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Digital Twin as the Basis of the Automated Monitoring System for the Technological Process of a Power Unit at a Power Plant

Abstract:
The relevance of the research topic is determined by several important factors that are key to the modern energy sector: real-time monitoring of technological parameters of a power unit, which is critical for maintaining the reliable and uninterrupted operation of a power plant; ensuring energy security management to prevent accidents, failures, and unforeseen emergency situations for the power unit; reducing operational costs, which allows increasing the economic efficiency of power plant operations in the context of rising energy resource prices. The relevance of the research topic is defined by the need to implement digital technologies to improve the efficiency, safety, and economic viability of power unit operations at power plants. The digital twin is an integrated tool for automated monitoring and management of technological processes in a power unit, which can be integrated with various control systems, sensor data, information systems, and cyber-physical systems, creating a unified digital ecosystem for power unit management. This ensures a high level of automation, reducing human error and enhancing the efficiency of power unit operations. The object of the study is the processes of automated monitoring and management of technological processes in a power unit using a digital twin. It is shown that the digital twin of a power unit is a virtual model that reproduces the physical state and behavior of a real power unit in real-time. It combines mathematical models, control algorithms, data from sensors, and automated control systems to ensure an accurate reflection of all key energy production processes. The main functions of the digital twin are highlighted: real-time monitoring of technological parameters; optimization of technological equipment operation modes and energy consumption; diagnosis of deviations and forecasting of emergency situations; decision support at the level of automated process control systems and management systems; integration with cyber-physical systems to ensure the connection between technical and economic indicators.

Keywords: digital twin, power unit, technological process, principles and functions of the digital twin.

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Автоматизовані процеси моніторингу та управління технологічними процесами енергоблоку електростанції на основі цифрового двійника

Анотація:
Актуальність тематики дослідження обумовлена кількома важливими чинниками, які є ключовими для сучасного енергетичного сектору: проведення контролю технологічних параметрів енергоблоку в режимі реального часу, що критично важливо для підтримання надійної та безперебійної роботи електростанції; забезпечення управління енергетичною безпекою для попередження аварій, збоїв і непередбачуваних нештатних ситуацій для енергеоблоку; зниження експлуатаційних витрат, що дозволяє підвищити економічну ефективність роботи електростанцій в умовах постійного зростання цін на енергоресурси. Актуальність тематики дослідження визначається необхідністю впровадження цифрових технологій для підвищення ефективності, безпеки та економічності роботи енергоблоків електростанцій. Цифровий двійник є інтегрованим інструментом автоматизованого моніторингу та управління технологічними процесами енергоблоку електростанції, який може бути інтегрований із різними системами управління, даними від сенсорів, інформаційними системами та кіберфізичними системами, що дозволяє створювати єдину цифрову екосистему для управління енергоблоком. Це забезпечує високий рівень автоматизації, зменшуючи людську помилку та підвищуючи ефективність експлуатації енергоблоків електростанції. Об'єктом дослідження є процеси автоматизованого моніторингу та управління технологічними процесами енергоблоку електростанції з використанням цифрового двійника. Показано, що цифровий двійник енергоблоку — це віртуальна модель, яка відтворює фізичний стан та поведінку реального енергоблоку електростанції у режимі реального часу. Він поєднує математичні моделі, алгоритми керування, дані від сенсорів та систем автоматизованого управління, щоб забезпечити точне відображення усіх ключових процесів виробництва енергії. Виділено основні функції цифрового двійника: моніторинг технологічних параметрів у режимі реального часу; оптимізація режимів роботи технологічного обладнання та енергоспоживання; діагностика відхилень і прогнозування аварійних ситуацій; підтримка прийняття рішень на рівні автоматизованої системи управління технологічним процесом та управлінських систем; інтеграція з кіберфізичними системами для забезпечення зв'язку технічних і економічних показників.

Ключові слова: цифровий двійник, енергоблок, технологічний процес, принципи та функції цифрового двійника.

Introduction

Modern nuclear and thermal power plants operate under complex conditions that require a high level of control and management of technological processes. Traditional methods of monitoring, control, and diagnostics of power units, based on manual data collection and processing, do not always allow for the timely detection of deviations, prediction of emergency situations, and optimisation of equipment operating modes. The increasing load on energy systems, high demands for efficiency and operational safety, as well as the need for integration with the economic and production indicators of power enterprises, create an acute problem of ensuring comprehensive, automated, and predictive monitoring of power plant units.

