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Sustainability assurance optimization-based approach to energy infrastructure diagnostics in energy systems management

Abstract: The study examines the factors and risks that affect the operational safety of energy infrastructure. Economic and technical diagnostics were performed, and the causes of equipment (turbine generator) failures were identified in order to develop effective approaches to managing the technical diagnostics of critical energy equipment and ensuring energy efficiency and safety of energy processes. This study presents a methodology for analyzing heat transfer in the stator winding core of turbine generators at South Ukrainian and Khmelnytsky NPPs, which allows us to gain insight into the temperature distribution and suggest ways to optimize thermal processes. The proposed

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approach facilitates the assessment of the temperature regime, identification of overheating risks and formulation of emergency measures. The results of the analysis of Khmelnytskyi NPP (Unit 2) and South Ukrainian NPP (Unit 1) showed that at Khmelnytskyi NPP the heat transfer parameters are within the permissible values for all rods, and at South Ukrainian NPP, the heat transfer parameter in rods 13 and 23 is 0 W, which requires immediate intervention to ensure the safety of further operation. This approach allows for timely response to power unit failures, ensuring safety and efficient management of power equipment operation and ensuring the continuous stable operation of the energy infrastructure with maximum efficiency. Further research will focus on the development of methods for predicting the stable operation of the power system based on preliminary technical assessments and thermal and mechanical analysis, which will allow for making science-based decisions on the stability of NPP equipment.

KEYWORDS: sustainable energy safety, energy technology, energy infrastructure, heat-transfer system, energy efficiency

Introduction

Ensuring the sustainability of energy complexes in modern realities is the most critical task, which involves technical diagnostics and modernization of energy equipment, ensuring the energy efficiency of processes, economic efficiency and the use of sustainable resources that have a minimal negative impact on the environment. Energy systems must strive to minimize adverse environmental impacts, including a structured risk management approach to ensure energy system resilience in the face of market volatility and technological change. These concerns require a comprehensive approach, considering societal needs and leveraging state-of-the-art technologies and energy management principles. The role of energy infrastructure diagnostics is to use approaches based on the benefits of optimization-based methods, such as increasing energy efficiency and reducing costs in managing energy systems. The sustainable development of nuclear energy involves implementing new technologies and methods to improve efficiency, safety, and management decisions.

Effective energy management to ensure the safe operation of energy complexes is only possible by considering operational experience, timely techno-economic diagnostics, and science-based decision-making. The issue of ensuring the energy efficiency of operating NPPs worldwide is relevant and is being addressed by various stakeholders, including governments, international organizations, and the nuclear industry. Ensuring the energy efficiency of operating nuclear power plants (NPPs) is crucial for maximizing the benefits of nuclear power while minimizing its environmental impact and ensuring the energy efficiency of water-water-energy reactor (WWER or VVER) power units operating in Ukraine and widely used in Europe and the world through timely diagnostics of technical systems to identify possible inefficiency points and their prompt elimination. WWERs are a series of pressurized water reactors (PWRs) operating in Ukraine. WWERs are widespread in Europe and the world, ensuring their sustainable energy efficiency includes regular maintenance, implementation of modern diagnostic and monitoring systems, data analytics to predict maintenance needs, and technology upgrades to improve efficiency. Considering the process launched in European countries to decommission WWERs due to technical safety, such reagents continue to be used in other countries. Operators of power units are also working to improve staff skills, implement energy management systems, and cooperate with international organizations to share experience and use advanced technologies in the energy sector (Olczak et al. 2023; Liu et al. 2023; Králik 2017).

The demand for electric energy in Ukraine is increasing daily because of the country's social and economic changes. The increasing demand and impossibility of reducing the power capacity force to improve the efficiency of existing power facilities. The leading cause of inefficient power generation at nuclear power plants is damage to turbine generators (TGs), significantly reducing power generation.

The damage factors affecting the turbine generator stator winding cores include the following degradation factors:

- temperature regimes during equipment operation, including possible cyclic fluctuations;
- unfavorable vibration-dynamic vibrations at the "distillate collector – branch pipes – external pipelines" assembly of the design of the frontal parts of the stator winding;
- impact of thermomechanical stresses arising in the stator winding under repeated changes of loading modes;
- impact of chemically active substances;
- mechanical damage during repair and installation works.

As a rule, degradation proceeds more intensively with the simultaneous influence of several damaging factors on the equipment, such as the presence of local overheating of the stator winding rods, the presence of mechanical impurities in the composition of the cooling distillate, and increased vibrations at the stator winding busbar terminals.

To ensure the safe operation of power equipment, it is necessary to develop a comprehensive regulatory approach to technical diagnostics, considering that it affects the degradation processes and ensures the efficiency and sustainability of further operations. Thus, Section 2 addresses ensuring the sustainability of energy systems, followed by Section 3, which discusses the assessment of the technical conditions of energy equipment to ensure sustainability, ending with Results and Discussions in Section 4 and Conclusions in Section 5.

1. Literature review

The current state of development of the nuclear power industry is focused on ensuring safety during the operation and disposal of nuclear materials. Research has focused on developing technologies that minimize the risk of accidents and facilitate rapid detection and elimination of emergencies (Sun et al. 2022; Li et al. 2022; Hrinchenko et al. 2023). Diagnostic methods and corresponding recommendations were also proposed to facilitate the timely identification of possible hazards during nuclear power plant equipment operation. Research (Sun et al. 2022; Hrinchenko et al. 2023) presents safety management methods that consider possible changes during operation and predict further safe operation. Cooperation between countries in nuclear energy is aimed at sharing knowledge, technologies, and safety standards. This is considered the development of standardized methods and algorithms for technical diagnostics of equipment and support processes (Li et al. 2022; Savina et al. 2021). Thus, a standardized algorithm for the technical diagnostics of power equipment of the main circulation pipeline was proposed, considering the influence of parameters that affect aging and degradation processes (Li et al. 2022). This approach can also be applied to other equipment, however, although the authors talk about a comprehensive safety analysis as part of regulatory support, they only provide examples for the main circulation pipeline without taking into account parameters that may affect the overall energy efficiency of the power unit.

