуальні датчики температури, а також термоперетворювач опору ТСП-0690, що широко застосовуються зараз на атомних електричних станціях України. На сьогодні в апаратурі АСУ ТП енергоблоків АЕС все ще поширена практика використання аналогових термодатчиків, проте розвиток сучасної мікросхемотехніки дозволяє організовувати більш ефективні та надійні системи автоматичного керування (контролю) за технологічним процесом, проте відсутність достатньої інформації про спроможність ефективної працездатності інтелектуальних датчиків в умовах АЕС стає перепоною на шляху до впровадження їх.

Мета. Теоретичний та емпіричний аналіз існуючих інтелектуальних датчиків температури, спрямований на виявлення найбільш відповідних датчиків температури, які можуть бути розглянуті для заміни морально застарілих аналогових датчиків.

Методи. Теоретичний підхід з використанням положень та апарату теорії інформації, адаптованих до вимірювальної техніки, та експериментальні дослідження.

Результати. Розглянуто актуальні питання оцінки застосовності інтелектуальних цифрових датчиків температури в системах теплотехнічного контролю на АЕС. Проведено порівняльний аналіз вимірювальних перетворювачів температури з точки зору інформаційно-енергетичної теорії вимірювань. Було встановлено, що усі розглянуті цифрові термодатчики мають кращі характеристики ніж штатний вимірювальний пристрій – термоперетворювач опору ТСП-0690, тому результатами є висновки, що подальші дослідження в даному напрямі є перспективними та актуальними.

Висновки. Датчик температури DS18B20 є найбільш відповідним для використання в апаратурі АСУ ТП енергоблоків АЕС, з точки зору теорії інформації та його практичних властивостей

Ключові слова: безпека АЕС, моніторинг і контроль, вимірювання температури, цифровий термодатчик, комп'ютеризована обробка сигнальної інформації