The study problem lies in developing an integrated approach that enables real-time tracking of technological processes within a power unit, identification of potential risks, and maintenance of optimal operating conditions of the equipment without overloading operators or being limited by traditional automated process control systems. The main challenge consists in combining large volumes of sensor data, historical records, and control algorithms into a single digital model capable not only of representing the current state but also of forecasting the development of technological processes. The proposed solution is based on the concept of a digital twin of a power plant unit.

The object of the study is the processes of automated monitoring and control of technological processes in a power plant unit using a digital twin.

The study aims to develop a concept and methodology for employing a digital twin as the foundation of a system for automated monitoring, control, and diagnostics of a power unit's technological process. This system should ensure a highly accurate representation of the physical state of equipment, predict emergency situations, and optimise operating regimes.

To achieve this purpose, the following study objectives have been defined:

- analysis of the current state of the digital twin concept in relation to technological processes of energy enterprises;
- development of a structure for the digital twin of a power unit, including physical process models, mathematical control models, informational and analytical blocks, as well as an integration layer for interaction with digital systems;
- determination of the functional capabilities of the digital twin of a power plant unit;
- utilisation of the digital twin for an interactive simulator designed for operational personnel training.

The implementation of these tasks ensures a comprehensive approach to improving the reliability, safety, and economic efficiency of power unit operation, forming the basis for the further development of predictive analytics and intelligent control systems in energy enterprises.

Literature Review

Today, both domestic and international scientific publications feature studies addressing the practical use of digital twins to improve existing automated control systems for technological processes at energy enterprises. In the study of I.A. Polishchuk and D.V. Stolbov (*2024*), the feasibility of applying digital twins in combination with machine learning algorithms to enhance the efficiency of biofuel combustion processes in boiler installations was demonstrated experimentally and analytically. The use of digital simulation enables flexible optimisation of combustion parameters in real time, contributing to resource savings and emission reductions. The practical value of the study lies in demonstrating the potential for adaptive control; however, the results are tied to a specific technical base, and the limited data sample constrains their representativeness.

T. Dombrovska (*2023*) conducted an in-depth review of the economic aspects of digitalisation in renewable energy. The research traces the relationship between innovative technologies and the economic efficiency of the sector, highlighting the need for new business models. The strength of this work lies in the systematic presentation, yet the absence of concrete economic calculations and quantitative examples reduces its practical relevance.

In the scientific paper of Ye. Merzhynskyi et al. (*2025*), global trends in the digitalisation of the energy sector are analysed in detail. Special emphasis is placed on the scalability of solutions based on big data, cloud computing, and artificial intelligence systems. The study is significant for understanding the prospects for transnational integration of digital solutions in energy.

However, the material is descriptive and does not sufficiently address regulatory and personnel barriers, which significantly constrain the practical implementation of the proposed approaches. The authors of study (*Orobchuk et al., 2025*) conducted a comparative analysis of modern digital twin platforms, identifying their advantages and disadvantages in terms of scalability, compatibility, and standardisation. The practical significance of the study lies in the development of criteria for assessing software solutions, which may be useful for developers and enterprises. Nevertheless, rapid progress in digital technology leads to the swift obsolescence of the obtained results.

The study of N. Nazarenko et al. (*2024*) presents a methodology for using digital substations in the educational process through real-time simulators. The importance of the research is defined by the implementation of practice-oriented technologies in the training of future engineers. The positive aspect lies in demonstrating the integration of digital technologies into the learning process; however, the issues of scalability and financial accessibility of the equipment remain unresolved. The work of T. Holotsukova and P. Lamonov (*2024*) illustrates practical aspects of implementing digital twins, supported by examples of real engineering solutions. A substantial advantage is the focus on applied recommendations for production and management. At the same time, the authors did not sufficiently address issues of cybersecurity, data flow management, and network resilience, which are crucial in large-scale systems.

The study of O. Klimenko (*2025*) explores the role of digital platforms in ensuring sustainable development, particularly in the formation of local energy markets. The authors adopted an interdisciplinary approach, combining technical and socio-economic analyses. However, there are almost no examples of full-scale implementation of these technologies in industrial practice, which limits the study's practical value. The paper of V.R. Shchehlov and O.I. Morozova (*2022*) examines the challenges and opportunities of integrating digital enterprises and digital twins. An important contribution is the identification of barriers—technological, organisational, and financial—that hinder implementation. Yet the proposed solutions are largely theoretical and require validation through practical case studies. The publication of O. Shapurov (*2023b*) systematises methods for creating digital twins for fault-tolerant systems. The author presented a classification of approaches and developed a basic framework for analysis. Clear systematisation is a major achievement of the study, but the optimisation aspects for resource-constrained devices are only superficially described, which complicates practical application. Yu. Storoshchuk et al. (*2025*) summarise the use of digital twins in industry and logistics. A significant advantage is the analysis of existing standards, forming a foundation for technological unification. However, the recommendations are general in nature and do not consider sectoral specifics, which limits their applied value.