Another area of sustainable development in the energy sector is ensuring the quality of operation, which includes safety, energy efficiency, and other parameters of the integrated assessment. The issue of quality assurance has been addressed from the perspective of defining qualimetric approaches and assessment criteria in previous papers (Elbayoumi and Tahvonen 2022; Sharma and Bandyopadhyay 2023; Blázquez et al. 2023; Dobaj et al. 2023). For example, the authors (Elbayoumi and Tahvonen 2022; Sharma and Bandyopadhyay 2023) proposed a methodology for the multi-criteria assessment of sustainable development indicators and risks affecting operation safety for multi-parameter systems. Qualimetric assessment methods have proven effective management mechanisms (Blázquez et al. 2023; Dobaj et al. 2023). However, these approaches always involve expert judgment, which can indirectly affect the assessment results.

In (Dobaj et al. 2023), a method of quality control of individual parameters and quantitative indicators of these criteria was proposed to determine the impact of these parameters on the stress state of equipment and the possibility of developing a system of regulatory data and requirements for equipment. Quality control based on quantitative characteristics and parameters provides more accurate assessments of the overall system but requires a significant amount of statistical data to collect and process, which is not appropriate and available in all areas of power equipment.

Previous research (Hózer et al. 2023; Lind et al. 2019; Meyer and Wiesenack 2022) reviewed the available experimental databases to support the safety analysis of nuclear power plants related to steam generator tube rupture (SGTR) and the loss of coolant accidents (LOCAs). This review examined occurrences associated with fuel failure, the release of fission products from fuel rods, and the activity transfer to the environment. The emergencies analyzed in the papers exhibit diverse parameters and encompass various scale facilities and experimental methods. The review includes presenting integrated tests and analyzing parameter measurements at nuclear power plants (NPPs). The extensive database, comprising over 40 experimental programs and a series of measurements, can be deemed a dependable foundation for developing and validating numerical models for safety analyses of steam generator ruptures and the loss of coolant accidents. The approach based on the analysis of existing failures and accidents due to the loss of coolant is an effective mechanism for further work to prevent such events, and it needs to be improved in terms of technical diagnostics before such an event occurs.

The research (Ciattaglia et al. 2019; Taylor et al. 2019; Chen et al. 2023) described the need for a pragmatic approach to the technical diagnostics of complex power equipment, especially for assessing and improving the readiness of technical solutions through particular physical and technological research and development. A system engineering approach based on a comprehensive design analysis of a nuclear power plant is proposed, which serves clearly defined goals such as safety, availability, and quality of electricity supply to the grid. It not only identifies critical points in the operation of the equipment but also sets the limits of possible solutions (Merk et al. 2023). In addition, it defines the defining parameters for the technical systems and focuses on the safety and operational balance of the power plant. Safety aspects that require early attention and constant reanalysis in the case of any significant changes in the design are identified (Xu and Zhang 2022; Kim and Kim 1987).

The authors (Gupta et al. 2019, 2021; Adamantiades and Kessides 2009) note that nuclear power makes a significant contribution to reducing greenhouse gas emissions and is important for the future in terms of sustainability. However, there are still issues of safety, radioactive waste disposal, and the proliferation of nuclear explosives that need to be addressed effectively to gain the necessary public support. The authors (Lee and Kang 2016; Csereklyei et al. 2016) note that the construction of new NPPs is largely determined by the duration of construction and affects economic growth, and such a strategy is ineffective without maintaining existing power capacities in a satisfactory condition.

In the broader context, nuclear power continues to be a significant element of the global energy landscape. However, its advancement is intricately linked to challenges related to safety, sustainability, and responsible utilization of resources. Recognizing the imperative for sustainable development and effective energy security management underscores the need to formulate a well-defined strategy with a clear vision. This strategy should ensure the efficiency of nuclear power plants across all life cycle stages, considering potential changes and their corresponding impacts (Kharchenko et al. 2021; Hrinchenko et al. 2024; Ji et al. 2022).

2. Theoretical framework

2.1. Economic diagnostic of energy infrastructure condition

Diagnosing energy safety problems is difficult due to the need for an unambiguous methodological approach to defining the scope of research and assessing the state of this safety. The explanation for the complexity of the energy safety concept stems from the need to consider various aspects of the country's functioning: economic, social, environmental, etc. To manage energy security and assess the impact of management decisions on its parameters, it is necessary to consider various aspects of energy supply organization that directly or indirectly affect the operation of the energy sector and its strategic planning. At the same time, systemic solutions are not possible without considering certain parameters and implementing specific actions.

The analysis of Ukraine's energy balance shows that nuclear power accounts for the bulk of electricity generation (Table 1), and in order to determine an effective energy development strategy and make management decisions in this area, it is necessary to ensure proper operating conditions, including safety and energy efficiency measures that directly affect economic stability in this sector. In 2021, electricity generation in Ukraine totaled 156,576 GW·h, up 5.2% compared to 2020. NPPs accounted for 55.1% of the total generation in 2021, TPPs and CHPPs for 29.3%, and HPPs and PSPs for 6.7%.

Table 1. Settled capacity of power plants and release of electricity by type of power plants

Tabela 1. Moc elektrowni i produkcja energii elektrycznej według typu elektrowni

Types of generating enterprises	Power plant capacity by year-end [MW]		Electricity output [GW·h]	
	2019	2020	2019	2020
Total Including:	51,444	55,138	141,213	137,197
heat power plants	22,265	22,311	40,910	36,300
combined heat and power plants	5,855	5,890	10,738	12,837
nuclear power plants	13,835	13,835	77,948	71,249
hydropower plant[1]	6,326	6,335	7,712	7,415
other power plants of which:	3,163	6,767	3,906	9,396
wind power plants	795	1,110	1,760	3,271
solar power plants	1,953	5,194	1,883	5,684

[1] Including pumped hydro power plants (own study).