The study of O. Shapurov (*2023a*) analyses the application of Industry 4.0 technologies in change management at energy enterprises. The authors emphasise the practical orientation of the proposed approaches. However, the research lacks long-term data to assess the sustainability of organisational transformations. The publication of S. Myskovets et al. (*2025*) confirms the findings of previous studies, particularly Yu. Storoshchuk et al. (*2025*), reiterating the importance of standards in industry. The novelty of the research is minimal, reducing its scientific significance. The paper of K.M. Alam and A. El Saddik (*2017*) presents an example of developing digital twins of production stations and testing the logic of programmable logic controllers. Its value lies in demonstrating the practical implementation of digital models in an educational environment. However, the results are difficult to generalise to other hardware–software complexes.

P.P. Loboda and I.S. Starovit (*2023*) once again analysed digital twin platforms, similarly to B. Orobchuk et al. (*2025*), but refined the evaluation criteria. This enhances the scientific precision of the study, yet the rapid pace of technological development necessitates constant data updates. The publication of K. Semenchuk (*2024*) proposes a digital twin model for managing the processes of the new safe confinement at the Chernobyl Nuclear Power Plant. This is an important example of applying digital solutions to critical infrastructure facilities. However, a lack of full validation under real operational conditions limits the reliability of the conclusions. The study of N.I. Lapychak (*2024*) describes the use of digital twins in logistics for supply chain management. The practical significance is confirmed by the development of a specific model, though the absence of quantitative efficiency indicators reduces the objectivity of the evaluation. The authors of paper (*Ostrovska et al., 2024*) analyse the impact of digitalisation on product standardisation and certification, exploring the potential use of blockchain and artificial intelligence. A notable achievement is the emphasis on transparency and harmonisation of processes. Yet the regulatory aspects are presented superficially, without an in-depth analysis of specific cases.

The study of D.S. Minchev et al. (*2025*) demonstrates the creation of digital twins based on cloud platforms. The scientific novelty is manifested in the practical demonstration of a prototype, relevant for industrial applications. However, there is no thorough assessment of economic efficiency and security risks. The study of I.A. Polishchuk et al. (*2024*) improves the diesel fuel combustion model for a digital twin of a marine engine. The authors show the applicability of digital technologies to high-load objects, though the lack of long-term testing under real operating conditions limits the practical value of the results.

The article of A. Semenyshen et al. (*2024*) focuses on microclimate modelling in buildings using digital twins and machine learning. The application of modern technologies is a strength of the work, yet the efficiency of the results requires confirmation through real experiments. In the study of I. Yepifanova (*2025*), the development of a digital twin of a robotic manipulator is justified to optimise trajectories and reduce energy consumption. An important contribution is the mathematical foundation of the design, although the results are not verified at the hardware level, limiting the applicability of the model.

Thus, an analysis of scientific publications shows that digital twins are increasingly applied in energy, industry, transport, construction, and logistics. The main advantages include improving the efficiency of technological processes, optimising resources, predicting emergency situations, and using digital twins for personnel training. At the same time, several limitations have been identified: most studies are applied in nature but restricted to narrow cases or specific equipment; insufficient attention is paid to cybersecurity, standardisation, and regulatory integration; and there is a lack of large-scale empirical validation and quantitative assessment of economic effects. This highlights the need for further development of universal methodologies for building digital twins, their integration with information and control systems, and the confirmation of their effectiveness through extensive practical implementation.

Results

Development of the Structure of a Digital Twin of a Power Plant Unit

A digital twin of a power plant unit is a virtual model that reproduces the physical state and behaviour of the real power unit in real time. It integrates mathematical models, control algorithms, and data from the unit's sensors to provide an accurate representation of all key energy-production processes. Moreover, the digital twin of the power unit is a cyber-physical system that connects the real object (the power plant unit) with its mathematical model and the information environment of the plant's technological process. This integration enables continuous monitoring, analysis, and optimisation of the unit's operation, thereby improving reliability and economic efficiency.

The digital twin of the power plant unit is designed for:

- real-time monitoring (process parameter control with visualisation);
- diagnostics and forecasting (detection of deviations from the normal mode, prediction of emergency situations);
- control optimisation (selection of optimal operating modes to minimise emissions and fuel consumption);
- staff training (use of the digital twin as a simulator for operators);
- virtual experimentation (testing new control algorithms without risk to the equipment).