Economic diagnostics are also necessary since losses from incorrectly made decisions to terminate the operation of the energy infrastructure or the unreasonability of extending the assigned life of equipment can only increase. Hence, it becomes imperative to devise novel analytical and computational methodologies to assess the remaining equipment lifespan and explore opportunities to prolong energy-related apparatus's serviceability.

These approaches should yield dependable outcomes reflective of real-world operational settings, particularly in contemporary contexts marked by a pressing demand for energy assets' secure and energy-efficient utilization. In order to guarantee the security of energy infrastructure and the operational excellence of energy equipment, it is imperative to establish a proficient mechanism for assessing its technical state. Such a mechanism should optimize performance while maintaining a favorable equilibrium between economic considerations and safety priorities.

The technical and economic diagnostics of the state of energy infrastructure assess the current state of infrastructure facilities and systems used for producing, transmitting, and distributing energy, considering technical and economic parameters. This analysis includes an assessment of the technical condition of the equipment, its performance, and its efficiency of use, as well as economic aspects such as operating costs, maintenance, possible risks, and potential income from improving or modernizing the infrastructure. Considering technical and economic factors, the techno-economic diagnostic determines optimal strategies for managing and developing energy infrastructures.

Economic diagnostics examine the relationship between energy consumption, technological change, and economic decisions and their impact on energy infrastructure investment. It highlights the key drivers of energy demand, consumption and investment, as well as the role of governments in the energy market (Edomah 2015). Infrastructure analysis systems, such as the Energy Systems Analysis System (GIQAAS), collect infrastructure-related economic data and conduct economic analyses based on that data. Users can use these systems to collect and analyze data (Zaher et al. 2012). Infrastructure diagnostics and analyses involve collecting system information, applying analysis rules, and generating analytical information about the target system and operational servers (Di et al. 2020). The impact of energy infrastructure on economic growth can be studied using variables that are part of the infrastructure, which has been found to impact economic growth significantly (Pandey 2020).

Economic diagnostics of energy infrastructure include the analysis of economic indicators associated with the production, transportation, and the distribution of energy. Figure 1 outlines some of the critical aspects that may be included in an economic diagnosis.

Economic diagnostics help understand the economic efficiency and sustainability of energy infrastructure and identify areas for improvement and optimization. The main direction of economic diagnostics is an investment analysis of the state and prospects for developing the current state of energy facilities, such as power plants and transmission and distribution networks.

Increasing risks and uncertainties in the energy sector (changes in energy prices, climate change policies) make it increasingly necessary to diagnose and analyze infrastructure systems from the perspective of their sustainability and decarbonization of electricity production, as this ensures economic sustainability (Andersson et al. 2021). In general, investment diagnostics of energy infrastructure includes assessment of the technical condition of equipment and infrastructure (wear, degree of obsolescence), optimization of energy consumption, regulatory regulation and financial stability, and investment attractiveness (potential return on investment and risks).

The wear and tear of energy equipment can be a severe problem in the uninterrupted functioning of energy systems, requiring investment in its renewal. This is especially true for power plants and transmission and distribution networks, which may need more modern equipment and better technical conditions (Andersson et al. 2021). To ensure operational safety and minimize risks for workers and the environment through technical obsolescence (significant wear and tear), investments are being made in updating energy equipment. Investment support for the renewal of energy equipment involves not only the replacement of outdated equipment but also the introduction of new technologies to increase energy efficiency and modernize existing energy

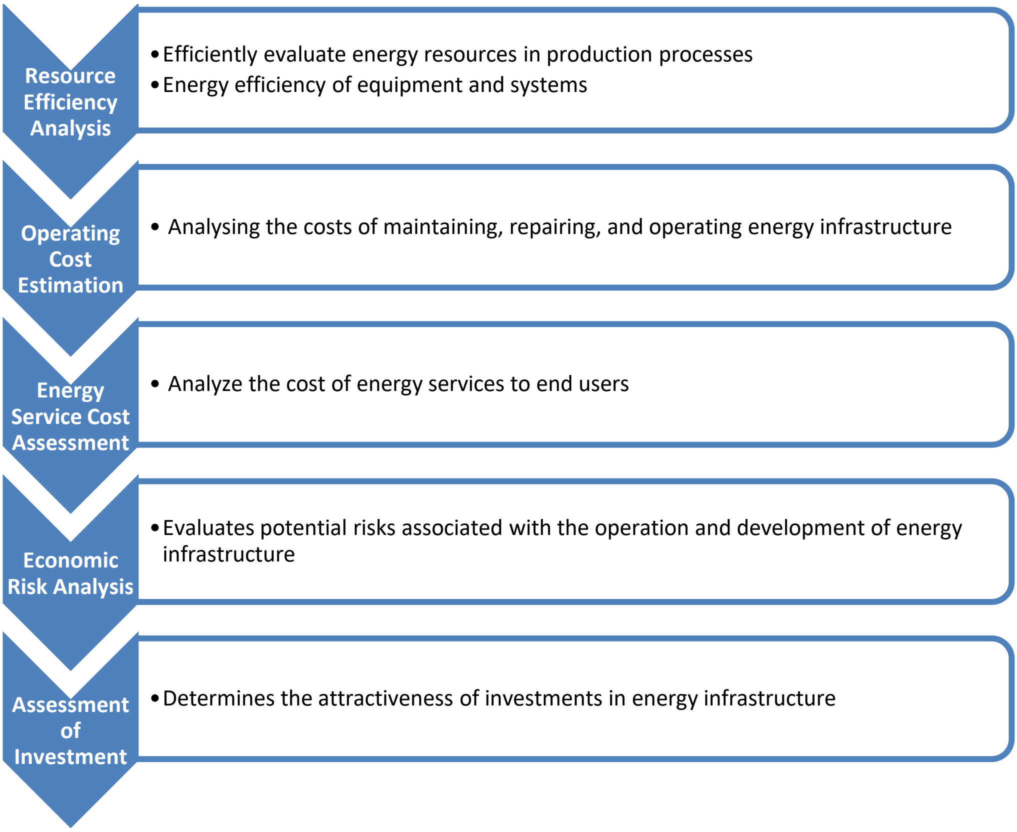

Fig. 1. The scheme of diagnostics of energy infrastructure (own study)

Rys. 1. Schemat diagnozy ekonomicznej infrastruktury energetycznej

systems. These investments help improve the reliability and efficiency of energy infrastructure, ensure its long-term sustainability, and reduce operating costs.

The level of wear and tear on equipment in nuclear power plants can vary significantly depending on many factors, including the age of the plant, the type of reactors used, operating conditions, the level of maintenance and modernization, and the safety standards applied at the particular nuclear power plant. The main components of nuclear power plants, such as reactors, turbines, and generators, are significantly subject to wear and tear.

Figure 1 shows the levels of wear and tear of energy equipment for electricity, gas, steam, and air conditioning supply for 2017 and 2021. The average wear and tear of fixed assets of electricity, gas, steam, and air conditioning supply enterprises has been at least 68% since 2018 (UKRSTAT 2023). In this case, manufacturers and operators usually set wear limits for each type of equipment; for example, a turbogenerator can be about 70–80% of the initially set value.

Therefore, a reasonable direction for updating and modernizing equipment is investments in significantly reducing wear and tear. Replacing outdated equipment with more modern and

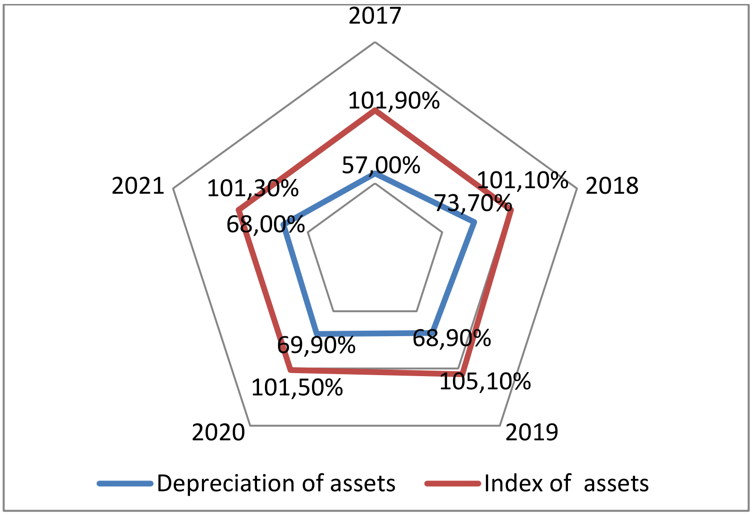

Fig. 2. Dynamics of asset depreciation rate and index of tangible assets for electricity, gas, steam and air conditioning in Ukraine in 2018–2021 (own study based on UKRSTAT 2023)

Rys. 2. Dynamika amortyzacji aktywów i indeksu aktywów trwałych w grupach: energia elektryczna, gaz, para wodna i klimatyzacja na Ukrainie w latach 2017–2021

efficient ones increases the reliability and performance of the system, reduces maintenance costs and increases the service life of the equipment. Additionally, investing in maintenance and regular upgrades helps prevent premature wear and tear and improves the overall operating efficiency of energy systems.

Technical renewal of machinery infrastructure and the modernization of energy infrastructure enterprises require investment support. Investments in decarbonizing electricity generation can provide sustainable impact and risk-adjusted returns (Pandey 2020; Andersson et al. 2021; UKRSTAT 2023; Gaska et al. 2019). In general, investments in modernizing energy infrastructure are necessary to improve competitiveness, adapt to environmental changes, and overcome the long-term consequences of climate change (Ciuła et al. 2023; Fang et al. 2021). Figure 3 shows the volume of foreign direct investment in the Ukrainian economy (Ciuła et al. 2023; Gaska et al. 2023).

The volumes of foreign direct investment in electricity, gas, steam and air conditioning supply in Ukraine did not grow significantly and, during the war, generally decreased, which negatively affected the stability of the operation of power equipment and its technical condition in the future, which requires an assessment of the technical condition (Chupryna et al. 2022).

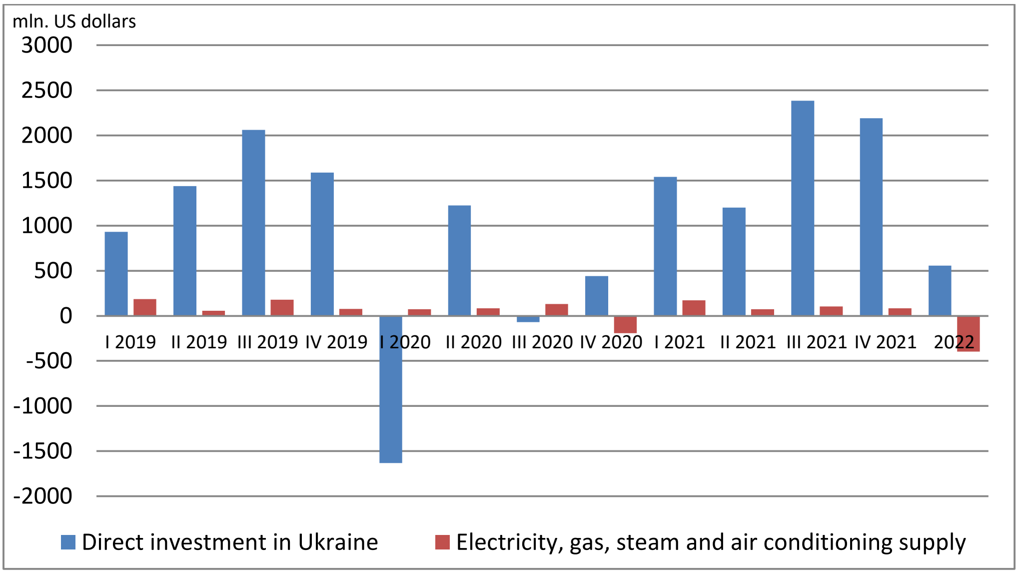

Fig. 3. Direct investments in Ukraine for 2019–2022 mln. US dollars (own study based on NBU 2023)