Main components of the digital twin of the power plant unit (*Figure 1*):

1. Physical and mathematical models:

- dynamic model of the turbine rotor (reflects mechanical vibrations, moment of inertia, and rotational stability);
- thermal model (energy balances in the boiler, steam pipelines, and condenser);
- hydraulic model (movement of the heat carrier, pressure losses, phase transitions);
- electrical model of the generator—electricity production.

2. Control models of the power unit:

- include regulators and optimisation algorithms;
- ensure maintenance of temperature, pressure, steam level, and turbine load;
- use data from sensors and adjust the operation of actuators (valves, pumps, fuel regulators).

3. Data acquisition and sensor system:

- temperature and pressure sensors, flow meters, vibration control systems, etc.;
- data are read through the power unit's automation systems in real time.

4. Information models:

- automated control system of the power unit's technological process;
- integration into the information environment;
- data are transmitted to a digital platform for modelling and forecasting;
- digital technologies are applied to detect dynamics in the variation of technological parameters and possible deviations.

Thus, as a result of the implementation of a digital twin of the power plant unit, a powerful tool is created for enhancing operational management, promptly detecting deviations in the performance of technological equipment, and predicting potential emergencies. This makes it possible to reduce economic losses from unscheduled shutdowns, minimise accident risks, and maintain high operational efficiency of the power unit under variable loads.

Functional Capabilities of the Digital Twin of a Power Plant Unit

An analysis of the functional capabilities of the digital twin of a power plant unit has been conducted (*Table 1*). The digital twin provides multi-level monitoring, control, and diagnostics of key operational parameters of the power unit in real time.

The use of a digital twin enables the collection of current data and its intelligent analysis. Comparison of actual values of temperature, pressure, steam and water flow rates, vibration levels, and electrical characteristics with the calculated values of reference models allows for timely detection of hidden deviations and diagnosis of faults. An important feature of the system is its ability to identify even minimal deviations that do not yet have a critical impact on operation but may potentially lead to serious failures in the future.

Equipment Condition Forecasting Function. Based on historical data accumulated in the knowledge base, the digital twin analyses material degradation processes, the dynamics of component wear, and patterns of failure. Using machine learning and predictive analytics methods, the digital twin generates forecasts of the remaining service life of turbine, boiler, condenser, and pipeline components, among others. This enables maintenance to be carried out not on a calendar basis, but according to the actual technical condition, which significantly reduces repair costs and increases the overall reliability of the power unit's operation.

Operating Modes Optimisation Function. The digital twin provides the ability to create and analyse alternative operating scenarios for the power unit. In particular, it enables the simulation of operations under various loads, during partial shutdowns, or when fuel quality or environmental conditions change. This makes it possible to determine the most economically feasible operating modes that minimise fuel consumption, reduce harmful emissions, and simultaneously ensure the safe operation of equipment. Optimisation of modes also enhances the flexibility of the power unit to operate under variable energy market conditions.

Personnel Training Function. The digital twin can serve as an interactive training platform for operational and technical personnel. The creation of digital simulators based on it allows the imitation of working processes, emergency, and pre-emergency situations without risk to real technological equipment. This significantly improves personnel training quality, allows the development and testing of emergency response algorithms, and promotes the acquisition of practical skills in a safe environment.

Safety Enhancement Function. One of the key functions of the digital twin is the modelling and analysis of emergency and pre-emergency scenarios. The system allows the assessment of potential consequences of deviations in the operation of technological equipment, identification of critical points, and verification of the effectiveness of emergency response plans.

Thus, the digital twin makes it possible to test new technologies and control methods without risk to real infrastructure. This creates an additional level of safety, reduces the likelihood of human error, and contributes to the formation of a culture of preventive safety. Altogether, these functional capabilities transform the digital twin of the power plant unit into a universal management tool that integrates monitoring, forecasting, optimisation, training, and safety within a single system.

Use of a Digital Twin for an Interactive Simulator for Operational Personnel

Based on the functions considered, the use of a digital twin for an interactive simulator for operational personnel is proposed, designed for work at an automated workstation of a nuclear power plant unit operator (*Figure 2*).

The interface of the interactive simulator for operational personnel of a nuclear power plant with a nuclear reactor has been examined. It represents a complex simulation model of a digital twin that imitates the operating modes of the power unit (*Figure 3*). The digital simulator has been developed for comprehensive training of power plant operators in managing the power unit under various operating conditions—from normal operation to complex emergency situations. The simulator interface is implemented as a professional control panel with real physical parameters, bringing the training conditions as close as possible to the real operation of a power plant.