Rys. 3. Inwestycje bezpośrednie w Ukrainie w latach 2019–2022, mln dolarów amerykańskich

2.2. Assessment of the technical condition of energy equipment

At present, diagnostics of the condition of hollow conductors are performed with the help of resistance thermocouples (RT) applied to the insulation of each rod on the distillate drain side or under the groove wedge near the exit from the groove. The turbogenerator specification recommends a permissible number of plugged hollow conductors, not more than one. If two conductors are plugged, their temperature is calculated to be three times higher than that of the normative conductor. However, as experience shows, there is not always a significant increase in temperature. For example, if there is a hollow conductor with distillate circulation between the clogged conductor and RT, the temperature rise may be insignificant (Riemersma et al. 2020; Hallowell et al. 2017; Kharazishvili et al. 2023). In addition, the sensitivity of RT to changes in the core copper temperature depends significantly on the degree to which RT is pressed against the core insulation. It decreases when the wedging of the groove is weakened. Thus, normative control methods have low efficiency in detecting hollow-conductor blockages.

To examine the cooling of generator stator winding rods, it is crucial to understand the underlying physical processes governing the transfer of heat energy. This transfer can occur directly, through contact, or indirectly, through a separating partition, such as bodies or media composed of some material (Moa and Go 2023; Sotnyk et al. 2021; Qi et al. 2021; Shvydanenko et al. 2023). When physical bodies within a system possess disparate temperatures, thermal energy, or heat, is transferred from the hotter body to the colder body until thermodynamic equilibrium is achieved. The spontaneous nature of this heat transfer, which constantly moves from a hotter to a colder body, aligns with the principles outlined in the second law of thermodynamics.

The ability of a substance to conduct heat is characterized by the coefficient of thermal conductivity (specific thermal conductivity). Numerically, this characteristic is equal to the amount of heat passing through a sample of material with thickness per unit length (1 m), area per unit area (1 m^2), per unit time (1 second) at a unit temperature gradient (1 K). In the metric system of measures, the unit of heat transfer coefficient is W/(m·K).

In the steady-state regime, the energy flux density transferred by heat conduction is proportional to the temperature gradient (20):

$$\vec{q} = -\aleph grad\left(T\right) \tag{1}$$

where:

$\vec{q}$ – heat flux density vector defined as the amount of energy passing per unit of time through a unit area perpendicular to each axis,
$\aleph$ – heat transfer coefficient (specific heat conductivity),
T – the temperature.

The minus on the right-hand side shows that the heat flux is directed opposite to the vector grad T (i.e., towards the fastest decreasing temperature). This expression is known as Fourier's law of heat conduction.

The heat transfer coefficient of gases (λ) is defined by the formula:

$$\lambda = \frac{ik}{3\pi^{3/2}d^2}\sqrt{\frac{RT}{M}} \tag{2}$$

where:

i – the sum of translational and rotational degrees of freedom of molecules (for a two-atom gas $i = 5$, for a one-atom gas $i = 3$),
k – Boltzmann's constant,
M – molar mass,
T – absolute temperature,
d – effective diameter of molecules,
R – the universal gas constant.

The formula shows that heavy one-atom (inert) gases have the lowest thermal conductivity, light multi-atom gases have the highest thermal conductivity (which is confirmed by practice), and hydrogen has the maximum thermal conductivity of all gases.

In the case of heat transfer through the surface, heat is transferred from the hotter fluid to the wall, heat is conducted in the wall, and heat is transferred from the wall to the cooler moving medium.

The intensity of the heat transfer is characterized by the heat transfer coefficient kT, numerically equal to the amount of heat that is transferred through a unit of wall surface per unit time at a temperature difference between liquids of 1 K; the dimensionality of k is wt/(m^2·K) [kcal/m^2·°C]. The value R, the inverse of the heat transfer coefficient, is called total thermal resistance.

For example, R of a single-layer wall is calculated according to the following formula:

$$R = \frac{1}{k_T} = \frac{1}{\alpha_1} + \frac{\delta}{\lambda} + \frac{1}{\alpha_2} \tag{3}$$

where:

α_1 – heat transfer coefficient from wall surface to cold liquid,
α_2 – heat transfer coefficient from hot liquid to wall surface,
δ – wall thickness,
λ – heat conductivity coefficient,
k_T – the heat transfer coefficient.

In most practical cases, the T coefficient is determined experimentally. The obtained results are processed using the similarity theory method in this case.

The principle of calculating the heat flow through a cylindrical wall is as follows. Consider a homogeneous pipe with thermal conductivity (Fig. 4). Inside the pipe there is a cold medium with temperature $t_f^{'}$, and outside, there is a cold medium with temperature $t_f^{''}$.

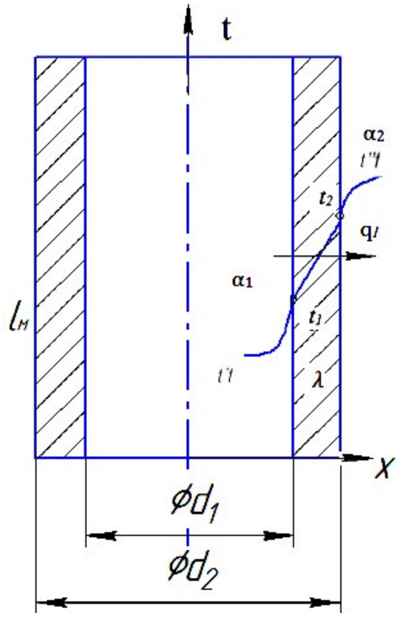

Fig. 4. The scheme of heat flow through the cylindrical wall (own study)

Rys. 4. Schemat przepływu ciepła przez ściankę cylindra

The amount of heat transferred from the hot medium to the inner wall of the pipe, according to the Newton-Richman law, is as follows:

$$Q = pd_1 a_1 l\left(t_f^{'} - t_1\right) \tag{4}$$

where:

a_1 – the heat transfer coefficient from the hot medium with temperature $t_f^{'}$ to the wall surface with temperature t_1,
d_1 – inner diameter,
l – length.

The heat flux transferred through the pipe wall is determined by the equation (d_2 – outer diameter):

$$Q = 2pl^2 \frac{\left(t_1 - t_2\right)}{\ln\left(d_2 / d_1\right)} \tag{5}$$

The heat flux from the second surface of the pipe wall to the cold medium is determined by the formula:

$$Q = pd_2 a_2\left(t_1 - t_f^{''}\right) \tag{6}$$

where:

a_2 – is the heat transfer coefficient from the second wall surface to the cold medium with temperature $t_f^{''}$.

Solving these three equations we obtain:

$$Q = pl\left(t_f^{'} - t_f^{''}\right)K \tag{7}$$

where:

$K_1 = 1/[1/a_1 d_1) + 1/(2l \ln(d_2/d_1) + 1/(a_2/d_2)]$ is the linear heat transfer coefficient, or $R_1 = /K_1 = 1/K_1 = [1/(a_1 d_1) + 1/(2l \ln(d_2/d_1) + 1/(a_2 d_2)]$ is the total linear thermal resistance to heat transfer through a single-layer cylindrical wall,
$1/(a_1 d_1)$, $1/(a_2 d_2)$ – thermal resistances of heat transfer of wall surfaces,
$1/(2\mathrm{l} \ln(d_2/d_1))$ – wall thermal resistance.

For a multilayer (n layers) cylindrical wall, the total linear thermal resistance will be determined by the following formula:

$$R_1 = 1/K_1 = \left[1/\left(a_1 d_1\right) + 1/\left(2l_1 \ln\left(d_2/d_1\right)\right) + 1/\begin{array}{c}\left(2l_3 \ln\left(d_3/d_2\right)\right) + \ldots \\ +1/\left(2l_n \ln\left(d_{n+1}/d_n\right)\right) + 1/a_2 d_n\end{array}\right] \tag{8}$$

It is also necessary to carry out a design analysis for heat transfer with different coolant velocities. For this purpose, it is necessary to calculate the heating surface by the next formula:

$$F = l \cdot \pi d \tag{9}$$

where:
l – channel length,
d – internal diameter of the channel.

Arithmetic mean water temperature (t_f) is calculated as:

$$t_f = 0.5\left(t_f^{'} + t_f^{''}\right) \tag{10}$$

where
$t_f^{'}, t_f^{''}$ – respectively, water temperature at the inlet and outlet channels (Fig. 1).

Prandtl number (Pr_f) is a criterion for the similarity of thermal processes in liquids and gases, considering the influence of the physical properties of the coolant on heat transfer.

$$Pr_f = 0.88$$

The amount of heat delivered (Q) is determined from the expression:

$$Q = Gc_f\left(t_{f1}^{''} - t_{f1}^{'}\right)$$

where
G – mass flow rate [kg/s].

Reynolds number for water flow (R_e) is calculated as:

$$Re = v_n d_k / \nu_f \tag{11}$$

Nusselt number (Nu) is a criterion of similarity of thermal processes, which characterizes the ratio between the intensity of heat transfer due to convection and the intensity of heat transfer is defined as:

$$Nu = 0.21\ Re^{0.8} Pr^{0.43} \tag{12}$$

Then the heat transfer coefficient (α,W/(m$^2\cdot$°C) is equal to:

$$\alpha = Nu \frac{\lambda_f}{d} \tag{13}$$

where f – heat transfer coefficient of the flow.

3. Results and discussion

Calculating the thermal conductivity of turbine generator rods requires knowledge of the physical properties of water and the materials used in generator design. This requires information on the thermal conductivities (thermal conductivity coefficients) of the materials and the properties of water at different temperatures. The coefficient of thermal conductivity (λ) for each material used in the turbine generator rods was obtained from the accompanying technical documents for the equipment. Water properties include the heat capacity of water and its temperature characteristics. Other possible aspects, such as convection and radiation, should also be considered depending on the specific operating conditions of the turbine generator. The physical properties of the water and the materials used are given below.

Physical properties of water at arithmetic mean temperature (Hrinchenko et al. 2023):

ρ_f = 1,000 kg/m^3;
c_f = 4.2 kJ/kg·K;
λ_f = 0.599 W/(m·°C);
ν_f = $0.658 \cdot 10^{-6}$ m^2/s;

Physical properties of copper

ρ_f = 8,800 kg/m^3;
c_f = 0.38 kJ/kg·K;
λ_f = 403.0 W/(m·°C);

Physical properties of steel

ρ_f = 7,850 kg/m^3;
c_f = 0.46·0.48 kJ/kg·K;
λ_f = 58.0 W/(m·°C).

Conduct of the calculation of heat transfer in the cooling circuit of stator winding rods of TVV-1000 turbogenerator.

The heating surface is calculated by formula:

$$F = 8 \cdot 3.14 \cdot 0.028 = 0.703 \text{ m}^2 \tag{14}$$

The average arithmetic temperature of water is counted off by formula:

$$t_a = 0.5(37.8 + 37) = 37.4°\text{C} \tag{15}$$

The quantity of transferred heat is determined from the expression:

$$Q = 0.39 - 4.2(37.5 - 37) = 0.81 \text{ W} \tag{16}$$

The diagrams show the rod heat transfer (W) for KhNPP Unit 2 (Fig. 5) and South Ukraine NPP Unit 1 (Fig. 6). The diagrams graphically represent the level of heat transfer in each of the 42 rods of KhNPP Unit 2 and for each of the 60 rods of SUNPP Unit 1.