On the left side of the interface is an extended parameter panel that displays the key technological indicators of the power unit in real time. The monitoring system includes reactor power at 1000 MW, pressure in the primary circuit at 160.5 bar, coolant temperature at 320.2°C, and water level in the steam generator at 85%. Each parameter is accompanied by detailed ranges of normal values and features a three-level colour-coded status indication system: green indicates a normal system state, yellow denotes a pre-emergency condition with parameter deviations, and red signifies an emergency state requiring immediate intervention.

On the right side of the interface, there is an extended monitoring system including four dynamic graphs. These graphs display the values of the main parameters for the last 30 seconds, allowing the operator to analyse the dynamics of changes in technological indicators. The control panel contains specialised operator action buttons grouped by functional purpose. The equipment status display system includes nine main components of the power unit: the nuclear reactor, turbine, generator, cooling system, PG–1000 steam generator, transformer, condenser, main circulation pump, and sprinkler system. The event log maintains a detailed record of all operator actions and emergency situations with second-by-second accuracy.

The simulator includes an extended system of training scenarios covering all aspects of power plant operation. Among them are the basic normal operation scenario, specialised scenarios for turbine failure, rapid pressure drop, cooling system failure, power grid instability, as well as complex combined scenarios of integrated accidents and emergency reactor shutdowns. Each scenario is accompanied by a detailed technical description and operator action recommendations.

For the instructor, advanced control functions of the training process are provided. The instructor can activate 8 types of malfunctions, including turbine vibration, pressure drop, coolant overheating, cooling failure, fuel assembly problems, grid instability, reactivity anomalies, and radiation increase. The system allows sending personalised messages to the operator, selecting from pre-configured training scenarios, monitoring operator performance in real time, and conducting error analysis.

The operator has access to a wide range of control functions. They can regulate key technological parameters, perform emergency procedures of varying complexity, stabilise the system using manual and automatic modes, activate backup systems, and conduct equipment diagnostics. The system provides for both standard operational procedures and emergency response actions.

The technical features of the simulator include realistic real-time simulation with data updates every second. The physical model of parameter behaviour takes into account real technological processes of a nuclear reactor. The operator performance assessment system calculates stability and efficiency indicators based on the analysis of parameter deviations. Automatic alerts about critical conditions are generated based on a comprehensive analysis of technological indicators. Interactive graphs provide scaling functions and detailed analysis of dynamic changes.

The modelling is highly realistic and considers complex interrelations between parameters. For instance, a pressure drop in the primary circuit automatically leads to a decrease in reactor power, while a cooling system failure causes a progressive increase in coolant temperature. The model accounts for the impact of malfunctions on adjacent systems, the response time of technological equipment to control inputs, and the physical limitations of technological parameters.

Thus, this simulator is a fully functional digital twin of a power unit, enabling realistic training without any risk to actual equipment. It fully complies with the modern concept of digital twins in the energy sector, ensuring not only the reproduction of technological processes but also the practice of rare and emergency situations. This represents an essential component of the preparation of highly qualified operational personnel for the nuclear energy industry. The system allows the development of practical response skills to abnormal situations, enhances operational thinking, and provides a deep understanding of the technological processes of a nuclear power unit.

Discussion

The research problem concerns the development and implementation of a digital twin as an integrated system for automated monitoring, control, and diagnostics of power unit technological processes, which includes the synthesis of physical, mathematical, and informational models using machine learning algorithms to predict complex technical processes. The digital twin must ensure high real-time accuracy by integrating diverse processes while simultaneously optimising the operational modes of the power unit. This requires further research into methods of integrating these models into a unified automated system capable of effectively responding to changes in both external and internal parameters.

The study problem lies in how to integrate physical models of power unit technological processes, mathematical control algorithms, and machine learning algorithms into a unified digital twin system capable of predicting possible emergency situations, optimising operating modes, and ensuring real-time monitoring of technological parameters without overloading operators.

To address this research problem, it is necessary to:

1. Develop and improve physical models for simulating the dynamics of power unit processes (turbine rotor dynamics, thermal and hydraulic balance, phase transitions, etc.) with high precision.
2. Create mathematical control models that include optimal control and regulation algorithms to ensure the stable operation of the power unit under variable operating loads.
3. Integrate machine learning algorithms to create predictive models capable of accurately forecasting failures and emergency situations based on real-time data.
4. Develop mechanisms for integrating sensor systems and automated systems into a unified platform for a closed "model–reality" loop.

Future research and development directions for this technology should include:

- applying approaches to integrating physical, mathematical, and informational models that are most effective in ensuring high accuracy and responsiveness of prediction in the power unit's digital twin;
- integrating physical models of thermal and hydraulic processes with machine learning algorithms;
- identifying optimal methods for synchronising sensor data with mathematical models in real time;
- maintaining a balance between modelling accuracy and system efficiency without overloading computational resources;
- employing methods to reduce computational costs when simulating complex physical processes;
- adapting models for real-time operation under high loads and changing conditions.