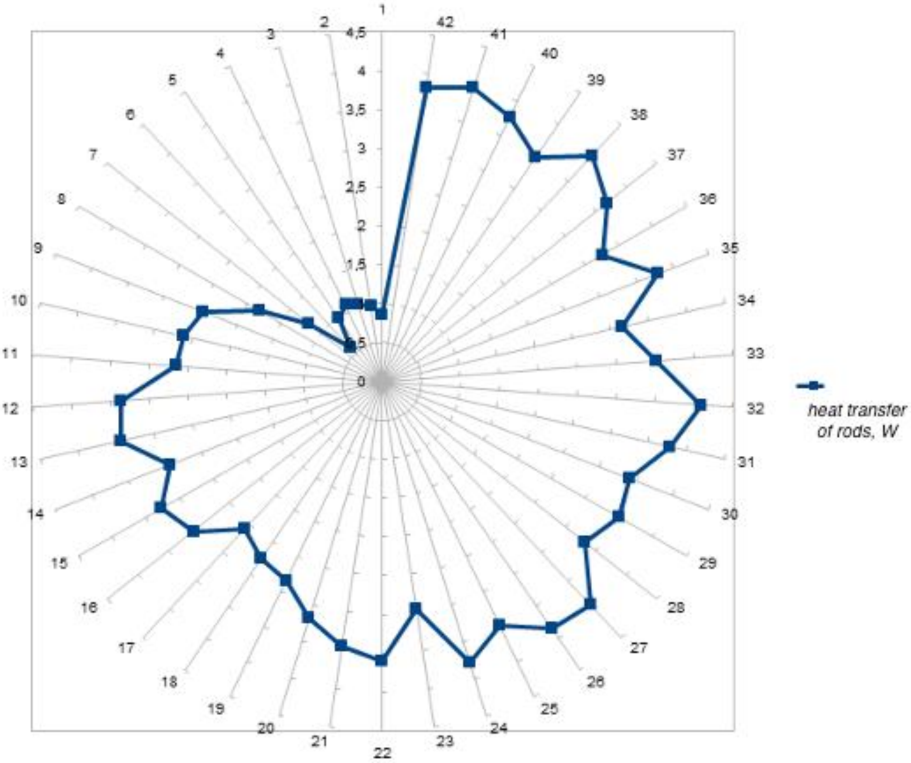

Fig. 5. Heat transfer of rods (KhNPP unit No. 2) (own study)

Rys. 5. Transfer ciepła przez pręty KhNPP nr 2

The experimental calculation analysis showed that the heat transfer at KhNPP Unit 2 satisfied the operational requirements (Fig. 5). Some rods had insufficient heat transfer at Unit 1 of the SUNPP (Fig. 6). It is necessary to check the condition of the rod conductors and clean them (channels 13, 23).

The suggested computational analysis enables the diagnostic assessment of turbine-generator stator rods, facilitating the identification of the required operations to enhance efficiency and safety during operation. Consistently implementing the proposed diagnostic evaluations, grounded in the calculated analysis of the stator winding rods of a turbogenerator, ensures the reliability of the equipment operation.

The proposed method for the technical diagnostics of turbogenerator rods based on the determination of heat transfer has several advantages over the existing methods (Králik 2017; Sun et al. 2022; Elbayoumi and Tahvonen 2022; Kim and Kim 1987). The technical diagnostic method for turbogenerator rods based on the determination of heat transfer is susceptible to even small changes in this parameter. Its advantages include the ability to identify localized problems, low equipment cost compared to other methods, the ability to perform diagnostics without stopping

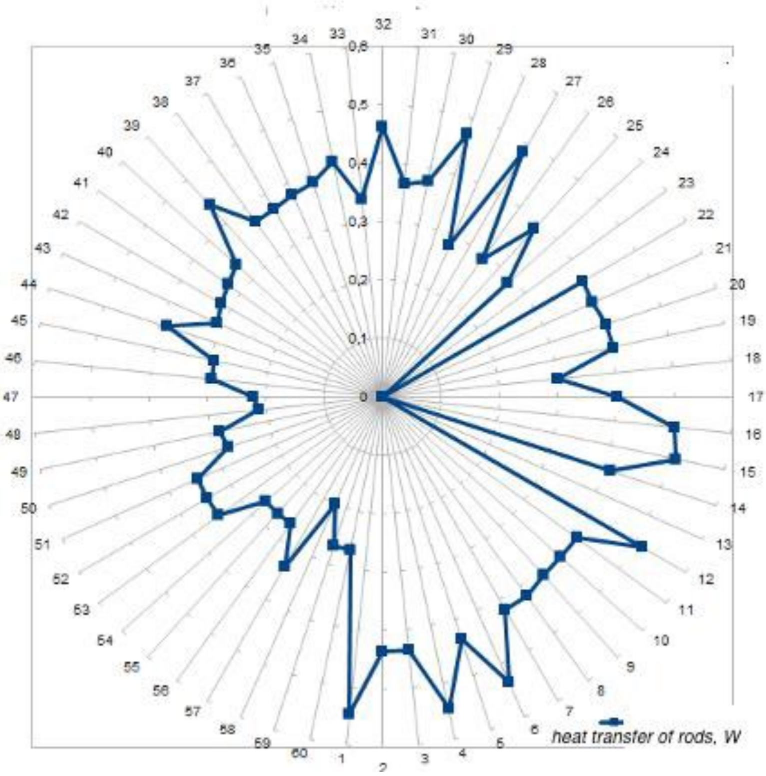

Fig. 6. Heat transfer of rods, W (Unit No.1 of SUNPP) (own study)

Rys. 6. Transfer ciepła przez pręty KhNPP nr 1

the turbine generator, the ability to periodically monitor, and high measurement accuracy (Sýkora et al. 2018; Todorov et al. 2023; Zhen et al. 2019; Kowalski et al. 2012; Kuzmynchuk et al. 2024; Gaska and Generowicz 2020). This method is an effective tool for the systematic monitoring and early detection of possible problems in turbine generator rods.