Thus, these issues contribute to a deeper understanding of the technological and scientific challenges associated with the development and implementation of digital twins in the energy sector and will help to identify directions for further research and advancement of this technology.

Conclusion

The results of implementing a digital twin of a power plant unit have been examined, which include:

1. Improved Fuel Efficiency and Reduced Energy Losses

   The digital twin enables comprehensive modelling of fuel and energy processes. As a result, operational personnel can optimise fuel consumption, ensuring maximum calorific efficiency with minimal emissions. In addition, energy losses during transmission and conversion are reduced by identifying "bottlenecks" in equipment performance. The use of predictive models facilitates timely adjustment of operating modes, which allows for the reduction of specific fuel consumption per unit of electricity generated.
2. Extended Intervals between Overhauls through Wear Prediction

   The application of predictive analytics algorithms makes it possible to determine the residual life of key components and mechanisms of the power unit. This means that instead of scheduled maintenance based on a calendar approach, condition-based maintenance can be implemented. As a result, the enterprise can significantly extend maintenance intervals, reduce the number of unplanned shutdowns, and optimise spare parts costs. Wear forecasting helps schedule repairs for the most convenient periods, thereby reducing economic losses caused by downtime.

3. Reduced Risk of Emergency Situations
   The digital twin allows for the timely detection of potentially hazardous deviations and the prediction of pre-emergency conditions. Integration with online monitoring systems enables rapid response to critical changes in equipment operation. Furthermore, simulation of emergency scenarios helps test the effectiveness of existing safety protocols and prepare personnel for emergency situations. This reduces the likelihood of accidents and minimises their consequences if they occur.
4. Economic Justification of Investment in Modernisation
   The digital twin provides a unique opportunity to assess the effectiveness of new technologies or modernisation projects before their implementation in the physical environment (for example, testing various options for boiler equipment reconstruction, automation system upgrades, or the introduction of new materials). This makes it possible to minimise investment risks, justify expenditures, and select optimal techno-economic solutions. In a competitive market environment, such an advantage becomes a key factor in strategic development.
5. Formation of the Enterprise's Information Potential as a Resource for Strategic Management.
   The use of a digital twin contributes to the accumulation and structuring of large volumes of data concerning the operation of the power plant unit. This data array becomes the enterprise's information potential, which can be utilised for strategic planning, management decision-making, economic efficiency assessment, and forecasting of future needs. Such an approach enables the enterprise to maintain digital coherence and act proactively rather than reactively.

Thus, the digital twin of a power plant unit represents an engineering model of energy production processes and a strategic instrument that establishes a new level of enterprise management. Its implementation simultaneously enhances technical reliability, ensures energy security, reduces costs, and substantiates long-term investment decisions. Through the digital twin, power enterprises transition from the traditional "problem-reaction" approach to a predictive management system that aligns with contemporary demands for digitalisation, environmental responsibility, and sustainable energy development. The digital twin serves as a crucial tool integrating advanced technologies into energy processes. Both its scientific and practical applications open new digital resources for the energy sector, improving reliability, safety, and economic efficiency of power unit operation. Future prospects include further efficiency gains, cost reductions, and the creation of adaptive and intelligent management systems for optimising power enterprise performance.