The proposed method of technical diagnostics of turbogenerator rods has a double impact: it ensures the safety of nuclear power plant equipment operation. It contributes to the improvement of operation energy efficiency. The implementation of comprehensive energy efficiency programs, including this approach to technical diagnostics, makes it possible to reduce the specific energy consumption in the economy by 3.8–6.4% by 2030, which will significantly reduce the burden on the economy, increase the energy independence of the state and the competitiveness of its GDP (according to the Energy Strategy of Ukraine until 2030).

Conclusions

This study analyses the types of risks affecting the operation safety of energy infrastructure and causes of failure of powerful turbine generators based on a computational analysis methodology to ensure the safety of their operation and the sustainability of energy processes. It is crucial to consider factors that impede heat transfer and may lead to emergencies at a power facility to maintain the durability of the energy infrastructure system and equipment. Based on the analysis, this study presents a methodology for calculating studies of heat transfer and quantitative results of calculated studies of heat transfer distribution in the elements of the stator winding core of the TVV-1000-2U3 turbogenerator for the South Ukrainian and Khmelnytsky NPP.

The results showed that the level of heat transfer from the rods significantly impacts the efficiency and safety of the power equipment, particularly turbine generators. A computational analysis of the heat transfer of turbogenerator rods can reveal various aspects that affect their operation and efficiency. Using the proposed mathematical models to determine the thermal processes in the turbogenerator rods allows the prediction of the temperature regime and the identification of effective ways to improve it. Timely technical diagnostics and calculated heat transfer analysis enable the effective management of energy security by coordinating the improvement of heat exchange systems, such as using new heat exchange elements or coolants, to ensure more efficient heat transfer.

The above analysis for two power units, namely Khmelnytska NPP (Unit 2) and South Ukrainian NPP (Unit 1), revealed that at Khmelnytska NPP, the heat transfer parameters were within the permissible limits for all cores. However, there is a low level of heat transfer in channels 1 and 5, 0.8 W and 0.5 W, respectively, which requires special attention and additional measures during scheduled maintenance.

For the South-Ukraine NPP Unit 2, the heat transfer parameter in rods No. 13 and No. 23 is 0 W, which requires immediate intervention to ensure the safety of further operation.

With the help of the proposed approach, it is possible to evaluate the temperature conditions, identify the possible risks of overheating, and determine measures to be taken in case of an emergency. The results of this analysis are useful for the ongoing enhancement of turbine generators, contributing to heightened efficiency and operational safety assurance. Planned and preventive maintenance are essential for identifying and resolving potential problems before they become serious. Regular inspections of critical components and systems help to ensure that the equipment operates efficiently and sustainably. Regular inspections of critical components and systems are necessary to ensure the continued sustainable operation of power equipment at optimum efficiency.

Further research will be aimed at developing a method for predicting the sustainable and efficient operation of power systems based on a preliminary assessment of their technical conditions, taking into account the proposed thermal and mechanical analyses. This will make it possible to make scientifically based predictive conclusions about the possibility of continuing the sustainable operation of NPP equipment.

Abbreviators:

NPP – Nuclear Power Plant
WWER or VVER – Water-Water-Energy Reactor
PWRs – Pressurized Water Reactors
SGTR – Steam Generator Tube Rupture
LOCAs – Loss of Coolant Accidents
GIQAAS – Energy Systems Analysis System
RT – Resistance Thermocouples
KhNPP – Khmelnitsky NPP
SUNPP – South Ukraine NPP
GDP – Gross Domestic Product

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Podejście do diagnostyki infrastruktury energetycznej w zarządzaniu systemami energetycznymi oparte na optymalizacji zapewnienia zrównoważonego rozwoju

Streszczenie

W zaprezentowanych wynikach badań przeanalizowano czynniki i zagrożenia wpływające na bezpieczeństwo eksploatacji infrastruktury energetycznej. Przeprowadzono schematy diagnostyki technicznej i ekonomicznej oraz zidentyfikowano przyczyny awarii urządzeń (turbiny generatora) w celu opracowania skutecznych podejść do zarządzania diagnostyką techniczną krytycznych urządzeń energetycznych oaz zapewnienia efektywności energetycznej i bezpieczeństwa procesów energetycznych. W artykule zaprezentowano metodykę analizy wymiany ciepła w rdzeniu uzwojenia stojana turbiny generatorów w elektrowniach jądrowych południowo-ukraińskiej i chmielnickiej, co pozwoliło nam uzyskać wgląd w rozkład temperatur i zaproponowanie sposobów optymalizacji procesów cieplnych. Proponowane podejście ułatwia ocenę reżimu temperaturowego, identyfikację ryzyka przegrzania i przygotowanie środków awaryjnych. Wyniki analizy Chmielnickiej Elektrowni Jądrowej (Blok 2) i Południowo-ukraińskiej Elektrowni Jądrowej (Blok 1) wykazały, że w Chmielnickiej Elektrowni Jądrowej parametry wymiany ciepła mieszczą się w dopuszczalnych granicach dla wszystkich prętów. W Południowo-ukraińskiej Elektrowni Jądrowej parametr wymiany ciepła w prętach 13 i 23 wynosi 0 W, co wymaga natychmiastowej interwencji w celu zapewnienia bezpieczeństwa dalszej eksploatacji. Zaproponowane podejście pozwala na szybką reakcję na awarie bloków energetycznych, zapewniając bezpieczeństwo i efektywne zarządzanie pracą urządzeń energetycznych oraz ciągłą stabilną pracę infrastruktury energetycznej z maksymalną wydajnością. Dalsze badania będą koncentrować się na opracowaniu metod diagnozy pracy systemu elektroenergetycznego w oparciu o wstępne oceny techniczne oraz analizę cieplną i mechaniczną, co pozwoli na podejmowanie opartych na wiedzy decyzji w zakresie stabilizowania pracy urządzeń elektrowni jądrowej.

Słowa kluczowe: zrównoważone bezpieczeństwo energetyczne, technologia energetyczna, infrastruktura energetyczna, systemy przesyłu ciepła, efektywność energetyczna