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Appendix

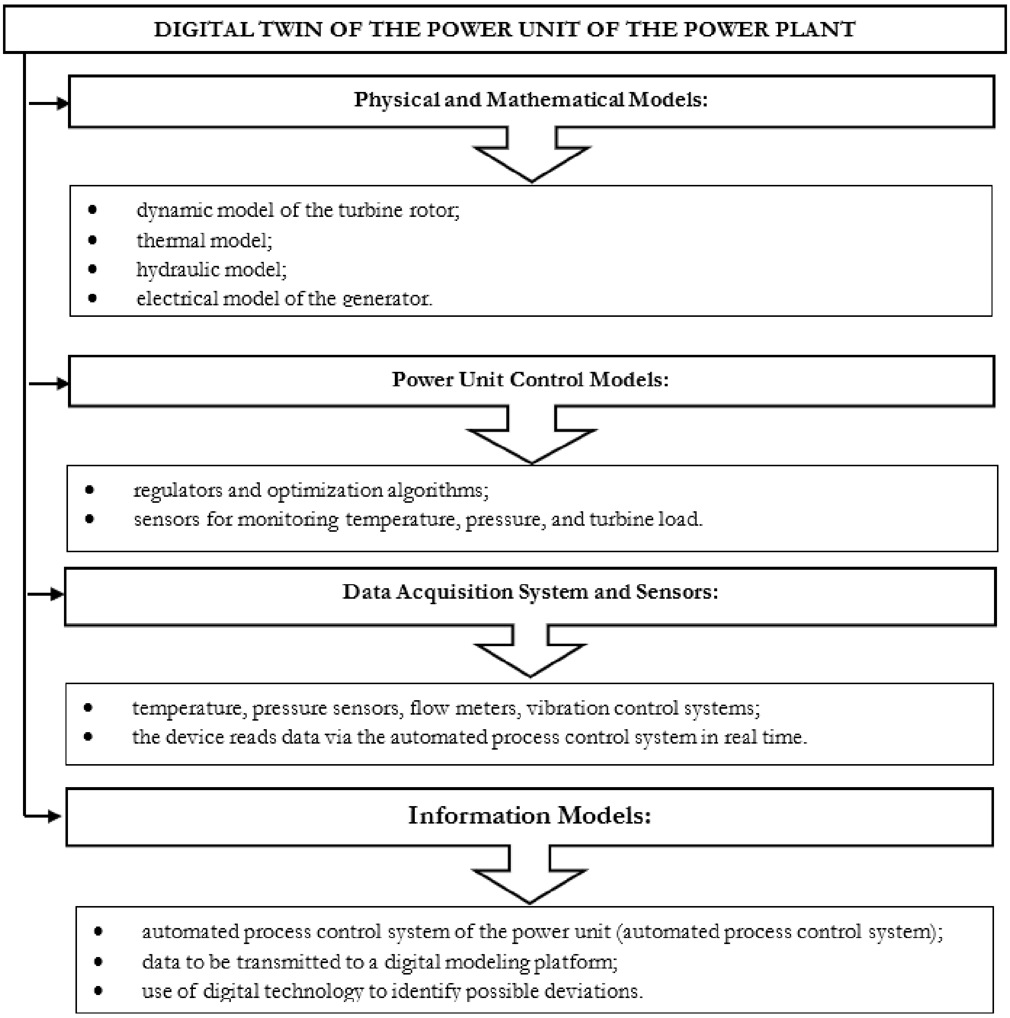

Figure 1. block diagram of the Digital Twin architecture of a power plant unit

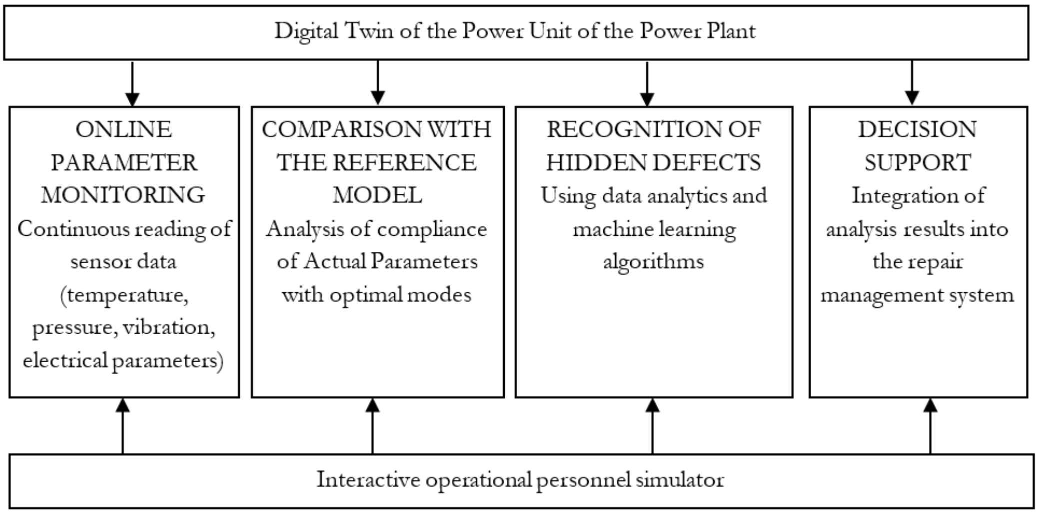

Figure 2. Scheme of Information connection between the functions of a Digital Twin and the functions of an interactive operational personnel simulator

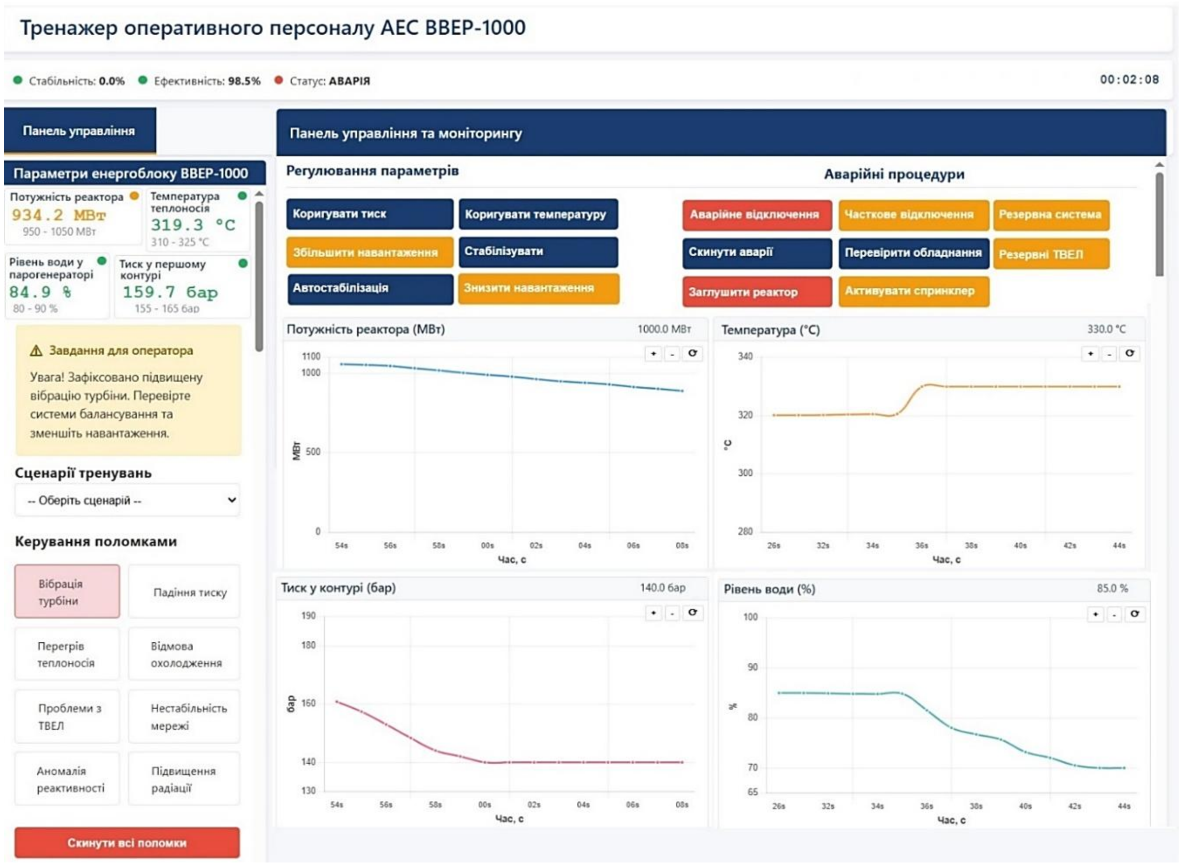

Figure 3. Digital Twin interface (simulator) for operator training (In Ukr.)

Table 1. Functionality of the Digital Twin of the power unit of the power plant

No.	Functional Feature	Implementations	Expected Effect
1	Monitoring and diagnostics	• continuous monitoring of boiler temperature and pressure; • comparison of the vibration characteristics of the rotor with the reference model; • automatic notification of exceeding critical parameters.	• reducing hardware downtime; • timely detection of malfunctions; • improving the reliability of work.
2	Predicting the state of equipment	• analysis of the operation history of pumps and pipelines; • using machine learning algorithms to determine the remaining turbine life; • making forecasts regarding the timing of node replacement.	• switching to maintenance based on the actual state; • optimisation of repair costs; • increasing the equipment readiness coefficient.
3	Optimisation of operating modes	• modelling the operation of a power unit under various loads; • determination of optimal fuel consumption for a given mode; • scenario analysis of emergency and repair stops.	• reduce fuel consumption; • improving economic efficiency; • flexibility of work in the context of changes in the energy market.
4	Staff training	• creation of digital simulators for automated workplace operators of automated process control systems; • simulation of emergency situations in a virtual environment; • modelling of normal and non-standard operating modes.	• professional development of personnel; • reducing the risk of human error; • faster response to emergency situations.
5	Improving security	• modelling of pre-Emergency States and consequences; • checking the effectiveness of emergency response plans; • testing of new management methods without risk to the equipment.	• reducing the likelihood of accidents; • reducing environmental and economic risks; • formation of a culture of preventive safety.